Correlating Lightning Data With Traveling Waves on Power Lines Aids Patrol Crews in Locating Faults

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***Abstract*—Utilities across the world are using traveling-wave-based (TW-based) devices to locate faults with an accuracy of one to two tower spans. This paper briefly discusses capabilities of line protective relays that include TW-based functions such as fault locating, line monitoring, and a line current differential scheme (TW87). The paper includes a tutorial on Vaisala's National Lightning Detection Network and lightning detection sensors. The paper shows how the time stamp reported from a lightning-detection system correlates to the TW arrival time reported by the line protective relay for lightning events.**

The paper discusses two lightning strikes captured in the field: one that hits only the shield wire and another that hits both the shield and phase conductors, creating a temporary fault. The paper discusses how the correlation of data from the lightning-detection network and the relays helps the patrol crew to locate the disturbance. PPL Electric Utilities Corporation uses this correlation to confirm the root cause of the disturbance and to verify performance of the lightning mitigation devices in the network.

In addition to fault locating and line monitoring, TWs are used for line protection applications, and this paper presents the performance of the TW-based line protection functions for these lightning events.

I. Introduction

Traveling-wave (TW) signals are used by line protective relays to accurately locate faults and to provide ultra-high-speed tripping on power lines [1] [2]. References [3], [4], [5], [6], and [7] document the performance of these devices. Accuracy of TW-based fault locating is on the order of one to two tower spans. Fig. 1 shows the insulator damage identified by a patrol crew at 38.15 mi on a 40 mi transmission line. The fault locator reported the distance at 37.97 mi using the double-ended TW-based fault-locating method. Fig. 2 shows the currents and voltages recorded at the terminals of a 345 kV, 40 mi transmission line for an internal Phase-C-to-ground fault. The TW-based current differential scheme operated in less than 1 ms, clearing the fault in 1.5 cycles.

Fig. 1. A flashed insulator bell identified by a patrol crew: UBP of Bonneville Power Administration [3].

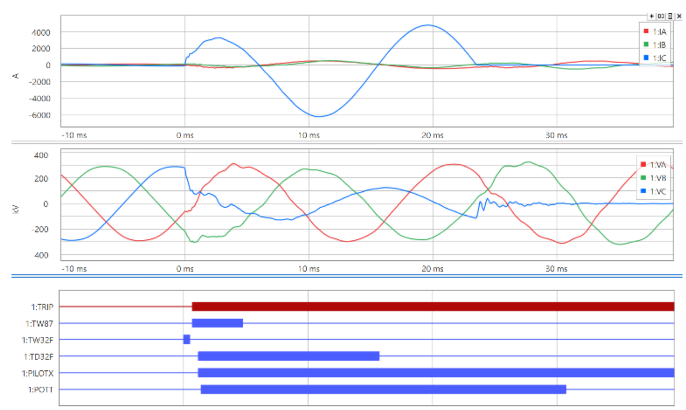

Fig. 2. The line protective relay and the breaker cleared the fault in 1.5 cycles.

TW-based fault locating is also available in standalone fault locators [8] [9] [10] [11]. These fault locators capture the traveling waves, and the data are retrieved by a centralized system that calculates the fault location using multi-ended methods. The application uses data from the fault locators along with the line information, such as line length and line propagation time. Fault locators exchange data using an IEEE C37.94-based multiplexed channel and calculate the fault location [1] [2] [11]. The fault location value is available at the device within 100 ms, and these devices do not require a centralized system with a dedicated application to provide the result. Section II provides a brief introduction to TWs and applications that use these signals for fault locating and line protection. Section III introduces the U.S. National Lightning Detection Network (NLDN®), its capabilities, and how industries use the data from the NLDN.

Section IV provides a discussion about the field data captured from line protective relays associated with three lightning events. One event resulted in a temporary phase-to-ground fault. The other two events did not cause a fault; in these cases, the TW line monitoring function triggered a record showing the transients [12].

Section V discusses how PPL Electric Utilities Corporation (PPL Electric) deployed line protective relays with TW-based functions with the primary goal of minimizing downtime as well as being proactive in identifying potential failure modes on power lines and preventing occurrence of faults [2]. We discuss how PPL Electric uses the data from these devices in combination with other tools and procedures to aid patrol teams in locating faults. Additionally, we discuss how PPL Electric benefits from the lightning-detection system and the correlation of data from TW-based devices and the NLDN.

Section VI discusses the design details of the TW-based current differential scheme in relation to its security for lightning-induced transient events that do not cause line faults.

