Preventing Line Faults With Continuous Monitoring Based on Current Traveling Waves

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PREVENTING LINE FAULTS WITH CONTINUOUS MONITORING BASED ON CURRENT TRAVELING WAVES

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Abstract

This paper presents a novel method to continuously monitor a power line for fault precursors. Based on a double-ended traveling-wave fault-locating method to locate disturbances, the monitoring logic triggers on current traveling waves as small as a few tens of primary amperes. The logic tabulates locations of the detected internal events and alarms if the event count exceeds a user-defined threshold for any location along the line. We expect the line-monitoring logic to detect organic and chemical contamination of insulators, cracked insulators, encroaching vegetation, and other events with accuracy of about 300 m. This paper describes the logic, shares key implementation details, and reports on selected field events captured from the prototype version of a line protective relay with an embedded line-monitoring logic.

1 Introduction

Most power system faults occur on power lines. Using air for insulation and stretching tens and hundreds of kilometers over diverse terrains, power lines are exposed to many factors that eventually cause faults. Some causes of line faults develop gradually over days, weeks, or even months, including vegetation encroachment, chemical and bird contamination of insulators, and aging. As the insulation degrades gradually, a power line may experience fault precursors—events that are not permanent faults, but rather low-energy events that last less than a millisecond and only cause transients. Line protective relays do not include any dedicated logic to detect, log, or respond to precursors.

Once the fault precursor current reaches a level of a few tens of primary amperes, the precursor may be detectable at the line terminals by using current traveling waves (TWs). The double-ended TW-based fault-locating method [1] is especially useful. To accurately locate an event, the method only needs to detect and time-stamp the very first waves from the event at both line terminals. Therefore, the method is not only simple, but also sensitive.

This paper presents the theory, implementation, and field experience with a TW-based line-monitoring logic, with the following key characteristics:

- It triggers on current TWs launched by fault precursors (with or without a protection operation),
- It locates events with high accuracy by using the double-ended TW-based fault-locating method,
- It tabulates events for locations along the line, and
- It alarms if the event count at any location along the line exceeds a user-settable threshold.

The line-monitoring logic allows users to monitor the line continuously for dirty or cracked insulators, encroaching vegetation, marginal clearances, marginal lightning protection, incipient faults on underground cables, conductor galloping (insufficient damping or faulty spacers), and ice unloading. A typical use case for this novel line-monitoring logic is to:

- Dispatch the line crew to the location of the problem.
- Confirm and rectify the problem such as by washing dirty insulators, trimming vegetation, installing line dampers or spacers, and so on.
- Reset the event counters for the location of the problem after performing adequate maintenance and addressing the underlying root cause.

Routine switching of in-line series capacitors or tapped loads generates TWs that would lead to spurious line-monitoring logic alarms for the locations of series capacitors and taps. Instead of running lifetime event counters for these locations, the logic runs a 24-hour event sum to monitor and alarm for the daily total event count. This allows users to monitor for unusual switching at series capacitors and tapped loads.

The double-ended TW-based fault-locating method requires a common time reference and a channel to exchange the TW time stamps. Our implementation uses satellite clocks at both line terminals and an economical, low-bandwidth multiplexed channel over synchronous digital hierarchy (SDH), synchronous optical network (SONET), or multiprotocol label switching (MPLS). Our implementation also works over a direct fiber channel (satellite clocks are not required).

When triggering on low-energy events without protection operation, the line-monitoring logic must distinguish internal events from the many external events that happen every day, such as routine switching or faults in the surrounding network. The described method works with current TWs only because acquisition of voltage TWs is not practical when using today's potential transformers. Without voltage TWs, it is more difficult to distinguish internal and external low-energy events. This paper presents several novel ways for obtaining the required selectivity. One of the methods compares the polarities of the current TWs between the line terminals and with respect to the pre-fault voltage. Another method distinguishes fault precursors from lightning strikes by comparing the TW ground mode with the TW aerial modes. This paper illustrates the introduced principles with field records from more than a dozen pilot installations of an experimental device based on [2] with a sampling rate of 1 MHz and a timing accuracy of 0.1 µs.

