Fault Detection Strategy for Distribution Feeders with OH and UG Main Line Sections

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Abstract

An unplanned customer outage is generally caused by a transient or sustained fault on the utility system, resulting in an overcurrent condition that is cleared by an interrupting device. While maintenance activities are used to reduce the overall feeder fault rate, investments in sectionalizing and automation systems, such as the design of isolation systems to better sectionalize the system after a fault, have major reliability improvement potential for any given fault rate. In many locations the utility company is converting overhead (OH) main line feeder sections to underground (UG) to improve reliability, system resiliency, or to meet other local customer demands. A hybrid distribution feeder is one with a mixture of OH and UG main line sections. Conventional protection philosophies, when applied to hybrid feeders, result in lower overall feeder reliability. This paper will examine an example feeder to demonstrate the impact of protection and isolation system improvements on predicted reliability for hybrid distribution feeders.

Index Terms – FLISR, SAIFI, SAIDI, MAIFIe, Distribution Feeder Reliability Improvement

I. Introduction

Distribution system overcurrent devices have been applied by electric company distribution engineers to detect and clear system faults to minimize the probability of damage to equipment due to sustained faults. Inspection and maintenance of lines is performed to minimize the number of faults that are experienced on the feeder. Despite these efforts, the exposure to weather, animals, vegetation, vehicles, and other hazards results in the expectation that some number of system faults will still be experienced. To mitigate the extent of outages, equipment is placed on the feeder to identify fault conditions and quickly isolate faulted sections of the distribution feeder.

Many electric utilities focus reliability improvement initiatives around maintenance activities, such as tree trimming, aimed at reducing the number of fault events. These activities should result in a lower fault rate for the feeder section as measured by faults per mile per year. It can be shown that investments in sectionalizing and automation systems, such as the design of overcurrent protection systems to better sectionalize the system after a fault, also have major reliability improvement potential for any given fault rate. If fault records indicate that many events were tree-related, then increased vegetation management expense may be justified. However, in many utility situations where fault records exist, "unknown" may be the largest category of fault causes listed.

In areas where high fault rates have been experienced, or areas where customer demands for various reasons warrant the investment, utilities are converting sections of the distribution feeder from overhead (OH) line construction to underground (UG) feeder construction. The reduced exposure to weather, animals, and other physical hazards normally results in a lower fault incidence rate for UG construction. Because cost is higher for UG construction, the application along the feeder may only be in limited areas, resulting in a mix of OH and UG main line feeder miles. This presents challenges to conventional overcurrent protection philosophies that can result in lower overall feeder reliability. This paper will examine the application using an example feeder and demonstrate that new protection equipment technology can achieve the intended reliability improvement.

II. Feeder Overcurrent Protection Strategies

Distribution system overcurrent conditions are detected and interrupted when needed using a variety of devices that include fuses, reclosing devices (single phase or three-phase), and circuit breakers in substations. The devices are designed to operate in a coordinated fashion to isolate the smallest part of the system possible for each fault event. Coordination studies are completed by system protection engineers for specific feeders with knowledge of system short circuit currents at points on the feeder. Protection philosophies are followed according to individual company developed standards, but the overall final design includes engineering judgements on the part of the distribution protection engineer. The application of the protection system also impacts the sectionalizing of the feeder that results in accumulated outage numbers used in calculating reliability indices for the feeder and overall system.

Electric distribution companies utilize strategies to recover from the fault events experienced on the distribution feeders, since faults may be transient or sustained. A transient fault is one where de-energizing the faulted line section allows the insulation to recover. If a transient fault is interrupted quickly, the circuit can be automatically reclosed after a few seconds to restore service with no service crew intervention required. A sustained fault cannot be re-energized without a service crew performing some equipment or line repair or replacement. The mix of transient and sustained faults on the feeder impacts the selection of overcurrent protection system philosophy regarding equipment interaction as a system.

When applying interrupting devices that can be reclosed along the main line and fuses at lateral connections to the main line, a choice is made between two overcurrent protection methodologies called "fuse saving" and "fuse sacrifice." Fuse saving utilizes a fast-trip-and-reclose scheme to clear transient faults on the laterals before the fuse has operated. This causes a momentary outage to all customers located downstream of the reclosing device but overall reduces sustained outages. This scheme is often used in rural areas or when repair time is longer due to the time for crews to get to the fuse location. A fuse-sacrifice philosophy can reduce momentary outages by eliminating fast tripping on relayed circuit breakers and downstream overcurrent devices. The elimination of fuse saving may reduce momentary operations, but it increases the overall sustained outage minutes because transient faults on fused laterals will result in a fuse operation and sustained outage. This scheme is often used in urban areas where crews can quickly arrive to the scene and make repairs and/or replace the fuse link.