II. Traveling Waves in Power Lines—Theory and Applications

TWs are step changes in voltage and current that are caused by power system disturbances. Specific to power lines, voltage and current TWs originate at the fault location. These are referred to as incident waves and they propagate at close to the speed of light on overhead power lines and approximately half the speed of light on underground cables. At the substation, depending on the termination impedance, part of the incident wave is transmitted and part is reflected [13]. To analyze TWs, we use the Clarke transformation [14]; the alpha, beta, and ground modes are the outputs of the Clarke transformation. Alpha and beta modes are referred to as aerial modes. For a Phase-A-to-ground fault on a power line, all the current flows through Phase A and half the current returns on Phase B and Phase C. For a Phase-B-to-Phase-C fault on a power line, all current flows through Phase B and returns on Phase C. For these faults on power lines, the aerial modes are more dominant than the ground mode. When lightning hits the transmission line shield wire, the ground mode is dominant. TW-based functions use the alpha or beta modes for their relatively lower attenuation and dispersion compared to the ground mode. Fig. 3 shows the comparison between the alpha (aerial mode) and the ground mode for a Phase-B-to-ground fault.

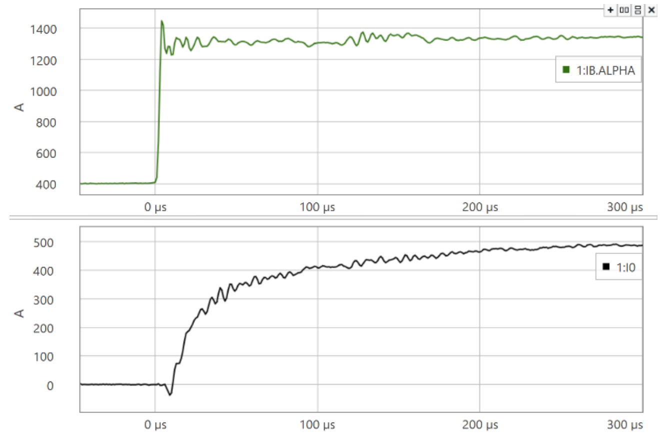

Fig. 3. The ground mode is more attenuated and dispersed than the aerial mode for the Phase-B-to-ground fault.

The relays discussed in this paper measure TWs using a differentiator-smoother (DS) filter. The filter combines the operations of numerical differentiation and low-pass filtering. The DS filter responds to an ideal step change in the input signal with a triangle-shaped output, and it responds to a ramp transition between two levels with a parabola-shaped output. Fig. 4 shows the DS filter output for the Phase-B-to-ground fault.

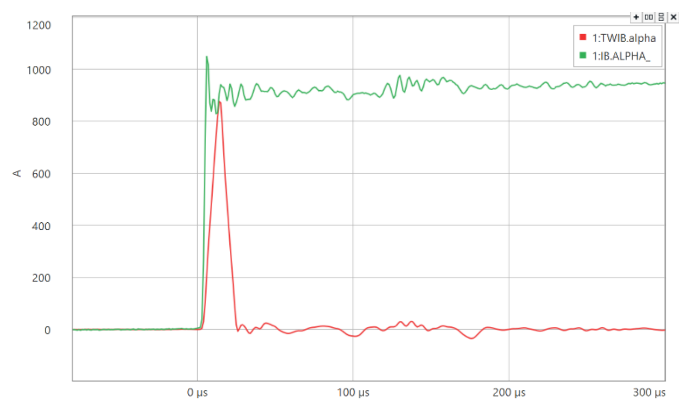

Fig. 4. The DS filter responds to the step change with a triangle-shaped output.

TW-based fault locating has been available for decades. Utilities have deployed these standalone fault locators on high-voltage transmission lines and have benefitted from their exceptional accuracy. With this capability available in line protective relays, users are deploying this technology in lower voltage transmission lines as well.

TW signals are also used to provide ultra-high-speed line protection and to monitor power lines for fault precursors, which are low-energy events that last for a few milliseconds.

A. *Line Monitoring*

Some line faults develop gradually over long periods of time. Before the actual fault occurs, some kinds of precursor activity (for example, incipient arcing on the surface of a dirty insulator) launch low-energy TWs that repeatedly originate at the same location. Some TW-based devices available today provide a function to monitor the power line for fault precursor activity [12]. The line monitoring function represents a two-terminal power line with intervals of 0.25 mi or km (depending on the line length unit setting). The line monitor 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. Each bin has a counter associated with it to count events located within that bin. When the line monitor detects an event on the line and obtains a valid event location from the double-ended TW-based fault-locating method, it determines the bin corresponding to that location and increments the counter associated with that bin. The logic alarms for a bin if the sum of the counter values in that bin and the two adjacent bins exceeds a user-configurable threshold. The line monitoring function provides a historical log of all events associated with fault precursors or fault events. It also flags events with dominant ground mode, which are typically associated with lightning strikes hitting a shield wire.

