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Distribution Automation in Residential Underground Laterals

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SUMMARY

Power system operators and utilities are generally measured on their performance against metrics like SAIDI and SAIFI, and have employed a variety of strategies to improve those metrics. As the benefits of automated metering, grid hardening, and feeder-level automation have been fulfilled in recent years, the need for continued operational improvement has now driven technology development towards applications at the furthest edges of the distribution grid. Concurrently, utilities are developing response plans to high-impact, low-frequency events like hurricanes, wildfires, and ice storms. These events can cause significant damage to overhead electric systems and are a source of tremendous economic impact in their regions. The installation of underground electric systems has been recognized as a key method to reduce SAIFI and SAIDI for day-to-day operations, while simultaneously increasing grid resiliency through reduced recovery time after major events. Underground systems, and specifically manually operated underground residential laterals, will still produce high SAIDI events when an outage or equipment failure does occur. Bringing feeder-level intelligence and automation to these laterals will further reduce impacts to customers. This can be accomplished with compact retrofittable sectionalizing switches installed in both new and existing underground distribution loop systems. Working together with lateral reclosers, these switches automatically detect faults, isolate them, and restore power until the underground fault can be repaired. This paper will discuss motivations for this technology development and the unique features and benefits it can provide to distribution power system operators.

KEYWORDS

System operator, metrics, undergrounding, grid edge, reliability, resilience, distribution automation, sectionalizing, restoration, SAIDI, SAIFI, FLISR

Metrics for Resilience

The System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) are the first two metrics defined in [1] and are two of the most commonly scrutinized metrics in electric power distribution. They gauge the frequency and duration, respectively, of outages averaged over all customers within a given service territory over a specified time period [4]. These metrics provide a macro-scale view of a system's overall reliability, demonstrating how well a system operator ensures the readily available supply of electricity to customers during typical system operation.

A 2013 U.S. Presidential Policy Directive defined infrastructure resilience as the ability to prepare for and adapt to changing conditions and withstand and recovery rapidly from disruptions [4], while CIGRE WG C2.25 defined resilience as the ability to limit the extent, severity and duration of system degradation following an extreme event. These definitions are driving utilities to plan and prepare for high-impact, low-frequency (HILF) [5] events and to provide a means for utilities and regulators to communicate about resilience issues. The manifestation of this can be complex and intricate, focusing on critical metrics like customer-hours of outages, time to recovery, and cost of recovery as suggested in Table 4.1 of [4]. The work by Watson et al. defines a specific Resilience Analysis Process (RAP). This process includes 7 total steps, and includes methods to help utilities characterize threats, calculate the consequences, and evaluate methods to improve system resilience [9].

Reliability and resilience are interrelated in power systems, but there are important distinctions. The industry has not yet settled on widely accepted metrics to quantitatively define resilience, while reliability metrics have been in common use for decades. Reliability and resilience are independent measures of a grid's performance, as a reliable grid may not be particularly resilient, nor does a resilient grid guarantee reliability. The kinds of HILF events that affect resilience – like hurricanes, wildfires, or other similar wide-area destruction (including cyber-attacks) – are typically ignored or separately categorized by traditional power system reliability metrics. Separately categorizing HILF events can therefore present difficulty in quantitatively determining if an infrastructure upgrade improved resilience since there is limited capability to compare with prior performance.

The work of CIGRE WG C2.25 concludes that increases in HILF events in the last two decades has focused the power industry on creating measures and processes to enhance power system resilience [5]. These metrics of course include damage to physical infrastructure, but also extend into the power interruptions caused by that damage, and the subsequent effects on regional economies (such as regional GDP reduction) when the scale and duration of outages is large [11]. It's not clear if the utilities are explicitly following the RAP defined in [9], but it's evident that a need exists for more methods to improve system resilience. Simultaneously, exhibiting a net cost-benefit to these investments is critical. Beyond the more direct impacts noted in [11], insurance companies have started taking notice, as total insured claims have been increasing in the wake of wide area outages [12].

