Accurate Single-End Fault Locating Using Traveling-Wave Reflection Information

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Abstract

This paper describes a single-ended traveling-wave-based fault-locating (SETWFL) method that works with currents only. The key to a robust SETWFL method is to correctly identify reflections from the fault point. This paper presents the SETWFL method by differentiating possible reflections and explains how to perform fault locating using ultra-high-resolution fault records from any recording device. This paper also presents laboratory test results and a field case to verify the method.

1 Introduction

Because fault location (FL) is important to avoid fault recurrences and the high cost associated with finding line faults, utilities require accurate fault-locating devices for transmission and distribution networks. Impedance- and traveling-wave-based fault-locating methods are the most common methods for locating faults on power transmission lines. These methods can be categorized as single-ended and multi-ended, depending on how many terminals provide measurements.

The single-ended impedance-based fault-locating (SEZFL) method uses local voltages and currents along with the positive- and zero-sequence line impedances to estimate the fault location. SEZFL method accuracy depends on several well-known factors, including the accuracy of the line impedance data, fault resistance, system nonhomogeneity, and mutual coupling [1]. For single-line-to-ground faults in nonhomogeneous systems with high resistance, expect fault location errors that are much greater than 5 percent using the SEZFL method.

The double-ended impedance-based fault-locating (DEZFL) method uses voltages and currents from the local and remote terminals and, therefore, requires a communications channel and a common angle reference for the local and remote phasors. It is immune to the remote infeed effect and works well for resistive faults in nonhomogeneous systems. Line nonhomogeneity affects the DEZFL method but to a lesser degree than it affects the SEZFL method. Expect better accuracy from the DEZFL method than the SEZFL method. However, do not expect accuracy better than approximately 1 to 2 percent of the line length for ground faults.

Overall, impedance-based fault-locating methods require the presence of a fault for a couple of cycles to provide accurate results. While this requirement is not an issue in subtransmission network applications, it can be an issue in extra-high voltage (EHV) and ultra-high voltage (UHV) applications, where faults are sometimes cleared in less than two cycles. Furthermore, impedance-based methods might not be applicable to lines with series compensation or lines that are close to series compensation because the combination of a series capacitor and its overvoltage protection creates a current-dependent voltage drop (and thus series impedance) that is not accounted for in the impedance-based FL equations.

Thus, some utilities have installed devices that use traveling-wave-based methods to locate faults. These methods provide accuracy on the order of one tower span.

The double-ended traveling-wave-based fault-locating (DETWFL) method uses the first traveling-wave (TW) arrival times at the local and remote terminals along with the line length (LL) and TW line propagation time (TWLPT) to estimate the FL. The local and remote devices acquiring the data require a common time reference. This method can provide accurate and dependable results but requires TW signals from two line terminals and a common time reference for these signals.

The single-ended traveling-wave-based fault-locating (SETWFL) method is an alternative that uses the time difference between the first TW from the fault and the first reflection from the fault, measured at the local terminal, to estimate the FL [2][3][4][5]. This paper (shortened from [6]) presents a method that identifies the first reflection from the fault to perform FL estimation. The method assumes several FLs based on the measured TWs. For each assumed FL, the method uses two approaches to identify the first reflection from the fault. The repeating travel time (RTT) approach identifies all TWs traveling from the local terminal to the fault and back to the local terminal, as well as TWs traveling from the fault to the remote terminal and from the remote terminal to the local terminal, passing through the fault along the way. The expected TW (ETW) approach generates a list of expected TWs for each assumed FL and inspects how well the measured TWs match the expected TWs. With the information from the two approaches, the algorithm selects the most likely FL. This paper presents laboratory test results as well as a field case in which the actual FL was found by the line crew and from which we can determine the fault-locating accuracy. The described SETWFL method can be applied to two-terminal lines and radial lines.

