Saving Lives Six Feet Under With Light-Based Arc-Flash Protection

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***Abstract*—The topology and protection of underground power systems in urban areas are very different from overhead distribution systems. Since the inception of these systems, network protectors and fuses have been used as the main forms of protection and isolation. Unfortunately, these devices do not provide the fastest isolation for arc-flash events that occur in underground systems. This lack of speed can put the safety of personnel working inside an underground vault, as well as the public above, at risk. Light-based arc-flash protection is a modern technology that has been used to successfully protect personnel from arc-flash events in industrial switchgear for years. This paper explains how a large utility in Texas modernized their underground protection schemes by adding light-based arc-flash protection to detect arc-flash events in the vaults. They also added an interrupting device to their vaults to provide faster and more selective isolation for transformer faults. These two improvements increased the speed of protection and improved personnel safety.**

I. Introduction

The design and protection of underground power systems in urban areas are niche topics that are often not well understood by most protection engineers. In this paper, we explain the fundamentals of these systems, including common topologies, protection challenges, and common protection schemes. Next, we provide a case study of Oncor Electric Delivery, a large utility with hundreds of underground vaults. Most of these vaults were initially protected with three traditional network protection devices: a network protector relay, a low-side fuse, and a heat-sensing system. Over the years, as part of their continuous improvement strategy, the utility added several isolation and protection devices including interrupting devices on the high-voltage side of their transformers as well as sudden pressure relays and heat probes.

More recently, the utility launched a project to investigate several options to improve personnel safety and fault clearing for arc-flash events on the load bus. The outcome of this analysis was the creation of a new standard for their underground vault protection. The final design added two relays to their vaults: one with a supervised instantaneous overcurrent element and another with light-based arc-flash protection. Although light-based arc-flash protection has been used reliably for years in switchgear applications, this is the first known application of the technology in underground vaults.

This paper describes the topologies, equipment, and common terminology of underground distribution systems. It also describes the traditional methods of protecting these systems, as well as the gaps in protection that may result. Finally, it describes the improvements that the utility made to their 480 V underground vaults and how they used dedicated arc-flash protection to improve safety.

II. Background

Underground power systems date back to the electrification efforts of the late 19th and early 20th centuries [1]. Densely populated areas were the first to be electrified, and engineers were tasked with delivering reliable power to these areas. Electrical topologies, such as the paralleling of sources and the connection of load buses together via tie points, allowed for higher reliability than radial topologies. To further ensure reliability, engineers installed the equipment underground to protect it from inclement weather, animals, and other frequent causes of faults. Keeping the energized equipment away from people also increased public safety. As a result of these decisions, the system topologies, equipment, and protection schemes for urban underground power systems were quite different from those of overhead radial distribution systems.

A. Underground Power System Topologies

Power is brought to urban areas through feeders from multiple distribution substations. These feeders may initially be overhead but can transition to underground cables as they approach the load centers. Fig. 1 shows a map of an underground distribution feeder supplying several loads in a city. Often, the feeder cables (shown in red lines on the map) are routed through ducts underneath the roadways, where the splice points between cables are accessible via manholes (shown as circles). Each of these feeder cables typically supplies several transformers spread throughout the city.

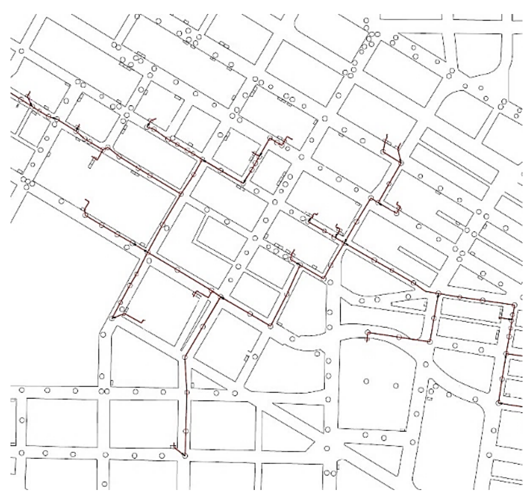

Fig. 1. Map of a distribution feeder supplying loads in a city.

These transformers (called network transformers) step down the voltage from the distribution level to the utilization level (typically 480 V or 208 V line-to-line). The secondary sides of multiple network transformers are connected together to feed a load bus, which directly supplies the load. Each transformer connected to a load bus is fed from a different distribution feeder for increased reliability. These transformers are protected by a network protector and a fuse, both of which will be shown and described in Section III. The network transformers and everything downstream of them is referred to as the network. There are two common types of network topologies—grid networks and spot networks.

1) Grid Networks

Fig. 2 shows a one-line diagram of a typical grid network, also called a street network. In a grid network, the load buses at several different locations are tied together through network cables to form one large geographically distributed load bus. Electrical loads, such as buildings, traffic lights, and streetlights tap off the load bus at multiple locations.

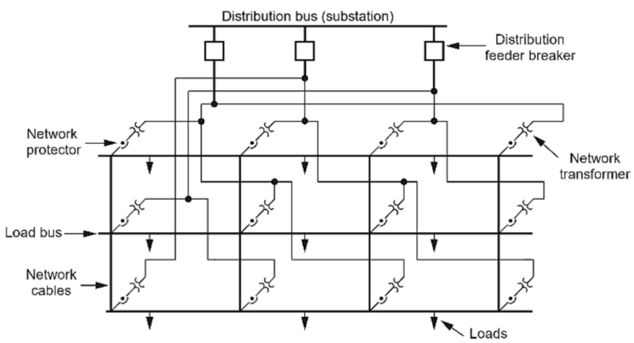

Fig. 2. One-line diagram of a typical grid network.