B. Line Protection

Fast fault-clearing times minimize equipment damage, improve power system stability, and enhance public safety. The TW-based line current differential (TW87) scheme can operate on the order of 1 ms (short lines) to 5 ms (long lines), allowing faults to be cleared practically within the breaker operating time [1] [2]. The scheme operating signal is calculated by summing the time-aligned first current TWs measured at the local and remote terminals. The restraining signal is calculated as the difference between the first current TW measured at the local terminal and the current TW measured at the remote terminal after the line propagation time. The scheme operates if the operating signal exceeds the restraining signal and all supervisory conditions are fulfilled. Section VI provides details of the supervisory conditions used for securing the scheme for transient conditions such as lightning events. Protection schemes based on TW-based quantities are well suited for series-compensated lines and for lines interfacing with unconventional sources [15].

III. Lightning-Detection Systems

The U.S. NLDN consists of more than 100 sensors distributed throughout the continental United States with typical sensor separations (i.e. “sensor baselines”) of 300–350 km. Each sensor (see Fig. 5) measures the time and angle of arrival (i.e., the direction of the signal detected by the sensor using geographic north as the reference) of radio-frequency (RF) pulses generated by lightning activity over a frequency range covering 0.5 kHz to 500 kHz.

Fig. 5. Lightning sensors measure RF pulses generated by lightning activity.

In addition to the time and angle, these RF signals also have a peak magnitude and waveshape characteristics that can be used to determine whether they are caused by the return strokes in cloud-to-ground lightning or by discharge processes occurring inside the cloud. The measurements from the sensors are transmitted to a central processing system that uses magnetic direction finding and time-of-arrival-based lightning location algorithms to resolve the time, location, estimated peak current, and classification of each event (either cloud-to-ground or intercloud).

Flashovers across insulators may be caused by either direct strikes or induction from nearby strikes due to large electromagnetic pulses [16]. For this reason, and because lightning locating systems like the NLDN do not have perfect location accuracy, queries of NLDN data are typically made using a spatial buffer region around the line or specific fault of interest. The basic data fields available from a query of the NLDN data are the time, latitude, longitude, estimated peak current, type of lightning, and distance from the center point of the query, as shown in Fig. 6.

Time (UTC +00:00) ↓	Latitude	Longitude	Cloud?	Signal strength (kA)	Distance from point (m)
2023-04-15 20:37:07.643	40.7991	-75.1511	false	-18.7	1838
2023-04-15 20:37:07.670	40.8002	-75.1505	false	-14.3	1749
2023-04-15 20:37:07.779	40.8191	-75.1438	false	-23.6	1894
2023-04-15 20:37:07.842	40.8009	-75.1517	false	-41.8	1823
2023-04-15 20:37:07.844	40.8003	-75.1528	false	-16.3	1930
2023-04-15 20:37:07.879	40.8001	-75.1516	false	-20.1	1840
2023-04-15 20:37:07.946	40.8002	-75.15	false	-11.8	1709
2023-04-15 20:37:12.797	40.6936	-75.0312	false	-91.2	14980
2023-04-15 20:37:12.838	40.6654	-75.1387	true	3.2	15559
2023-04-15 20:37:12.838	40.6936	-75.0322	false	-55.6	14933
2023-04-15 20:37:12.860	40.6936	-75.0322	false	-11.1	14933
2023-04-15 20:37:12.861	40.6952	-75.0221	true	-10.2	15279
2023-04-15 20:37:12.910	40.6932	-75.03	false	-38.1	15073
2023-04-15 20:37:12.946	40.6936	-75.0335	false	-13.5	14872
2023-04-15 20:37:13.008	40.6728	-75.0595	false	34.2	15901
2023-04-15 20:37:47.013	40.8052	-75.1308	false	-16.3	0

Fig. 6. The NLDN provides key information related to each lightning event.

The data in the "Cloud?" column indicates whether the detected event was a return stroke in a cloud-to-ground lightning flash or some discharge process that occurred in the cloud. Only cloud-to-ground return strokes contact ground and have the potential to cause damage. These are identified as **true** in the Cloud? column. The accuracy of lightning type determination is approximately 95 percent. Given the imperfect location accuracy, the distance from the center point of the query can be used together with a position confidence region to assist in identifying the most likely lightning event(s) associated with a fault. The position confidence region has the form of an ellipse, which can be described by three parameters: the semi-major axis, semi-minor axis, and angle of orientation of the major axis relative to north. The confidence region converges to a circle when adequate sensors surround the lightning activity.

Recent evaluations of the performance of the NLDN discussed in [17], [18], and [19] and references therein indicate that the NLDN detects between 92 and 97 percent of cloud-to-ground strokes with a median location accuracy of 84 m. The location accuracy is consistent with a random time error better than 0.5 µs, such that the estimated times of cloud-to-ground strokes from the NLDN can be accurately matched to measurements from fault locators on transmission lines.

