An Unlikely Pair? Combining Traveling Waves and Phasors for Reclosing on Hybrid Lines

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***Abstract*—Hybrid lines are lines with both overhead and underground sections. The double-ended traveling-wave fault location (DETWFL) method can be used on these lines to identify the faulted section and make reclosing decisions. If the fault is on the overhead section, reclosing is allowed to quickly re-energize the line after a temporary fault. If the fault is on the underground section, reclosing is blocked to prevent any further damage to the cable by the permanent fault.**

The DETWFL method, however, might not calculate a fault location during faults that occur at a voltage zero-crossing, as these faults do not generate traveling waves (TWs). The method also does not calculate a fault location if the local relay does not receive TW data from the remote relay due to a communication channel failure, or if a transformer is the only impedance behind one of the relay terminals under N–1 conditions. When the fault location is unknown, most applications choose to block reclosing even if the fault is on the overhead section.

This paper shows how distance elements can back up the DETWFL method when making reclosing decisions on simple hybrid lines, such as lines with one overhead and one underground section. The DETWFL method is the primary method, as it allows reclosing for a larger portion of the overhead section, compared to the distance elements. However, when the DETWFL method is unable to calculate a fault location, instead of blocking reclosing for all faults, the distance elements allow reclosing for those faults on the overhead section that are within its reach. The paper applies this principle to a 138 kV hybrid line and demonstrates its performance with field data.

I. INTRODUCTION

Hybrid transmission lines have both overhead and underground sections. They are commonly found in urban areas where the overhead line transitions to underground cable for a part of its run to cross densely populated areas, such as airports and highways, where it is difficult to get right-of-way. Because underground cables are 10 to 15 times more expensive to install than overhead lines [1], underground sections in hybrid lines are generally shorter than overhead sections.

Overhead lines primarily experience faults due to lightning, animals, bad weather, or tree branches. Because these faults are temporary and can clear on their own after the fault arc is extinguished, automatic reclosing is typically enabled on these lines. The automatic reclosing allows the line to be restored back to service after a temporary fault much quicker than is possible by manually closing the breaker.

Underground cables, on the other hand, experience faults due to aging insulation [2] or drilling/boring accidents. Because these faults are permanent and require human intervention to repair, automatic reclosing must be blocked to prevent any further damage to the cable.

Since hybrid lines have both overhead and underground sections, the question for protection engineers then becomes: should reclosing be enabled or disabled on such lines?

One philosophy is to disable reclosing altogether and avoid any risk of reclosing into a fault on the underground section [3]. Another philosophy is to simply ignore the underground sections and enable reclosing for the entire line if the lengths of the underground sections are significantly shorter than the lengths of the overhead sections. The assumption here is that, because the majority of faults will be on the overhead sections, the benefits of reclosing far outweigh the risks of reclosing into a fault on the underground sections. The most selective philosophy is to make reclosing dependent on which line section experienced the fault. Reclosing is allowed if the fault is on the overhead section and blocked if the fault is on the underground section.

One approach to identify the faulted section is to separately protect the underground sections with line current differential relays [4]. When the relays trip, indicating a fault on the underground section, a blocking signal is sent to the reclosing relays at the line terminals. This approach, however, is costly, as it requires installation of current transformers (CTs) at each transition between the overhead and underground sections.

A second approach to identify the faulted section is to use distance elements [4] [5]. In a simple hybrid line with one overhead and one underground section, distance elements can be enabled in the relay at the overhead line terminal to cover the overhead section. Reclosing is allowed only if the distance elements pick up. Alternatively, distance elements can also be enabled in the line relay at the underground cable terminal to cover the underground section. Reclosing is allowed only if the distance elements do not pick up. These distance elements are separate from the ones used for tripping the line.

The benefit of using distance elements is that they are available in the existing line relays at no additional cost. The security margin used when setting the reach of the distance elements, however, reduces the portion of overhead line on which reclosing can be enabled. In addition, this approach can be applied only on simple hybrid lines. If the hybrid line has multiple overhead and underground sections, this approach can become difficult and impractical to apply.

A third approach to identify the faulted section is to use fault location calculated by the double-ended traveling-wave fault location (DETWFL) method [6] [7] [8]. The DETWFL method calculates fault location by measuring when the traveling waves (TWs) launched by the fault first arrive at the local and remote line terminals [9]. The TWs can be measured by existing CTs at the line terminals but require installation of relays equipped with TW functions at both line terminals. A communications channel allows the relays to exchange TW arrival times at their respective terminals.

The benefit of the DETWFL method is that it is accurate to within a tower span. The high accuracy allows for smaller security margins, which in turn enables reclosing for a larger portion of the overhead line. The method can also be applied to hybrid lines with multiple overhead and underground sections.

The DETWFL method, however, might not calculate a fault location if the fault occurs at a voltage zero-crossing, as these faults do not launch TWs. The method also does not calculate fault location if the local relay does not receive TW data from the remote relay due to a communication channel failure, or if a transformer is the only impedance behind one of the relay terminals under N–1 conditions. When the fault location is unknown, most applications choose to block reclosing even if the fault is on the overhead section.

In this paper, we show how distance elements can back up the DETWFL method on simple hybrid lines and maximize the ability to reclose for faults on the overhead section. The DETWFL method is the primary method because of its higher accuracy and smaller security margins. However, when the DETWFL method is not available, instead of blocking reclosing for all faults, the distance elements allow reclosing for those faults on the overhead section that are within the reach of these elements. We apply this principle to a 138 kV hybrid line in this paper and demonstrate its performance during an actual fault.

II. REVIEW OF EXISTING TECHNOLOGY

Before we discuss how to combine the DETWFL method with distance elements, it is important to understand how each method identifies the faulted section of the line, how soon that decision is available, and how long that decision is maintained. We discuss these topics in the following subsections.

A. Identifying the Faulted Section Using the DETWFL Method

Fig. 1 shows the logic used by the DETWFL method to identify the faulted section of a hybrid line in [10] and [11].

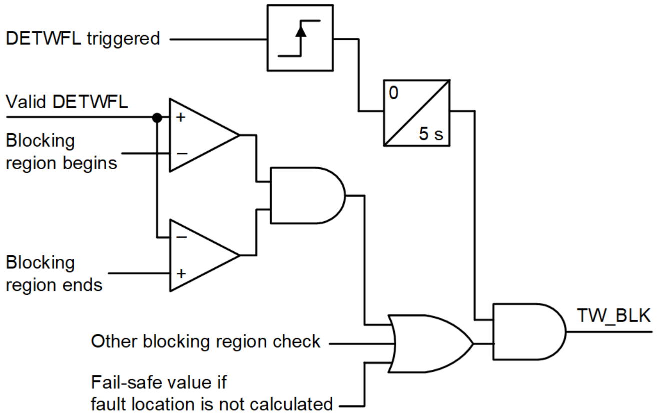


Fig. 1. Logic used by the DETWFL method to identify the faulted section of a hybrid line and make a reclose decision.