2) Spot Networks

Unlike a grid network, a spot network only feeds the load at a specific load center and is not directly connected to the load buses of other spot networks. Fig. 3 shows an example topology of two geographically separated spot networks. The number of distribution feeders and the capacity of the transformers in a spot network are selected such that they are able to fully supply the load center if one or more of them were to fail.

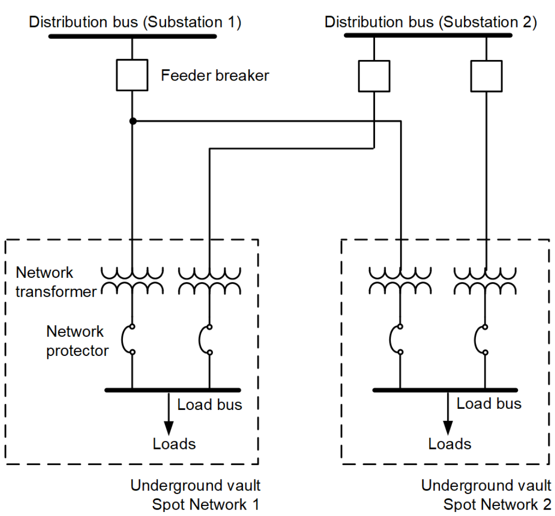

Fig. 3. One-line diagram of a typical spot network [2].

B. Vaults

Vaults are concrete rooms usually located underground where the power system equipment is installed. They can be located under streets or sidewalks or in building basements. Vaults vary in size and may consist of multiple rooms. It is common to refer to the vault by the voltage level of the load bus. For example, a 480Y/277 V vault refers to a network vault with a load bus that is operated at 480 V line-to-line or 277 V line-to-neutral. In this paper, this vault type is simply referred to as a 480 V vault.

Fig. 4 shows the entrance of a network vault from the street, and Fig. 5 shows the same entrance from below. Fig. 6 shows the inside of a space-constrained network vault, while Fig. 7 shows a large network vault.

Fig. 4. Entrance to a network vault.

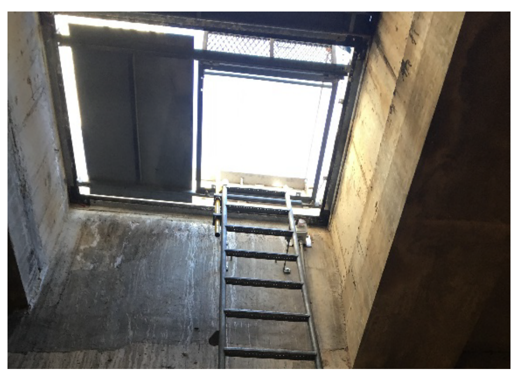

Fig. 5. Entrance to a network vault from below.

Fig. 6. Inside a small 480 V network vault.

Fig. 7. Inside a large 480 V network vault.

C. *Faults on Underground Networks*

When faults occur on a power system, a large amount of energy is released through the fault path. This sudden release of energy can cause damage to electrical equipment and harm any personnel in the area.

Faults in underground networks are especially dangerous for several reasons. Underground networks are usually located in densely populated areas, and their entrances are often located on sidewalks and streets. Therefore, if a fault is not cleared quickly, its resulting effects (fire, explosions, etc.) can create a manhole event—a release of smoke, flames, or explosions in underground structures like vaults, manholes, or cable ducts [3]. Two examples of manhole events are shown in Fig. 8.

Fig.8a

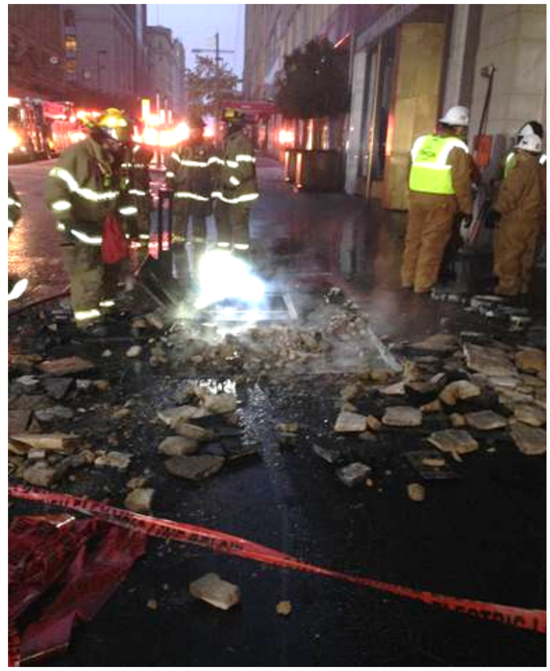

Fig.8b

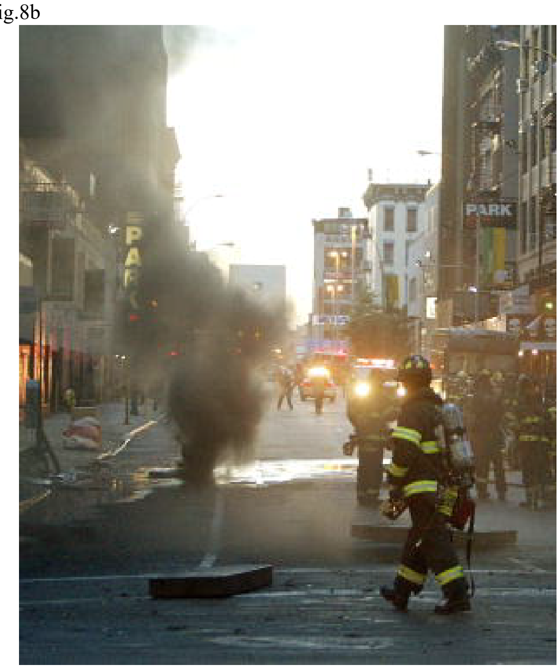

Fig. 8. (a) Manhole event in an underground vault (b) Smoke from an active fire in an underground vault [4].