2 Field Example of a Fault Precursor

The relay [2] has been installed on a 110 kV, 56.3 km line in a 50 Hz system. The purpose of this trial was to verify protection elements and schemes based on TWs and incremental quantities as well as the TW-based fault locating. In January of 2018, a Phase-A-to-ground (AG) internal fault occurred about 14 km from a line terminal. The local relay incremental-quantity-based distance element, TD21 [3], operated in 2 ms, including the relay processing time and the closure time of a solid-state trip-rated output. Fig. 1 shows the local voltages and currents for this fault (the trip output was not connected to the circuit breaker).

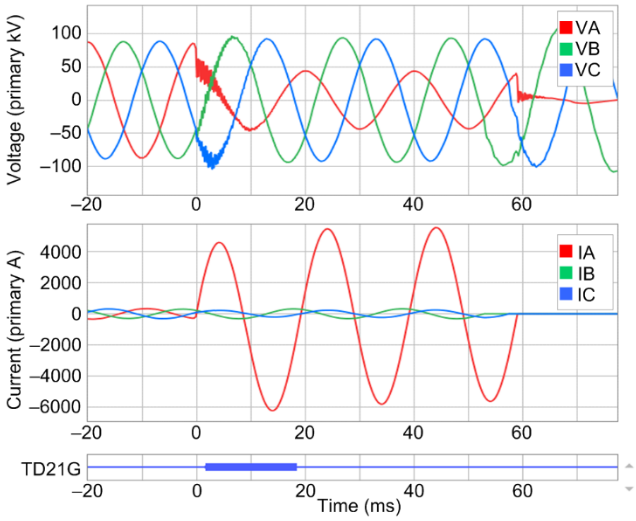

Fig. 1. Voltages and currents for an AG fault.

Fig. 2 shows the local (red) and remote (blue) current TWs based on the 1 MHz relay IEEE COMTRADE record. The relay calculates these signals by using a differentiator-smoother filter [1] [2] [3]. The local current TW arrived 97.306 µs ahead of the remote current TW, which, given the line length of 56.31 km and the TW line propagation time of 196.68 µs, means the fault was located 14.226 km from the local terminal (see (4)). The current TWs were at the level of 50 A primary, which is low but expected for a 110 kV line.

A close inspection of these current TWs reveals, however, that small current TWs were present in the currents 10 ms before the fault (see Fig. 3). During this fault precursor, the local current TW arrived 98.042 µs ahead of the remote current TW, a time difference nearly identical to the measurement during the fault (97.306 µs). The fault occurred when the voltage was near the peak (Fig. 1), as expected for a line with a relatively low nominal voltage. 10 ms before the fault, the voltage was also at its peak, which explains the time of the precursor. Fig. 4 shows the 1 MHz voltage signal for the time of the precursor. We can see small transients in the voltage signal. When decimated to 10 kHz (Fig. 1), these small transients are not visible at all. Relays that sample at several kilohertz would not record any signatures of this precursor.

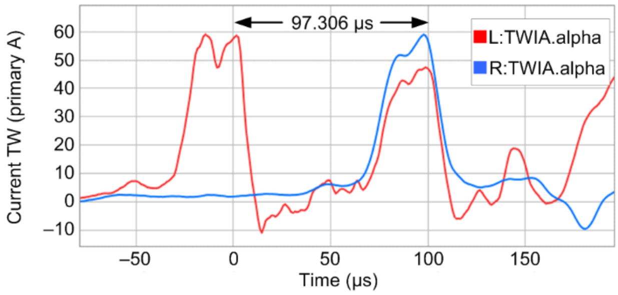

Fig. 2. Current TWs during the fault.

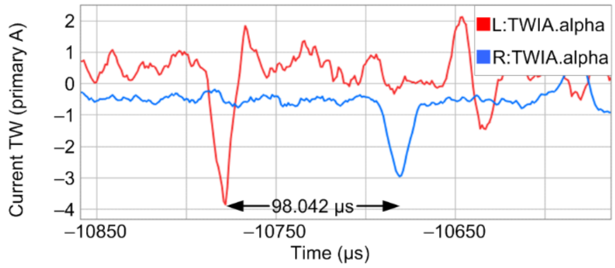

Fig. 3. Current TWs 10 ms before the fault.