The logic uses blocking regions. On hybrid lines, the beginning and end locations of the blocking region are defined as the beginning and end locations of the underground section. If the line has more than one underground section, additional blocking regions can be defined.

A security margin is generally added when defining the beginning and end locations of the underground sections. The margin ensures that the logic always blocks reclosing for faults at the transition between the overhead and underground sections. Because the fault location estimated by the DETWFL method is accurate to within a tower span, this margin is small, typically 2 to 3 percent of the line or 0.6 miles, whichever distance is longer.

The logic makes its decision when an internal fault on the line triggers the DETWFL method to calculate a fault location. If the DETWFL method is able to calculate the location, the logic checks whether the fault location is inside or outside one of the blocking regions.

If the fault location is inside one of the blocking regions, the logic asserts TW_BLK, which can be used to send a blocking signal to the reclosing relay. If the fault location is outside of the blocking regions, TW_BLK remains deasserted, allowing the reclosing relay to reclose.

If the DETWFL method is unable to calculate a fault location due to a fault that occurs at a voltage zero-crossing, a communication channel failure, or a transformer behind one of the relay terminals under N–1 conditions, the logic defaults to the fail-safe value defined by the user. The fail-safe value can be set to either allow or block reclosing. This value is usually chosen to block reclosing to avoid any risk of reclosing into a fault on the underground section.

When the TW relays use direct fiber as the communications channel, the TW_BLK decision (allow or block) is available quickly, usually within 10 milliseconds after the fault. This decision is then maintained for the complete duration of the reclose sequence. (See dropout timer equal to 5 seconds in Fig. 1.) The assumption here is that faults usually do not evolve from the overhead to the underground section or vice versa during a reclose sequence.

B. Identifying the Faulted Section Using Distance Elements

Distance elements are widely used for protecting transmission lines. These elements calculate an apparent impedance using voltage and current phasors measured during a fault. When the apparent impedance is less than the reach, set as a percent of the line impedance, these elements assert within 13 to 32 milliseconds and remain asserted until the fault is cleared.

In addition to being used for line protection, distance elements can also be used to identify faulted sections of simple hybrid lines and make reclose decisions, as explained in [4] and [5]. Phase and ground distance elements can be set in the relay at the overhead line terminal to detect phase and ground faults, respectively, on the overhead section. (These distance elements are separate from the ones used for tripping the line.) If either of the distance elements picks up, the fault is on the overhead section, and reclosing is allowed. If none of the distance elements picks up, the fault is on the underground section, and reclosing is blocked.

Alternatively, phase and ground distance elements can be set in the relay at the underground cable terminal to identify phase and ground faults, respectively, on the underground section. If either of the distance elements picks up, the fault is on the underground section and reclosing is blocked. If none of the distance elements picks up, the fault is on the overhead section and reclosing is allowed.

The apparent impedance calculated by distance elements should, ideally, equal the line impedance to the fault. However, because of the error sources in Table I, and system conditions such as fault resistance, short lines, and mutual coupling, the apparent impedance might not equal the actual line impedance to the fault.

For this reason, when detecting faults on the overhead section, the distance elements in the relay at the overhead line terminal need to underreach the overhead-to-underground transition by a margin. When detecting faults on the underground cable section, the distance elements in the relay at the underground cable terminal need to overreach the underground-to-overhead transition by a margin. The margin is for security and ensures that the distance elements do not allow a reclose for a fault on the underground section, considering all possible sources of error.

The worst-case security margin when considering only the error sources in Table I is 26 percent for phase distance elements and 31 percent for ground distance elements. Additional margin is required for the system conditions (fault resistance, mutual coupling, and short lines) that will be discussed in Section III. The security margin required for the distance elements method is significantly greater than the security margin required for the DETWFL method. This high margin reduces the portion of the overhead section on which reclosing can be allowed by the distance elements, as compared to the DETWFL method.

TABLE I
SOURCES OF ERROR FOR DISTANCE ELEMENTS [12]

Error Source	Typical Reach Error (%)
Potential transformer (PT) error	5
CT error	10
Line impedance error	5 (phase distance) 10 (ground distance)
Relay transient error	5
Relay steady-state error	1
Total (worst-case additive)	26 (phase distance) 31 (ground distance)

III. COMBINING TWS AND PHASORS

Now that we have reviewed how to identify the faulted section with the DETWFL method and distance elements, we discuss the logic used to combine the two for simple hybrid lines. This logic needs to be programmed into the reclosing relay at the leader terminal. The leader terminal is the line terminal that recloses first to test the line, and the follower terminal is the line terminal that recloses second by voltage and synchronism checks only if the reclose by the leader terminal is successful [3]. Because the logic to identify the faulted section using both methods depends on which terminal is the leader terminal, the logic is first built with the overhead line terminal as the leader terminal. The logic is then built with the underground cable terminal as the leader terminal. Finally, the section discusses what factors protection engineers should consider when applying this logic.

A. Leader: Overhead Line Terminal

In the simple hybrid line shown in Fig. 2, the overhead line terminal is assumed to be the leader terminal. The logic to identify the faulted section using distance elements and the DETWFL method needs to be programmed in R1, which is the reclosing relay at the leader terminal.

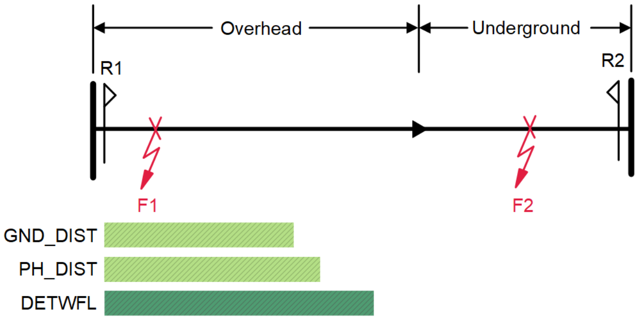


Fig. 2. Example hybrid line with first reclose from the overhead line leader terminal.

The portion of the overhead section on which reclosing is allowed by the phase or ground distance elements in R1, after including the security margins discussed in Section II, is shown shaded in light green. The portion of the overhead section on which reclosing is allowed by the DETWFL method, after including the security margins discussed in Section II, is shown shaded in dark green.

The logic combining the two methods to identify the faulted section is shown in Fig. 3.

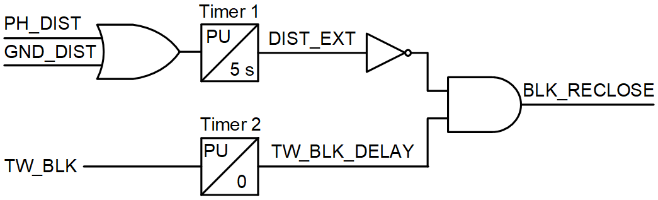


Fig. 3. Combined logic that identifies the faulted section from the overhead leader terminal and makes reclose decisions.

For faults on the overhead section, such as Fault F1 in Fig. 2, reclosing is expected to be allowed. If the DETWFL method is able to calculate a fault location, then the TW_BLK signal is zero, because the fault is on the overhead section. Based on the logic diagram in Fig. 3, if TW_BLK is zero, the logic to block reclosing is also zero, regardless of the decision of the distance elements.