2 Fault location estimation using local current TWs

TWs can be extracted from current signals and time-stamped using the method described in [7]. A SETWFL device works with multiple TWs that often travel a long distance and are reflected and transmitted through a number of discontinuities. Fig. 1 shows the Bewley diagram [8] for a fault on a line of length LL. The fault is m (pu) away from the Local Terminal, L, and (1 – m) away from the Remote Terminal, R. Consider Bus B behind the Local Terminal, L, to be a bus terminating a line connected to the Local Terminal, L. A current TW launched at the fault point arrives at the Local Terminal, L, at t_1. Part of it reflects, travels back toward the fault, reflects back from the fault, and then returns to the Local Terminal, L, at t_4. During the $t_4 – t_1$ time interval, the TW traveled a distance of 2 • m (pu).

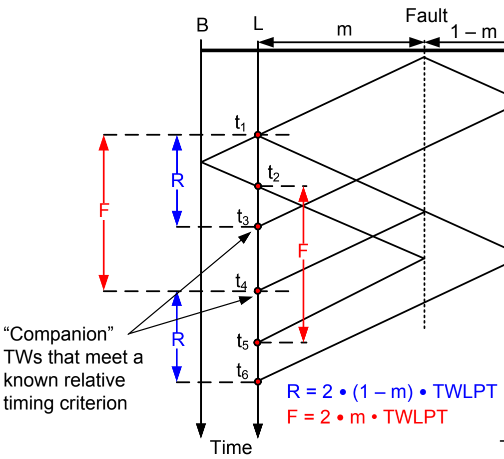

Fig. 1. Bewley diagram explaining the SETWFL method.

The SETWFL method works well if it correctly identifies the first return from the fault (at t_4 time, in this example). The SETWFL method calculates the FL using (1) when it identifies the reflection from the fault (t_4).

$$M = \frac{(t_4 - t_1)}{2 \cdot \text{TWLPT}} \cdot \text{LL} \tag{1}$$

where M is the FL in the same unit of LL. It is challenging to find the TW that is the first reflection from the fault among all of the other TWs that may arrive at the local terminal, including the TWs that arrive from behind the relay (at t_2 in Fig. 1) or from the buses in front of the relay (at t_3 and t_6 in Fig. 1).

The SETWFL method uses the amplitudes, VPKs, and time stamps, TPKs, of the TWs that the algorithm identifies as possible (valid) TW reflections within an observation window that is greater than twice the TWLPT (e.g., 2.4 • TWLPT). The method considers up to 15 FL hypotheses using the polarities (obtained from VPKs) and time stamps of the valid TWs. If the reflected TW is valid and it matches the polarity of the first wave, then the TW is assumed to be one of the hypotheses (i.e., the TW is considered to be the first return from the fault point), as long as the time difference between the time stamps of this TW and the TW associated with first wave arrival is less than 2 • TWLPT plus a small margin (e.g., 10 µs).

The SETWFL method also uses all available FL estimations DETWFL, DEZFL, and SEZFL (single-ended impedance-based estimation for nonground faults) to determine the initial FL (m_{INI}) based on the following priorities: DETWFL, DEZFL, and SEZFL. Based on the availability of the results from any of the above methods, the SETWFL algorithm selects the FL hypothesis as follows: if the DETWFL result is available, the algorithm selects the hypothesis that is closest to the DETWFL estimation; else if the DEZFL result is available, the algorithm selects the hypothesis that is closest to the DEZFL estimation; else if the SEZFL result is available and the fault is not a ground fault, the algorithm selects the hypothesis that is closest to the SEZFL estimation.

If the DETWFL, DEZFL, or SEZFL result is not available, the algorithm ranks the hypotheses based on the TW reflections using the RTT and ETW methods, as described in the following subsections.

If there are DETWFL, DEZFL, and SEZFL results available but there is no hypothesis matching any of these results, the SETWFL is not calculated.

2.1 Repeating travel time (RTT) method

The RTT method uses the time difference between the selected reflection from the fault and TPK(0) as one of the time references: F(H) = TPK(H) – TPK(0). This time reference is associated with 2 • m (see Fig. 2). TPK(0) corresponds to the time associated with the first TW from the fault; the time F shown in Fig. 2 corresponds to the time reference of the first hypothesis F(1).

