Whispers in the Underground: Detecting Incipient Cable Faults Before They Become Disastrous

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***Abstract*—Underground cable failures are sometimes preceded by incipient faults—short-duration, self-clearing current surges—caused by insulation degradation that are difficult to detect using conventional phasor-based protection. This paper presents a case study of two consecutive failures on separate 12.5 kV underground feeders supplying a power distribution center. In both cases, transient subcycle current bursts were observed weeks before permanent failures. We investigate these events and evaluate an incipient fault detection algorithm implemented in a modern microprocessor-based relay. The detection algorithm identifies short-duration overcurrent signatures, distinguishes them from benign transients, and provides actionable early warning of cable deterioration. We also present a protection scheme that combines phase-current and ground-current monitoring using a summing CT to improve detection sensitivity for underground cable faults. Our validation of the scheme, using real-world field event data, demonstrates its ability to detect incipient fault activity that would otherwise go unnoticed, enabling condition-based maintenance and reducing the risk of catastrophic cable failures.**

I. Introduction

Permanent failures in medium-voltage cable systems are sometimes preceded by short-duration, self-clearing current surges lasting between subcycle to one cycle of the power system frequency. These events, commonly referred to as incipient cable faults, are caused by localized insulation degradation, which produces a temporary fault path that extinguishes before developing into a sustained fault condition [1]. As the insulation deterioration progresses, these current surges happen more often until a permanent cable failure eventually occurs.

In the power systems studied in [2], between 10 and 15 percent of permanent cable failures were preceded by incipient cable faults. However, there are no data to determine whether similar percentages apply to different utilities, cable designs, installation methods, and operating environments. Nevertheless, the potential benefits of early warning increase as the percentage of permanent failures preceded by incipient fault activity increases.

Traditional phasor-based protective elements cannot dependably detect incipient cable faults. For example, if instantaneous overcurrent elements are set sensitively enough to detect incipient faults, they will also be activated by a multitude of normal power system events, such as the energization transients of transformers, motors, or other loads. This paper presents a case study of two underground cable failures that were preceded by incipient fault activity and evaluates a relay-based detection method designed to identify incipient cable faults. This detection method operates on instantaneous current samples rather than phasor quantities and creates a time-stamped log of current surges to show the progress of incipient faults [3].

Applying this detection method across a representative portion of the power system could reveal factors, such as cable construction, insulation materials, installation practices, and environmental conditions, associated with a high prevalence of incipient faults leading to permanent cable failures.

The remainder of this paper is organized as follows. In Section II we describe the system under study, including the power distribution center (PDC) configuration and the two underground cable failures that motivated this investigation. In Section III we present the incipient cable fault detection logic, including its operating principles, event classification method, and reporting functions. We validate the detection algorithm using replayed field event records and discuss the resulting relay performance in Section IV. In Section V we introduce a practical protection scheme that combines phase-current and ground-current measurements to improve the detection of underground cable incipient faults. Finally, in Section VI we summarize the key findings and conclusions of this work.

II. Power Distribution Center and Cable Failures

The study was performed on two feeders extending from a utility substation to a PDC. The PDC is a centralized electrical distribution facility designed to provide reliable, safe, and efficient power distribution to the end-user. It serves as the primary interface between the utility power sources and downstream electrical systems by receiving medium-voltage power, providing protection and switching capabilities, and distributing power through multiple feeders to various buildings. The PDC consists of two independent switchgear lineups, each supplied from a separate utility substation, as shown in Fig. 1. This dual-source configuration improves system reliability by providing two independent power sources and reducing the risk of a complete system outage due to a single utility source failure.

