# Protection of Mixed Overhead and Underground Cable Lines

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## Abstract

This paper describes the protection challenges of ac underground cables and transmission circuits with mixed conductor technologies. In addition, the paper discusses the challenges of calculating the relay ac input quantities for faults along the underground cable circuit and of determining the fault loop impedances measured by ground distance relays. The paper provides application solutions for the proper protection and autoreclosing of underground cables and mixed conductor technology circuits.

## 1 Introduction

Extra-high-voltage (EHV) ac underground cable lines are often used because the public strongly opposes the construction of new overhead transmission lines, especially in urban areas. In addition, the progress made in cross-linked polyethylene (XLPE) extruded insulation technology has increased the use of EHV underground cables. Some EHV transmission circuits are composed of both overhead and underground cable lines. They are typically referred to in literature as mixed conductor technology circuits, mixed circuits, or hybrid circuits.

High-voltage (HV) underground ac transmission cables have significantly different electrical characteristics than overhead transmission lines. In addition, underground ac transmission cables have sheaths or shields that are grounded in one or several locations along the cable length. The calculation of the series sequence impedances of cable circuits is more complex than that of overhead lines because there is magnetic coupling among the phase currents and, in some cases, among the currents in the cable sheaths. The zero-sequence impedance depends upon the cable sheath grounding and the presence of parallel cable circuits, and it is difficult to determine this impedance precisely.

Ground fault current can return through the sheath or the ground alone, the sheath and the ground in parallel, or through the ground and the sheath of adjacent cables. Understanding how the cable grounding method affects the apparent impedances of ground distance relays is fundamental for properly protecting underground cables and mixed conductor technology circuits.

Short-circuit calculations are extremely important in the application and setting of protective relays. Short-circuit calculations in mixed circuits present a challenge to protection engineers, especially when faults along the underground cable are studied and when taking into consideration the underground cable sheath grounding and bonding method.

Utilities typically autoreclose on overhead transmission lines because most faults are transient in nature. Reclosing on a circuit that contains an underground cable is typically not recommended or allowed because cable faults are permanent and reclosing can cause significant additional damage to the underground cable.

This paper discusses the protection and autoreclosing challenges of underground cable circuits and mixed conductor technology circuits and provides application solutions. The paper also discusses how underground cable electrical characteristics and grounding methods impact different protection principles. In addition, the paper discusses the challenges of calculating faults along the circuit and proposes the use of a phase domain approach instead of the symmetrical component method. The phase domain approach easily handles the complexity of cable core-to-core and core-to-sheath coupling, cable cross-bonding, and the different types of cable sheath grounding and bonding.

## 2 Short-circuit protection of underground cables

An underground cable must be protected against excessive overheating caused by fault currents. Excessive heating could damage the cable, requiring lengthy and costly repairs. Because most cable faults involve ground initially, ground fault protection sensitivity is of utmost importance. Therefore, high-speed pilot relaying schemes are the most common relaying schemes applied for HV cable protection.

Long underground cable circuits produce high charging current, which may be an appreciable fraction of the load current. This limits the choice of minimum fault current settings. In addition, cable circuit energization and de-energization create high transient currents. Similar high transient discharging and charging currents flow in the cable circuit during faults external to the cable zone of protection. The protection schemes must be designed to cope with these transient currents, and a current pickup setting of several times the steady-state cable charging current may be necessary to ensure the protection scheme security.

The protection principles applied to underground cable circuits and mixed conductor technology circuits are similar to those applied in EHV overhead transmission circuits.

However, the differences in the electrical characteristics of underground cables and their method of grounding create challenges for some protective relaying principles, especially for ground distance protection [1] [2]. The protection engineer must fully understand the fundamental differences between the two applications to provide proper protection of underground cables or mixed conductor circuits.

The three pilot protection schemes applied for cable protection are current differential, phase comparison, and directional comparison. Backup protection of underground cables is provided using phase distance, directional ground overcurrent, or ground distance protection.

**2.1 Distance protection application considerations**

Most faults in underground single-conductor cables involve ground. For that reason, it is important to calculate the fault quantities seen by relays during line-to-ground faults along the cable in order to calculate the apparent impedances seen by ground distance relays.