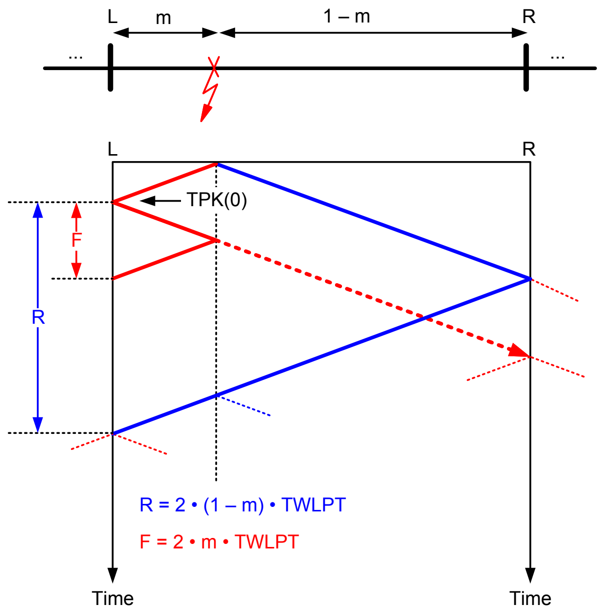

Fig. 2. Time references for the reflection from the fault and from the remote terminal for the first hypothesis.

For each hypothesis, the algorithm calculates another time reference using the reflection from the remote terminal that corresponds to 2 • (1 – m), i.e., R(H) = 2 • TWLPT – F(H). The time R in Fig. 2, corresponds to time reference R(1). We can think of that reflection from the remote terminal as a "companion." The companion TW must arrive at the time coherent with the first wave from the fault. Fig. 2 shows the F(1) and R(1) time references of the first hypothesis.

The algorithm creates a vector, DT, that includes all of the possible time differences using all TPKs in the observation window and counts how many elements of the DT vector match F(H) and R(H) within a predefined tolerance, TWTOL1 (e.g., 10 µs), using the NM(H) and N1_M(H) counters:

- NM(H) is the number of instances that elements in DT match F(H).
- N1_M(H) is the number of instances that elements in DT match R(H).

The main benefit of the RTT method is that it takes advantage of the information provided by TWs reflected from external network elements close to the local terminal. This method uses this information when determining the number of instances, NM(H) and N1_M(H). The dashed blue traces in Fig. 3 indicate additional TWs along the line caused by a reflection from Substation B behind the local terminal that provide information to identify the first reflection from the fault.

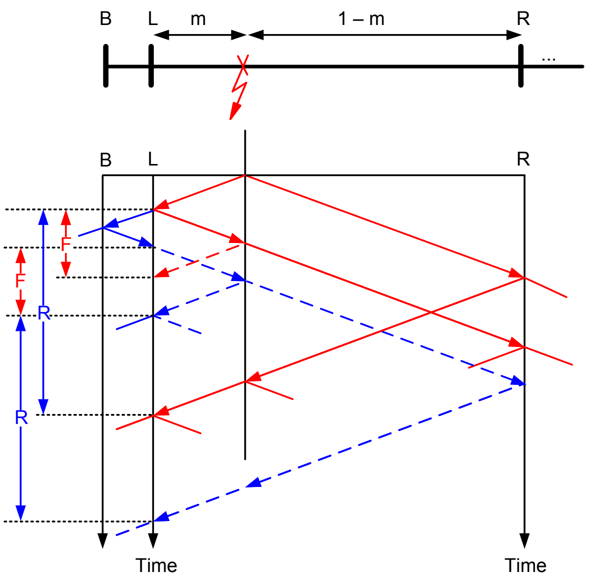

Fig. 3. Reflection from the external network element B provides additional information for selecting the right hypothesis.

2.2 Expected TW (ETW) method

For each hypothesis, the algorithm in the ETW method determines a weighting factor, WGHT(H), and sets it to logical 1 if the reflection from the remote terminal R(H) that corresponds to the particular reflection from the fault F(H) can be found in the measured TPKs. If WGHT(H) = 1, the algorithm includes the number of times that the measured TWs match the expected TWs for the particular hypothesis when ranking the hypotheses.