In addition, underground vaults are often space-constrained, making the consequences for personnel that are working in the vault more severe if a fault occurs.

III. Protection Schemes for Underground Networks

Faults are less likely to occur in underground power systems than on overhead lines, but it is still critical for protection systems to detect and clear them as quickly as possible. Because underground power systems serve critical loads and large population centers, it is important for faults to be cleared quickly to limit damage to equipment and prevent manhole events. Unfortunately, the space constraints inside vaults bring several unique challenges when designing protection systems, particularly for systems with network topologies.

When a fault occurs, all sources of energy feeding the fault must be disconnected. Although this is fairly straightforward for medium-voltage distribution feeders that are radial, it becomes more challenging for network topologies. If the fault is on the distribution feeder or the transformer, the fault current is contributed by both the substation serving that feeder and all other transformers connected to the load bus. The feeder breaker will interrupt the fault current from the substation, but a separate device is required to interrupt the fault current from the transformers on the load bus. Therefore, a protection and isolation device must be placed on the low-voltage side of every transformer to detect this condition and isolate the fault from the load bus.

The number of interrupting devices that can be installed in the network may be limited by the space available inside the vault. In most network vaults, an interrupting device exists on the low-voltage side of the transformer but not on the high-voltage side. Because of this, the entire distribution feeder must be tripped offline for a fault on the transformer. This is typically not an issue, as the other transformers in the vault are fed by different feeders. This allows the load bus to continue to operate with the loss of one or more feeders. However, a lost feeder increases the chance of the load experiencing an outage if subsequent faults occur on other feeders or transformers.

It is possible to improve selectivity by adding an interrupting device to the high-voltage side of the transformer, but there is usually not enough space for these devices in the vault. If this is done, any transformer protection devices can now operate the interrupting devices on the high- and low-voltage sides of the transformer, disconnecting only the faulted transformer from the system. Any other transformers connected to the same distribution feeder will remain in service.

Space constraints may also limit the types of protection that can be used in a vault. For example, current differential protection is the most robust method of protecting transformers, but it requires space for current transformers (CTs) on both sides of the transformer. If there is not enough room for this equipment, we must find another way to protect the transformer. This often results in compromises where it may not be possible or practical to use the most robust form of protection.

The common protection devices used to protect an underground spot network are shown in Fig. 9, along with their zones of protection [5]. Each device is described in the sections that follow.

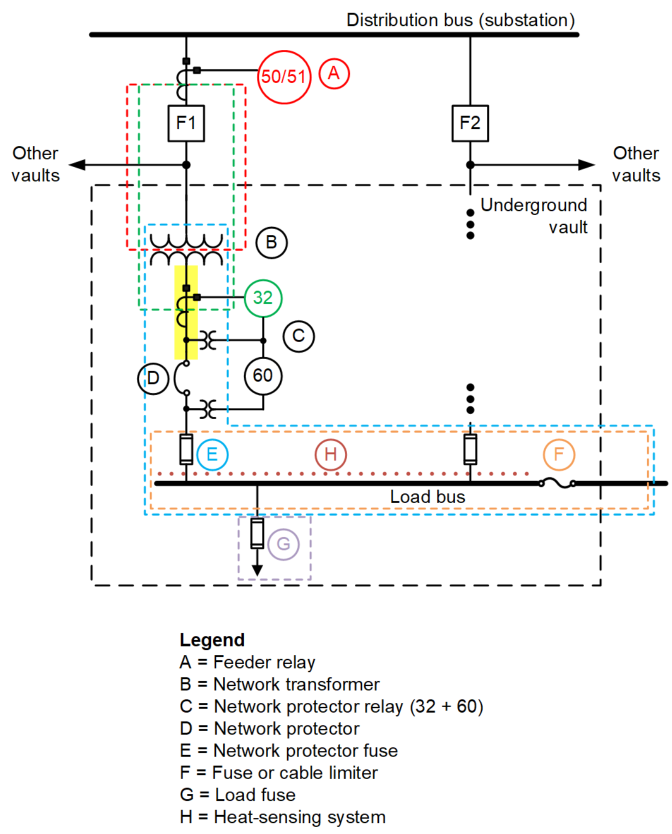

Fig. 9. Primary zones of protection in an underground spot network.

A. Network Protectors

A network protector is a combination of a protection device and a breaking mechanism that is capable of interrupting fault current. Network protectors are unique to underground networks and are typically mounted on the low-voltage side of the network transformer in submersible enclosures. One example of this mounting is shown in Fig. 10. A copper conductor connected to the secondary winding of the transformer is passed through a flex connector to the outside of the transformer. This flex connector provides insulation between the energized conductor and the grounded transformer tank. The conductor comes out the other end of the flex connector and is bolted on to the transformer bus—a long, vertical, copper busbar that is part of the back of the network protector. There is an open window in the back of the network protector case to allow for the transformer's secondary conductor to attach to this transformer bus. The network protector CT is wrapped around the transformer bus to measure current. Another copper conductor connects the bottom of the transformer bus to the breaking mechanism, which is then connected to the load side bushing on the top of the network protector. A conductor from this bushing connects directly to the load bus. Potential transformers (not shown) are used to measure voltage on both sides of the breaking mechanism. For the remainder of this paper, we refer to the breaking mechanism as the network protector and the associated protection device as the network protector relay.