The study of intermediate faults in underground cables using symmetrical component theory is quite complex. One limitation of symmetrical component theory is the assumption that power system element impedances are balanced. This is not true in underground cables because of the different methods used for cable sheath bonding and grounding. Another difficulty in applying symmetrical component theory is the requirement to retain the sheaths, including their transpositions and grounding along the cable path, to properly study faults along the entire cable length or mixed conductor technology circuit. All of these difficulties are overcome by using the phase frame of reference approach (instead of using the symmetrical component frame of reference) and by using a software program like Electromagnetic Transients Program (EMTP) or good mathematical programming software as discussed in great detail in [3]. The phase frame of reference approach allows modeling of complex cable installations where the protection engineer can introduce additional complexities such as multiple cable sections with sheath and/or core transpositions, different sheath grounding methods, the presence of a ground continuity conductor, core-to-sheath or core-to-sheath-to-ground faults, and faults through an impedance.

The positive-sequence impedance of underground cables is much lower than the positive-sequence impedance of overhead lines in ohms per unit of length. In some cases, the total cable circuit positive-sequence impedance may be less than the minimum distance relay setting range value. The cable zero-sequence impedance angle is also much lower than the zero-sequence impedance angle for overhead lines. Therefore, zero-sequence angle compensation requires a complex zero-sequence compensation factor and a large setting range that accommodates all possible cable and overhead line angles.

The ground current path for faults in the underground cable depends upon the cable sheath bonding and grounding method and any other conducting path(s) in parallel with the cable. The presence of water pipes, gas pipes, railways, and other parallel cables makes the zero-sequence current return path rather complex. All of the above factors make the zero-sequence impedance calculations often difficult to perform precisely and, in many cases, questionable, even with the use of modern computers. Therefore, many utilities perform field tests during cable commissioning to measure the zero-sequence impedance value of single-conductor cables.

Note that in overhead transmission lines, the positive- and zero-sequence impedances are proportional to distance, assuming the total line length has homogeneous tower geometry, line conductors, and earth resistivity. However, this is not true for underground cables, where the zero-sequence impedance may be nonlinear with respect to distance [1]. The zero-sequence compensation factor ($k_0$) for solid and cross-bonded cables is not constant for internal cable faults, and it depends on the location of the fault along the cable circuit. Because ground distance relays use a single value of $k_0$, the compensated fault loop impedance displays a nonlinear behavior [2].

Distance relay element application for cable protection requires knowledge of cable electrical parameters and cable grounding and bonding methods, as well as a good understanding of the relay functionality. Calculating the compensated ground loop impedance seen by ground distance relays for ground faults along the cable or in mixed conductor technology circuits is very important in determining appropriate relay settings to discriminate internal from external faults and faults in the cable section of the mixed conductor technology circuit.

Let us look at the A-phase compensated ground loop impedances of the underground cable shown in Fig. 1. The cable in this example is a 3,000 meter, 230 kV, single-conductor 1,200 $mm^2$ solidly bonded copper cable [3]. The cable sheaths are solidly grounded at both ends of the cable. For this reason, the compensated ground loop impedance varies continuously without any discontinuities for internal or external cable faults [2].

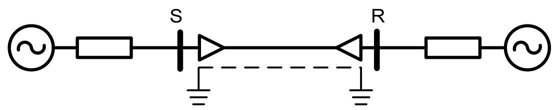


Fig. 1. Solidly bonded cable with sheaths grounded at cable ends.

Fig. 2 and Fig. 3 show the A-phase compensated ground loop impedances for the sending and receiving ends, respectively, with a ground zero-sequence current compensation factor of $k_0 = 0.66\angle 0°$.

There are two ground fault current return paths for faults that involve the cable core with its own sheath. The first path is directly in the faulted cable sheath. The second path is the faulted cable sheath, the sheaths of the other two phases of the cable, and the ground via the grounding of the sheaths at the cable ends.

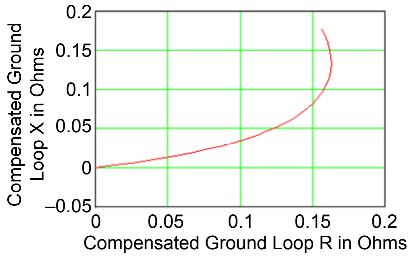


Fig. 2. Bus S compensated ground loop impedance ($k_0 = 0.66\angle 0°$).