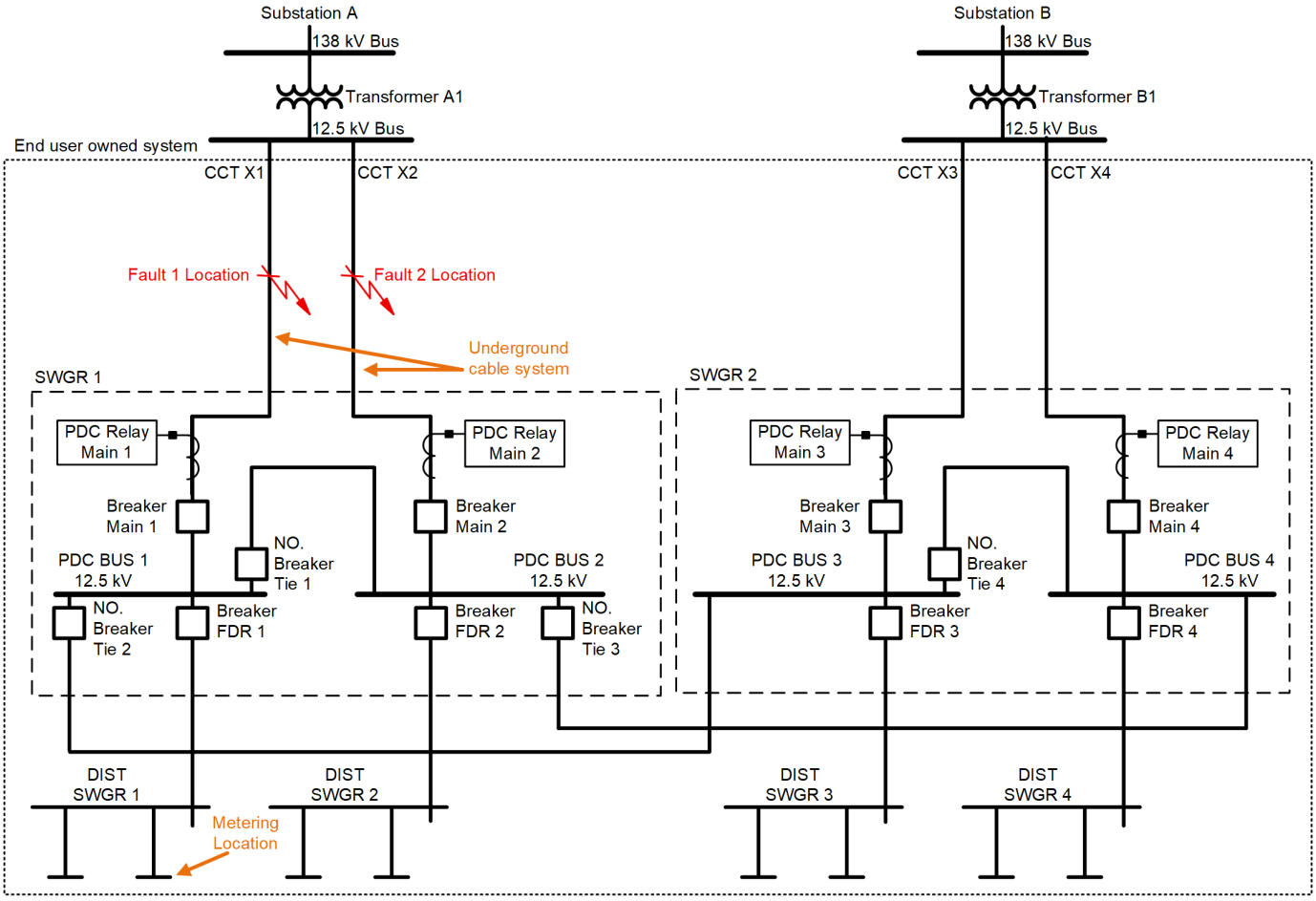

Fig. 1. Single line diagram of PDC.

The two switchgear lineups are interconnected through tie breakers, allowing operational flexibility and load transfer between the substations when required. The PDC design also supports future expansion by providing additional feeder capacity and allowing new loads to be integrated without major modifications to the existing electrical infrastructure.

Fig. 1 also illustrates the arrangement of the PDC buses, associated feeders, and tie connections. Each bus has two tie points, enabling alternate power paths during a substation feeder outage and thereby enhancing service continuity. The underground cables used in the PDC are single-conductor cables. Section V provides details of the cable configuration and includes an image illustrating the cable geometry.

The first cable failure occurred when one of the substation feeders supplying the PDC experienced a single-line-to-ground (SLG) fault within the underground duct bank system in Circuit X1, in Fig. 1 (CCT X1). Upon detection of the fault, the feeder protection at the utility substation operated as intended, isolating the faulted feeder. Following isolation, the PDC operators opened BREAKER MAIN 1 and then closed the designated bus tie connections (BREAKER TIE 1) to establish an alternate power path, thereby restoring service to the downstream distribution feeder without requiring an extended outage. Fig. 2 shows the extent of the cable damage.

Fig. 2. Damaged underground cable.

Approximately one month later, a second event occurred under similar conditions in CCT X2. The alternate substation feeder (CCT X2), which has been used to back feed the affected PDC bus, also failed due to an SLG fault within the same underground duct bank system. This second failure again resulted in the loss of supply to the associated PDC bus. By the time the damaged section of medium-voltage cable in CCT X1 was replaced, the bus was reconfigured back to its original operating state, and normal feeder assignments were restored.

A post-failure analysis was performed on the failed cable segment to identify conditions that may have contributed to the event. The investigation found evidence of localized thermal damage, corrosion products associated with the copper shield system, and indications that moisture had likely been present within the cable structure. Material testing confirmed that the cable insulation and jacket retained mechanical properties consistent with normal service performance, suggesting that the cable materials remained generally intact at the time of examination. While the precise sequence of events could not be definitively established, the findings support the conclusion that a combination of moisture ingress, corrosion development, and localized degradation likely contributed to the eventual breakdown of the cable insulation system and resulting failure. Overall, the analysis points to a degradation process localized around the failure site rather than a single identifiable initiating event.

These consecutive failures highlight the need for proactive monitoring, making early detection of cable deterioration essential for minimizing unplanned outages and improving overall system reliability. Effective application of early underground cable degradation detection methods, such as incipient fault monitoring, typically require measurements obtained at the upstream source of the feeder. In the system under study, these measurements are available through the feeder protective relay installed at the 12.5 kV side of the 138/12.5 kV utility substation transformer. However, as illustrated in Fig. 1, the feeder protection at the utility substation is owned and operated by the utility provider, while the underground feeder cable between the substation and the PDC is owned and maintained by the end user. Although the end user is responsible for the cable asset, they do not have direct access to the utility relay measurements, event records, or fault reports needed to implement conventional incipient cable fault monitoring techniques. Consequently, condition-based monitoring approaches that depend on upstream utility protection data are not practical.