If the DETWFL method is unable to determine the fault location due to one of the reasons outlined in the previous section, TW_BLK defaults to the fail-safe value and asserts (fail-safe value chosen to block reclosing). However, since the fault is at F1, the phase or ground distance elements pick up. This forces the output of the AND gate in Fig. 3 to be zero, allowing reclosing to occur.

For faults on the underground section, such as F2 in Fig. 2, TW_BLK asserts regardless of whether the DETWFL method is able to determine the fault location or not. Neither of the distance elements asserts. As a result, the output of the AND gate asserts and blocks reclosing.

In this manner, the logic in Fig. 3 gives priority to the DETWFL method when it is available and when it calls for a reclose. However, when a fault location cannot be determined by the DETWFL method, the distance elements provide a backup by allowing reclosing for faults on the overhead section but blocking reclosing for faults on the underground section.

In addition to the logic just discussed, there are two timers in Fig. 3. Timer 1 has a pickup time and a dropout time. The pickup time is necessary because distance elements can overreach during a poor coupling capacitor voltage transformer (CCVT) transient response to a fault. Timer 1 can be set to 25 milliseconds for security when CCVT transients are a concern (see [13] on how to determine if CCVT transients are a concern) and when the distance elements do not have inbuilt CCVT transient detection logic. It can be set to zero otherwise.

The dropout time in Timer 1 is necessary because the distance elements drop out as soon as the fault is cleared, while the decision of the DETWFL method is maintained for a duration of 5 seconds (see Section II). Having the dropout time also set to 5 seconds extends the decision of the distance elements and ensures reclosing for faults on the overhead section, even after the fault is cleared and the distance elements drop out.

Timer 2 has a pickup time and a zero-dropout time. The pickup time is necessary because the TW_BLK decision is available within 10 milliseconds after a fault occurs (when TW relays communicate over direct fiber), while the distance elements can take up to 32 milliseconds to assert (see Section II). The pickup timer delays the TW_BLK signal to ensure that if there is a fault on the overhead section and the DETWFL method is unavailable to calculate a fault location, the distance elements have time to assert and allow reclosing. Timer 2 can be set to slightly longer than the maximum expected operate time of the distance elements. An additional 25 milliseconds can be added to the pickup time when CCVT transients are a concern and the pickup timer of Timer 1 is set to 25 milliseconds, or the inbuilt CCVT transient logic of the distance elements is being used.

B. Leader: Underground Cable Terminal

In this section, we consider the same simple hybrid line with the underground cable terminal as the leader instead, as shown in Fig. 4. The logic to identify the faulted section using distance elements and the DETWFL method needs to be programmed in R2, which is the reclosing relay at the underground cable terminal.

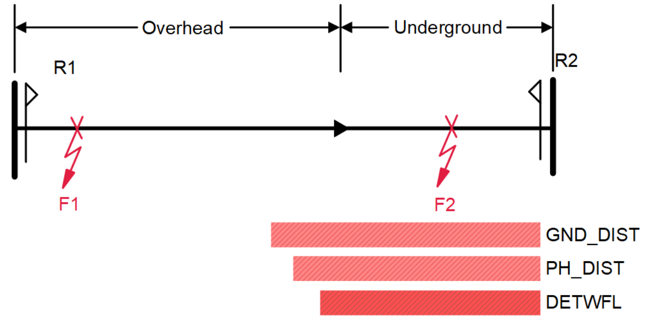


Fig. 4. Example hybrid line with first reclose from the underground cable leader terminal.

The portion of the line on which reclosing is blocked by the phase or ground distance elements in R2, after including all security margins discussed in Section II, is shown shaded in light red. The portion of the line on which reclosing is blocked by the DETWFL method, after including the security margins discussed in Section II, is shown shaded in dark red.

The logic combining the two methods to identify the faulted section is shown in Fig. 5.

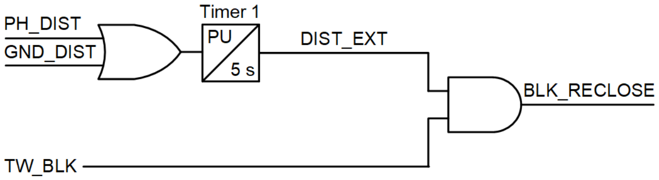


Fig. 5. Combined logic to identify the faulted section from the underground leader terminal and make reclose decisions.

For faults on the overhead section, such as Fault F1 in Fig. 4, the logic is expected to allow reclosing. If the DETWFL method is able to calculate a fault location, then the TW_BLK signal is zero, because the fault is on the overhead section. From the logic diagram in Fig. 5, if TW_BLK is zero, the logic to block reclosing is also zero, regardless of the decision of the distance elements.

If the DETWFL method is unable to determine the fault location, TW_BLK defaults to the fail-safe value and asserts to block reclosing (fail-safe value chosen to block reclosing). However, since the fault is at F1, the phase or ground distance elements do not pick up. This forces the output of the AND gate in Fig. 5 to be zero, effectively allowing reclosing to occur.

For faults on the underground section, such as F2 in Fig. 4, TW_BLK asserts whether the DETWFL method is able to determine the fault location or not. One of the distance elements also asserts. This makes the output of the AND gate assert to block reclosing.

The pickup time of Timer 1 is set the same as in Fig. 3 with one important difference. The purpose of the pickup time is to maintain dependability during CCVT transients rather than security. For Fault F1, if the DETWFL method is unable to determine a fault location, and if the distance elements overreach and pick up due to CCVT transients, the logic unnecessarily blocks reclosing, even though the fault is on the overhead section.

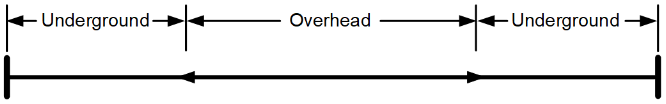
C. *Application Considerations*

In this subsection, we discuss what factors to consider when applying the logic developed in the previous subsections. First, we discuss the types of hybrid lines to which the logic can be applied. Then we discuss how fault resistance, short lines, and mutual coupling can affect the security and dependability of the logic, and what actions to take.

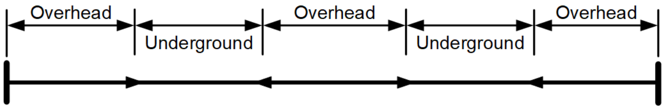
1) *Types of Hybrid Lines to Which This Logic Can Be Applied*

The logic in the previous two subsections was developed for simple hybrid lines, such as the one shown in Fig. 2. Hybrid lines can have multiple sections of overhead and underground cable in various locations, as shown in Fig. 6. Although the DETWFL method can accommodate hybrid lines with multiple underground sections, setting up the distance elements to back up the DETWFL method can become difficult and impractical on these lines. For such lines, the decision to reclose or not must be made solely by the DETWFL method.