IV. Field Events Caused by Lightning Activity

When lightning strikes the shield wire on an overhead line, the voltage at the base of the phase insulator string could exceed the phase voltage, resulting in a back flashover. Such a lightning strike typically lasts tens of microseconds, after which the voltage at the base of the phase insulator reduces to zero. However, if the insulator surface is adequately ionized, it provides a path for the current from the sources at the line terminals, thereby driving the fault.

This section presents three field events caused by lightning activity and captured by line protective relays. One lightning event caused a phase-to-ground fault and the other two events did not result in a fault. The time stamp associated with these three events was correlated with the time stamp from the NLDN.

A. Lightning Strike Resulting in a Phase-A-to-Ground Fault (138 kV, 21 mi Line)

Fig. 7 shows the relay record for the Phase-A-to-ground fault on a 138 kV, 21 mi line. The relay issued the trip in 5 ms and the fault was cleared in 2.5 cycles by a 2-cycle breaker.

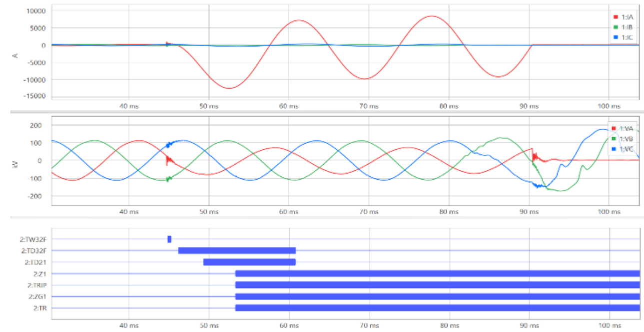

Fig. 7. The line protective relay and the breaker cleared the fault in 2.5 cycles.

The built-in TW-based fault locator reported the location at 5.1 mi. Fig. 8 shows the flashed insulators identified by the aerial patrol crew at the location reported by the relay.

Fig. 8. A flashed insulator identified by the aerial patrol crew.

Based on the data from the NLDN, the cause of the fault was confirmed to be lightning. Fig. 9 shows the data from the NLDN; the fault location of 5.1 mi is used as the center point (target location) when querying the NLDN. Fig. 10 shows the aerial mode and ground mode associated with the current TWs captured at the terminal closest (5.1 mi) to the fault location. The time stamp highlighted in Fig. 10 at the start of the TW signals matches with the time stamp highlighted in Fig. 9 from the NLDN, confirming lightning as the cause for the fault.

Time (UTC +00:00) ↓	Latitude	Longitude	Cloud?	Signal strength (kA)	Distance from point (m)
2023-04-01 21:46:17.932	40.0934	-76.3468	true	-3.6	4875
2023-04-01 21:46:18.044	40.098	-76.2898	true	-5.8	149
2023-04-01 21:46:18.178	40.099	-76.2896	true	-6.9	112
2023-04-01 21:46:37.020	40.1403	-76.346	false	-20.6	6705
2023-04-01 21:46:37.046	40.1461	-76.3364	true	-7.8	6656
2023-04-01 21:47:34.951	40.1097	-76.3595	true	-4.4	6069

Fig. 9. NLDN data indicating a 5.8 kA lightning strike located 149 m (0.09 mi) from the target location.

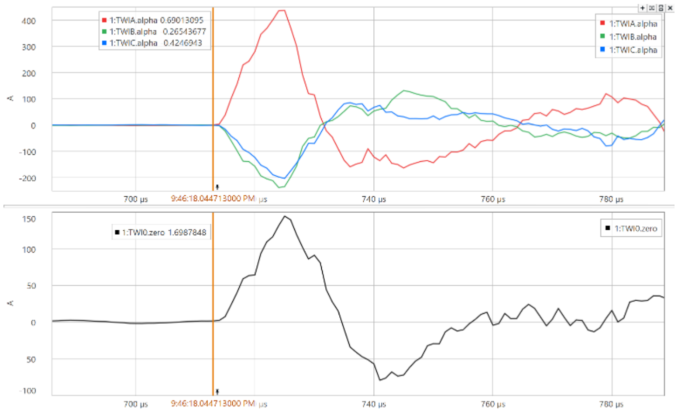

Fig. 10. The TW alpha aerial mode magnitude referenced to the faulted phase (Phase A) is greater than that of the ground mode.

Fig. 10 shows that the TW alpha aerial mode magnitude (437 A) referenced to Phase A is higher than the TW ground mode magnitude (144 A). The ratio of the aerial mode to ground mode magnitude (3.03) is a good indicator to verify whether the lightning strike caused a back flashover.