Undergrounding for Resilience

Undergrounding has a well-known track record for reducing SAIDI and SAIFI in distribution systems. The data analyzed in [7] and displayed in Figures 3.2 and 3.3 of that report show a stark difference in performance between the two systems[1]. A summary of those two charts, which present data from 2004-2011, is shown here in Table 1.

Table 1 : Approximate Average SAIFI and SAIDI in the United States from 2004-2011 [7]

	SAIFI (interruptions/ customer)	SAIDI (minutes)
Overhead	1.099	337.5
Underground	0.1075	21.25

Many studies have concluded that undergrounding the entire power system is not financially feasible, also noting that repair times for underground facilities are substantially higher than overhead. States and utilities that have policies to underground electric lines therefore often encourage converting select overhead areas to underground [7]. The following items are excerpted from the EEI report:

Table 2: Conclusions of State and Locality Studies in [7]

Location	Date	Conclusions
Maryland	2012	The current state of reliability is insufficient. Strategic increased expenditure to improve resilience will reduce outages and improve restoration time due to storms.
Houston	2009	Questions the state of the grid after Hurricane Ike took two full weeks to recover from 3.5 million customers out of power. Predominant root cause was falling tree limbs (not wind or water directly). Selective undergrounding makes sense.
Virginia	2005	Stated that undergrounding all new distribution lines is probably reasonable.
North Carolina	2003	Determined repair time is 60% longer for UG lines than OH, but recommended placing lines UG when requested and paid, or when load density and congestion make it logical.

Additionally, DNV GL completed a survey for Gulf Power regarding damages after Hurricane Michael in 2018. Based on that survey data, this study concluded that underground transformers and junction structures were found to have very low (0.01%) failure rates (likely attributed to minimal storm surge from this event). During that same storm, analysis shows that wind gusts were a critical factor in determining damage to equipment (see Figure 1), where 68% of overall pole damage was due to wind-caused damage from trees [3]. Another study in Florida similarly uncovered that the primary cause for pole and wire failures during Hurricanes Matthew and Irma resulted from uprooted trees, broken trunks, and broken limbs outside of the utility's right-of-way [2]. These kinds of findings have led a number of U.S. distribution utilities to begin improving resilience through targeted undergrounding.

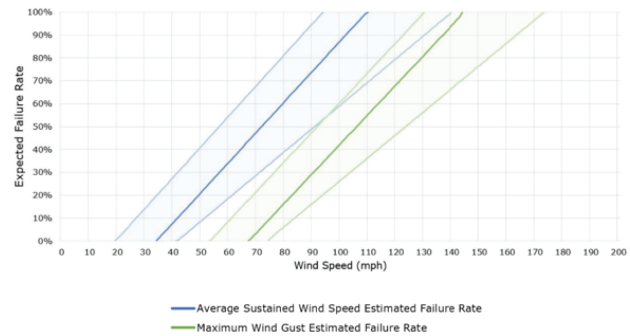


Figure 1: Failure rates of average wind speed and maximum wind gust (mph)

All studies in [8] concluded that undergrounding of lines significantly reduces the number of outages but makes troubleshooting of outages more difficult. In 2008, Oklahoma's PUC recommended burying all new lateral distribution lines except where low population density makes it impractical. North Carolina discovered the differences between their overhead and underground systems as shown in Table 2, concluding that undergrounding the entire system would not provide sufficient cost benefits but still recommended targeted undergrounding [8]. This is corroborated in [10] when selective undergrounding is listed as a tactic to assure service is not interrupted due to extreme events. That same report concedes that underground lines can reduce the speed of recovery.