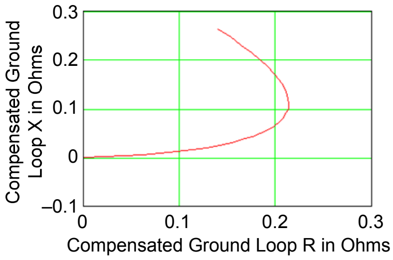


Fig. 3. Bus R compensated ground loop impedance ($k_0 = 0.66\angle 0°$).

Fig. 4 and Fig. 5 show the sending-end (Bus S) compensated ground loop resistance and reactance ($k_0 = 0.66\angle 0°$). Note that the A-phase-to-ground faults are applied every 300 meters along the cable length, starting with $m = 0$ pu at the sending end (Bus S) and $m = 1$ pu at the receiving end (Bus R).

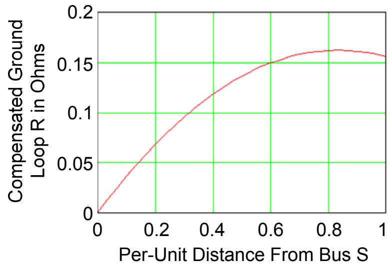


Fig. 4. Bus S compensated ground loop resistance ($k_0 = 0.66\angle 0°$).

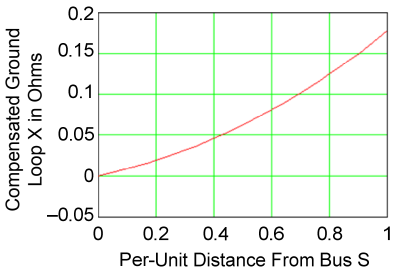


Fig. 5. Bus S compensated ground loop reactance ($k_0 = 0.66\angle 0°$).

Next we look at the compensated ground loop impedances of the same cable with a cross-bonded arrangement. The cable consists of three minor sections (1,000 meters each). The sheaths are transposed at each section and solidly grounded at each cable end.

Fig. 6 shows the compensated ground loop resistance, and Fig. 7 shows the compensated ground loop reactance in ohms as seen from Bus S. The ground current compensation factor was set to $k_0 = 0.66\angle 0°$ for illustration purposes, which is typical of a transmission line where the zero-sequence impedance is three times the positive-sequence impedance.

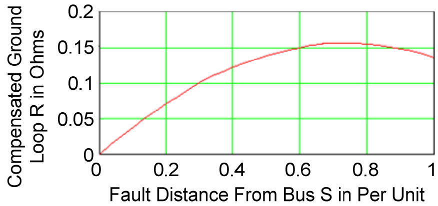


Fig. 6. Compensated ground loop resistance ($k_0 = 0.66\angle 0°$).

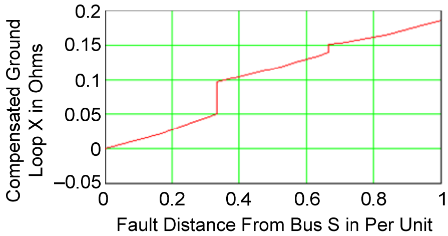


Fig. 7. Compensated ground loop reactance ($k_0 = 0.66\angle 0°$).

Note that in cross-bonded cables where the sheaths are transposed at each section and grounded at both cable ends, the compensated loop resistance is not the maximum for a fault at the remote end. Note also that moving the fault from the end of a section to the beginning of the next section causes a different return path for the ground fault current and, consequently, causes a discontinuity in the compensated ground loop impedance. This discontinuity, shown in Fig. 7, offers some advantages in obtaining selectivity for a Zone 1 distance element for faults in the last section. Note that the discontinuity is more pronounced when the fault is moved from the first to the second section.

Ground distance elements measure fault impedance in terms of positive-sequence impedance only. Set the zero-sequence current compensation factor so that the Zone 1 ground distance elements do not see faults external to the protected cable, while the Zone 2 and Zone 3 overreaching ground distance elements see all internal cable faults and coordinate with distance relays on adjacent line or cable circuits.

The choice of a zero-sequence current compensation factor can influence the reach and performance of ground distance elements. Choose a zero-sequence current compensation factor that obtains a constant or increasing slope of the compensated ground loop reactance for faults at the end of the cable. Additional setting guidelines for protecting underground cables are provided in [1], [2], [3], and [4].