B. Lightning Strike on the Shield Wire Resulting in a Transient Event (230 kV, 24 mi Line)

Fig. 11 shows the voltages and currents captured for a transient caused by lightning on a 230 kV, 24 mi line. The protective relay scheme was secure for this event. The line monitoring function asserted for this event and reported the event location at 22 mi from the relay terminal.

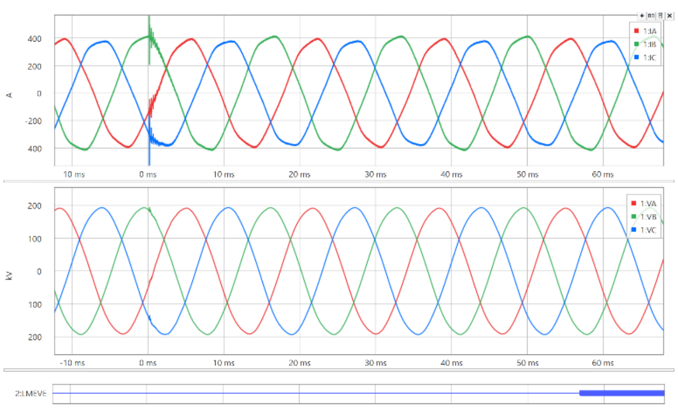

Fig. 11. The line monitoring function triggered the relay record for a transient event at 22 mi from one of the line terminals.

The NLDN was queried with the latitude and longitude of the event location value and a search radius. Fig. 12 shows the data from the NLDN. The highlighted entry confirms lightning activity in the vicinity of the line.

Time (UTC +00:00) ↓	Latitude	Longitude	Cloud?	Signal strength (kA)	Distance from point (m)
2023-04-15 20:37:07.643	40.7991	-75.1511	false	-18.7	1434
2023-04-15 20:37:07.670	40.8002	-75.1505	false	-14.3	1311
2023-04-15 20:37:07.779	40.8191	-75.1438	false	-23.6	1225
2023-04-15 20:37:07.842	40.8009	-75.1517	false	-41.8	1333
2023-04-15 20:37:07.844	40.8003	-75.1528	false	-16.3	1447
2023-04-15 20:37:07.879	40.8001	-75.1516	false	-20.1	1386
2023-04-15 20:37:07.946	40.8002	-75.15	false	-11.8	1282
2023-04-15 20:37:47.013	40.8052	-75.1308	false	-16.3	825

‹ Previous 1 Next › 20 row

Fig. 12. NLDN data indicating a 16.3 kA lightning strike located 825 m (0.51 mi) from the target location.

Fig. 13 shows the alpha aerial and ground modes associated with the current TWs captured at the line terminal close to the fault location. The time stamp highlighted in Fig. 13 at the start of the TW signals matches with the time stamp highlighted in Fig. 12 from the NLDN, confirming lightning as the cause of the disturbance.

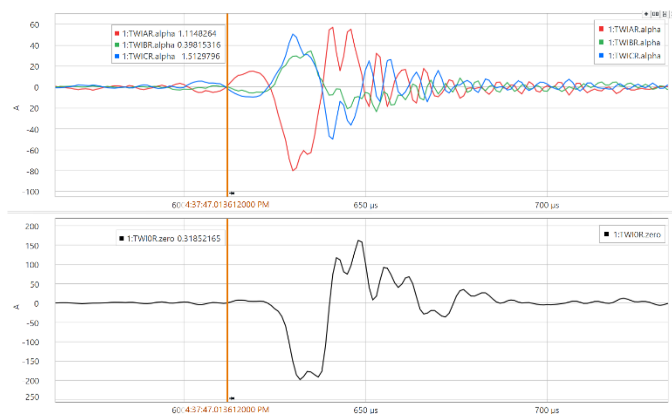

Fig. 13. The ground mode magnitude is greater than the aerial mode magnitude for the lightning-induced transient event.

The ratio of the aerial to ground mode magnitudes in this event is 0.4. In this case, lightning did not cause a back flashover resulting in a fault on the power line. Fig. 14 shows a burn mark on the shield wire at the reported location.

Fig. 14. A burn mark identified by the aerial patrol crew on the shield wire at the reported location.

C. *Lightning Strike on the Shield Wire Resulting in a Transient Event (230 kV, 14 mi Line)*

Fig. 15 shows the voltages and currents captured for a transient event caused by lightning on a 230 kV, 14 mi line. The protective relay scheme was secure for this event. The line monitoring function asserted for this event, as indicated by the LMEVE bit. The line monitoring function reported the event location at 11.25 mi from one of the line terminals.