Table 3: North Carolina Overhead vs. Underground Performance (2003) [8]

	interruptions/Mile /Year	Restoration Time (min)
Overhead	0.57	92
Underground	0.3	145

Targeted undergrounding obviously does not make sense in all applications. Many studies estimated the cost of undergrounding at anywhere from 200% to 800% higher than the relative cost of overhead construction and did not find sufficient return on investment based solely on quantitative metrics like system performance and operations

[1] That same report states "because parts of the underground systems are supplied by overhead systems, it is not conclusive if underground customers consistently experience a higher level of system reliability from a national average perspective."

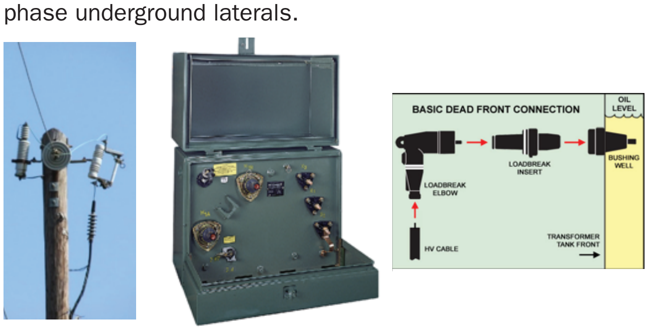
& maintenance costs [8]. When it comes to resilience to HILF events, studies in Florida (2007-2008) uncovered that underground distribution lines in areas where storm surge is likely may withstand more damage and endure longer restoration times.

Despite the well-known costs of underground construction, these studies, policies, and directives from the last two decades have influenced utilities to begin implementing targeted undergrounding in an effort to improve resiliency while simultaneously gaining reliability benefits. FPL began targeted undergrounding programs in the late 2010s [2] and has placed approximately of 90% its new construction underground. Virginia concluded in 2005 that placing new construction underground as logical (see Table 2). Gulf Power included targeted undergrounding plans as part of their 10-year plan starting in 2020 [3]. On July 21, 2021, Pacific Gas & Electric announced a plan to underground approximately 10,000 miles of its system, which today contains over 25,000 miles of overhead distribution. A wide variety of other United States utilities have explicit policies for new underground construction as well as converting existing overhead facilities to underground based on undergrounding studies, as reported in Appendix C of [7].

Programs to construct or convert underground distribution across the industry have generally been targeted to the most needed portions of the system's distribution grid. Recent programs at utilities like FPL, Gulf, and PG&E show the trend is accelerating from targeted undergrounding to more wide area undergrounding. Given the reports from utilities that undergrounded systems are more difficult to restore, there is an emerging need for technology that minimizes SAIDI of underground systems when equipment failures inevitably occur.

Underground Residential Distribution Automation

While there is significant improvement in system reliability purely from undergrounding as a grid hardening strategy, the prior section showed it does not entirely eliminate outages or repair work. In fact, studies have determined that while outages will occur less frequently, undergrounding a circuit can increase restoration and repair times. It then follows that implementing methods to reduce restoration time on underground circuits is highly valuable to sustain customer satisfaction. This section will discuss the benefits of a fault location, isolation, and restoration (FLISR) solution in single-phase underground laterals.



(a) (b) (c)

Figure 2. (a) Typical riser pole with overhead fuse cutout (3) Eaton single-phase pad-mounted transformer (c) Diagram of typical UG cable connection to transformer

The system is installed in a typical URD loop as shown in Figure 3. Single-phase underground laterals like this are common in solidly earthed distribution systems in North America, with typical voltages between 5 and 20 kV line-to-ground. Today, the operation of these circuits is entirely manual, with both sides of the loop fed by fuses. These fuses can be installed overhead on riser poles (Figure 2a), in pad-mounted gear, or even in metal-enclosed switchgear, with pad-mounted gear typically the most common. From these fuses, underground cables run to and from each transformer (Figure 2b). The incoming and outgoing cable connections to each transformer are affixed with loadbreak elbows (Figure 2c), which are spliced to the end of the cable. This elbow allows the line crew to make and break the electrical connection to each transformer while keeping the system energized. Near the midpoint of the circuit, one cable elbow is typically "parked" or mounted on a parking stand, fully insulated (Figure 3). This provides the alternate source for situations where an equipment failure causes a break in the loop.