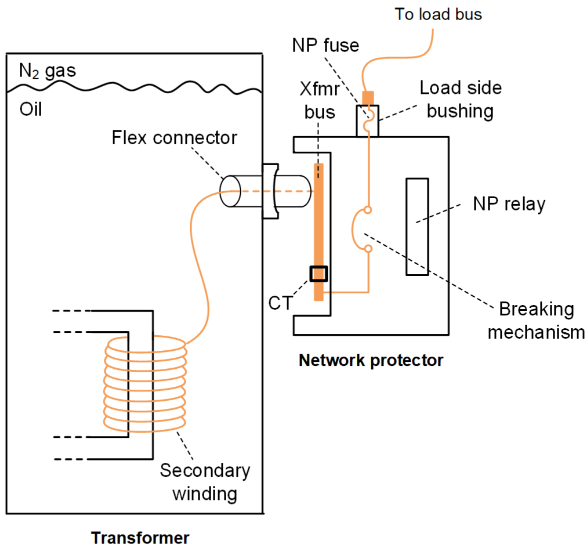

Fig. 10. Network protector mounted to network transformer.

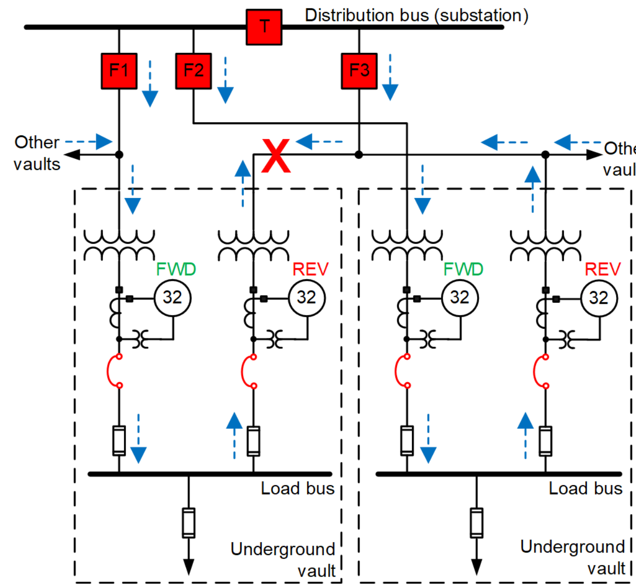

Fig. 11. Backfeed to a distribution feeder fault on a spot network.

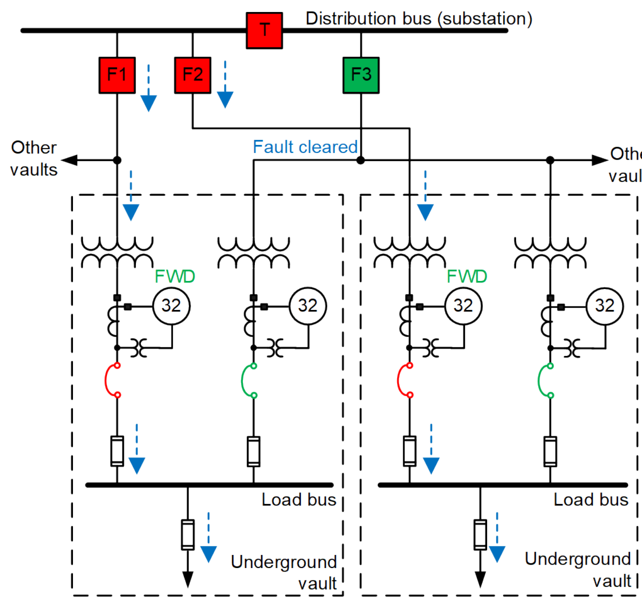

Fig. 12. System configuration on a spot network after the fault is cleared.

A network protector relay allows forward power flow from the transformer toward the load bus and uses a reverse power element (32) to trip for reverse power flow from the load bus toward the transformer. The 32 element is set to detect low levels of reverse power flow. It also detects reverse power flow caused by faults on the high-voltage side of the transformer that are fed from all the other transformers on the load bus [5].

Network protector relays require greater sensitivity than typical overhead distribution relays. This is because the 32 element must be capable of tripping for the low levels of reverse power that occur when the distribution feeder breaker is open and the transformer is energized by the load bus. In this case, the power measured by the 32 element is only as much as the transformer losses. It is typical to use metering-class CTs to measure the current and to set the pickup of the 32 element in amperes secondary in the range of 0.05 percent to 5 percent of the CT secondary nominal current (2.5 mA to 250 mA secondary for a 5 A nominal CT) [6]. Due to this sensitivity, the 32 element can detect faults on the transformer's high-voltage winding as well as the distribution feeder. It also operates for faults on the low-voltage winding of the transformer, as shown by its zone of protection in the dotted green box on the left side of Fig. 9.

An example of how network protector relays operate is shown in Fig. 11. This figure shows three distribution feeders that supply transformers in two spot network vaults. A fault on Feeder F3 is fed primarily by Feeder F3, but it is also backfed from Feeders F1 and F2, as shown by the blue dashed arrows representing current flow. Feeder F3 and all the network protectors that measure reverse power must trip to isolate this fault.

Fig. 12 shows the system configuration after the fault is cleared. The spot connection topology allows the load to remain energized even after Feeder F3 is de-energized.

B. Feeder Relays

Feeder relays at the substation provide phase (50/51P) and ground (50/51G) overcurrent protection to detect faults on the distribution feeder and the high-voltage winding of the transformer. These elements are typically not sensitive enough to detect faults on the low-voltage winding of the transformer. This means that even if the network protector relay trips for a fault on the low-voltage winding of the transformer, the fault will continue to be fed by the distribution feeder until it evolves to include the high-voltage winding. At this point, the feeder relays at the substation will detect the fault and trip. This speed can be improved by sending a transfer trip from the network protector relay to the feeder relay (or another high-side interrupting device, if it exists) when a transformer fault is detected.