For each hypothesis, the algorithm creates a vector, ET, that includes all expected TW arrival times within the observation window. Assuming that TPK(0) is the arrival time of the first detected TW and m is the FL in pu of the line length, the following patterns can be obtained:

- Pattern 1, Fault-Local-Fault-Local:
  k • m • TWLPT, k = 1, 3, 5 …
- Pattern 2, Fault-Remote-Fault-Local:
  [2 • k • (1 – m) + m] • TWLPT, k = 1, 2, 3 …
- Pattern 3, Local-Fault-Remote-Fault-Local:
  (k • m + 2) • TWLPT, k = 1, 2, 3 …
- Pattern 4, Local-Fault-Remote-Fault-Remote-Fault-Local: [k • m + 2 • (2 – m)] • TWLPT, k = 1, 2, 3 …

Fig 4 shows the expected TW arrival times for all of the above patterns (fault at m = 0.3).

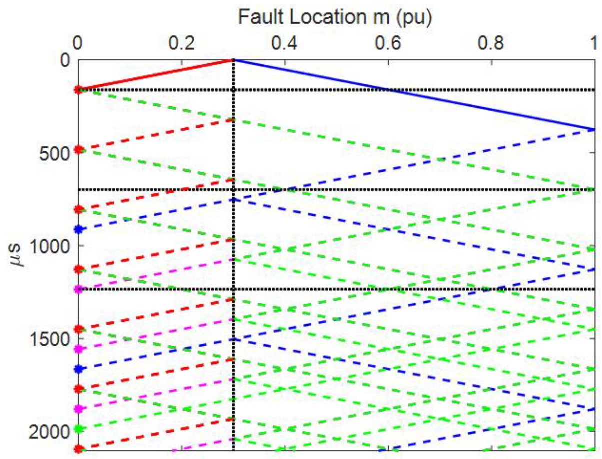

Fig 4. Expected TW arrival times (all asterisk marks) for a fault at m = 0.3 on a line with a line propagation time of 537 µs.

The algorithm counts how many of the measured time stamps, TPKs, match the elements of the ET vector within a predefined tolerance, TWTOL2 (e.g., 5 µs), using the NS(H) counter; NS(H) is the number of instances that measured time stamps, TPKs, match the elements in vector ET.

2.3 Determining the SETWFL result

Given that there is no reflected TW from the external network and the fault is close to the local terminal, the first reflection to arrive at the local terminal is the reflection from the fault. However, when the fault is close to the remote terminal, the first reflection to arrive at the local terminal is the reflection from the remote terminal. For this reason, the algorithm divides the line into three sections to determine the SETWFL result:

- Section 1: 0 <= m_{INI} < 0.3 pu.
- Section 2: 0.3 <= m_{INI} <= 0.7 pu.
- Section 3: 0.7 < m_{INI} <= 1 pu.

With the initial fault location, m_{INI}, information, the algorithm identifies the faulted section and orders the hypotheses in descending order as follows:

- If the fault is in Section 1, the algorithm orders the hypotheses using NM(H).
- If the fault is in Section 2, the algorithm orders the hypotheses using N(H), where:

$$N(H) = NM(H) + N1\_M(H) + NS(H) \bullet WGHT(H) \quad (2)$$

- If the fault is in Section 3, the algorithm orders the hypotheses using N1_M(H).

If m_{INI} is not available, the algorithm assumes that m_{INI} = 0.5 pu.

After all of the hypotheses are ordered, the algorithm uses the time difference F(H), which corresponds to ($t_4 - t_1$) in (1), to calculate the FL for each hypothesis.

3 Fault location accuracy analysis

We analyzed the accuracy of the SETWFL method assuming that the other methods do not provide any FL results for the initial FL guess of the SETWFL method. Therefore, the SETWFL method estimates the FL using only local currents. We used relays that include this method to determine the FL. It is worth noting that in our implementation, we use the modal current that yields the highest initial TW magnitude for time stamping its corresponding TWs. This is because alpha mode is a good representation of the three phase TWs for ground faults and beta mode is a good representation of the three phase TWs for phase-to-phase faults. Also, the mode current with the highest magnitude among the six aerial modes is the right representation of the fault type and the TW signal launched by that fault.

We performed laboratory tests using current signals from a power system model with the ability to simulate power system transients. We also used the currents captured by relays in the field that include the SETWFL method to estimate the FL and then compared the results with the FL provided by the line crews.