(a) Underground cable sections on line ends



(b) Multiple underground and overhead sections



(c) Underground cable section in the middle

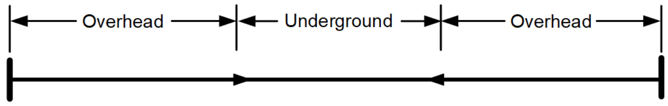


Fig. 6. Hybrid lines for which the distance elements cannot back up the DETWFL method.

2) *Short Lines*

For the purpose of setting protective relays, line length is generally defined in terms of its source-to-impedance ratio (SIR). The ratio is calculated by dividing the source impedance by the line impedance. Reference [12] describes how to correctly calculate the SIR. A line with an SIR less than 0.5 is considered a long line, a line with an SIR between 0.5 and 4 is considered a medium line, and a line with an SIR greater than 4 is considered a short line.

In the application described in this paper, when the overhead line terminal is the leader terminal, a short overhead section can cause the distance elements to overreach and challenge the security of the logic in Section III, Subsection A. Therefore, it is important to check for this condition and add additional margin to the underreaching distance elements to ensure that they never overreach and they never allow a reclose for a fault on the underground section. Engineers can use (7) in [14] to calculate this additional margin.

If the overhead section is too short, the underreaching distance elements might need to be disabled altogether. In such a case, the decision to reclose or not must be made solely by the DETWFL method.

When the underground cable terminal is the leader terminal, a short underground section with high SIR values can challenge the dependability of the logic in Section III, Subsection B. For example, in Fig. 4, if a high SIR causes the overreaching distance elements to overreach even farther into the overhead section and pick up for Fault F1, then the distance elements are unable to provide an effective backup to the DETWFL method when the method is not available. In such cases, the decision to reclose or not must be made solely by the DETWFL method.

3) *Mutual Coupling*

Mutual coupling in parallel lines can affect the reach of the ground distance elements and can cause them to overreach or underreach. When the overhead line terminal is the leader terminal, overreaching is a security concern for the logic in Section III, Subsection A, and underreaching is a dependability concern. When the underground cable terminal is the leader terminal, underreaching is a security concern for the logic in Section III, Subsection B, and overreaching is a dependability concern. Reference [15] offers practical advice on where mutual coupling needs to be considered and how to set the reach of the ground distance elements if mutual coupling is a concern.

4) *Fault Resistance*

Fault resistance can also affect the reach of the distance elements. When using the mho operating characteristic, distance elements generally do not overreach, but they can underreach during faults with fault resistance [12] [16]. This can cause dependability or security issues, depending on which line terminal is the leader terminal.

When the overhead line terminal is the leader terminal, if the distance elements underreach due to fault resistance, they can cause dependability issues for the logic in Section III, Subsection A. For example, Fig. 7 represents the line in two sections, with one lumped impedance as the overhead portion (Z_{OH}), and the other as the underground cable (Z_{UG}). An underreaching mho distance element covers a portion of the overhead section from the overhead line terminal to allow reclosing. (For simplicity, we do not show the other distance elements used for tripping the line.) Because of fault resistance R_F, Fault F1 despite being on the overhead section plots outside the mho operating characteristic. This means that if the DETWFL method is unavailable, the distance elements do not back up the DETWFL method and do not allow a reclose for this fault.

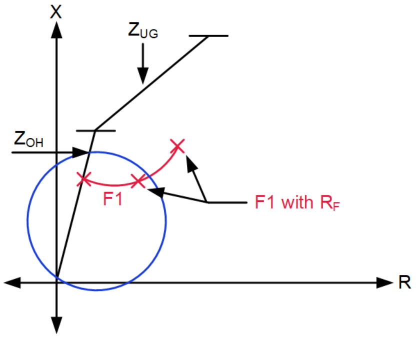


Fig. 7. Impedance diagram showing the impact of the fault resistance R_F on mho distance elements.

When the underground cable terminal is the leader, if the distance elements underreach due to fault resistance, it can cause security issues for the logic in Section III, Subsection B. Care must be taken when setting the overreaching distance elements so that they pick up for all faults on the underground section, even those with fault resistance. Reference [4] suggests adding additional margin, specifically, setting the reach of the overreaching distance elements to 150 percent of the cable impedance. Another option is to use the quadrilateral distance characteristic. Reference [12] describes how to set the quadrilateral characteristic.

IV. APPLICATION OF PROPOSED LOGIC ON A UTILITY'S HYBRID LINE

This section describes how the logic proposed in Section III was applied in the system of an electric transmission and distribution utility that serves a major metropolitan area. Two of the utility's 138 kV transmission lines are simple hybrid lines, with one overhead section and one underground section each. (The lines go underground to cross a large highway.)

The lines had experienced a total of four faults since being commissioned for service, all on the overhead sections. Three out of the four faults were temporary faults due to lightning. Despite this, protective relaying for the faulted line locked out after the initial trip, because the utility had disabled reclosing to avoid any risk of reclosing into a fault on the underground section.

With the advent of TW relays with DETWFL capabilities, the utility decided to install these relays on both lines and allow one reclose attempt if the fault was on the overhead section. The reclose attempt was intended to reduce outage durations and increase service reliability for temporary faults. The utility also decided to enable spare distance elements in their existing line relays to back up the DETWFL method and maximize the ability to identify the faulted section.

In this section, we describe one of the 138 kV hybrid lines, explain the existing protection scheme, and show how the logic scheme in Section III was applied to this line.

A. *Existing System*

Fig. 8 shows a simplified one-line diagram of the two-terminal hybrid line.

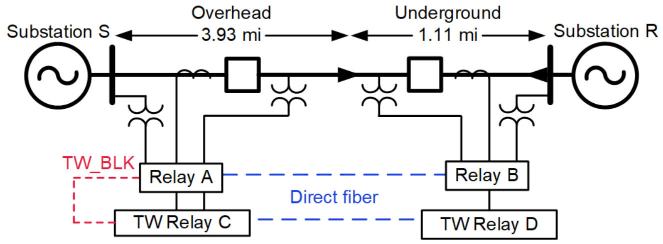


Fig. 8. Simplified one-line diagram.

The hybrid line has a total length of 5.04 miles and connects Substation S with Substation R. Out of the 5.04 miles, 3.93 miles are overhead, and 1.11 miles are underground. The underground section is made up of three solid dielectric cross-linked polyethylene (XLPE-type) cables with individual shields.

Table II shows the positive- and zero-sequence impedance of the underground and overhead line sections in ohms secondary. The underground cable impedances were measured by field tests at the time of commissioning and are known with a high degree of confidence. The table also shows the positive- and zero-sequence impedances of the sources behind Substation S and Substation R in ohms secondary.

TABLE II
SYSTEM DATA

System Component	Parameter	Value*
Overhead section	Length	3.93 mi
	Positive-sequence impedance	0.99∠79.09 Ω sec
	Zero-sequence impedance	2.91∠77.90 Ω sec
Underground section	Length	1.11 mi
	Positive-sequence impedance	0.14∠85.97 Ω sec
	Zero-sequence impedance	0.15∠28.61 Ω sec
Substation S source	Positive-sequence impedance	1.05∠85.72 Ω sec
	Zero-sequence impedance	0.71∠90.32 Ω sec
Substation R source	Positive-sequence impedance	2.67∠84.28 Ω sec
	Zero-sequence impedance	2.52∠81.06 Ω sec

[*] A CT ratio (CTR) of 400 and a PT ratio (PTR) of 1200 were used to convert all impedance values from ohms primary to ohms secondary.