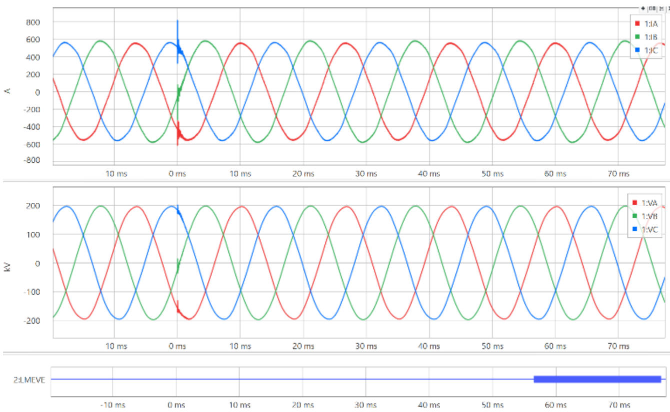

Fig. 15. The line monitoring function triggered a relay record for the lightning-induced, low-energy event.

Data from the NLDN confirmed lightning activity based on the provided event location value. Fig. 16 shows the current TWs recorded at the line terminal farthest from the event location.

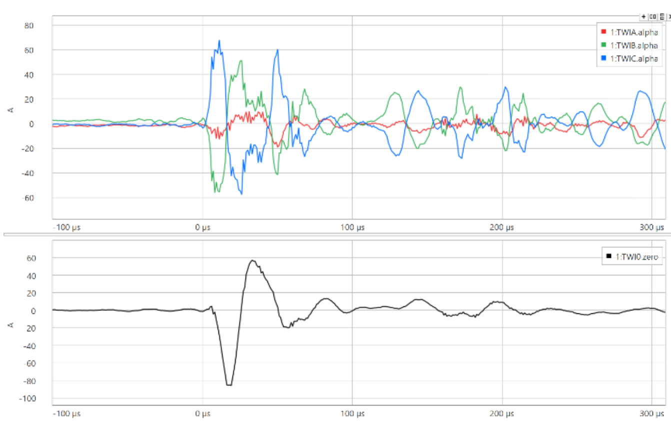

Fig. 16. The ground mode magnitude is greater than the aerial mode magnitude for the transient low-energy event.

The ratio of the aerial to ground mode magnitudes is 0.7 for this low-energy lightning event.

V. PPL Electric's Approach to Improve Power Line Availability

PPL Electric presently uses line protective relays with TW-based functionality such as fault locating, line monitoring, line current differential protection, and ultra-high-resolution fault recording [1]. To improve power line availability, PPL Electric was interested in using the line monitoring function to record low-energy disturbances and high-energy faults causing line tripping. High-resolution event records allowed PPL Electric to use the measured TWs to obtain more information about event types, locations, and magnitudes.

A. *Line Monitoring Data and Fault Location Aids Patrol Team*

The relay line monitor function computes the event location and logs the event in a historical list. The relays also provide high-resolution records for post-event analysis. PPL Electric was particularly interested in recording the low-energy events that could be precursors of high-energy faults causing line outages. To analyze all these events efficiently and effectively, PPL Electric developed an event data retrieval, organization, and automated analytics system.

Using basic scripting tools such as Python and PowerShell, the PPL Electric team created scripts to periodically pull all the key report files from their relays. These reports include the history, sequence-of-events, and line monitoring reports. After each retrieval, a script was used to tabulate any new events in a simple SQL database. The automation allowed for developing a simple Power BI application that allows operators and relay engineers to easily explore, analyze, categorize, and take action on low-energy events on the line in addition to the high-energy fault events.

This relay event system was also integrated with other PPL Electric internal and external data systems to streamline and automate some of the analytics processes such as the following:

- Automatic lightning correlation analysis with the NLDN.
- System switching and fault data correlation with PPL Electric's time series data archive system.
- Tower location identification from the distance to fault location output from the relay against its electric facility database.
- Continuous visualization of the bin information from the line monitoring function to help highlight events and areas of concern.

Using these tools, PPL Electric can quickly analyze all the disturbance events recorded by the relays.

The event data collection and correlation processes performed by the PPL Electric relay event system helped identify and categorize low-energy events caused by lightning strikes in the vicinity of their lines. This information helps with pinpointing and prioritizing exact locations to patrol and inspect for lightning disturbances. Fig. 14 shows an example of very minor lightning strike damage to a 230 kV line shield wire that went undiscovered after a helicopter patrol of a line. After correlating the NLDN data with low-energy event TW measurements, PPL Electric sent a drone to specifically patrol the shield wire in the mid-span line section and quickly discovered the damage caused by the lightning strike to the shield wire.

Without this extraordinary depth of event data, finding a very small burn mark caused by lightning on an overhead transmission line shield wire would be much more difficult and cost prohibitive.