C. Network Protector Fuses

A network protector fuse provides backup protection for the transformer if the network protector fails to operate, and it provides primary protection for faults on the load bus. There are two common types of network protector fuses—current-limiting fuses and fusible links.

A current-limiting fuse is sized to interrupt high-current faults on the low-voltage side of the transformer in less than one cycle. It is important to size these fuses so that they are never overloaded. Relatively low overcurrent conditions can cause the fuse to melt but not interrupt, resulting in the fuse possibly catching fire. These fuses give the fastest clearing time for faults on the low-voltage side of the transformer, but they do not provide any protection for low-magnitude arcing faults or bus faults with fault resistance. These fuses do not normally detect faults on the high-voltage side of the transformer.

Fusible links, on the other hand, can handle lower currents without becoming damaged. This allows for the selection of more sensitive fuses that can detect faults on the high-voltage side of the transformer and the primary feeder. However, the fuse must always operate slower than the network protector for these faults. Because these fuses are able to handle fault currents for a longer time, they can be sized to coordinate with the transformer damage curve. However, fusible links are more sensitive to high ambient temperatures and can prematurely activate if exposed to high heat.

Both types of fuses also provide primary protection for bolted faults on the load bus. The network protector relay, however, does not operate for faults on the load bus due to the direction of fault current.

D. Isolating Devices (Fuses and Cable Limiters)

Isolating devices, such as fuses or cable limiters, are used to isolate the faulted bus section from the rest of the network. Fuses are used in locations where load buses are interconnected between vault rooms in spot networks. Cable limiters are used to isolate the network cables that connect the grid network to the faulted load bus. While fuses are generally sized to provide both overload and short-circuit protection, cable limiters are generally sized to operate only on short-circuit fault current. These isolating devices must be selected to handle the total current provided by all the transformers on the load bus and should operate before the network protector fuses.

E. Load Fuses

Load fuses are used to isolate a faulted load from the load bus. This load fuse is sized to operate faster than the network protector fuse for faults on the load.

F. Unprotected Zone

The "unprotected zone" is the name given by IEEE to the area between the secondary terminals of the transformer and the breaking mechanism of the network protector [6]. This area is highlighted in yellow on the left side in Fig. 9 and is shown in further detail in Fig. 10. This area is considered unprotected because faults in this location are likely to be high-resistance arcing faults, which are difficult to detect by the protection devices covering that area. Even if the network protector relay or network protector fuse are able to detect and clear the fault, the fault will still be fed from the distribution feeder. As explained in Section III.B, the feeder protection at the substation is not sensitive enough to detect a fault on the low-voltage side of the transformer. Therefore, the fault can continue to burn until it evolves to include the high-voltage winding, at which point the distribution feeder relays can detect it.

Faults in the unprotected zone are rare, but not impossible—Oncor has experienced one such case, and [7] describes a very similar type of fault that occurred at a utility in Indiana. Additional protection, such as the heat-sensing systems described in the next section, are required to detect these faults.

G. Heat-Sensing Systems

Heat-sensing systems are used to detect arcing faults in the vault. While bolted faults produce significant current and are cleared by the network protector fuses and cable limiters, faults with high resistance may not produce enough current for these devices to operate. This can result in a fault arcing for several minutes, or even hours, while creating combustible gases that can lead to explosions, fires, and massive damage [8].

Heat-sensing devices do not rely on current measurements to operate. Instead, they use materials that are sensitive to changes in temperature to detect a fault. Depending on the type of construction, a changing temperature can cause a part of the sensor to bend, melt, or change resistance—which in turn results in a trip. The trip can take longer to occur during slow temperature increases compared to fast temperature increases. The heat-sensing system typically trips the network protector and any high-side interrupting devices that may exist.

There are two common types of heat-sensing systems that are used to detect arcing faults in enclosed areas: heat probes and heat wire. Heat probes are typically used in smaller areas, while heat wire is used across larger areas.

H. Load Restoration

Once a faulted feeder is repaired, a phasing element (60) is used to restore service. This element is typically included in the network protector relay but may also be in a separate relay. This element automatically closes the network protector when the transformer low-voltage side is energized, and the load bus is de-energized. If both sides are energized, a close only occurs when the voltage magnitudes and phase angles between the two sides are within preset limits and the voltage on the transformer low-voltage side is leading the voltage on the load bus. This ensures that power will flow in the forward direction when the network protector is closed.

IV. Network Protection Upgrades in 480 V Vaults

The utility operates several underground networks. Each network supplies 208 V and 480 V spot and grid topologies. As part of the utility's continuous improvement strategy, the protection department launched a project to review the protection schemes in all their underground vaults, identify any gaps, and make improvements where necessary. This effort resulted in the creation of two new protection standards: one for their 480 V vaults and one for their 208 V vaults. This paper focuses on the standard for their 480 V network vaults.

A. Initial Upgrades to 480 V Vaults

The original protection in most 480 V vaults was the same as the general network protection scheme described in Section III. Over the years, the utility took advantage of advancements in protection and isolation technology to improve their network protection schemes. These continuous improvement efforts resulted in the additions described below and shown in Fig. 13.