The line is protected by primary and backup microprocessor-based line relays. For simplicity, only the primary relays, Relay A and Relay B, are shown in Fig. 8. The relays are programmed to trip on phase and ground line current differential elements. These elements are the preferred choice when protecting hybrid lines, because they are not affected by the nonhomogeneity of hybrid lines. The differential protection is performed over a direct fiber channel that runs below the overhead lines and is buried underground with the underground cables.

In addition to providing line current differential protection, the primary relays are programmed to trip on phase distance and directional ground overcurrent elements. These elements back up the line current differential elements in the event of a communications channel failure.

B. *Enabling Reclosing for Overhead Faults*

The utility decided to enable reclosing in Relay A and Relay B for faults on the overhead section. They also decided to make Substation S the leader terminal and Substation R the follower terminal. Because Substation S is the leader terminal, the determination of whether the fault is on the overhead or on the underground section must be made by Relay A, using the logic in Fig. 3.

Table III shows the reclose settings in Relay A and Relay B. Both relays are set for one reclose attempt. Relay A recloses first after 1 second only if BLK_RECLOSE is deasserted, the line is dead (indicating that the remote end has opened to clear the fault), and the bus is hot. If any of these conditions are not true, the relay goes to lockout.

Relay B, on the other hand, attempts a close after 10 seconds only if the line is hot (indicating that Relay A has reclosed and that the reclose was successful), the bus is hot, and the synchronism check condition across the breaker is satisfied. If any of these conditions are not true, the relay goes to lockout.

TABLE III
RECLOSE SETTINGS IN RELAY A AND RELAY B

Setting Description	**Relay A**	**Relay B**
Enable reclosing	Y	Y
Number of shots	1	1
Open interval	1 second	10 seconds
Drive to lockout	BLK_RECLOSE	—
Close supervision	DEAD LINE AND HOT BUS	HOT LINE AND HOT BUS AND SYNCHRONISM CHECK

To implement the BLK_RECLOSE logic, the utility enabled additional phase and ground distance elements in Relay A to identify the faulted section. They also installed TW relays with DETWFL capability (Relay C and Relay D) at both ends of the line, as shown in Fig. 8. The TW relays communicate over a spare fiber channel available in the existing fiber run. The following subsections describe the settings for the DETWFL method, the distance elements, and the timers.

1) *DETWFL Method*

The DETWFL function was configured using the line length data in Table II and TW propagation times of 22 microseconds for the overhead section and 10.53 microseconds for the underground section. The TW propagation time of the overhead section was measured with a line energization test, as described in Appendix A. The TW propagation time of the underground section could not be measured (as explained in Appendix A). It was instead estimated by assuming that TWs travel at 55 percent of the speed of light on underground cables.

The blocking region was set equal to the length of the underground cable and a ±0.6-mile margin. (The blocking region started at 3.33 miles and ended at 5.64 miles.) Relay C was set to send TW_BLK to Relay A if the fault location estimated by the DETWFL method fell inside the blocking region. In cases where the fault location information is unavailable, the fail-safe setting was set to block reclosing.

2) *Distance Elements*

In Relay A, phase mho and ground mho distance elements were enabled to detect phase and ground faults, respectively, on the overhead section. The SIR seen by Relay A for the overhead section was 1.06 for three-phase faults and 0.58 for ground faults. Because these SIR values indicated that the overhead section was a medium line for both phase and ground faults, additional margin was not required for the distance elements. Because the line impedance values were known with a high degree of confidence, the worst-case margins listed in Table I were reduced, and the reach of the phase and ground distance elements was set to 80 percent and 75 percent of the overhead section, respectively.

3) *Timers*

The pickup time of Timer 1 was set to 0 milliseconds, because CCVT transients were not a concern. The pickup time of Timer 2 was set to 33.3 milliseconds, because the instruction manual for Relay A [17] indicated that the maximum operating time of the phase and ground distance elements was less than 33.3 milliseconds.

V. FIELD EVENT

After the BLK_RECLOSE logic was tested (see Appendix B) and commissioned for service, the logic was called into action a week later when there was a phase-to-phase fault on the line. Once the line relays tripped, Relay A called for a reclose after 1 second. When a different phase-to-phase fault occurred on reclose, Relay A tripped again and locked out. Because the reclose by Relay A was unsuccessful, Relay B did not reclose and went straight to lockout after 10 seconds.

The utility patrolled the overhead line section but did not find any visual evidence of the fault. Since there was a winter storm in the area at the time of the trip, the utility suspected that strong winds and icy precipitation had caused the overhead lines to gallop and create multiple phase-to-phase faults on the overhead section. After the line was successfully re-energized, the event reports from the line relays were analyzed to understand the sequence of events and evaluate the performance of the BLK_RECLOSE logic.

A. *Initial Fault*

Fig. 9 shows the event report from Relay A during the fault.

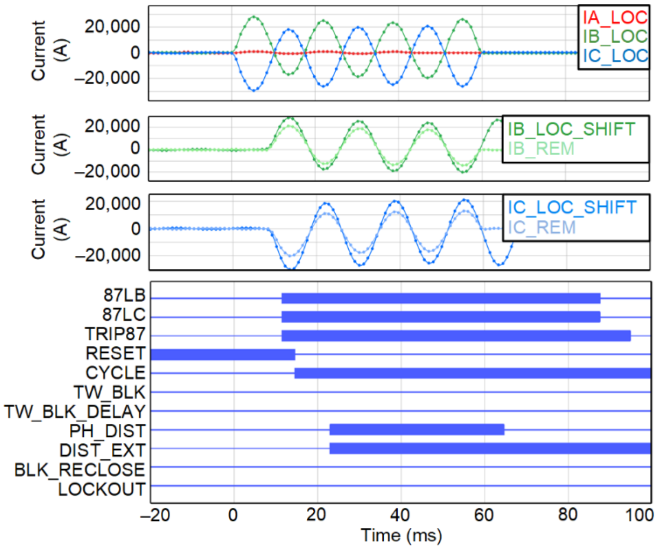


Fig. 9. Event report captured by Relay A.

The first graph in the event report shows the local phase currents that are used by the backup distance and ground directional overcurrent elements. The local B- and C-phase currents are equal and opposite to each other, indicating a BC fault.

The second and third graphs in the event report show the local B- and C-phase currents shifted in time to align with remote B- and C-phase currents, respectively. These currents are used by the 87L elements. The alignment is necessary to account for the delay in receiving the currents from the remote relay via the communication channel. The local and remote currents are in phase with each other and have different magnitudes, indicating an internal fault.

