Field Experience Using Double-Ended Traveling-Wave Fault Locating Without Relay-to-Relay Communications

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FIELD EXPERIENCE USING DOUBLE-ENDED TRAVELING-WAVE FAULT LOCATING WITHOUT RELAY-TO-RELAY COMMUNICATIONS

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Abstract

This paper discusses how Red Eléctrica de España, the transmission system operator in Spain, successfully applied double-ended traveling-wave-based fault locating (DETWFL) on a pilot project where relay-to-relay communications were unavailable. When relay-to-relay communications are unavailable, an offline DETWFL methodology may be used, in which traveling-wave (TW) arrival time information is manually collected from time-synchronized relays at both ends of the line after an internal fault occurs and the fault location is computed. The paper describes the offline DETWFL method and includes an analysis of a B-phase-to-ground fault on a transmission line to illustrate the performance of this method. It provides a summary of results from five faults that occurred on this line while relay-to-relay communications were unavailable.

1 Introduction

The double-ended traveling-wave-based fault-locating (DETWFL) method using current traveling waves (TWs) in a transmission line protective relay was first introduced in 2012 [1]. Since then, the DETWFL method has also been made available in ultra-high-speed (UHS) relays. TW-based fault locating is widely popular with transmission system operators, largely due to its field-proven track record with reported errors being within one tower span (300 m; 1,000 ft) on average, regardless of line length. The DETWFL method incorporated in UHS relays provides accurate results, but it requires TW data from the two line terminals. When relay-to-relay communications are available, the UHS relay can collect the necessary time stamps of the initial TW that arrives at each terminal when a fault occurs, automatically calculate the fault location using the DETWFL method, and make the result available to the user within tens of milliseconds. As described in [2], relay-to-relay communications can be achieved by using a dedicated point-to-point fiber-optic channel (i.e., direct fiber) or an IEEE C37.94 multiplexed channel. However, there are situations where relay-to-relay communications may not be available. In this case, the offline DETWFL methodology described in this paper (a shortened version of [3]) can be used to obtain accurate fault location results.

This paper begins with a general overview of the DETWFL method. The availability of a precise time reference applied to UHS relays at both line terminals allows for accurate time-stamping of the TW arrival information and enables calculations of the DETWFL results using information from the two UHS relays. This time-stamping process is summarized in Section 2.3 and is critical for implementing the analysis and calculations. The offline DETWFL methodologies described in Section 3 require the extraction of TW time stamps from the UHS relays using one of the methods described in Section 4. This paper also describes the use of event analysis software that can analyze TWs and estimate the fault location using TWs.

Red Eléctrica de España (REE) is the transmission grid owner and operator for the transmission system in Spain. With more than 44,000 km of high-voltage transmission lines, REE is responsible for ensuring the proper operation of the Spanish electrical system, coordinating the generation transport system, and planning the long-term growth of the transmission network to provide secure and continuous power supply to the country. With the intent to explore and gain experience with TW-based fault-locating technology (particularly, improved accuracy of the results and ability to adaptively control autoreclosing on hybrid lines), REE decided to install several UHS relays in their transmission system. In the early stages of their evaluation, relay-to-relay communications were not yet in place on one of the transmission lines where the UHS relays were installed—the 220 kV, 61.98 km overhead line between the Casaquemada and Onuba terminals. However, the relays were connected to high-accuracy Global Positioning System (GPS) clocks, allowing event data to be time-synchronized and enabling the ability to use offline DETWFL methods. A detailed event analysis from a B-phase-to-ground fault on the line between the Casaquemada and Onuba terminals shows the application of the different offline DETWFL strategies explained in this paper. The results from five faults on this line that occurred while relay-to-relay communications were unavailable are also provided. These results highlight the improved accuracy of the DETWFL method as compared to the single-ended impedance-based fault-locating (SEZFL) method and the single-ended traveling-wave-based fault-locating (SETWFL) method. Additional information about the background, project drivers, transmission lines used for the installation of UHS relays in the REE system, and relay-to-relay communications that are now in place are provided in [3].

2 Double-Ended Traveling-Wave-Based Fault Locating

2.1 Principle of Operation

Fig. 1 shows a Bewley diagram, which is a time-spatial chart that shows TWs progressing along the time axis (vertically down) and simultaneously progressing along the distance axis (left to right and right to left) for a fault at Location F on a line of length LL. The fault is M (km or mi) from the local terminal (L), and LL – M (km or mi) from the remote terminal (R). Faults launch TWs that propagate with a velocity (PV) equal to LL divided by the TW line propagation time, TWLPT (i.e., PV = LL/TWLPT) [2]. TWLPT is the one-way end-to-end travel time of a TW along the transmission line.

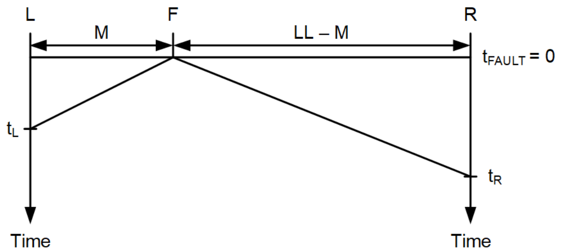

Fig. 1. Bewley diagram explaining the DETWFL method.