B. *Lightning Data Use Cases*

Utilities typically use lightning-detection system data in two major ways:

- The first and most common use is for determining whether lightning was a potential cause or contributing factor to a power line fault. When engineers analyze a protection system operation event to find the fault cause, they can query the lightning data to see if any lightning activity was detected in the line area around the time of the event. Based on the results of that query, engineers can determine if lightning caused the fault. This information helps in preparing a patrol plan to look for line damage. Having detailed information about the detected lightning strike magnitude and type can also help with predicting the type of damage to expect. It can also help with performing bulk classifications of events for recordkeeping.
- The second use is for performing statistical analysis, including performing statistical lightning studies to quantify the lightning performance of the power system or system subcomponents. For example, aggregating all the lightning events in a given year and comparing the result to the total lightning-related events by line and by year could help indicate which lightning mitigation designs are most effective. The data can also be used to highlight areas of the utility system that are more prone to lightning issues and can help with performing design enhancements.

C. Data From TW Devices and Lightning Data Benefits

Lightning data for power system protection operation events have several uses beyond determining if an operation was caused by lightning. These data can be used to identify details about the operation, such as the current magnitude of the stroke and the type of lightning. For example, a low-magnitude strike correlation may suggest a line shield wire failure, while a high-magnitude strike correlation may suggest a back flashover [20]. The magnitude of the strike that caused a flashover can also be used to determine how the line design performed for the particular lightning event. For instance, if the lightning strike current magnitude was below the expected design level, then the line grounding system should be inspected.

PPL Electric configured the relay recorder to trigger for low-energy disturbances. In this scenario, performing automated lightning analysis using Vaisala's API (application programming interface) on all the event files helps categorize potential causes of low-energy disturbances on the line.

Furthermore, analyzing on a power system level the recorded low-energy events for lightning strikes that hit the shield wire or tower but do not cause a flashover provides information on the performance of the lightning mitigation infrastructure deployed in the transmission network.

VI. TW-Based Current Differential Scheme Performance for Lightning Events

The TW87 scheme includes supervisory checks to secure the scheme operation for nonfault events such as lightning strikes that do not result in a back flashover.

Fig. 17 shows the phase current TWs captured at the local and remote line terminals for the 230 kV, 24 mi line discussed in Section IV.

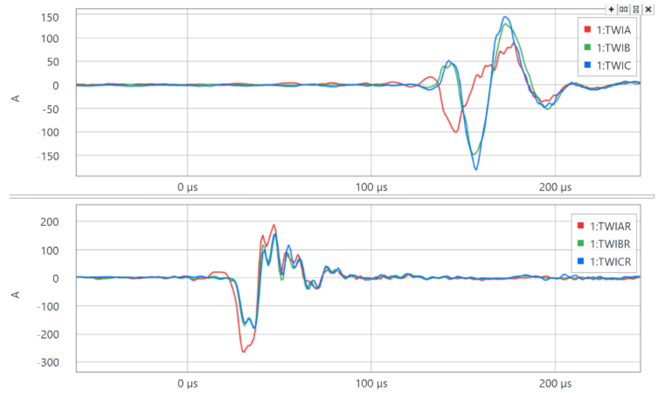

Fig. 17. Phase current TWs recorded for a lightning event.

In this section we discuss the following two key TW87 scheme supervisory conditions that provide security for nonfault lightning events:

- Ground mode supervision: This condition requires the local and remote aerial mode current TWs to be at least 1.5 times greater than the corresponding ground mode current TWs. As discussed in Section IV, ground mode current is relatively higher compared to aerial mode in lightning events that do not result in a back flashover. Fig. 18 shows the comparison between the dominant alpha aerial mode and ground mode at one of the terminals. At both terminals, this disturbance did not qualify the ground mode supervisory condition.