Therefore, this study investigates whether incipient fault activity occurring on the underground cable between the utility substation and the PDC can be detected using only measurements available from a relay installed at the PDC (PDC Relay Main in Fig. 1). The proposed approach relies on local measurements, including phase-current signatures associated with load-side fault contributions and as discussed later in the paper, ground-current measurements obtained using a summing CT. This enables operators to monitor the upstream cable deterioration and provides for the early warning of emerging cable failures without requiring access to utility-owned protection systems or event data.

III. Incipient Cable Fault Detection Logic

This section describes a relay algorithm developed to identify incipient cable faults characterized by short-duration, subcycle overcurrent events. The logic is shown in Fig. 3 and will be referred to as 50INC logic.

A. Detection of Potential Incipient Fault Condition

The element continuously monitors raw instantaneous current samples from phase currents (IA, IB, and IC) and the neutral current (IN). The sampling rate is 32 samples per power system cycle, providing sufficient temporal resolution to capture subcycle phenomena.

An incipient fault condition is suspected when the absolute value of any monitored current exceeds a user-defined threshold for at least two consecutive samples, as indicated by 50INCA in Fig. 3. This corresponds to a minimum detection duration of 2/32 of a cycle, ensuring sensitivity to short-lived transients, while avoiding spurious pickups due to noise.

The pickup threshold is governed by the setting E50INC, which defines the overcurrent sensitivity for phase channels. To maintain equivalent sensitivity between phase and neutral elements, the relay applies a scaling factor to the neutral threshold based on the current transformer ratios (CTRs), shown in (1) and (2).

$$50INCTH_{PHASE} = E50INC \tag{1}$$

$$50INCTH_{NEUTRAL} = E50INC \bullet \frac{CTR}{CTRN} \tag{2}$$

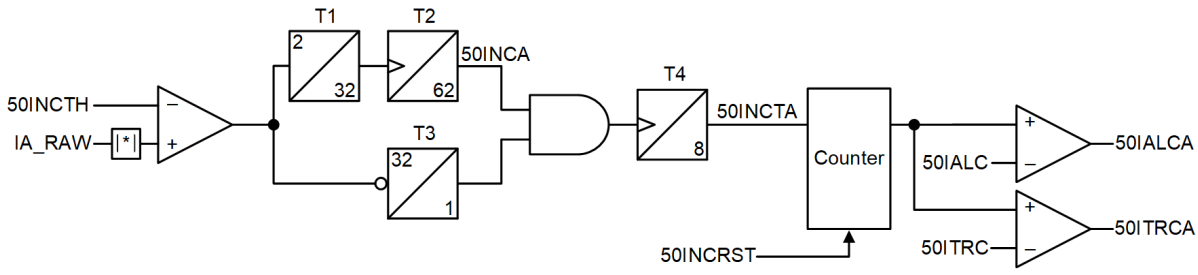

Fig. 3. Incipient cable fault detection (50INC) logic. Phase A logic is shown; Phase B, C, and neutral are the same.

Where *CTR* and *CTRN* represent the phase and neutral-CTRs, respectively. This normalization ensures that both phase and neutral elements assert for the same primary current magnitude. Note that this element is set considering the peak magnitude of the current measurements, not the RMS magnitude, as is normally applied with overcurrent elements, as shown in (3), where 50P is the overcurrent element setting in RMS.

$$E50INC = sqrt(2) \bullet 50P \quad (3)$$

B. Confirmation of an Incipient Event

If two consecutive absolute current samples exceed the corresponding threshold, the relay asserts the appropriate incipient overcurrent binary element, denoted as 50INCx (where x = A, B, C, N).

To control the detection process and avoid multiple triggers for the same disturbance, the logic incorporates a set of timers:

1) Timer T1 (Dropout: 32 Samples):

Ensures that the rising edge of the detection window occurs only once per overcurrent event. This prevents repeated triggering from successive half-cycles that may also exceed the threshold.

2) Timer T2 (Detection Window):

Defines the time interval during which the element evaluates whether the detected overcurrent corresponds to an incipient fault. This window includes up to one full cycle for initial detection and additional time for confirming self-clearing behavior (62 Samples).

3) Timer T3 (Clearing Verification):

Verifies that the detected overcurrent has completely cleared by ensuring that all current samples remain below the pickup threshold (50INCTH) for one full power system cycle (32 samples). Rather than simply checking for a momentary drop below threshold, T3 confirms that the current has returned to normal load conditions and remains below the threshold long enough to rule out a sustained fault condition. This verification step is important because an incipient fault is characterized by a short-duration, self-clearing current surge, whereas a permanent fault would continue to produce samples above the threshold.

The outputs of Timer T2 and Timer T3 are combined to assert Timer T4, indicating that a transient overcurrent event was detected and successfully classified as a potential incipient fault.

4) Timer T4 (Pickup Hold Timer):

Timer T4 extends the assertion of the incipient fault indication for a short period following detection. This ensures that transient detections produced by the fast-sampling logic are visible to logic functions that execute every 8 samples, allowing reliable event counting, reporting, and supervisory processing.

C. Self-Clearing Fault Identification

A key characteristic of incipient cable faults is their self-clearing nature [2]. The logic declares a detected event as an incipient fault if the following conditions are met:

1. Overcurrent is detected (via 50INCx assertion).
2. The current remains below the threshold for at least one full cycle (validated by T3).