3.1 Laboratory testing

We modeled the power system shown in Fig. 5 using an Electromagnetic Transients Program (EMTP) to evaluate the SETWFL method. The line is 100 mi long, and the system nominal operating voltage is 525 kV. The corresponding TWLPT for this line is 537 µs. There are 25 mi, double-circuit lines behind Terminals L and R of the 100 mi line. We applied an A-phase-to-ground (AG) fault at 30 mi from Terminal L on the 100 mi line. We used a low-level signal test source to apply the voltage and current signals to the relays at Terminals L and R.

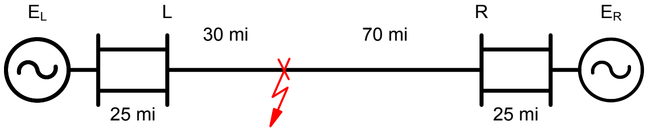

Fig. 5. EMTP power system model with an AG fault at 30 mi from Terminal L to evaluate the SETWFL method.

Fig. 6 shows the phase currents captured by the relay at Terminal L, and Fig. 7 shows the corresponding alpha current TWs with the reflections from the fault.

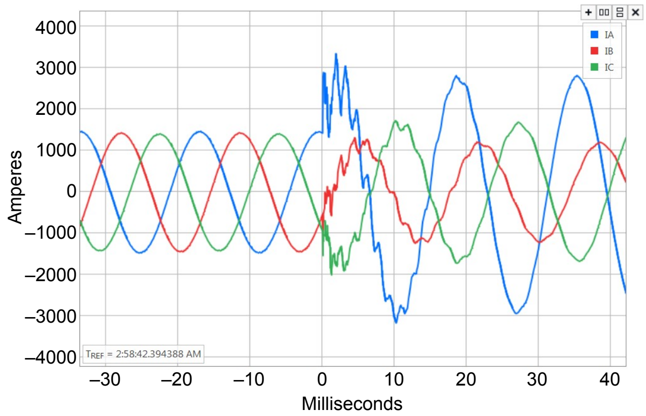

Fig. 6. Phase currents recorded by the relay at Terminal L.

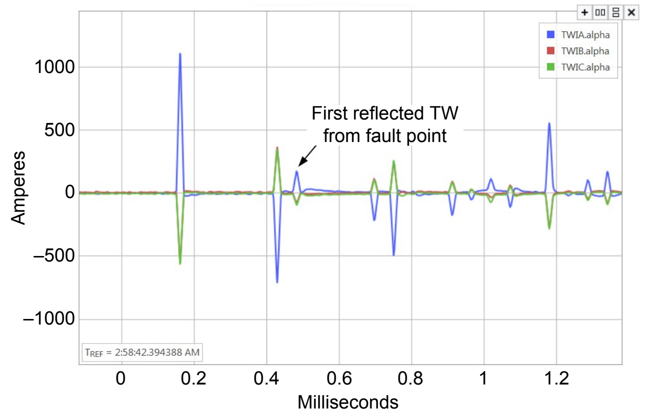

Fig. 7. Alpha current TWs at Terminal L and the reflection from the fault that the method identified to estimate the FL.

The algorithm selected the alpha-A current, which is the maximum alpha current. Fig. 8 shows the selected alpha-A current TW and its Bewley diagram; notice that the time, t = 0, is the time of the fault (it is not the time of the arrival of the first TW at the local terminal). The relay at Terminal L reported the SETWFL at 29.934 mi.