The general approach used to design higher reliability distribution service on radial feeders includes the following initiatives:

1. Use automatic reclosing to eliminate outages caused by transient faults on OH sections. General industry practice avoids reclosing on UG systems because cable faults are normally of the sustained type. Therefore, hybrid main line distribution feeders present a protection challenge with the mix of UG and OH construction. State-of-the-art devices are now using a new technology to avoid reclosing into sustained faults and further stressing system components.
2. Use automatic reclosing on lateral circuits to eliminate momentary operations of main line devices for faults on the lateral circuits. UG and hybrid circuits essentially preclude the fuse-saving philosophy. The steps taken on this example feeder will show the benefits of re-introducing reclosing and fuse-saving at the lateral level.
3. Sectionalize the system to limit the number of customers affected by a sustained fault and reduce the time necessary to locate a fault. Smart switches can accomplish this, but fault interrupting devices can further limit the affected area.
4. Reduce device hazard rates. This can be driven by a root cause analysis to determine maintenance levels required to drive feeder fault rate to target levels.

The subsequent sections examine a typical radial utility distribution feeder with the objective being improvement of reliability indices through selection and application of appropriate fault-interrupting equipment. Calculations are performed for each equipment addition to demonstrate the improvement that each step provides in the reliability indices.

III. Example Feeder Examination for Reliability Improvement

Figure 1 shows a simplified one-line diagram of a distribution feeder served by a substation bus located at the left side of the figure. The main line is approximately 5.9 miles in length and it is essentially a radial service to customers that are served on laterals at the end of the feeder. There is a short section of main line underground (270 feet of UG construction shown in red). The remainder of the main line is OH distribution line. Total circuit miles for all 3-phase, 2-phase, and 1-phase lines are 20.18 miles of OH and 1.81 miles of UG construction.

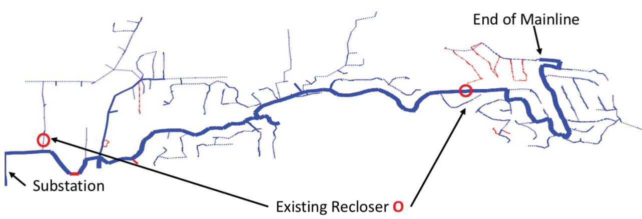

Fig. 1. One-line diagram of a distribution feeder used for analysis.

The feeder being analyzed is a problem 12.47 kV feeder that is primarily OH construction with a customer count of approximately 1300 and poor reliability. Outage data were broken into a variety of categories with the largest numbers being due to lightning and vegetation. The feeder is mostly radial, as shown in Figure 1, with many laterals connected to the main line. Total feeder load is approximately 9000 kW.

The base case reliability calculations used fuse saving on the main line and branch reclosers. Fuse saving was disabled on the substation circuit breaker to help reduce momentary interruptions to customers on the feeder. Most laterals are fused at the connection to the main line, and there are several long laterals that have additional fuses downline in series. The following are the base case reliability indices for the feeder:

SAIFI: 11.97 Sustained Outages / Customer-year
SAIDI: 20.44 Outage Hours / Customer-year
MAIFIe: 22.83 Momentary Outages / Customer-year

IV. Circuit Changes Implemented to Improve Reliability

Next, improvements to the feeder construction and the protection system design will be applied and the resulting changes in the reliability indices calculated. The following sections summarize the changes to the circuit.

A. Convert selected sections of the main line from OH to UG and add selected lateral circuit devices

The existing sections of the main line are predominantly overhead construction. There are many utility companies that are converting sections of OH to UG, either to meet local demands for aesthetic improvements or to improve the overall feeder reliability. In this feeder example, three sections of the main line have been converted to UG cable. They are shown in Figure 2 as sections shown in red. The end-of-line UG section is 5500 ft, the midline UG section is 2600 ft., and the section near the substation is 2200 ft. The underground part of the main line is 38% of the feeder.