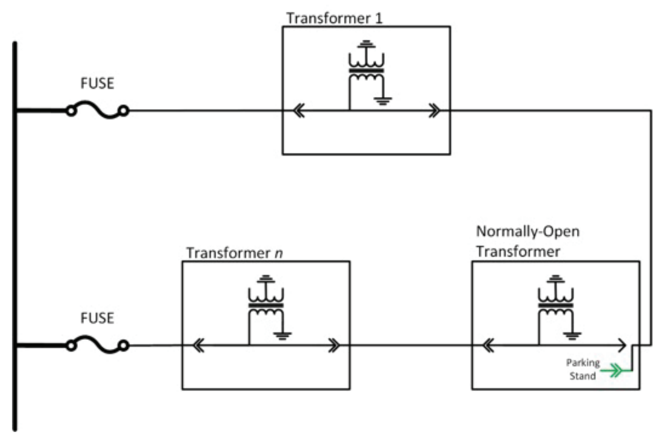


Figure 3: Typical Underground Residential Distribution Lateral

When restoration, repair or maintenance work is required in an underground loop today, specially trained line crews are dispatched to the location. In the case of a faulted cable, the crew typically locate the fault by manually disconnecting load break elbows at each transformer and testing the circuit by closing in new fuses at the riser pole, or by using special fault locating equipment commonly referred to as "thumpers." Once the faulted cable section is identified, the two ends of that cable are parked and the affected transformers are energized from the alternate source until a cable repair crew can be dispatched. During this fault location and restoration period, the customers on the affected half of the loop are without power.

The automation scheme described in this paper converts this manually operated circuit to a circuit that operates autonomously, eliminating the long-duration outage experienced by customers during a cable fault. The FLISR scheme is accomplished first by replacing the lateral fuses with fault interrupting lateral reclosers. A submersible sectionalizing switching device is directly installed in each bushing well of the padmount transformers in the underground loop. The sectionalizers physically interface with existing load-break cable elbows as well, so no physical modifications are required to existing equipment in the loop. Electrical making and breaking within each transformer is nominally accomplished via with an automated scheme that operates the vacuum interrupter in each sectionalizer. In situations where manual operations are required, each sectionalizer can be operated with standard line tools.

A one-line diagram of the loop with these devices is presented in Figure 4. Note that while this particular application is intended for solidly earthed single-phase medium-voltage laterals typically found in North America, the general concept is typically applicable to any looped circuit, including ring-mains.

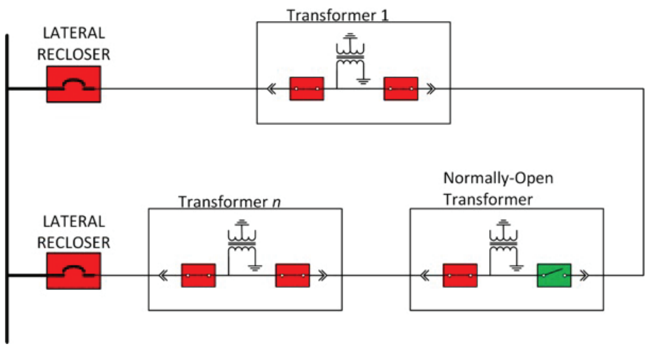


Figure 4. Future State of Underground Lateral with Automation

Theory of Operation

While there are many possible power system scenarios a URD loop could experience, the two most common are

(1) a faulted cable within the boundaries of the loop
(2) a loss of source(s) to the loop itself
  a. permanent loss of both sources
  b. permanent loss of one source

For Case (1), the system shown above uses the lateral recloser to interrupt the fault. There is no change in coordination required from the fuse formerly applied in that circuit. Once the recloser has interrupted and enters its idle open period with the faulted half-loop de-energized, the sectionalizing switches share information locally within the loop and make switching decisions that isolate the faulted segment from both the primary and alternate sources. This sequence of switching operations is completed before the lateral recloser re-energizes the system to test if the fault is permanent. Because of the sectionalization, the lateral recloser's test detects no fault current, and the outage is not sustained. The resulting configuration is shown in Figure 5.