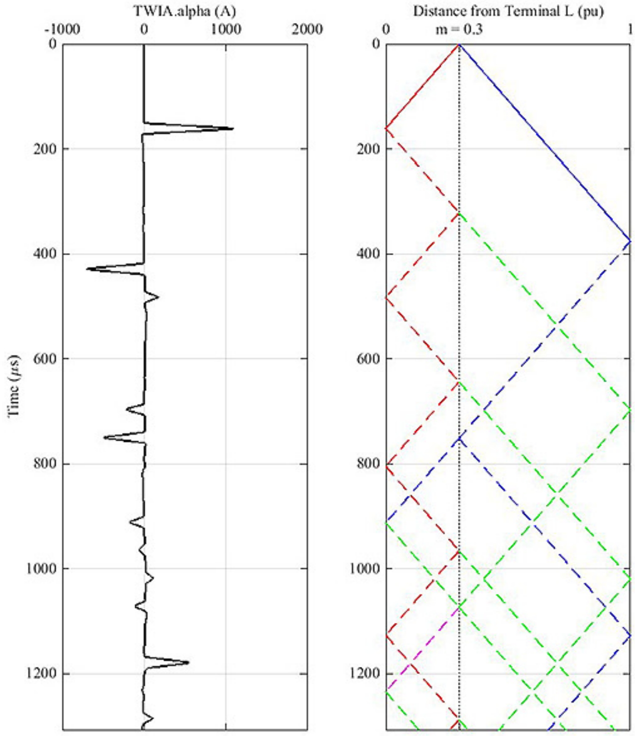

Fig. 8. Alpha-A current TW at Terminal L and associated Bewley diagram.

3.2 Field case

Comisión Federal de Electricidad (CFE), the Mexican electrical utility, owns one 400 kV transmission network where two relays are installed at the terminals of the line that connects the MID and TMD substations. The MID–TMD 400 kV line is 223.80 km long, and the TWLPT for this line is 76.3 μs, according to line energization tests.

Fig. 9 shows the phase currents captured at the MID terminal for a C-phase-to-ground (CG) fault, and Fig. 10 shows the corresponding alpha current TWs. Fig. 11 shows the alpha-C current TWs and associated Bewley diagram. Based on the measured TW arrival times, the SETWFL algorithm reported that the fault was at 135.03 km from the MID terminal. The line crew found the fault at 135 km from the MID terminal.

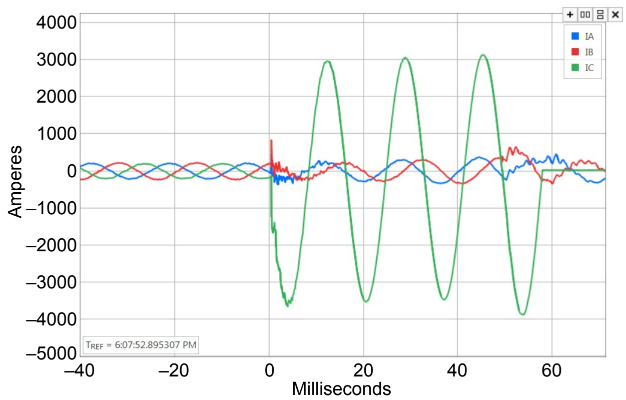

Fig. 9. Phase currents at the MID terminal for a CG fault at 135 km from the MID terminal.

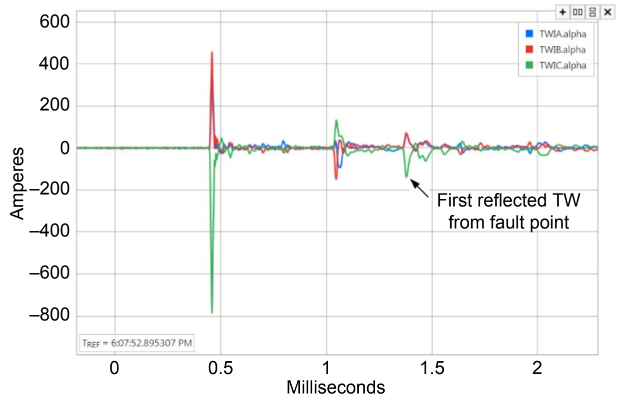

Fig. 10. Alpha-C current TWs at the MID terminal, and the reflection from the fault that the method identified to estimate the FL.