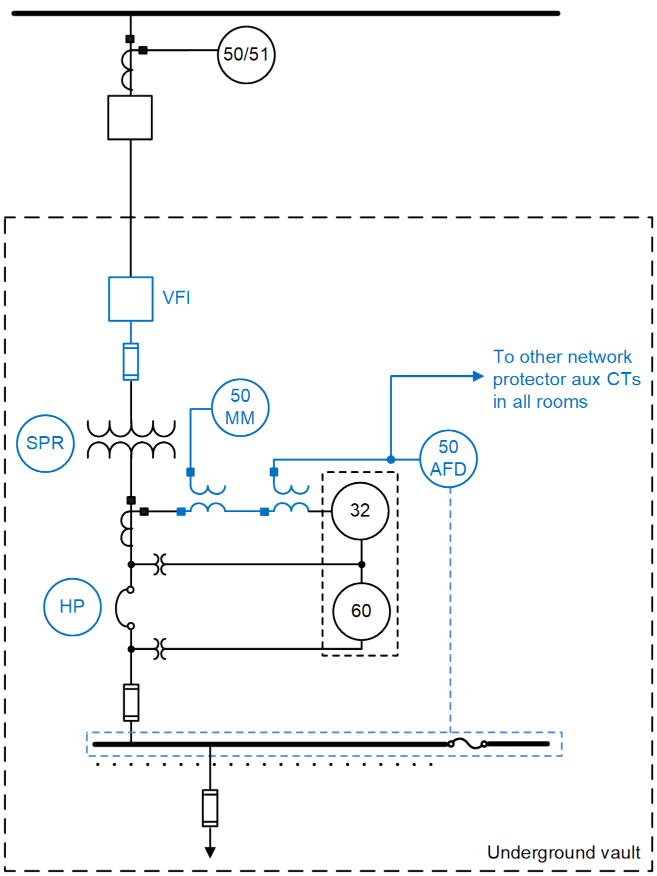

Fig. 13. Upgraded protection standard for 480 V vaults.

1. A new vacuum fault interrupter (VFI) and fuse were added to the high-voltage side of the transformer. The VFI serves two purposes. First, it provides local isolation for a faulted transformer. Second, it provides a significant improvement in the time to trip for faults on the low-voltage winding of the transformer as well as faults between the transformer and the network protector. Previously, the feeder relay would only be able to detect these faults after they evolved to the high-voltage winding of the transformer. This used to result in a long fault clearing time, which increased the risk of fires. Adding a VFI to the high-voltage side of the transformer that is operated when a transformer fault is detected significantly reduces the clearing time. This is a major enhancement that can improve safety and prevent manhole events. The high-side fuse provides backup isolation if the VFI fails to clear a fault.
2. A sudden pressure relay (SPR) was added to every transformer to improve protection for internal turn-to-turn faults. The SPR trips the VFI and the network protector, isolating the faulted transformer from the rest of the network.
3. Heat probes (HP) were added inside the network protector cabinet to detect faults inside the network protector. At 480 V, faults may result in sustained arcing that is not easily detected by the network protector relay or the network protector fuse. The increase in heat from these faults, however, can quickly be detected by the HP, which then trips the same devices as the SPR.

These additions have now been standardized for all new 480 V vaults.

B. Adding Arc-Flash Protection

During the utility's review, one significant gap that was identified was protection for faults on the load bus, specifically when personnel are present. In 2022, Sandia National Laboratories commissioned a report on underground networks that included interviews with three different utilities in the United States, including Oncor. This report identifies five areas with opportunities for technical exploration. The first area focuses on "Increasing demands for fault energy and arc-flash reduction, along with reduced tolerance for rare but threatening uncleared faults and resulting burndown events" [9]. This report briefly documents the methods used by Oncor to detect and trip for these faults, which will be further expanded upon in the following section.

As part of their network protection review, the utility evaluated the risk of arcing faults and arc-flash events in their 480 V vaults. Arcing faults occur when the dielectric strength of air is lowered by the presence of contaminants or volatile organic compounds. Arcing faults have low currents that may not exceed the pickup of an overcurrent relay or fuse. Other methods used to detect arcing faults on overhead distribution systems, like high-impedance fault detection, could possibly be used. However, their effectiveness in underground vaults remains a topic for further research [10]. Arc-flash events occur when a fault produces a sudden release of energy near personnel. These faults typically have large current magnitudes. Although an arc flash can occur anywhere, these faults are particularly concerning in underground vaults for the reasons presented in Section II.C.

Even with the improvements made to the utility's network protection thus far, only the network protector fuses and the heat wire provide protection for arc-flash events on the load bus. This is not optimal because the network protector fuses may not reliably interrupt arc-flash events that result in a lower current magnitude than a bolted fault. Additionally, the speed of a heat-sensing system is dependent on where the fault occurs in proximity to the temperature sensors as well as how quickly the room heats up. Because of this, the utility chose not to depend on these devices as the primary method of protection for arc-flash events. Instead, they required a high-speed dedicated arc-flash scheme. The goal of dedicated arc-flash protection is to reduce the amount of energy released during an arc-flash event. This energy can be estimated by using (1) [11].

$$E = I^2 \cdot R \cdot t \quad (1)$$

where:

E is the energy in joules.

I is the arcing current in amperes.

R is the arc resistance in ohms.

t is the arcing time in seconds.

In underground vaults, it is not possible to control the amount of current or arc resistance that occurs during an arc-flash event. We can, however, control the amount of time that the arc flash is allowed to persist. By lowering t in (1), we can drastically reduce the amount of energy released during the arc-flash event.

Many dedicated arc-flash protection schemes exist that reduce equipment damage and improve the safety of personnel by operating as quickly as possible. The utility opted to use two different methods to provide arc-flash protection: a supervised low-set instantaneous overcurrent element and an element that combines overcurrent and light.