Because there is no sustained outage, customers are unlikely to contact the utility about any potential issues with the physical equipment in that loop. For systems with automated metering, it's possible the meters will be unable to identify the disturbance. For these reasons, a device with the capability to communicate with the utility is installed at the normally open transformer. This device detects any abnormality in the loop and notifies the system operator (typically via SCADA) that the loop has experienced a fault and repairs are required. The system operator can then schedule the repairs at a convenient time for its crews.

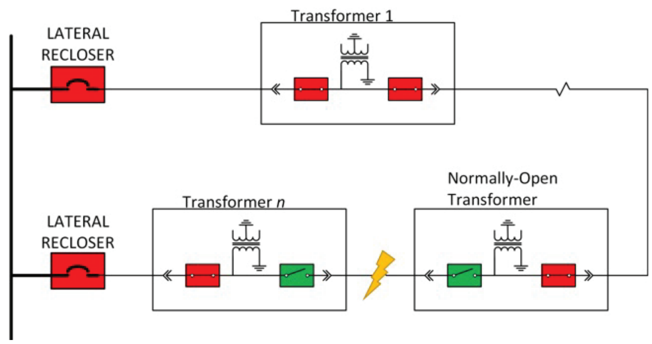


Figure 5. Isolation of a Faulted Segment

Case 2(a) does not instigate a response from the system due to the nature of scheme. This does require the first switch in the loop after each lateral recloser is identified locally as a "head end" during installation. Additionally, the normally open switch must be identified as such. The identifications are made locally at the relevant control unit before or during installation.

Case 2(b), as depicted in Figure 6, does not require a response. It is noted, however, that additional improvement in SAIDI can be achieved by temporarily moving the normally open point from its nominal position to the head-end position of the side that lost its normal source.

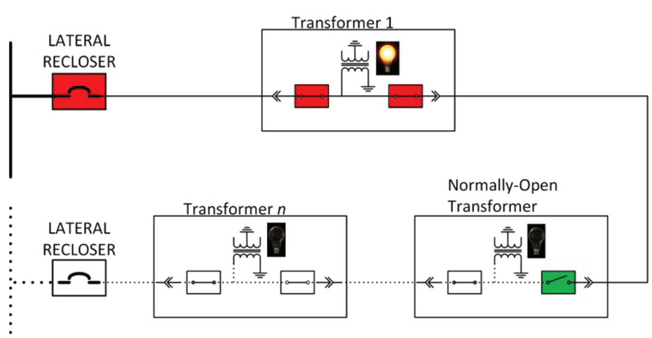


Figure 6. Loss of Voltage Case 2 – before restoration

Note: In this image, energized lines are depicted as solid black, while de-energized lines are dotted.

The restored circuit for Case 2(b) is shown in Figure 7. When the lost source is re-energized, the system automatically detects this and returns the normally open switch back to its nominal position (Figure 4). This is typically accomplished through an open-transition operation, but a closed-transition with a duration of less than 1 power frequency cycle is also possible.