D. Event Recording and Reporting

Upon successful detection of a self-clearing fault, the relay performs the following actions:

- Records the event in the history report.
- Increments the event counter corresponding to the affected phase.
- Stores key information, including:
  - Faulted phase (A, B, C, or N)
  - Total number of detected events per phase
  - Time stamps of individual events

An example record is shown in Fig. 4, providing valuable diagnostic insight into cable condition and fault progression trends. The report displays the date and time of each detected incipient fault event. The counters CNTA, CNTB, CNTC, and CNTN indicate the cumulative number of incipient fault detections recorded on phases A, B, C, and the neutral respectively. These counters allow operators to track the frequency and progression of incipient activity over time. The field INCF PHASE identifies the phase (A, B, C, or N) associated with the detected event, enabling the user to determine which conductor or current path exhibited the incipient fault signature. By maintaining a time-stamped history and cumulative event counts, the report provides useful information for trending cable conditions, identifying recurring fault activity, and supporting condition-based maintenance decisions.

#	Date	Time	CNTA	CNTB	CNTC	CNTN	INCF PHASE
1	16/07/2026	19:00:12.882	1	0	0	0	A
2	16/07/2026	19:04:12.224	1	1	0	0	B
3	16/07/2026	19:04:13.407	1	1	1	0	C
4	17/07/2026	19:18:11.074	2	1	1	0	A
5	17/07/2026	12:47:59.811	3	1	1	0	A
6	17/07/2026	12:48:00.669	3	2	1	0	B
7	17/07/2026	12:48:01.353	3	2	2	0	C
8	17/07/2026	12:48:06.951	4	2	2	0	A

LAST RESET = 05/07/2026 19:06:28.232

Fig. 4. An example 50INC Report Response.

E. Counter Management

The resetting of event counters and clearing of stored history is controlled by the 50INCRST setting, which is configurable as a logic equation. A rising edge on this signal resets all counters and clears the associated event records, enabling flexible integration with supervisory or maintenance logic.

F. Alarm and Trip Thresholds

To support condition-based monitoring and protection, the scheme includes configurable thresholds for alarming and tripping:

- 50IALC (Alarm Threshold): Generates an alarm when the number of detected incipient events on a given phase exceeds a predefined limit.
- 50ITRC (Trip Threshold): Initiates a trip signal when repeated incipient faults indicate a high probability of impending failure.

Each threshold has corresponding binary elements (50IALCx and 50ITRCx) for phase-specific indication. This allows operators to distinguish localized degradation and take targeted corrective actions. It is important to note that the 50INC element is intended primarily for radial system applications and does not include directional or reach functionality. Therefore, any application of the 50ITRCx output should consider these limitations and the overall protection philosophy of the system.

The described logic combines raw instantaneous current samples, configurable setting thresholds, and time-based validation to reliably detect and classify subcycle overcurrent events associated with incipient cable faults. By distinguishing self-clearing disturbances from sustained faults, the scheme enhances situational awareness, while minimizing unnecessary operations.

IV. Validation Results

The purpose of this validation is to demonstrate that the discussed incipient fault detection logic is capable of reliably identifying short-duration, self-clearing current signatures associated with real underground cable incipient faults. These events typically precede permanent insulation failure but are not detectable using conventional protection elements. Therefore, the validation focuses on confirming that the logic can detect subcycle and near-cycle current bursts, correctly classify them as self-clearing disturbances, and operate consistently for transient magnitudes that do not produce a conventional overcurrent response. The results also verify that the binary element indications align with the intended logic operation and provide meaningful diagnostic information.

To evaluate the logic under realistic system conditions, a replay-based testing approach was used. Three recorded COMTRADE events were selected to represent actual incipient fault behavior. Unfortunately, no upstream utility relay data related to the PDC discussed in the paper were available to characterize system conditions prior to the cable failures on the underground feeder supplying the PDC. However, a revenue meter located downstream of the PDC, as shown in Fig. 1, had previously captured several incipient fault events occurring within the end user system before these cable failures. These recordings, along with two additional events involving incipient activity from a different power system, were therefore used to validate the 50INC element.

The first event, shown in Fig. 5, was obtained from the monitored underground cable system associated with the PDC and represents a real incipient fault condition observed in the field. Multiple similar events were recorded on the same cable, although only one example is presented because the recorded signatures were nearly identical. The second and third events, shown in Fig. 6 and Fig. 7, captured on different underground cables, were included to demonstrate the range of transient characteristics and event durations associated with incipient cable faults. All events were recorded during normal system operation, confirming their self-clearing nature and suitability for validating incipient fault detection.