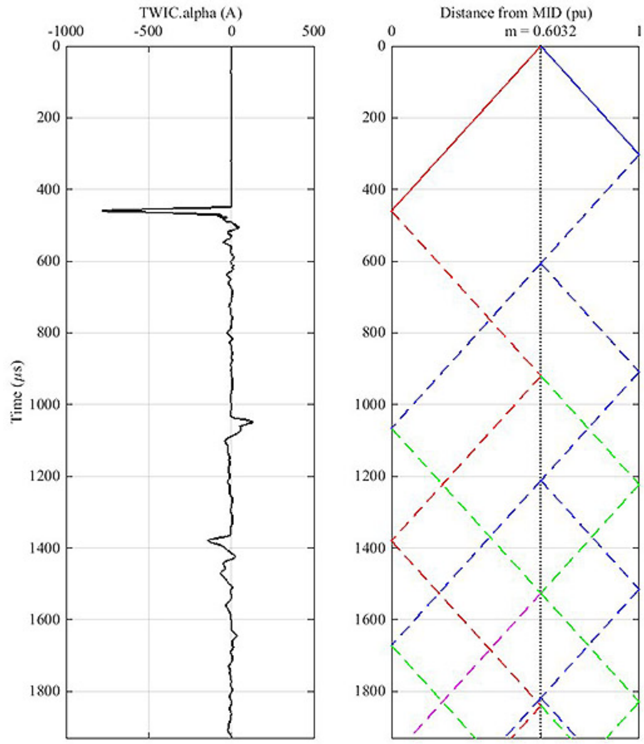

Fig. 11. Alpha-C current TW at the MID terminal and associated Bewley diagram (135 km is 0.6032 pu).

4 Conclusion

TW-based fault locators are accurate to within a tower span and offer great operational benefits by reducing the time and cost of repairing for permanent faults and preventing reoccurrence of faults. Double-ended TW fault locators use a simple operating principle but require communications to two devices and a common time reference. They are more expensive to apply and are exposed to more sources of errors or failure modes. Single-ended TW fault locators eliminate the need for the communications channel and common time reference, but their operating principle is more complex.

This paper describes a practical SETWFL method that uses only local line currents. This method uses the impedance-based FL results to find the approximate FL and refines the approximation using TW measurements. This method also works if the impedance-based FL information is not available by analyzing multiple TWs for consistency in order to correctly identify the first reflection from the fault in a train of TWs.

The SETWFL method takes advantage of the fact that many TWs arriving at the line terminal provide information to identify the first reflection from the fault, including TWs reflected from network elements external to the line.

The SETWFL method has been implemented in a protective relay and provides FL results autonomously without the need for a human operator. The method can be applied manually using high-resolution oscillography records from a device that does not provide single-ended fault locating.

Acknowledgements

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References

[1] E. O. Schweitzer, III, "A Review of Impedance-Based Fault Locating Experience," proceedings of the Northwest Electric Light & Power Association Conference, Bellevue, WA, April 1988.

[2] M. Ando, E. O. Schweitzer, III, and R. A. Baker, "Development and Field-Data Evaluation of Single-End Fault Locator for Two-Terminal HVDC Transmission Lines, Part I: Data Collection System and Field Data," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS 104, Issue 12, December 1985, pp. 3524–3530.

[3] M. Ando, E. O. Schweitzer, III, and R. A. Baker, "Development and Field-Data Evaluation of Single-End Fault Locator for Two-Terminal HVDC Transmission Lines, Part II: Algorithm and Evaluation," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-104, Issue 12, December 1985, pp. 3531–3537.

[4] M. Aurangzeb, P. A. Crossley, and P. Gale, "Fault Location on a Transmission Line Using High Frequency Travelling Waves Measured at a Single Line End," proceedings of the 2000 IEEE Power Engineering Society Winter Meeting, Vol. 4, Singapore, January 2000, pp. 2437–2442.

[5] X. Dong, Z. Chen, X. He, K. Wang, and C. Luo, "Optimizing solution of fault location," proceedings of the 2002 IEEE Power Engineering Society Summer Meeting, Vol. 3, Chicago, IL, July 2002, pp. 1113–1117.

[6] A. Guzmán, B. Kasztenny, Y. Tong, and M. V. Mynam, "Accurate and Economical Traveling-Wave Fault Locating Without Communications," proceedings of the 44th Annual Western Protective Relay Conference, Spokane, WA, October 2017.

[7] E. O. Schweitzer, III, A. Guzmán, M. V. Mynam, V. Skendzic, B. Kasztenny, and S. Marx, "Locating Faults by the Traveling Waves They Launch," proceedings of the 67th Annual Conference for Protective Relay Engineers, College Station, TX, March 2014.

[8] L. V. Bewley, *Traveling Waves on Transmission Systems*. Dover Publications, New York, NY, 1963.

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