The fourth graph in the event report shows the response of the protection elements in Relay A. The B- and C-phase line current differential elements (87LB and 87LC) detected the internal fault and called for a trip. The relay identified the fault to be on the overhead section (BLK_RECLOSE = 0). As a result, after the relay tripped, it went from the reset to the cycle state and started timing on the first open interval. The following subsections walk through an evaluation to determine if this decision was correct.

1) Where Was the Fault?

To determine if the decision of the faulted section identification logic was correct, the first task is to establish the location of the fault. Fig. 10 shows the TW beta current of the faulted phases at Substation S and Substation R. Using the time stamps of when the TW beta current first arrived at Substation S and when it first arrived at Substation R, the DETWFL method estimated the fault to be at 2.64 miles from Substation S, which is on the overhead section.

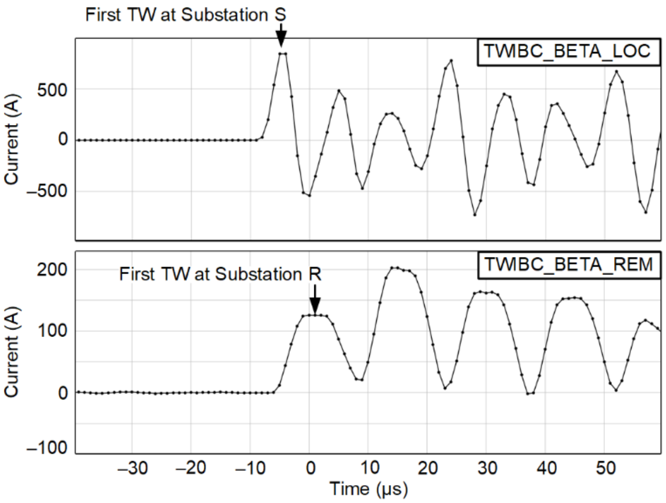


Fig. 10. TW beta current of the faulted phases at Substation S and Substation R.

2) Did the BLK_RECLOSE Logic Work as Expected?

Because the fault location estimated by the DETWFL method was outside the blocking region, Relay C correctly identified the fault to be on the overhead section and did not send a TW_BLK signal to Relay A, as shown in Fig. 9. As a result, Relay A correctly entered the cycle state after tripping on 87L and started timing on the first open interval.

The phase distance element also picked up for this fault, as shown in Fig. 11, and identified the fault to be on the overhead section. The actual line impedance to the fault was 0.67 ohms secondary (based on the fault location of 2.64 miles from Substation S), while the apparent impedance calculated by the relay was 0.64 ohms secondary. Because the BLK_RECLOSE logic gives priority to the DETWFL method when this method is available and calls for a reclose, the decision of the phase distance element did not play a role in this event.

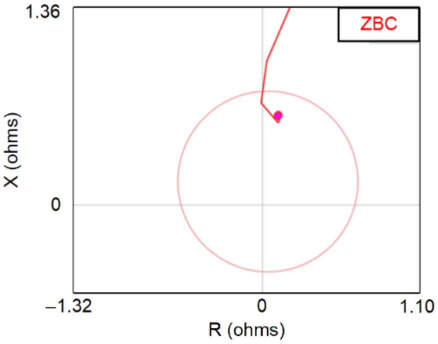


Fig. 11. Mho phase distance element picks up for the fault.

3) Would Relay A Have Reclosed if the DETWFL Method Was Unavailable?

To verify whether the phase distance element would have allowed a reclose should the DETWFL method have failed to calculate a fault location, the communication channels between Relay C and Relay D were intentionally disconnected and the fault events were replayed back to the relays. Relay C, unable to calculate fault location using the DETWFL method, defaulted to the fail-safe value and sent a TW_BLK signal to Relay A, as shown in Fig. 12. However, because the phase distance element picked up for this fault, BLK_RECLOSE evaluated to zero and allowed a reclose.

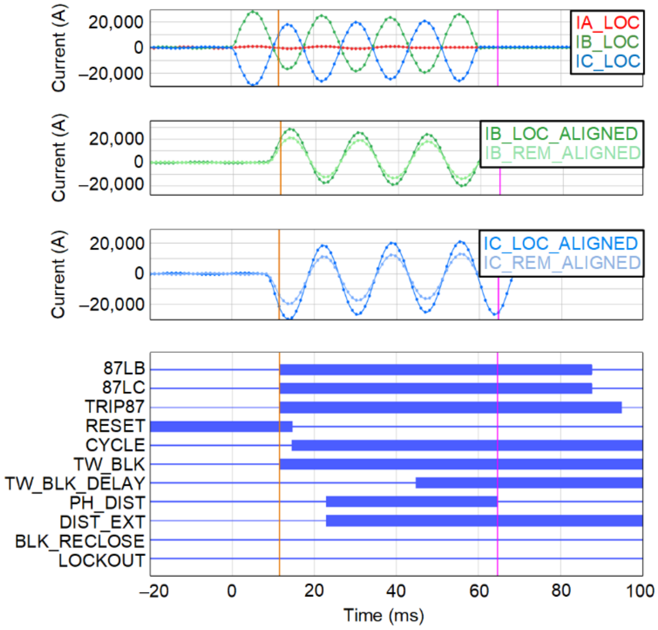


Fig. 12. Phase distance element allows reclose when DETWFL method is unable to calculate fault location.

4) Why Are Timer 1 and Timer 2 Needed?

Fig. 12 shows why Timer 1 and Timer 2 are needed to coordinate the DETWFL method with the distance elements. The TW_BLK decision arrived extremely fast, within 10 milliseconds after the fault began. However, the PH_DIST element took 23 milliseconds to assert for this fault. If Timer 2 did not delay the TW_BLK signal, the logic would have gone to lockout the instant that the TW_BLK signal was received by the relay (the location of the first vertical cursor in the report). By delaying the TW_BLK signal and using the TW_BLK_DELAY signal, the logic gave the distance elements enough time to operate and contribute to identifying the faulted section.

Similarly, when the fault was cleared, the PH_DIST element deasserted. The TW_BLK signal, on the other hand, stayed asserted for the next 5 seconds. If Timer 1 had not existed to extend the decision of the PH_DIST element by the same timespan, the logic would have gone to lockout the instant that the PH_DIST element deasserted (the location of the second vertical cursor). By extending the decision of the PH_DIST element for the entire reclose sequence, the logic ensured that reclosing was allowed.

B. Fault on Reclose

On reclose, Relay A saw an AB fault, as shown in Fig. 13. After tripping on Zone 1 distance, Relay A went to lockout, because the reclose scheme was set up for one reclose attempt. Because reclosing by Relay A was unsuccessful, Relay B never reclosed, but went straight to lockout soon after.