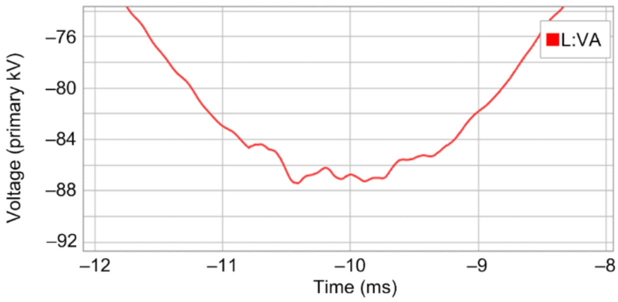

Fig. 4. Local Phase A voltage 10 ms before the fault.

The user had configured the 1 MHz prefault record to only 100 ms, and we did not find any earlier precursors in that short prefault time interval. However, inspecting the record further, we saw a second precursor 0.5 ms before the fault (see Fig. 5). Again, the difference in the current TW arrival time was 98.005 µs—a nearly identical value to the fault and the first precursor.

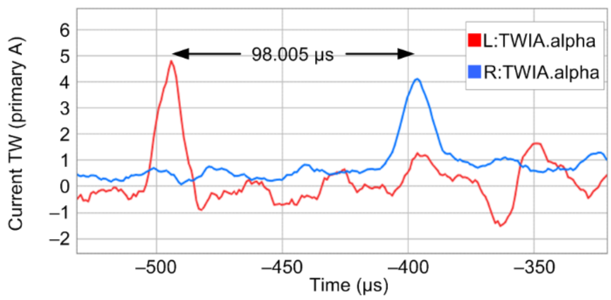

Fig. 5. Current TWs 0.5 ms before the fault.

Note that the current TW signal levels for precursors were only on the order of 4–5 A primary. Yet, the relay [2] was able to measure these signals (the TWs in Fig. 5 are clearly above the noise). In lines of higher voltages, these signals will be proportionally higher. Also, note that the polarity of the current TWs follows the polarity of pre-event voltage—the current TWs in Fig. 2 and Fig. 5 are positive, as is the faulted phase voltage at 0 ms; the current TWs in Fig. 3 are negative, as is the faulted phase voltage at –10 ms.

In this sample field event, 10 ms before the fault, the first precursor signaled that there was a problem at 14.120 km; 0.5 ms before the fault, the second precursor signaled that there was a problem at 14.126 km; finally, a fault occurred at 14.226 km (the locations of precursors and the location of the fault agree within about 100 m).

3 Causes of Fault Precursors

It is justified to assume that precursors predict many line faults, with the obvious exceptions of purely mechanical causes such as flying objects and debris and abrupt structural problems with towers, power conductors, ground wires, or insulators.

3.1 Organic Contamination of Insulators

Organic contamination from birds develops over time. In the process of contamination buildup, the contaminating substance goes through cycles of addition, drying, moistening and washing with rain, drying due to partial discharge, and so on. This cycle may last for days and weeks. During that time, low-energy events occur at the contaminated location.

3.2 Chemical Contamination of Insulators

Chemical contamination develops due to semiconductive chemical compounds, especially salt. Chemical contamination may go through a similar cycle of depositing, washing with rain, burning away with partial discharge, and so on. These cycles may last days and weeks before a high-current fault occurs. Chemical contamination occurs on lines along ocean shorelines, chemical plants, or roads de-iced with salt. Utilities regularly wash insulators at those chemically active locations, and their washing schedules provide a good indication regarding the time period it takes for the chemical contamination to start causing faults.

3.3 Encroaching Vegetation

Encroaching vegetation (trees and fast-growing brush) also may lead to extended periods of time when electrical activity takes place, but without causing a high-current permanent fault. Vegetation progresses relatively slowly, and when leaves, twigs, and small branches get close to an energized power conductor, they are exposed to the line electric and magnetic fields. As a result, they dry out and partially die, and their poor conductivity (due to a small size) becomes even poorer because of drying out with current. A negative feedback loop takes place where the encroaching branch gets treated electrically, and, as a result, becomes less conductive, and therefore can stay in that state further without causing a fault. Tree contacts become high-current faults only if something changes such as a tree leans over because of problems with roots, a large branch breaks off, or a strong wind sways a larger branch closer to a conductor. Before that change, encroaching vegetation may generate electrical activity for days and weeks.

Because of strict pruning requirements, encroaching vegetation is not supposed to happen on transmission lines. However, it may happen on sub-transmission lines and on overloaded transmission lines due to conductor sagging (overloaded lines sagging and faulting due to inadequate vegetation management contributed to the 2003 North American blackout).