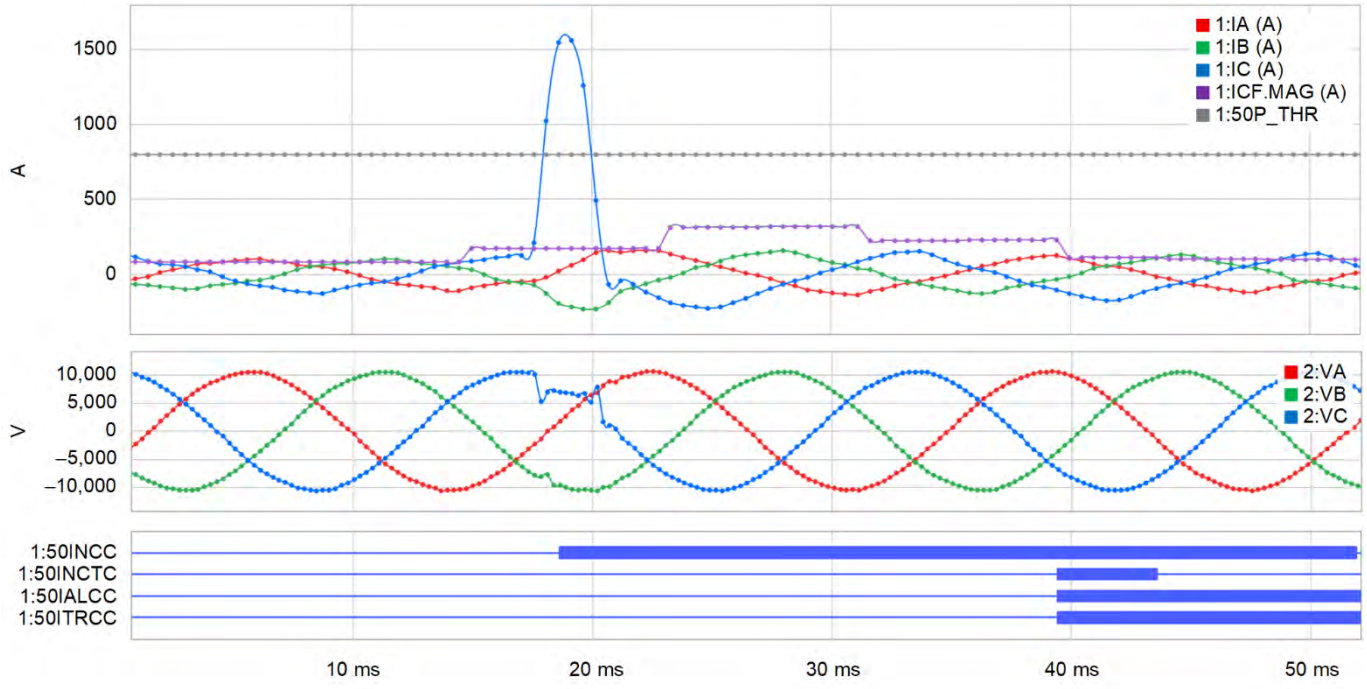

Fig. 5. Phase C 50INC event from the PDC underground cable. 50P_THR is the overcurrent pickup in RMS value for comparison.

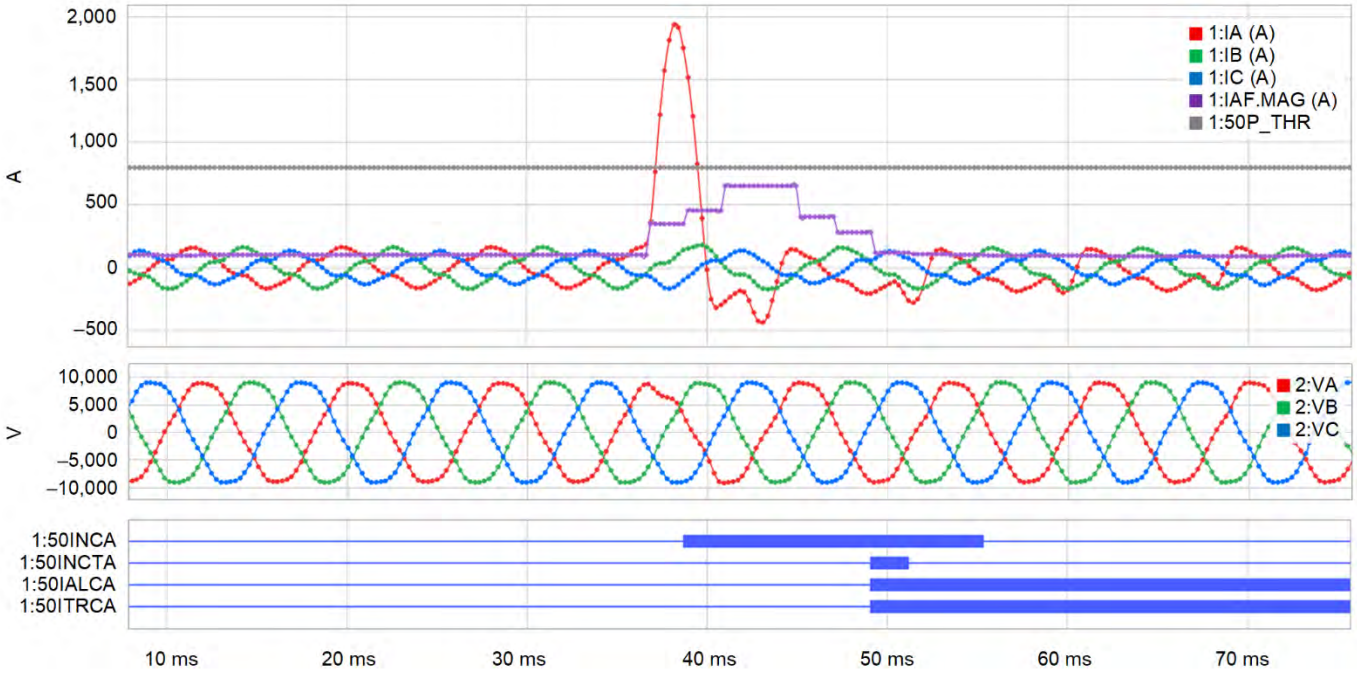

Fig. 6. Phase A 50INC event from a different underground cable. 50P_THR is the overcurrent pickup in RMS value for comparison.