Although most of the discussion thus far has been on ground distance elements, phase distance elements can also be affected by large capacitive charging currents. Large charging currents could result in an overreaching effect of a Zone 1 phase distance element.

Protecting underground cables with distance relays can be quite challenging and difficult to achieve because of cable electrical characteristics, the influence of grounding methods and return currents in the zero-sequence impedance of the cable, the nonlinear behavior of the compensated ground loop impedance, and the short cable length in many applications. For all these reasons and the complexities involved in calculating the proper settings, most users prefer to protect HV and EHV underground cables using line current differential protection schemes.

### 2.2 Current differential protection

Current differential protection is the best protection principle because it is secure, sensitive, fast, and easy to apply. A current differential protection scheme compares the currents from a local terminal with the currents received through a communications channel from a remote terminal to determine whether the fault is inside or outside the underground cable zone of protection.

Current differential protection is most frequently applied to protect cables because this scheme is less dependent on cable electrical characteristics. The current differential scheme requires a wide-bandwidth communications channel to transmit and receive current information to and from the remote terminal. Its availability depends on channel availability. The current differential scheme does not provide backup protection. However, modern digital line protection relays integrate the current differential scheme with a full distance protection scheme and include other functions such as sequence differential elements, sequence directional elements, communications-assisted protection logic, charging current compensation, and current transformer (CT) saturation detection to maintain security during external faults [5].

The current differential principle is immune to power swings and current reversal conditions. The relaying settings for current differential schemes are few and easy to compute.

### 2.3 Phase comparison protection

Phase comparison relaying schemes compare the phase angles of the local and remote terminal line currents. Therefore, this scheme requires a communications channel. Like the current differential relaying scheme, the phase comparison scheme depends on communications channel availability.

Phase comparison relaying schemes are either of the segregated phase or the composite type. Phase angle comparison is performed on a per-phase basis in the segregated phase comparison scheme. All other phase comparison schemes use a composite signal that is a function of the positive-, negative-, and zero-sequence currents to provide protection for all fault types. In this scheme, the composite signal is passed through a squaring amplifier to obtain a square wave signal that contains phase angle information. The relay compares the local squared signal against the remote squared signal; if the coincidence angle of the two signals is greater than a certain value (e.g., 90 degrees), the scheme declares an internal fault condition.

This scheme has been very popular in the past because it has minimal communications channel requirements. Because the current signals contain phase angle information, this scheme is more secure than the current differential scheme for external fault conditions with CT saturation. Although the sensitivity of the phase comparison relaying scheme is normally lower than that of the current differential relaying scheme, all other characteristics are the same.

### 2.4 Directional comparison protection

Directional comparison schemes compare the fault direction information from both ends of the cable to determine whether the fault is internal or external to the cable zone of protection. Directional comparison schemes use phase distance, ground distance, and zero- or negative-sequence directional elements at each end of the cable circuit [6].

Directional comparison schemes require a communications channel for the exchange of directional information between terminals to provide high-speed protection for the entire cable circuit. The minimum channel requirements have made this scheme, both blocking and unblocking types, very popular in cable protection applications. Loss of the communications channel only disables directional comparison functions. It does not disable directional overcurrent or distance protection functions for local and remote backup.

Directional comparison schemes require both voltage and current inputs. It is a good practice to avoid using relay elements that depend on the cable characteristics in directional comparison schemes. Ground distance element settings and measurements depend, to a great degree, on the cable characteristics and the ground current return path.

Modern digital relays have, in addition to ground distance elements, zero- and negative-sequence directional elements available for cable protection. Negative-sequence directional elements provide excellent fault resistance coverage.

## 3 Cable protection applications

In this section, we look at a number of cable protection application examples and offer some recommendations for protecting underground cables, including other considerations, such as autoreclosing in mixed overhead and underground cable circuits.

### 3.1 Circuits consisting of underground cables only

The most common protection for circuits consisting of underground cables only is line current differential. Typically, in such a circuit, two line current differential relay schemes, a Main One and a Main Two system, are applied, each one interfacing with a digital communications channel connected to separate and independent communications paths. For instance, one may be on a directly buried fiber cable and the second on a multiplexed fiber or a digital microwave communications network. Overreaching time-delayed zones of phase distance protection and directional overcurrent elements typically provide backup protection in both Main One and Main Two protection systems.