1) Instantaneous Overcurrent Detection

Because an arc-flash event always generates a large amount of current, an instantaneous overcurrent element can be used to detect these faults. An instantaneous overcurrent element in a microprocessor-based relay that operates on the magnitude of a filtered current phasor (50) can trip in 1.25 cycles or less. This is due to the time required for filtering and for phasor calculations to occur. Instantaneous overcurrent elements that use high-speed measurement methods, such as raw samples or analog circuits, can operate faster—within a few milliseconds.

Because instantaneous overcurrent elements operate quickly, their pickups are often set above any transient overcurrent conditions (e.g., the transformer inrush or the starting current of a motor) to prevent false operations, but still below the minimum available arc-flash current. These elements are not coordinated with any other protection elements, so it is critical that they are only allowed to operate when personnel are in the vault. This is accomplished by supervising the instantaneous overcurrent element with a maintenance mode switch or a pushbutton that is enabled when personnel are in the vault.

The utility decided to add a manually enabled, nondirectional instantaneous overcurrent element (50MM) that operates in 4 ms for arc-flash protection. This element uses an analog circuit and was implemented through a module that could be added to their network protector. The module has an auxiliary CT to measure current from the network protector relay on the low-voltage side of the transformer. When the element operates, it trips the network protector.

All the 50MM elements in the vault are manually enabled by personnel using a single maintenance mode switch. This method is not ideal, as it leaves personnel exposed to an arc-flash event during the time they open the door to the vault, climb down the ladder, walk over to the switch, and enable the elements. This means that unless workers are present, the 50MM elements are not enabled and will not provide fast clearing for arc-flash events. Therefore, an additional solution is needed to ensure that workers are protected for the entire time they are in the vault.

2) Overcurrent and Light Detection

A more modern method of dedicated arc-flash protection (50AFD) uses instantaneous samples of both current and light to operate within 2–5 ms. These two quantities are always produced by an arc-flash event, and there are several benefits of requiring both of them to operate. First, the scheme is secure when unexpected light is present (e.g., sunshine through an open vault door or personnel shining a bright flashlight in the vault) or unexpected overcurrent is present (e.g., starting current of a downstream motor). Second, the overcurrent pickup can be set below transient conditions without having to worry about false operations. Third, personnel do not need to remember to activate the scheme when they enter the vault because it can remain active all the time. This provides fast clearing for faults on the load bus regardless of the presence of personnel.

The 50AFD relay measures light using the optical sensor shown in Fig. 14. The optical sensor consists of two sections: a clear-jacketed fiber section and a black-jacketed fiber section. The clear-jacketed fiber section captures light over a large area. The black-jacketed fiber section brings the captured light to the relay. A single relay can be connected to eight optical sensors, each connected via a set of V-pin terminators.

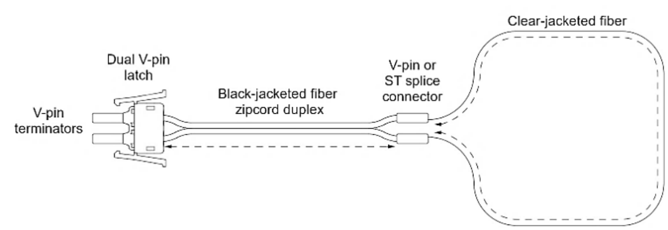

Fig. 14. Arc-flash optical sensor [12].

The light that is measured by the relay is compared to a light pickup setting, which must be above ambient light conditions and is determined onsite during installation. The relay reports the amount of ambient light measured by each sensor to assist with this process. The light produced during an arc-flash event is so bright that it will immediately exceed any pickup setting based on ambient light—even if the sensor is covered in a layer of dust or dirt.

The physical integrity of the optical sensors is critical to the dependability of the 50AFD relay. The relay periodically performs an automatic self-test on each sensor by injecting a series of light pulses through the sensor and asserting an alarm if the sensor fails. This alarm can be monitored by the supervisory control and data acquisition system to alert operators that further investigation is required.

Although 50AFD relays have been widely used for arc-flash protection in industrial switchgear, they have yet to be adopted for underground applications [13] [14]. Due to the many benefits listed previously, the utility opted to add a 50AFD relay as the primary protection for arc-flash events.

Because a 50AFD relay application in an underground network is quite different from a typical switchgear application, careful thought had to be given regarding its implementation. In a typical switchgear application, a 50AFD relay would be placed on each transformer and would measure the current flowing from that transformer to the load bus as well as the light around the load bus [15]. Although this could also be done in a network application, space constraints and wiring complexity may make using numerous 50AFD relays impractical.

Because the utility already had 50MM protection on every network protector, they opted to use a single 50AFD relay for the entire vault, with a large zone of protection that includes all the load buses in all the rooms. To disconnect all the sources when a fault occurs on the load bus, the 50AFD relay trips all the network protectors (and all the VFIs) in all the rooms. The relay measures light above the load bus in each room, as well as the total current flowing into the load buses of all the rooms.

The optical sensors are hung from the ceiling above the load bus in each room, as shown by the green dotted line in Fig. 15. Each room is covered by its own optical sensor that connects to the 50AFD relay.

Fig. 15. Loop sensor installation in 480 V vault.

To measure the total current flowing into the load buses in all the rooms, current is measured at each network protector and combined using the parallel connection shown in Fig. 13. Because it is not possible to obtain measurements directly from the network protector relays for this purpose, auxiliary CTs are used to measure the currents at each network protector. The parallel sum of all the auxiliary CTs of each phase is connected to the corresponding phase current input on the 50AFD relay. This type of connection, which only measures the current flowing into the bus, is called a partial differential connection. The zone of protection of the overcurrent element covers all load buses in all the vault rooms, as well as the downstream loads. The current pickup setting for the 50AFD relay is set higher than the maximum load possible on the bus.