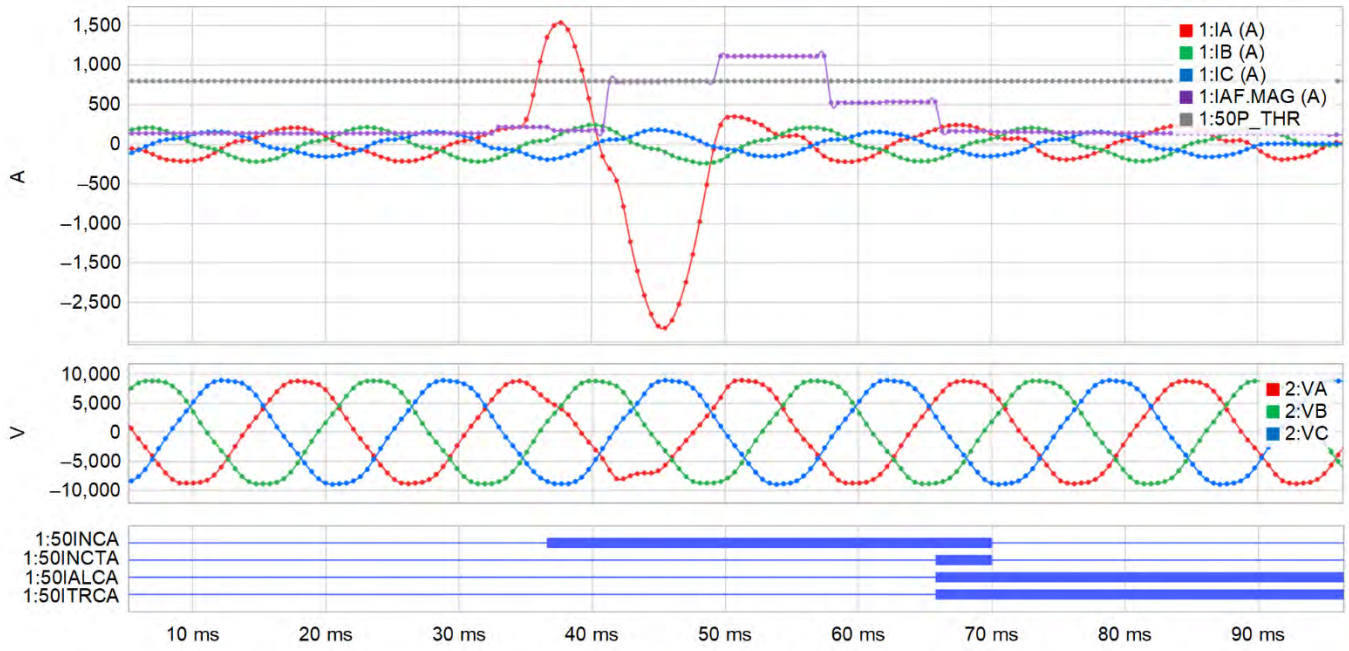

Fig. 7. Phase A 50INC event showing a different signature. 50P_THR is the overcurrent pickup in RMS value for comparison.

The validation was performed by replaying these COMTRADE records into a protective relay configured with the 50INC logic. During the replay, the instantaneous current waveforms preserved the original magnitude and timing characteristics of the field events, and the relay processed the signals at its native sampling rate. This ensured that the results reflect actual relay behavior under field-equivalent conditions. By observing the internal element assertions, timers, and binary elements during replay, it was possible to directly verify the performance of the detection algorithm. The voltage waveforms are included to provide system context and to demonstrate that these events do not exhibit the voltage depression or sustained fault characteristics typically associated with conventional shunt faults.

The relay settings were selected to provide a direct comparison between conventional overcurrent detection and the 50INC logic. The 50INC pickup threshold (E50INC) was set equal to the phase instantaneous overcurrent pickup (50P) derived from the application data, with a value of 4 A secondary corresponding to a CTR of 200. This approach ensures that both elements operate at the same sensitivity level, highlighting the difference in detection capability rather than differences in

pickup magnitude. The alarm and trip counters (50IALC and 50ITRC) were both set to one spike count for demonstration purposes.

The above presented results show that the 50INC logic successfully detects a range of incipient fault signatures with varying durations and waveform characteristics. In the event shown in Fig. 5, the current exhibits a very short-duration transient, lasting less than one-quarter cycle. Despite its short duration, the waveform includes at least two consecutive samples above the threshold, allowing the 50INC element to assert. The current then quickly returns below the pickup level and remains below threshold for at least one cycle, satisfying the self-clearing criteria defined by the logic. This confirms that the algorithm is capable of detecting extremely fast transients that are well below the operating window of conventional protection elements.

The event shown in Fig. 6 demonstrates another short-duration transient, with the overcurrent condition persisting for approximately quarter of a cycle. In this case, the 50INC element asserts in the affected phase, and the detection window defined by the internal timers captures the full duration of the event. The subsequent verification of current clearance confirms that the disturbance is self-clearing rather than a sustained fault. This behavior validates the ability of the logic to correctly classify events across a wider time range without misoperation.