A protection system upgrade to this feeder shown in Figure 2 includes the replacement of fuses at 5 feeder lateral locations using a cutout-mounted reclosing device. This type of device can sense overcurrent conditions and trip and reclose to clear transient faults. It can also be configured to provide the fuse-saving strategy for sections of the lateral that have fusing to sectionalize the lateral further for sustained faults. The five lateral locations selected were the longer lateral circuits that would be expected to experience one or more faults per year.

The number of faults that would be expected in the new UG sections of the main line is lower than for the OH line sections. After the conversion of the OH to UG of 38% of the main feeder length, the reliability experienced by the customer population served by the feeder would be expected to improve. Applying a lower fault rate to the new underground feeder sections results in the following expected reliability indices:

SAIFI: 7.63 Sustained Outages / Customer-year
SAIDI: 13.85 Outage Hours / Customer-year
MAIFIe: 18.84 Momentary Outages / Customer-year

As expected, all the reliability indices have improved, and this is a direct result of the lower number of fault events expected along the main line with 38% of it now underground.

However, with a significant part of the main line now UG construction, the use of standard reclosing philosophies becomes questionable due to the higher probability that a fault might be in the UG line sections. Faults in UG cable are a result of punctures of the solid insulation system in the cable and removing the applied voltage does not result in the insulation system restoring to full capability as would be the case with OH construction. Reclosing will result in a second (or third, or fourth) fault-current event until the protection device locks out. This re-application of fault current results in additional equipment stress. As a result of the UG main line conversion, the reclosing on the feeder overcurrent devices will need to be blocked, but the tradeoff is that any main line-fault event becomes a single operation to lockout of the main line recloser or the substation relayed circuit breaker.

Likewise, any faults on fused laterals will result in a sustained outage. Transient faults downline of lateral reclosers are the only faults that will be automatically cleared, and service restored.

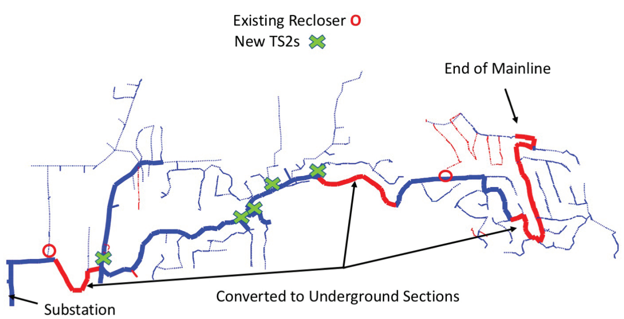

Fig. 2. One-line diagram with sections changed to underground construction.

A simulation of the feeder reliability with the reclosing turned off on the feeder results in the following reliability indices:

SAIFI: 18.27 Sustained Outages / Customer-year
SAIDI: 23.31 Outage Hours / Customer-year
MAIFIe: 1.32 Momentary Outages / Customer-year

The change to the feeder construction and the protection system has resulted in dramatic changes to the reliability indices for the feeder. Despite the reduction in the expected number of faults by converting 38% of the feeder to UG, the overall sustained reliability has not improved when compared to the expected performance of the original OH feeder design. The momentary events have been reduced by a large amount because there is no longer any main line device reclosing. This is due to the fact that any main line fault event, whether transient or sustained, results in a sustained outage because a protection device opens and does not reclose. Any fused lateral fault also results in a sustained outage, even for transient faults. The result is higher sustained outage numbers, with SAIFI increasing by over 50% relative to the base circuit configuration. This is direct result of the inability to use traditional reclosing on main line devices without any ability to test the circuit for sustained faults in the UG line sections.

The continued industry innovation in distribution line protection equipment has resulted in the development of PulseClosing® Technology (available in S&C's IntelliRupter® PulseCloser® Fault Interrupter) that can be effectively applied in situations such as this example feeder. In circuits that have UG sections of the line, PulseClosing Technology can identify whether a fault continues to be present on the circuit and prevent a reclosing operation when there is a cable fault. If the fault is present in an overhead line section and is transient, it will determine that the fault has cleared after the circuit has been de-energized and then the circuit can be reclosed. The application of circuit protection devices with the PulseClosing Technology feature allows the system to take advantage of the presence of transient faults on the OH sections of the line and block reclosing for sustained faults in the either in the OH or UG sections of the feeder.