3) *Summary of Arc-Flash Detection Methods*

As a result of these upgrades, the two new dedicated arc-flash protection methods are expected to operate as follows.

If a fault occurs on the load bus, both the overcurrent and light requirements of the 50AFD relay will be met and the relay will issue a trip within 2–5 ms. The manually enabled 50MM element will provide backup protection when personnel are in the vault, and the network protector fuse may provide backup protection when nobody is in the vault. As a last line of defense, the heat wire will also protect for faults on the load bus and possibly other locations inside the vault.

If a fault occurs on the low-voltage side of the transformer, but upstream of the 50AFD relay's CTs, the overcurrent requirement will not be met because the net current flowing into the load bus will be zero. In this case, the 50AFD relay will not operate. If personnel are in the vault and have enabled the 50MM element, it will assert and trip high speed. Otherwise, the network protector relay will operate, with the network protector fuse possibly serving as backup. This may result in a slower but still sufficient clearing time for cases when personnel are not in the vault.

If a fault occurs downstream of the bus, the overcurrent requirement of the 50AFD relay will be met. Regardless, the relay will remain secure because the light requirement will not be met for any faults outside of the vault. The 50MM element will operate for these faults if it is enabled.

4) *CT Saturation Concerns*

When using current-based protection methods, CT saturation can cause the relay to measure currents that are lower than those on the system. This lower current measurement may prevent the relay from operating during a high-current fault. CT saturation is more of a concern when lower-class CTs are used, which is often the case in underground vaults due to space constraints. The metering-class CTs used in many underground vaults do not perform as well as protection-class CTs when exposed to high levels of fault current. If the CT does not deliver the appropriate values to the relay, can the relay be counted on to operate during a fault?

The overcurrent requirement in the 50AFD relay requires the CTs to perform well for 2.08 ms to ensure proper operation. For traditional applications using protection-class CTs, the time it will take a CT to saturate can be calculated using equations from [16]. However, manufacturers of metering-class CTs are not required to publish the excitation curves that are needed to perform these calculations. The use of auxiliary CTs in addition to metering-class CTs complicates these calculations even further.

To address this concern, the utility performed laboratory testing of the main and auxiliary CTs of the network protectors to confirm that they would perform adequately during fault conditions. It is critical that studies are performed prior to reducing arc-flash hazard ratings in vaults using a 50AFD relay. There is an opportunity for future work in examining the performance of CTs in underground networks and exploring nontraditional CT options such as air-cored Rogowski coils for these applications.

C. *Oncor's 480 V Network Project Schedule*

The utility plans to construct all new 480 V vaults to conform to their new protection standard. Their existing vaults are being upgraded on a schedule, with the highest priority being given to vaults that have enough space to fit all the equipment needed to meet the requirements of the new standards. If the vault is too small to fit all the necessary equipment, a team reviews the vault to determine what modifications can be made to obtain the most benefit. For example, in some cases, installing the VFI may not be possible. The arc-flash protection in the new standard has yet to face real-world validation, as no bus faults have occurred in the upgraded vaults at the time of this writing.

V. Conclusion

Underground networks are used in densely populated areas to ensure reliability, reduce the chance of faults, and improve safety. The system topologies, equipment, and protection schemes used underground are very different from those in overhead radial distribution systems that many protection engineers are familiar with. Although faults in underground networks are relatively rare, they can be extremely dangerous, and it is critical that they be cleared as quickly as possible.

Over the years, as a part of the utility's continuous improvement efforts, their traditional protection (mostly consisting of network protectors, fuses, and heat wire) was improved using modern methods and additional isolation equipment.

The utility added high-side VFIs and high-side fuses to the transformers to improve selectivity and reduce clearing time for transformer faults. They also added SPRs to every transformer to detect turn-to-turn faults, as well as HP to detect faults inside the network protectors. In addition, the utility investigated how to best protect for arc-flash events on the load bus. Their new standard uses two dedicated arc-flash detection methods in combination: a relay with a manually enabled low-set instantaneous overcurrent element (50MM) and a relay that uses both current and light to operate (50AFD).

The addition of a 50AFD relay is a huge improvement to personnel safety inside the vault, because it will detect faults on the load bus and trip high speed. It also does not require any manual intervention because it is always enabled. Although 50AFD relays have been used successfully in switchgear applications for many years, Oncor has pioneered the use of this technology in network vaults. The authors hope that other utilities that own and operate underground networks can use this experience to improve the safety of their network vaults.

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VII. Biographies

Jean Farias received his BS in electrical engineering from the University of Texas at Austin in 2014. He worked for the United States Navy as an aviation electrician and as an organizational maintenance technician from 2005–2010. In 2014, he joined the System Protection and Relay Support group at Oncor. Since 2018, he has worked as a senior engineer in the SCADA Automation group at Oncor. He is a registered professional engineer in the state of Texas.

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Ariana Hargrave earned her BSEE, magna cum laude, from St. Mary's University in San Antonio, Texas, in 2007. She graduated with a Master of Engineering in Electrical Engineering from Texas A&M University in 2009, specializing in power systems. Ariana joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2009 and works as a principal engineer in Boerne, Texas. She has published more than 30 application guides and technical papers and authored the chapter on system protection in the book *Women in Power*. Ariana was honored to receive the Walter A. Elmore Best Paper Award from the Georgia Institute of Technology Protective Relaying Conference in 2017, 2018, and 2023. She is an IEEE Senior Member and a registered professional engineer in the state of Texas.

Tom McQuilken earned his BS in electrical engineering from the University of Texas at Austin in 2008. Tom worked at a local utility doing relay and control print design and system protection until joining Schweitzer Engineering Laboratories, Inc. (SEL), in 2015. He is a registered professional engineer in the states of Texas and California.

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