The third event, shown in Fig. 7, illustrates a longer-duration (approximately 1 cycle) waveform signature characterized by a high-magnitude spike followed by oscillatory decay. Despite the distorted waveform shape and varying amplitudes, the logic continues to track instantaneous threshold crossings and asserts the 50INC element consistently. The clearing verification stage confirms that the event is transient, demonstrating that the algorithm is not dependent on sinusoidal waveforms or phasor estimation. This robustness is a direct result of operating on instantaneous sampled data rather than filtered quantities.

A key observation in the first two events (Fig. 5 and Fig. 6) is that, although the instantaneous current briefly exceeds the defined threshold, the effective magnitude remains below the conventional 50P pickup level. Traditional overcurrent elements use fundamental-frequency current measurements derived from finite impulse response filtering algorithms. These filters typically require a full cycle of fault current samples before producing an accurate estimate of the fault current magnitude. As a result, these short-duration current bursts may not produce sufficient current magnitude to trigger a conventional overcurrent response, making such elements inherently insensitive to incipient fault activity.

The observed binary element behavior in all tests aligns with the intended operation of the detection logic. The 50INCx bit, where *x* represents the monitored phase or neutral (A, B, C, or N), asserts when the instantaneous current exceeds the threshold for the required number of consecutive samples. The internal timing elements enforce a single detection per transient event and verify the self-clearing nature of the disturbance by confirming that the current falls below the threshold and remains below it for the required duration. This self-clearing verification is reflected in the proper dropout of the 50INCx bit following assertion, consistent with the clearing criteria defined in the logic. Upon successful classification, the alarm and trip indications are provided through the corresponding binary elements 50IALCx and 50ITRCx, respectively, where each bit asserts when the configured count threshold is met. This consistent sequence of pickup, validation, and indication across all test cases confirms that the logic performs as designed and provides reliable detection and reporting of incipient cable fault activity.

Overall, the relay-based validation using real field events demonstrates that the 50INC logic effectively detects short-duration, self-clearing current signatures associated with underground cable degradation. The results confirm that the scheme identifies events that are not detectable by conventional overcurrent elements, while maintaining consistent and predictable operation across a range of waveform characteristics and durations. This capability provides a practical means for early detection of cable deterioration and supports condition-based maintenance strategies to reduce the likelihood of catastrophic failures.

V. Proposed Protection Scheme for the PDC

This section describes the methods the end user plans to implement to improve the probability of detecting incipient fault signatures at the PDC. As discussed in Section II, feeder protection for the incoming feeders to the PDC is provided by relays installed at the upstream utility-owned substation. The utility owns and operates the substation equipment, while the underground feeder cable between the substation and the PDC is owned and maintained by the end user. The objective of this scheme is to use measurements available at the PDC relay to monitor incipient fault activity occurring on the upstream underground cable.

Although the end user does not have access to utility relay measurements or event records, the PDC relay can observe local current signatures associated with incipient faults on the upstream cable. In particular, momentary fault current contributions from downstream loads, especially motors, can produce detectable disturbances in the measured phase currents. Therefore, phase-based incipient fault detection is investigated using only measurements available at the PDC relay to identify these transient current signatures and provide early indication of cable deterioration.

For an incipient fault occurring on the underground cable between the substation and the PDC, the relay located at the PDC may not detect significant phase-current disturbances, particularly when there is little or no fault current contribution from downstream motor loads. Therefore, an alternative detection method is needed to increase the likelihood of identifying incipient cable fault signatures from the PDC user side of the system.

To understand this approach, it is helpful to first review the underground cable construction and grounding configuration. Cross sections of typical underground cables are shown in Fig. 8.

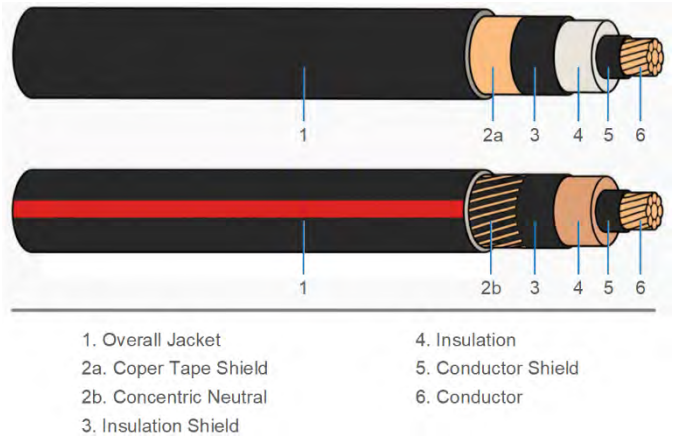

Fig. 8. Single conductor underground cable cross section (top tape shield, bottom concentric neutral).

The copper tape shield or concentric neutral serves as the ground/neutral return path and is grounded at both ends of the cable, as shown in Fig. 9. This type of grounding is typical of multigrounded wye-connected systems like most North American utility systems.

Although the phase-current contribution from downstream loads may be small during an incipient fault, the incipient fault current can flow through the underground cable copper tape shield from the fault location toward both the substation and the PDC, as shown in Fig. 9. The magnitude of this current depends on the ground resistance of the system. When underground cables are installed in conduits or concrete duct banks, the copper tape shield often serves as a primary return path for ground fault current. Because the conduit system typically presents a relatively high-impedance path to ground, the cable shield becomes the preferred fault current return path and may carry a significant portion of the ground fault current [4] [5].