B. Add main line devices with PulseClosing Technology capability and additional lateral reclosing devices

The circuit with the new UG main line sections can be sectionalized to provide improved reliability for the customers connected to the feeder using three interrupting devices that use the PulseClosing Technology. The devices can be placed upstream of each of the UG main line sections in parts of the circuit that remain OH construction. Options exist for pad-mounted equipment if there is a desire to place the equipment at the transition point to the UG construction. The result is each section has a mix of UG and OH main line and the PulseClosing Technology feature of the devices will be applied to allow reclosing after successful interruption of transient faults in the OH line sections and prevent reclosing for sustained faults either in the OH or UG sections of the feeder. The device locations are shown on the one-line diagram in Figure 3.

This intelligent reclosing following a test of the circuit is applied to regain the reliability improvement expected by converting OH main line sections to UG. A simulation of the feeder reliability with the PulseClosing Technology applied on the feeder results in the following reliability indices:

SAIFI: 7.16 Sustained Outages / Customer-year
SAIDI: 11.82 Outage Hours / Customer-year
MAIFIe: 4.29 Momentary Outages / Customer-year

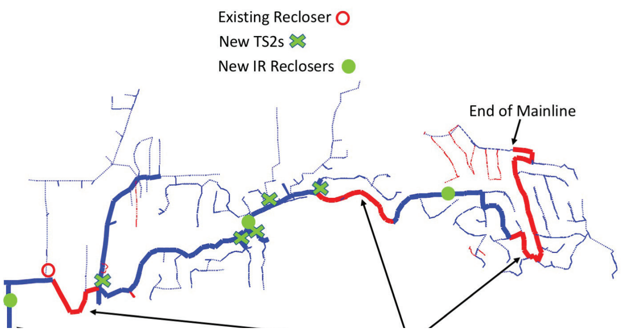

Fig. 3. One-line diagram with device locations shown.

The combination of the effective fault-interruption equipment using the PulseClosing Technology results in a significant reduction in the reliability indices for the feeder compared to the original feeder design. The sustained outage rate experienced by the average customer on the feeder has been reduced by approximately 40% (11.96 to 7.16). The momentary outage rate experienced by the average customer on the feeder has been reduced by approximately 81% (22.82 to 4.29). The dramatic reduction in the momentary outage rate is due to the lower main line transient fault rate due to the UG conversion plus the protection system operating in a fuse sacrifice mode.

C. Add lateral reclosers in the heavy customer concentration at the far end of the feeder

Laterals connected to the feeder are predominantly OH construction that typically would have a large number of transient fault events. The lateral exposure is approximately 70% of the total feeder construction. The main line devices are not configured in a fuse saving protection mode, so these transient faults result in a sustained outage for the lateral customers when the fuse operates. This will add to the sustained outages experienced by customers connected to the feeder.

The design of the fault-detection system for a distribution feeder requires that decisions must be made that impact operations as well as overall outage rates. Automatic reclosing devices placed at lateral connection points can help reduce the number of sustained outages by tripping and reclosing when transient faults are experienced. In the case of a fuse operation a service crew would need to be dispatched to replace the fuse to restore service. Overhead laterals that have sufficient length to experience frequent faults can quickly justify the cost of a TripSaver® II Cutout-Mounted Recloser. Payback is typically achieved after a TripSaver II recloser clears four transient outages, saving four field visits by a line crew. In the next alternative examined, five additional lateral locations were selected near the end of the feeder for application of lateral reclosing devices. This results in the 10 longest laterals on the feeder that are equipped with TripSaver II reclosers that can trip and reclose only the faulted lateral circuit. The additional locations are shown in Figure 4.

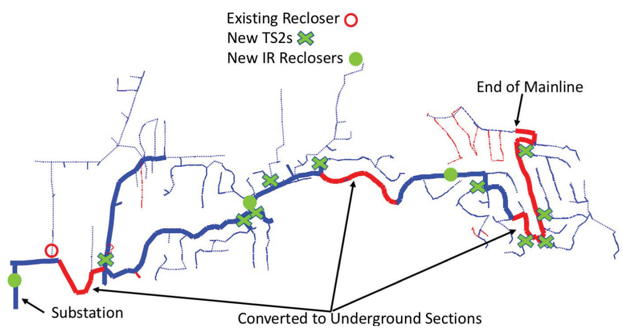

Fig. 4. One-line diagram with device locations shown.