3.4 Brush Fires

A brush fire along the line right-of-way creates smoke and hot ionized air that rises small debris and soot. This contamination may severely degrade the quality of the air as the insulating media between the conductors and may start a discharge activity before a high-current fault. Detecting this activity can help in the cause-effect analysis (determining if a line fault started a fire or a fire caused a line fault).

3.5 Insulator Hidden Failures and Aging

Discharge due to insulator hidden failures and aging are likely to be spread over some time. Also, transient faults followed by successful autoreclosing may progressively weaken an insulator through contamination with arc by-products and mechanical stress from electromagnetic forces. Detecting low-energy activity and keeping track of the number of transient faults at the same location allows us to identify insulators that are likely to fail.

4 Line-Monitoring Logic

4.1 Locating Events

The line-monitoring logic uses a double-ended TW-based fault-locating method to locate line events [1]. Fig. 6 shows a Bewley diagram for a fault at location F on a line of length LL. (Section 4.1 includes material taken directly from [1].)

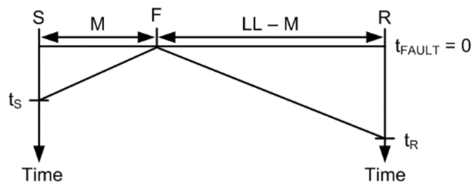

Fig. 6. Bewley diagram for a line fault.

The fault is M (km or mi) away from the local terminal (S) and LL – M (km or mi) away from the remote terminal (R). The TW propagation velocity (PV) for the line is the ratio of the total line length (LL) and the TW line propagation time (TWLPT) settings of the line-monitoring device:

$$PV = \frac{LL}{TWLPT} \tag{1}$$

The first current TW arrives at Terminal S at:

$$t_S = \frac{M}{PV} \tag{2}$$

The first current TW arrives at Terminal R at:

$$t_R = \frac{LL - M}{PV} \tag{3}$$

Solving (2) and (3) for the fault location, M, and factoring in (1) for the propagation velocity, we obtain the following fault-locating equation:

$$M = \frac{LL}{2} \bullet \left(1 + \frac{t_S - t_R}{TWLPT}\right) \tag{4}$$

The double-ended TW-based fault-locating method (4) is simple, yet very accurate. It requires identifying and time-stamping only the very first TWs at both line terminals. Not having to isolate and identify the origin of any subsequent TWs is a great advantage of the double-ended fault-locating method in line-monitoring applications. Low-energy events launch only small current TWs. We cannot count on these TWs to reflect back and forth between the terminals and the event location. We can only count on the first wave from the event location (see Fig. 3 and Fig. 5 for sample TW signal levels).

The double-ended TW-based fault-locating method (4) has a field-proven track record with reported accuracy within one tower span (300 m or 1000 ft) on average [1]. When tested under ideal conditions, the double-ended TW-based fault-locating method (4) implemented on a hardware platform [2] yields a 90th percentile error considerably below 20 m (66 ft) and a median error less than 10 m (33 ft).

Our implementation of the double-ended TW-based fault locator [2] allows applications on hybrid lines, i.e., lines comprising overhead line sections as well as cable sections [1]. The line-monitoring logic leverages implementation [1], and, therefore, it also works on hybrid lines.

4.2 Tabulating Events and Alarming

With reference to Fig. 7, the line-monitoring logic represents a two-terminal power line with 0.25 mi intervals (or 0.25 km intervals depending on the line length unit setting). The logic assigns a bin to each of the intervals and marks each bin with the midpoint location of the corresponding interval, such as 0.25, 0.50, 0.75, and so on. Except for the first bin and the last bin, a bin marked as L covers event locations from (L – 0.125) to (L + 0.125). Each bin has a counter associated with it to count events located within that bin. The counter range is from 0 to 255. When the counter reaches its upper limit, it is not incremented anymore but remains at 255 until it is cleared by the user.

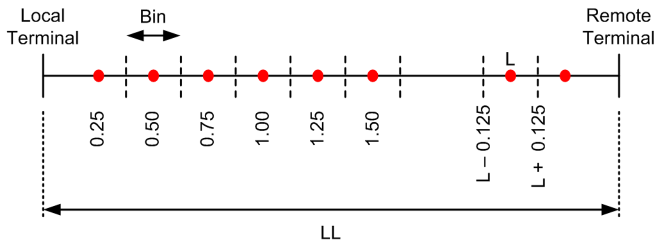

Fig. 7. Power line divided into bins for counting line events.