Modern digital relays include many protection functions, including the capability for relay-to-relay communications. A user can choose several relay functions to provide high-speed protection of the underground cable. For example, a user can use the current differential function of the digital relay with a high-bandwidth digital communications channel and a directional comparison pilot scheme, taking advantage of the relay-to-relay communications, distance elements, and negative-sequence directional elements that are included in the same digital relay.

This application could also have direct transfer tripping for breaker failure conditions on the same digital channels, taking advantage of relay-to-relay communications. Autoreclosing is not typically allowed because the protective circuit consists of an underground cable only.

### 3.2 Cable circuits terminated in transformers

Quite often, EHV cable circuits terminate in transformers to serve the load of a major metropolitan area. In some applications, the transformers do not have a high-voltage-side breaker, as shown in Fig. 8.

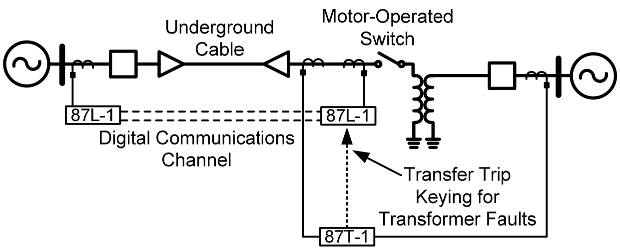


Fig. 8. EHV cable terminated in a transformer.

In such applications, the Main One and Main Two cable protection systems could consist of either current differential protection and/or directional comparison protection schemes, using phase distance and negative-sequence directional elements for sensitive ground fault protection. Overreaching time-delayed zones of distance protection and directional overcurrent elements provide backup protection in both Main One and Main Two protection systems. Again, digital communications channels can provide the wide bandwidth required for current differential protection scheme(s) or for the directional comparison scheme(s). Fig. 8 does not show the Main Two protection system.

The lack of high-side breakers in the transformer make it necessary to directly transfer trip the remote terminal in case of transformer faults. Typically, this arrangement requires two transfer trip channels to ensure that one channel is always available in case of required maintenance or communications system outages.

In these types of applications, we can take advantage of digital relay-to-relay communications and send the direct transfer trip (DTT) bits for transformer faults to the remote station using the same digital channels that are used for the line current differential or the directional comparison scheme [7]. This way, we can eliminate all four sets of transmitters and receivers that would have been required for the cable and transformer protection. This solution reduces installation and maintenance costs, while at the same time increases the protection system reliability.

Likewise, autoreclosing is not appropriate because the protective section consists of an underground cable only.

### 3.3 Mixed overhead and underground cable circuits

Protection schemes for mixed overhead transmission line(s) with underground cables are similar to the protection schemes for HV and EHV transmission lines. One important difference from cable circuits is that many users allow high-speed reclosing if the overhead line length is much greater than the underground cable length. Systems where the cable length is less than 15 to 25 percent of the total circuit length may have autoreclosing.

Another important factor is whether the cable portion is at the beginning of either terminal or whether it is between two overhead line sections. In Fig. 9a, the cable is at the beginning of the transmission line, and the line length is much longer than the cable section length. In this application, two instantaneous Zone 1 elements are set at the relay near the cable terminal to discriminate between faults in the cable and the overhead line section and to block autoreclosing for cable faults. The first instantaneous Zone 1 element ($Z_{1\text{-}1}$) is set at 120 to 150 percent of the cable positive-sequence impedance. Operation of this element trips the local breaker and sends a DTT to the remote terminal to trip the remote breaker and block its high-speed reclosing. In addition, the $Z_{1\text{-}1}$ element blocks high-speed reclosing at the local terminal. The second instantaneous Zone 1 element ($Z_{1\text{-}2}$) is set at the typical Zone 1 reach, which is 80 percent of the total cable plus overhead line positive-sequence impedance. For faults in the $Z_{1\text{-}2}$ zone and not in the $Z_{1\text{-}1}$ zone, the relay sends a DTT to trip and to allow high-speed reclosing at the remote end for single-line-to-ground faults.

In Fig. 9a, at the terminal farther away from the cable, the distance relay has only one Zone 1 element ($Z_1$). The reach of this element is set at 80 percent of the overhead line positive-sequence impedance. Operation of this element trips the local breaker, sends a DTT to trip the remote breaker, and allows high-speed reclosing. Operation of the overreaching Zone 2 element ($Z_2$) trips the local breaker and blocks its high-speed reclosing.