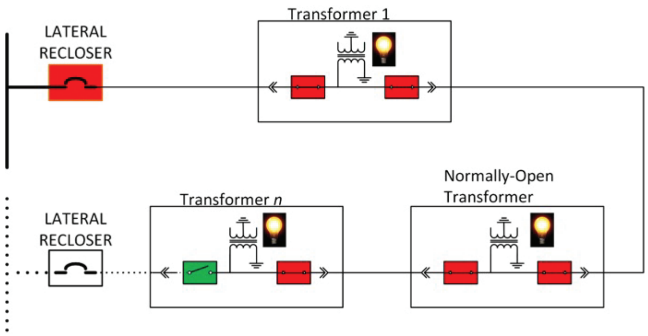


Figure 7: Loss of Voltage Case 2 – after restoration

Note: In this image, energized lines are depicted as solid black, while de-energized lines are dotted.

System Benefits

In addition to the system operation benefits described in the previous section, the following benefits can be realized:

- No change to existing hardware or cabling. All equipment can fit within standard Type I and Type II transformers as defined in [6].
- Operational safety improvements for crews through load-switching in a vacuum interrupter. There is no longer a need to make and break with load-break elbows on live connections.
- These operational safety improvements and the simple interfaces may allow mutual aid crews that normally avoid underground installations to work safely at underground locations with much less time spent in training.
- Restoration is completed quickly enough (<60 seconds) that a single cable failure will not add to CMI or SAIDI[2]
- Minimal configuration required during installation. Only the head-end and normally open devices need identification in any given loop, and that identification need only be given at the particular device. In other words, the other devices in the loop need not be configured with their relative position within the loop.
- Very minimal and simple interface since most operation is autonomous, and other switching operations are completed with typical line tools and a mechanical handle.

As the furthest edges of the distribution infrastructure go underground, significant improvements in SAIFI will be realized at the cost of much longer outage durations when an event does occur. Incorporation of the kind of URD automation system described here would also significantly reduce SAIDI in those loops. The exact improvement in SAIDI experienced by a particular system operator due to URD lateral automation is variable, depending on existing conditions & construction, rate of occurrence of HILF events, and overall coverage of the URD lateral automation products in the system. It also depends on the amount of hardening and automation deployments in the system overall.

NEETRAC report 17-047 references a variety of equipment used in residential subdivisions. Joints and cables are reported as having the lowest reliability, which are frequently used in the construction of URD loops. Slide 31 of the closeout report lists specific failure rates for joints and cables, among other components. The sectionalizer approach described here eliminates any CMI due to failures of joints and elbows, which results in an overall 43% improvement in the listed reliability metrics [13]. Table 4 summarizes the general benefits of typical distribution system improvements, and posits an approximate level of improvement for a future grid that includes undergrounded residential laterals with the automation scheme described here.

Table 4: Approximate realized improvements

	Prior State	Current State	Future State	Future + URD Automation
Feeder Construction	OH	OH	OH	OH
Feeder Protection	Automated	Automated	Automated	Automated
Lateral Construction	OH	OH	UG	UG
Lateral Protection	Fuses	Reclosers	Reclosers	Reclosers + URD Sectionalizers
Pct. Lateral Faults Result in Perm. Outage	100%	30%	90%	0%[3]
HILF Susceptibility	High	High	Low	Low[4]

2 Depends on the minimum duration that defines a recorded outage. Note: Multiple cable failures within the same URD loop would result in an outage for all customers between the affected segments

3 Single contingency is 0%. See footnote2

4 Primary HILF susceptibility is from storm surge

Conclusions

Utilities and regulators alike strive for cost-conscious infrastructure upgrades to improve both reliability and resilience of distribution systems. The tactics used in recent decades have focused around providing information from automated metering, and operational practices like reclosing that reduce the impact of temporary faults. As reliability has improved, the focus has turned to resiliency because high-impact, low-frequency events can disable or destroy physical infrastructure that requires significant time and effort to replace. Upgrading systems for resiliency does not come without its downsides, and utilities will likely need to maintain their reliability as they increase resiliency, especially at the grid edge. One way to accomplish this goal is the conversion of overhead laterals to underground loops with the simultaneous implementation of a fault location, isolation, and restoration system. The sectionalizing method described in this paper is one such way to achieve these goals.

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