When the line-monitoring logic detects an event on the line and obtains a valid event location M (mi or km) from the double-ended TW-based fault-locating method, it determines the bin for location M and increments the counter for that bin.

The line-monitoring logic triggers for two types of events: low-energy events and high-energy events (faults). We define a low-energy event as an event that asserts the TW disturbance detectors at both line terminals, but line protection does not operate. Expect low-energy events to be fault precursors such as a discharge across a dirty or defective insulator, an incipient cable fault, discharge due to encroaching vegetation, ionized air with airborne soot from a fire underneath the line conductors, coupling from a lightning strike to the ground wires, and other similar circumstances. We define a high-energy event or a fault as an event that asserts TW disturbance detectors at both line terminals and is followed by a line protection operation.

The line-monitoring logic compares the values of all the counters with the user-defined alarm threshold. It is possible that a recurring event at the same location increments three adjacent counters because of the natural spread in fault-location results of about ±300 m. Fig. 8 shows this phenomenon. To address the potential spread problem, the line-monitoring logic alarms for bin n if the sum of counters in bins $n - 1$, n, and $n + 1$ exceeds the threshold and if the value of the counter in bin n is the highest among the $n - 1$, n, and $n + 1$ counters.

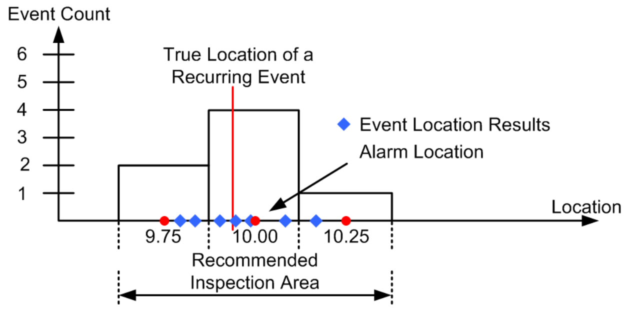

Fig. 8. Recurring events at the same location may increment counters in three adjacent bins (spread in location error).

4.3 Series Capacitors and Tapped Loads

Any sudden change in voltage launches current TWs. Bypassing or reinserting in-line series capacitors and switching tapped loads on or off causes sudden voltage changes and launches TWs. Sometimes disconnect switches or circuit switchers are used on tapped loads instead of breakers. These devices are prone to restrikes, and restrikes also generate current TWs. Operations of tap changers on tapped transformers are likely to generate current TWs that arrive at the line terminals. Finally, small TWs can arrive at line terminals for faults downstream from the tapped loads. The line-monitoring logic would detect such switching events as low-energy events. Our implementation solves this challenge by establishing blocking regions around the locations of taps and series capacitors (see Fig. 9). The logic counts events inside the blocking regions differently. Instead of a lifetime sum, the logic counts a daily total and applies a separate alarm threshold to monitor series capacitors and taps.

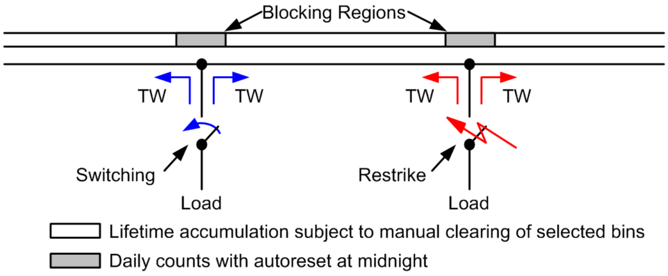

Fig. 9. Blocking regions for accommodating switching events at taps and series capacitors.

5 Selectivity and Event Classification

Being intentionally very sensitive, the line-monitoring logic will trigger on many events daily. Most of these events are switching events external to the monitored line. In order to avoid generating false alarms, the line-monitoring logic must be selective and distinguish between events internal to the line and all the other events.

5.1 Internal and External Events

To appear as if located on the monitored line, the local and remote current TWs must arrive within a time interval not greater than the TW propagation time for the entire line, TWLPT (see (4) and Fig. 6). If the difference in the TW arrival times between the local and remote terminals is greater than the TW line propagation time, then the event is classified as external and is not tabulated.