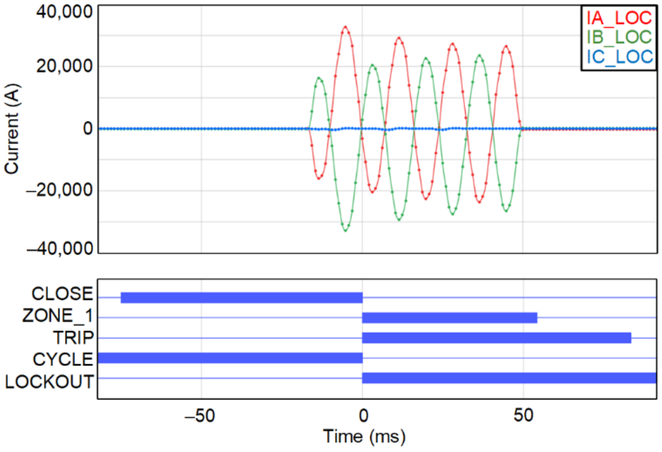


Fig. 13. Relay A sees an AB fault on reclose.

VI. Conclusion

The decision of whether to reclose or not is a challenge on hybrid lines. If reclosing is enabled, protective relaying for these lines runs the risk of reclosing into a fault on underground cable sections. If reclosing is disabled, protective relaying runs the risk of going to lockout for all internal faults, including temporary faults on overhead line sections.

The most selective approach is to use fault location, as estimated by the DETWFL method, to identify which line section experienced the fault and to allow a reclose only if the fault is on an overhead section. This method, however, might not calculate a fault location when there is a fault that occurs at a voltage zero-crossing, a communications channel failure between the local and remote relays, or a transformer located behind one of the relay terminals under N–1 conditions. When the fault location is unknown, most applications choose to block reclosing even if the fault is on an overhead section.

In this paper, we showed how distance elements can back up the DETWFL method for making reclose decisions on simple hybrid lines. The proposed logic gives priority to the DETWFL method, because it is more accurate and therefore allows reclosing for a larger portion of an overhead section, compared to the distance elements. However, when the DETWFL method is unable to calculate a fault location, instead of blocking reclosing for all faults, the distance elements allow reclosing for faults on overhead sections but block reclosing for faults on underground sections.

We developed the logic for two scenarios: when the overhead line terminal is the leader terminal, and when the underground cable terminal is the leader terminal. We also discussed how fault resistance, short lines, and mutual coupling needs to be considered when setting the distance elements to keep the logic secure and prevent a reclose when the fault is on the overhead section. We then applied the logic to a 138 kV hybrid line and proved that even though distance elements have a completely different operating principle than the DETWFL method, these two methods are not such an unlikely pair after all, and can complement one another to make reclose decisions on simple hybrid lines.

VII. Appendix A: Line Energization Test

TWs typically travel at a speed that is 98 percent of the speed of light on overhead sections and 55 percent of the speed of light on underground sections [8]. Using these typical values, the TW propagation time through the 3.93-mile overhead section in Fig. 8 is expected to be 21.53 microseconds and the TW propagation time through the 1.11-mile underground section is expected to be 10.83 microseconds. Although the actual TW propagation times should be close to the expected values, even a 1-microsecond error can result in a fault location error of as much as 500 feet for overhead lines and as much as 250 feet for underground cables. For this reason, it is best to perform a line energization test and measure actual TW propagation times. In this section, we describe the line energization test performed by the utility on their hybrid line. The line was energized from Substation S.

A. Expected TWs

It is important to first understand the TWs that are expected at Substation S during the line energization test. When the breaker at Substation S closes, the step change in voltage launches current TWs, as shown in Fig. 14. As one of the waves travels toward Substation R, it encounters the transition between the overhead and underground sections.

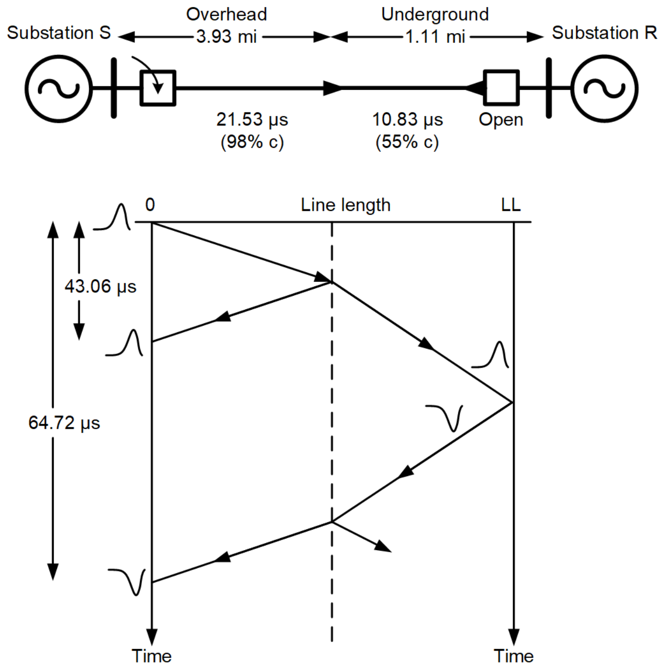


Fig. 14. Bewley diagram showing the expected TWs at Substation S during the line energization test.

Overhead lines have a higher characteristic impedance than underground cables [6]. This decrease in characteristic impedance at the transition causes a portion of the wave to be reflected back to Substation S with the same polarity as the first wave, while the rest gets transmitted toward Substation R.

The reflected wave reaches Substation S after a time equal to the round-trip time of the overhead section, which is expected to be 43.06 microseconds. Identifying this wave during the line energization test gives the actual round-trip time of the overhead section.

The wave transmitted toward Substation R reflects completely from the open breaker with an opposite polarity. After encountering the underground-to-overhead transition, a portion of this wave arrives at Substation S. The time difference between when this wave arrives at Substation S and when the breaker first closes is equal to the round-trip time of the hybrid line, which is expected to be 64.72 microseconds. Identifying this wave during the line energization test gives the actual round-trip time of the hybrid line.

Subtracting the actual round-trip time of the overhead section from the actual round-trip time of the hybrid line gives the actual round-trip time of the underground section.

B. Actual TWs

The next step is to look at the actual TWs recorded at Substation S during the line energization test and measure the TW propagation times. To do this, [10] recommends using the TW alpha current of the breaker pole that closed last, which is C-phase in this test. This current is shown in Fig. 15.

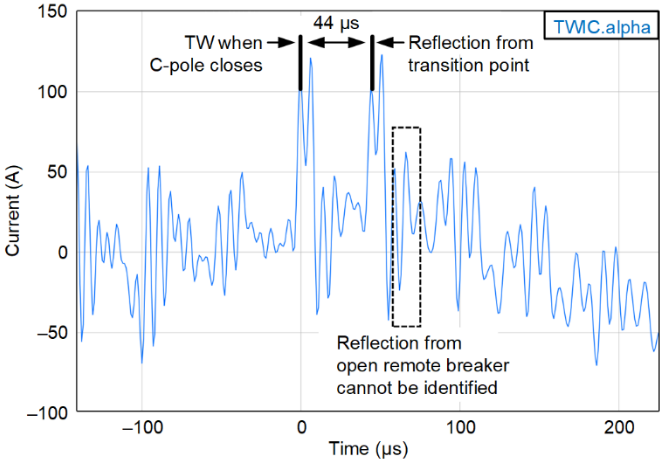


Fig. 15. C-phase TW alpha current at Substation S during the line energization test.