The addition of the TripSaver II reclosers on the longest laterals connected to the circuit in the downline location, coordinated to work with the upstream IntelliRupter PulseCloser Fault Interrupter-equipped device is expected to reduce the number of sustained outages further. The following are the resulting reliability indices for the feeder:

SAIFI: 6.86 Sustained Outages / Customer-year
SAIDI: 6.69 Outage Hours / Customer-year
MAIFIe: 4.64 Momentary Outages / Customer-year

Momentary interruptions increase slightly with the application of the lateral reclosing devices since the customers on those lateral circuits will experience brief interruptions instead of sustained outages as the transient faults are sensed and cleared by the cutout mounted TripSaver II reclosers. The sustained outages experienced for the average customer served by the feeder has decreased as a result of clearing of these transient fault events.

V. Economic Considerations in Feeder Resiliency Improvements

The installation or conversion of distribution feeders from overhead to underground is recognized to improve resiliency since the feeder is less exposed to the fault hazards common to overhead construction. However, both the initial construction costs and the conversion cost of OH to UG feeder-style construction is higher. Information collected and published by the Edison Electric Institute [1] shows a range of costs for converting OH to UG Distribution

Table 2: Cost Estimates for OH to UG Conversion (per mile)

	Urban	*Suburban*	*Rural*
Minimum	$1,000,000	$313,600	$158,100
Maximum	$5,000,000	$2,420,000	$1,960,000

A general estimate is somewhat difficult for this example because the range of conversion costs has a wide variance depending on the location, as indicated in Table 2. The total length of main line conversion on this example feeder is approximately 2 miles. An average cost of the values in Table 2 is approximately $1.8M per mile of feeder converted from OH to UG. On this feeder example the cost of the conversion is $3.53M.

A key point is that the whole feeder does not need to be converted to underground to achieve reliability goals. It is feasible to convert only the worst-performing feeder sections to underground and use new lateral and hybrid feeder-protection technologies to optimize fault response. The changes in protection system equipment discussed in this analysis can be accomplished with budget of only a few percent of the undergrounding project cost.

VI. Summary and Conclusions

This paper has examined the impact of converting a distribution feeder from entirely OH design to a hybrid design that has multiple sections of the main line converted to UG construction. The initial change included the OH to UG conversion and addition of several lateral overcurrent protection devices but no change to the main line feeder overcurrent protection devices. The application of UG feeder construction will normally result in reclosing being undesirable using conventional protection equipment because faults in the UG sections are typically sustained fault events. The reliability is negatively impacted by eliminating reclosing with a significant part of the feeder remaining OH construction. Reclosing can be applied if the protection equipment has the ability to test the feeder prior to a reclose attempt and the availability of IntelliRupter PulseCloser Fault Interrupter equipment provides that technology. Applying these devices upstream of the three cable sections in the example feeder allows reclosing strategy to be applied without risking a reclose with a fault on the circuit.

TripSaver II Cutout-Mounted Reclosers have also been applied at 10 locations on the feeder to provide fuse saving for transient faults on the lateral circuits. This equipment provides improvements to overall feeder reliability, as reflected in the summary of the predictive reliability analysis shown in Table 3. In addition to the reliability benefits, the TripSaver II reclosers also offer reduced O&M costs by eliminating the time required to replace fuses for transient fault events. Long laterals were selected to result in an estimated payback on this example feeder in less than two years due to the high fault rate.

The final alternative examined applies state-of-the-art protective devices using PulseClosing Technology along the main line and cutout-mounted reclosing devices at selected lateral locations. The result is a reduction in sustained outage indices by approximately 43% compared to the average customer experience with the original OH circuit design. The momentary outages experienced by the average customer is reduced by approximately 80%. Table 3 is a summary of the reliability values for each alternative discussed in this paper.

Table 3: Summary of Example Feeder Alternatives

Section	*Description*	*SAIFI*	*MAIFIe*	*SAIDI*
III	Base case - All OH Feeder	11.97	22.83	20.44
III-A	OH main line sections converted to UG. Added lateral devices at five locations with reclosing enabled.	7.63	18.84	13.85
III-A	OH main line sections converted to UG. Applied TripSaver II reclosers on five selected lateral locations. Main line device reclosing disabled.	18.27	1.32	23.31
III-B	OH main line sections converted to UG. Applied TripSaver II reclosers on five selected lateral locations. Main line device reclosing enabled using 3 IntelliRupter® fault interrupters.	7.16	4.29	11.82
III-C	OH main line sections converted to UG. Applied TripSaver II reclosers on 10 selected lateral locations. Main line device reclosing enabled using 3 IntelliRupter fault interrupters.	6.86	4.64	11.61

VII. References

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