However, external events (faults or switching) that are located at a similar TW travel time from the two terminals of the monitored line will send TWs that arrive at the line terminals with a time difference that is close to the TWLPT value. Our solution differentiates between external and internal events by comparing the polarities of the first current TWs at both the line terminals [3]. For an external event, a current TW that entered the line at one terminal with a certain polarity will leave the line after the TW propagation time with the opposite polarity (factoring in polarity of current transformers [CTs]). For an internal event, the first TWs at both the line terminals are of the same polarity (both positive or both negative). Our implementation decides which of the six current TW aerial modes to use, and it checks the polarity of that aerial mode at both the line terminals.

Still, there may be cases where the two current TWs will be of the same polarity for an external event. A fault on a parallel line is such a case. The fault launches two current TWs that travel away from the fault on the parallel line toward the terminals of the monitored line. These current TWs enter the monitored line from outside and have the same polarity. We solve this problem by comparing the current TW polarity with the polarity of the pre-fault voltage. A short-circuit depresses pre-event voltage—a positive voltage goes down toward zero and the negative voltage goes up toward zero. Assume an event occurred when the pre-event voltage was positive. The event causes a negative voltage change (positive voltage goes down) and therefore launches a negative current TW. For an event on the monitored line, this negative current TW arrives from the direction opposite to the polarity of the CT, and, therefore, it appears to the line-monitoring device as a positive current TW. As a result, events on the monitored line that occur when the pre-event voltage is positive generate positive current TWs; reverse events that occur when the pre-event voltage is positive generate negative current TWs.

Of course, when comparing the current TW polarity and the pre-event voltage polarity, we must match the voltage mode to the current TW aerial mode. For example, if we selected the Phase A-referenced alpha mode for the current TW, we use the instantaneous pre-event V_A voltage. If we selected the Phase B-C-referenced beta mode for the current TW, we use the instantaneous pre-event $V_B - V_C$ voltage.

Ideally, we would like to use the pre-event voltage at the event location because the terminal voltages will differ from the voltage at the event location because of the voltage drop across the loaded line. If the line-monitoring logic has access to voltages from both line terminals (direct fiber applications), it can approximate the voltage at the location of the event as an average between the two terminal voltages weighted with the calculated per-unit fault location. If the line-monitoring logic has access to the local voltage only (multiplexed channel applications), it uses the local voltage at the expense of slightly degraded selectivity.

5.2 Current TWs Induced by Lightning Strikes

Our field experience shows that lightning strikes can induce current TWs in power conductors and appear as if caused by internal events. The strike current in the ground wire (if the lightning strike hit the ground wire) or in the air close to the line induces current TWs in the power conductors (power conductors act as long antennae). However, the three power conductors are located at a similar distance with respect to the lightning strike current. As a result, the TWs induced in the power conductors are similar (same polarity, similar magnitudes). Therefore, current TWs caused by lightning strikes contain a very large ground mode. By contrast, current TWs caused by faults contain a large aerial mode with patterns influenced by the fault type and voltage point-on-wave. We identify lightning strikes by checking the level of the TW ground mode with respect to the highest TW aerial mode [3].

5.3 Incipient Cable Faults

Cables attenuate current TWs much more than overhead lines. Nonetheless, we can apply the line-monitoring concept to cables if these cables are not too long. Incipient cable faults eventually turn into high-current but short-lived events, with the fault current lasting one, two, or just a few half-cycles. We can detect these one, two, or multiple half-cycle patterns and associate them with prior low-energy activity. Regardless of whether the high-current incipient cable fault is the first event detected or was preceded by low-energy events, the line-monitoring logic provides accurate fault location. The fault-locating function alone is a very significant improvement over impedance-based fault locating for those incipient cable faults.

5.4 *Event Classification*

Our focus is on dependability (sensitivity) and security of the line-monitoring logic, and we therefore classify events only as internal and external. A more detailed analysis of the internal events can be performed by examining signatures of current TWs. For example, one may attempt to distinguish between a tree contact and an organic contamination of insulators. Such analysis is outside the scope of this paper.