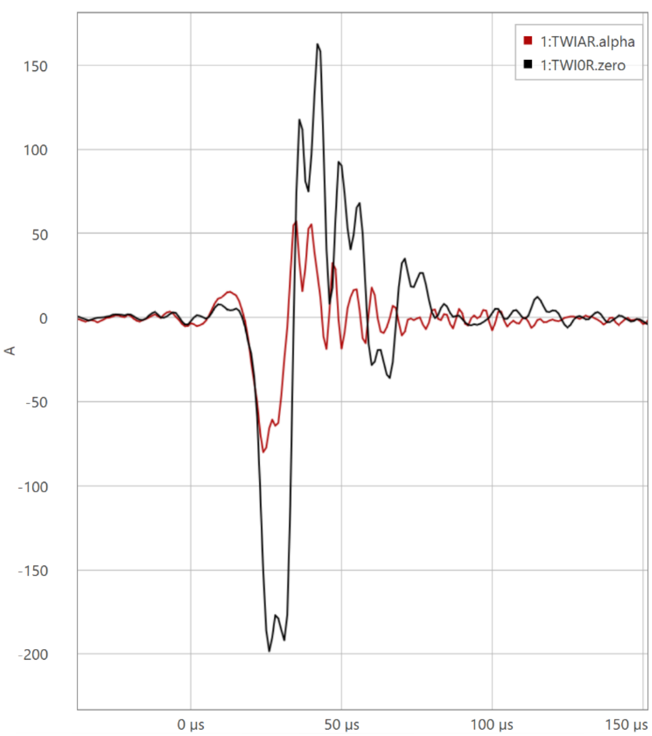

Fig. 18. The aerial mode current TW magnitude did not exceed 1.5 times the ground mode current TW magnitude.

- Incremental-quantity overcurrent supervision: This condition verifies that the incremental replica current level in the loop corresponding to the mode selected by the TW87 logic exceeds a threshold. Overcurrent supervision verifies that an in-zone event has enough energy in the power frequency spectrum to be considered a fault and to warrant a TW87 scheme trip. The top chart in Fig. 19 shows the operating quantities of the ground overcurrent elements. These elements did not operate (their threshold is set to 2.1 A secondary) because of the low-energy nature of the event.

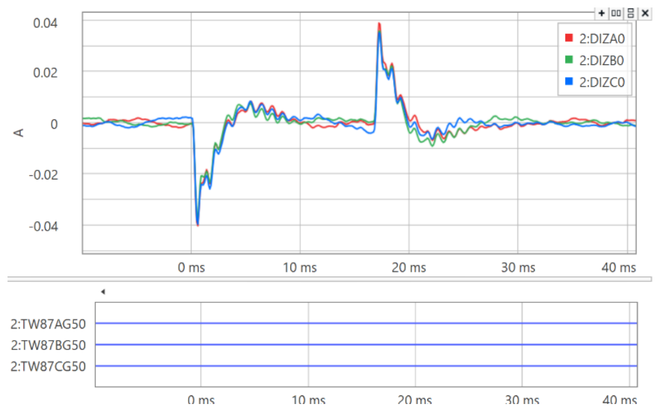

Fig. 19. The incremental-quantity overcurrent supervisory condition is not met for this disturbance.

Additional supervisory conditions such as a quality check of the traveling wave, a TW magnitude check, and a TW fault location value check are typically included to secure the TW87 scheme for external faults and nonfault transient events such as lightning strikes [1] [2].

VII. Conclusion

Line protective relays with TW-based functions use TW signatures for various functions such as fault locating, line monitoring, and ultra-high-speed line protection. In this paper, we presented the performance of these functions for disturbances caused by lightning strikes. The NLDN tracks lightning activity and captures information such as lightning strike location and type (cloud-to-ground or cloud-to-cloud), signal strength, and distance of the strike from a specified location. We showed how the data from the NLDN system correlate to the relay TW time stamps and how that correlation helps utility patrol teams find faults or lightning strike locations and identify the damage caused by lightning strikes. We also explained how utilities can use the lightning data to identify the root cause of the event and to evaluate the performance of the lightning mitigation devices. We also reviewed the supervisory conditions that the TW87 scheme uses to remain secure for lightning events that do not cause line faults.

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IX. Biographies

Eric Rosenberger received his BS in electrical engineering from the Pennsylvania State University in 2011. He is also a licensed professional Engineer in the state of Pennsylvania. He joined PPL Electric Utilities Corporation in 2011 upon graduation. He is currently a principal engineer in PPL Electric's Equipment Monitoring and Automation group and is working on several major development programs at PPL Electric aimed at advancing technology use on the transmission system. The Dynamic Line Ratings project he led won the prestigious Edison Award in 2023.

Martin J. Murphy received his BS in meteorology from the Pennsylvania State University in 1992, and MS and PhD in atmospheric sciences from the University of Arizona in 1994 and 1996, respectively. He was involved in the field of thunderstorm electrification and lightning detection. He is currently with Vaisala, Inc., in Boulder, CO, where he is a senior scientist. He is currently engaged in research on lightning-locating systems and short-term forecasts of thunderstorms. He has authored or coauthored several scientific papers and holds eight U.S. patents.

Mangapathirao (Venkat) Mynam received his MSEE from the University of Idaho in 2003 and his BE in electrical and electronics engineering from Andhra University College of Engineering in 2000. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2003 as an associate protection engineer in the Engineering Services division. He is presently working as a senior engineering director in SEL Research and Development. He is a senior member of IEEE and holds patents in the areas of power system protection, control, and fault locating. He was selected to participate in the National Academy of Engineering (NAE) 15th Annual U.S. Frontiers of Engineering Symposium.

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