If the underground cable is of the pipe type, reclosing may be prohibited unless line current differential schemes are protecting the cable portion separately, as shown in Fig. 9b. In such a case, we can positively identify that the fault is on the cable circuit and, via communications, block autoreclosing at the two ends of the line.

When the cable is very short (for instance, less than 300 meters) and not a pipe-type cable, some users ignore the cable and allow high-speed reclosing because they assume that the majority of the faults will be on the overhead line section. In some cases, it is economical for short cable lengths to be thermally dimensioned for autoreclosing. However, for longer cable lengths, autoreclosing may or may not be feasible, depending on the thermal rating of the cable.

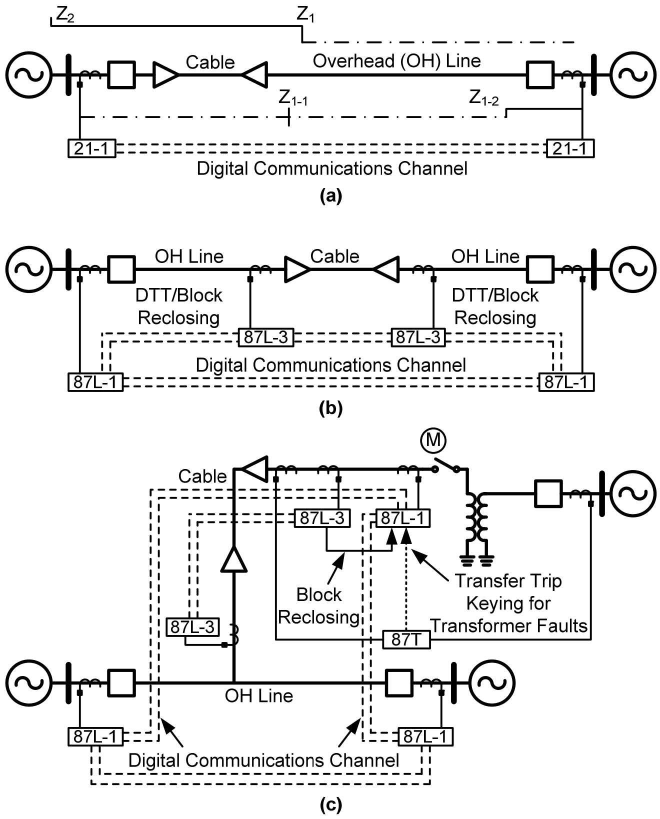


Fig. 9. Mixed overhead and underground circuits.

Fig. 9c shows a three-terminal application in which the cable is protected by a separate line current differential scheme for high-speed detection of cable faults and for blocking high-speed reclosing at the other two terminals. Fig. 9 does not show the Main Two protection systems. In all three examples of mixed overhead line with cable applications shown in Fig. 9, the protection and reclosing logic is quite complex. However, with modern digital relay communications capability and logic programmability, the task of designing a secure and dependable protection and high-speed reclosing scheme is greatly simplified.

Modern digital relays provide us a choice of many different relay elements for the protection of underground cables, some of which may be better suited than others. Supplementing ground distance elements with negative-sequence directional elements in a communications-assisted tripping scheme provides excellent resistance coverage for high-resistance ground faults, for example, during a flashover of a contaminated pothead. Use of negative-sequence directional elements has also been successful in a directional comparison scheme for the protection of submarine cables [6].

## 4 Conclusion

Current differential protection schemes with sequence current differential elements provide the best protection selectivity and sensitivity for cable and mixed conductor technology circuits.

Directional comparison schemes using distance elements, especially if they are supplemented with negative-sequence directional elements, ensure the required sensitivity for high-resistance faults.

Take special care when calculating ground distance element settings, including proper selection of the zero-sequence current compensation factor, because the zero-sequence impedance of the cable is not a linear function of the fault distance and is affected by cable bonding and grounding methods.

Apply modern relays that offer integrated line current differential protection, full distance schemes, negative-sequence directional elements, pilot scheme logic, and relay-to-relay communications. Functional integration in digital relays offers the most in cable protection.

Use relay-to-relay communications to create new protection schemes and to combine traditional schemes to reduce costs, increase reliability, and enhance performance of cable protection systems.

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