6 Field Examples

At the time of finalizing this paper, we have about half a dozen pilot installations of the line-monitoring device [2] with another dozen pending. These lines range from 69 kV to 500 kV and 8 mi to more than 200 mi. The purpose of the field trials is to confirm that when the fault precursors become large enough to be reliably detected with current TWs at the line terminals, there is still enough time (days, not milliseconds) to address the problem and prevent faults.

Fig. 10 shows the voltage and current (±4 ms from the event) and the local and remote current TWs (–50 to +150 µs) for an event on a 20.65-mile, 115 kV line in a 60 Hz system.

The local and remote current TWs arrive with the same polarity only 0.9 µs apart, pointing to the event location at half the line length (10.243 mi from the remote terminal).

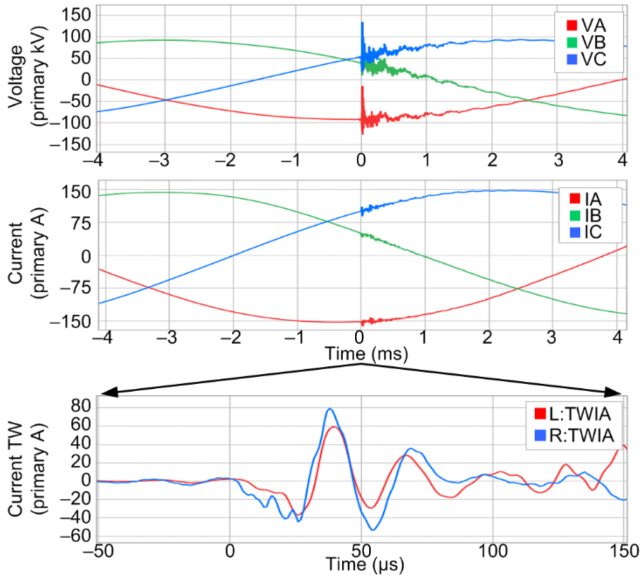

Fig. 10. Local voltages and currents, and local and remote current TWs (1 MHz record) for a 115 kV pilot installation.

Fig. 11 shows the voltage and current (±4 ms from the event) and the local and remote current TWs (–50 to +150 µs) for an event on an 8.49-mile, 69 kV line in a 60 Hz system.

The local and remote current TWs arrive with the same polarity 31.464 µs apart, pointing to the event location 1.373 mi from the remote terminal.

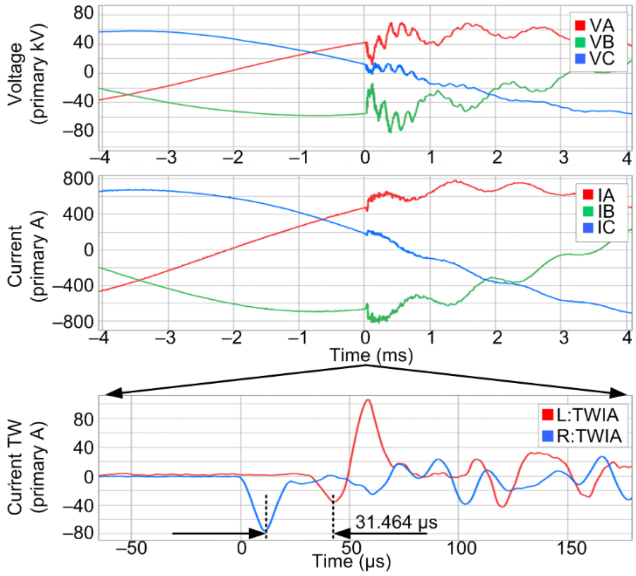

Fig. 11. Local voltages and currents, and local and remote current TWs (1 MHz record) for a 69 kV pilot installation.

7 Conclusion

This paper presents a line-monitoring logic for continuous monitoring of high-voltage power lines for preventive maintenance applications through identifying and locating fault precursors by using traveling waves. This monitoring application has a high potential to reduce the count of line faults and unscheduled outages. The paper describes the logic in detail, shares its implementation on a relay hardware platform [2], and shows several field events from pilot installations. We expect the logic to detect insulator contamination and cracks, encroaching vegetation, temporary recurring faults, and so on. At the time of finalizing this paper, we have captured multiple field events from half a dozen pilot installations but did not inspect the suspect locations yet for signs of potential pending problems. Such positive validation takes time because we are concerned not with line faults, but with fault precursors, i.e., potential future faults.

8 References

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