A CT can be installed to measure the ground current flowing in the shield. Monitoring this ground current provides an opportunity to detect incipient cable fault signatures even when the protective relay is installed downstream of the utility substation and phase-current signatures are not observable.

A summing CT will be installed to measure the ground current, as shown in Fig. 9. The summing CT is encompassing both the drain wires (tape shield/neutral) and phase. The phase conductors are routed through the summing CT together with the shield/drain conductors to cancel normal load-induced components. In cables with tape shields or concentric neutrals grounded at both ends, mutual coupling between the phase conductors and the shield system can produce circulating currents under normal loading. In addition, load switching and other system transients can induce current spikes in both the phase and shield conductors. Including both conductors within the CT window allows these normal current components to cancel, improving sensitivity to fault-related current in the shield path.

The current measured by the summing CT through the IN channel of the PDC relay will be used in the neutral incipient cable fault detection logic and combined with the phase incipient fault detection logic to improve the overall sensitivity and dependability of underground cable fault detection. Measurements from CT-A, -B, and -C will be used in the phase incipient fault detection logic in the PDC relay.

The proposed scheme is most effective when the cable shield is grounded only at the cable terminations. If intermediate junction boxes or sectionalizers include local shield bonding and grounding, fault current may return through those local ground points instead of flowing back to the relay location. In such cases, part or all of the fault current may bypass the summing CT, reducing the sensitivity of the method or preventing detection of faults beyond the intermediate grounding location.

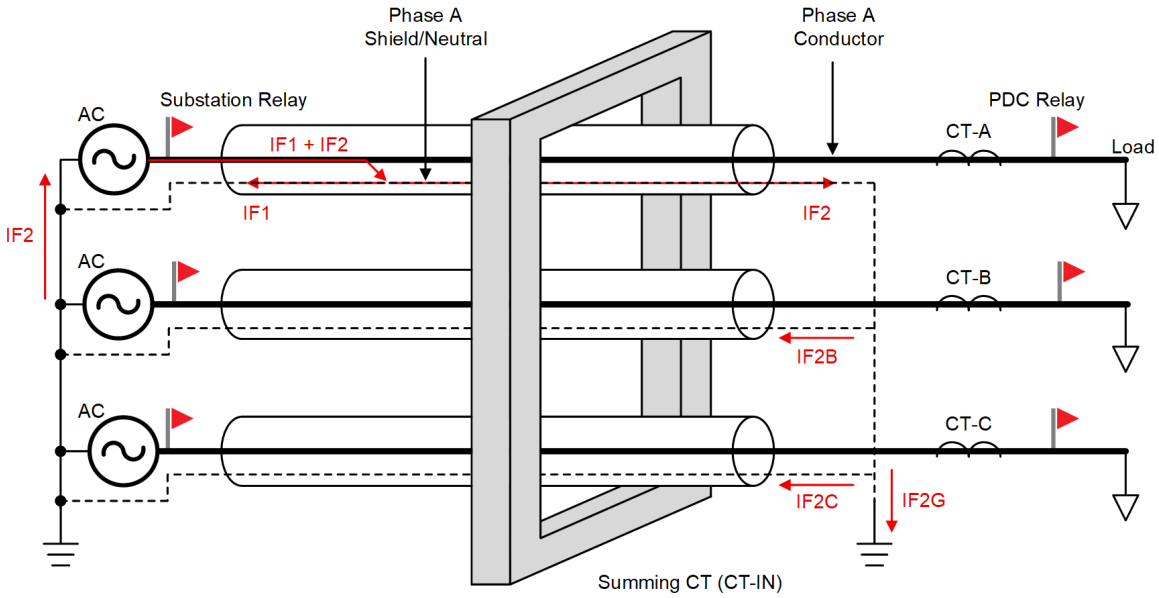

Fig. 9. Use of a summing CT to detect incipient signatures that involve tape shield/concentric neutral of the underground cable.

VI. Conclusion

Underground cable failures are sometimes preceded by incipient, self-clearing fault activity that cannot be reliably detected by conventional overcurrent protection based on fundamental-frequency quantities. This paper presents a real-world case study in which transient current signatures were observed on underground cables within the system prior to two separate underground cable failures affecting a PDC. Analysis of these events demonstrates that short-duration current bursts can provide early indication of insulation degradation and impending cable failure.

The 50INC incipient cable fault detection logic discussed in this paper uses instantaneous current samples to detect and classify self-clearing overcurrent events associated with incipient faults. Validation using replayed field event records confirmed that the algorithm reliably identifies subcycle and near-cycle fault signatures that would otherwise go undetected by traditional protection elements. In addition, the proposed protection scheme uses both phase-current monitoring and ground-current measurement using a summing CT. Phase-current monitoring is used to detect incipient fault signatures associated with fault contributions from downstream loads, while the neutral-current element provides enhanced sensitivity to upstream underground cable faults, particularly in conduit-installed cable systems where phase-current signatures are weak or not observable.

By providing early warning of cable deterioration, the proposed approach enables condition-based maintenance, improves operator awareness, and helps reduce the likelihood of catastrophic underground cable failures and unplanned outages.

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VIII. Biographies

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