The first TW when C-pole closes is at the 0-microsecond mark. This wave has a positive polarity. After 44 microseconds, there is another TW with a large positive spike (same polarity as the first TW). Per the analysis in the previous subsection, this is the reflection from the overhead-to-underground transition. This means that the actual round-trip time of the overhead section is 44 microseconds. The one-way propagation time is therefore half this value, or 22 microseconds.

As mentioned in the previous subsection, we expect to see another TW with a large negative spike (polarity opposite to the first TW) at around the 64.72-microsecond mark. This wave would be the reflection from the open breaker. However, in the ±9-microsecond window around the 64.72-microsecond mark in Fig. 15, there is no TW with a large negative spike that stands above the noise. Most likely, this wave was lost due to attenuation and dispersion as it traveled through the underground section. It is for this reason that [6] recommends performing a line energization test from both ends of a line.

VIII. APPENDIX B: TESTING THE PROPOSED LOGIC

This section shows how the BLK_RECLOSE logic in Relay A was tested and verified. A test setup was used that was capable of injecting the TW relays, Relay C and Relay D, with nominal-frequency signals superimposed with high-frequency TWs. Fig. 16 illustrates this test setup.

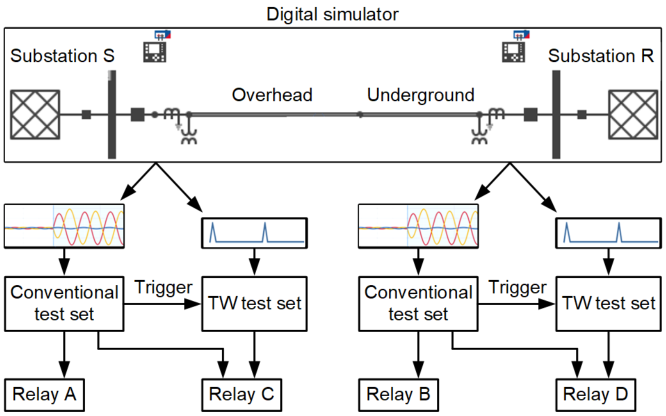


Fig. 16. Test setup.

TABLE IV
SUMMARY OF TESTS

Test Number	Description*	DETWFL	TW_BLK	Distance Elements	BLK_RECLOSE
1	AG fault at 4.49 mi; voltage peak	4.51 mi	Asserted	Deasserted	Asserted (pass)
2a	AG fault at 3.93 mi; voltage peak	3.97 mi	Asserted	Deasserted	Asserted (pass)
2b	AG fault at 3.93 mi; voltage zero	—	Asserted (fail-safe)	Deasserted	Asserted (pass)
3a	AG fault at 1.53 mi; voltage peak	1.56 mi	Deasserted	Asserted	Deasserted (pass)
3b	AG fault at 1.53 mi; voltage zero	—	Asserted (fail-safe)	Asserted	Deasserted (pass)

* All distances listed in the table are calculated from Substation S.

The hybrid line was modeled in a digital simulator, and faults were placed at different locations on the line and at different inception angles. (An inception angle of 90 degrees means that the fault is applied at voltage peak, while an inception angle of 0 degrees means that the fault is applied at voltage zero.) Based on the selections, the simulator automatically calculated the nominal frequency and TW signals that would be measured at each substation during the fault and sent the signals to a conventional test set and a TW test set for that substation.

The conventional test sets injected the nominal-frequency signals at Substation S to Relay A and Relay C and the nominal-frequency signals at Substation R to Relay B and Relay D. At the same time, they triggered the TW test sets to inject the TWs at Substation S to Relay C and the TWs at Substation R to Relay D. Because the TW test sets were triggered to inject by the conventional test sets, Relay C and Relay D measured fault signals in which the TW pulses were precisely superimposed on the nominal-frequency signals. For more details, see [18].

For Test 1, an AG fault was simulated in the underground section and located 4.49 miles from Substation S, with an inception angle of 90 degrees (voltage peak). This simulation was performed to ensure that BLK_RECLOSE asserted for this fault. Because a fault at voltage peak launches high-magnitude TWs, Relay C used the DETWFL method to calculate a fault location of 4.51 miles from Substation S. Since this was inside the blocking region, Relay C sent TW_BLK to Relay A.

Relay A received the TW_BLK block signal 9 milliseconds after the fault, as shown in Fig. 17. Timer 2 delayed this signal by 33.3 milliseconds to give the distance elements enough time to operate. During this time, the relay momentarily entered the cycle state. The ground distance element correctly identified the fault to be outside its reach, and did not assert. As a result, when TW_BLK_DELAY asserted at the end of 33.3 milliseconds, BLK_RECLOSE also asserted and drove Relay A to lockout.

For Tests 2a through 3b, AG faults were simulated at two other locations, one on the overhead-to-underground transition (3.93 miles from Substation S) and one on the overhead section (1.53 miles from Substation S). At each location, the fault was simulated at an inception angle of 90 degrees (voltage peak) and at an inception angle of 0 degrees (voltage zero). BLK_RECLOSE was expected to assert and block reclosing for the faults on the overhead-to-underground transition, and deassert and allow reclosing for the faults on the overhead section. The results are summarized in Table IV.

Test 2a was performed to verify that the distance elements did not overreach for a fault at the overhead-to-underground transition. Test 2b was performed to check if the DETWFL method successfully switched to the fail-safe value and blocked reclosing when it was unable to calculate a fault location at voltage zero. The purpose of Test 3a was to confirm whether or not the logic allowed a reclose for a fault on the overhead section. Test 3b was performed to check if the distance elements backed up the DETWFL method and allowed a reclose when the DETWFL method was unable to calculate fault location (due to the fault occurring at voltage zero).

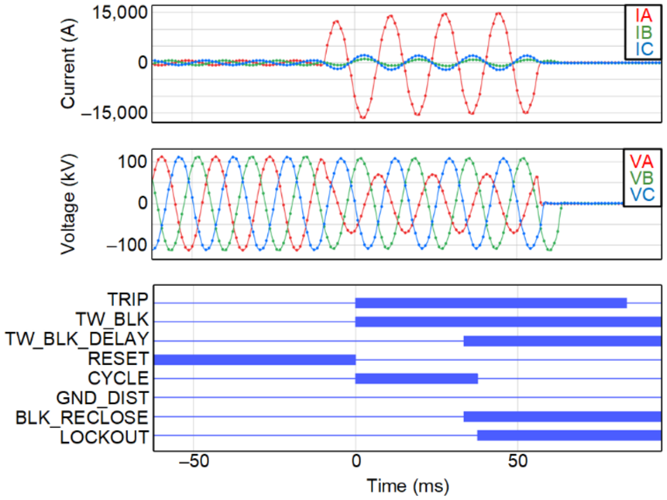


Fig. 17. Event report captured by Relay A during Test 1.

IX. ACKNOWLEDGMENT

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XI. BIOGRAPHIES

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