When a fault occurs at time $t_{FAULT} = 0$, the first TW arrives at Terminal L at time $t_L = M/PV = M \cdot TWLPT/LL$. Similarly, the first TW arrives at Terminal R at time $t_R = (LL – M)/PV = (LL – M) \cdot TWLPT/LL$. Solving these two equations for M produces (1) as the equation for the DETWFL method.

$$M = \frac{LL}{2}\left(1 + \frac{t_L - t_R}{TWLPT}\right) \quad (1)$$

When the propagation time through current transformer (CT) secondary cables is significantly different at each line terminal, the accuracy of this method can be affected. To increase accuracy, the fault locator compensates for the time delay associated with the cables between the CTs and the relay by backdating the time stamp of the initial TW through use of the TW cable propagation time (TWCPT) setting.

When relay-to-relay communications are obtained through a direct fiber-optic channel, the UHS relays synchronize their internal clocks to each other, providing a common time reference and making the operation of the DETWFL method independent of an external time source. When relay-to-relay communications are obtained through an IEEE C37.94 multiplexed channel, each UHS relay must be synchronized to an absolute time reference by connecting the IRIG-B input to an external IEEE C37.118-compliant clock with accuracy of tens of nanoseconds. This requirement also applies when using the offline DETWFL method described in this paper when relay-to-relay communications are unavailable.

2.2 Mode and Phase Reference Selection

UHS relays use the measured current signals to obtain the phase TWs (TWA, TWB, and TWC), obtain the modal TWs (zero, alpha, and beta Clarke components), and apply them accordingly in various functions. The alpha components are appropriate for analyzing TWs launched by single-line-to-ground faults and the beta components for line-to-line faults. Reference [2] provides details about how the UHS relays calculate and apply the modal TWs.

2.3 Time-Stamping the Arrival Time of TWs

Since the accuracy of the calculated fault location from (1) is highly dependent on TW arrival times with nanosecond resolution, the method the fault locator applies to estimate the TW arrival time is critical to its accuracy. As [2] describes, a differentiator-smoother filter provides a simple and robust method for extracting the TWs from the input signals sampled at 1 MHz. To get a time resolution better than 1 µs, which translates to better fault location accuracy, the TW arrival times can be estimated using interpolation between samples, fitting a parabola to the output of the differentiator-smoother filter using the least-squared error method. The time of the peak of the best-fitting parabola is the TW arrival time and provides a time-stamping accuracy of approximately 0.1 µs [2] [4].

3 Offline Methodology

There are two general approaches to the methodology for offline calculations of the DETWFL result: manual calculations and software tools.

3.1 Manual Calculations

Manual calculation of DETWFL results requires that the time stamps of the initial TWs that arrive at both line terminals be obtained and then applied (along with the LL and TWLPT settings) to (1). Section 4 explains how the TW time stamps may be manually obtained from IEEE COMTRADE header files (Section 4.1) or from analog TW signals contained in transient records with a 1 MHz sampling rate (Section 4.2). As described in [3], the retrieval of the time stamps may be automated by using DNP3 LAN/WAN over Ethernet, allowing for the DETWFL results to be calculated in a central device.

3.2 Software Tools: Bewley Diagram

Event analysis software is available that allows the user to open MHR IEEE COMTRADE records (which are described in Sections 4.1 and 4.2) and plot the voltage and current signals. This software also provides the ability to plot and analyze Bewley diagrams. DETWFL results may be obtained offline by retrieving the MHR IEEE COMTRADE record from each end of the line, opening them in a single session of the event analysis software, and plotting the appropriate modal TW signals in the Bewley diagram. After the time cursors are manually aligned to the initial TW peak at the local and remote ends, the DETWFL results are automatically displayed in an information pane within the software tool. Section 5.1 provides an example of how REE used this method to verify the DETWFL results for an internal BG fault in their system and includes the Bewley diagram used for the analysis (see Fig. 7).

4 Extracting TW Time Stamps

As stated in Section 3.1, the DETWFL results may be obtained offline by using a manual process of obtaining the necessary information—including the time stamps of the initial TWs that arrive at both line terminals—and performing calculations using (1). This section describes two methods to manually obtain the TW time stamps.

4.1 IEEE COMTRADE Header Files

The UHS relay provides a transient recording functionality with two types of records: 1) ultra-high-resolution record containing voltages and currents (megahertz record [MHR], 1 MHz sampling) and 2) high-resolution record containing voltages and currents, derived protection quantities, and all digital bits (time-domain record [TDR], 10 kHz sampling). Both types of records are stored in the IEEE C37.111-2013 COMTRADE format. Per this format, both the MHR and TDR IEEE COMTRADE records comprise three files: a configuration (CFG), data (DAT), and header (HDR) file, where the three-letter abbreviations serve as the file extension type. The CFG file describes the content of the DAT file, the DAT file contains the values for each input channel for each sample in the record, and the HDR file contains relay settings and event-related analog quantities (such as prefault and fault voltages and currents, fault type and location, etc.), which are helpful in analyzing power system events and relay operation [2]. Fig. 2 shows the portion of the HDR file that contains fault location information. This information is available in the HDR file for both the MHR and TDR IEEE COMTRADE records. If the UHS relay can estimate the fault location using one of the available methods (single- and double-ended TW- and impedance-based fault locating: SETWFL, DETWFL, SEZFL, and DEZFL, respectively, with as many as four possible alternatives for the SETWFL method), the results are populated in the respective fields.

```
[Fault_Location]
SE_TW_Location1
SE_TW_Location2
SE_TW_Location3
SE_TW_Location4
DE_TW_Location
SE_Z-Based_Location
DE_Z-Based_Location
First_TW_Time_Local
First_TW_Time_Remote
```

Fig. 2. Portion of the IEEE COMTRADE header file that contains fault location information.

The fields in Fig. 2 are described as follows:

- SE_TW_Location*n* (n = 1, 2, 3, 4) are the fault locations from the SETWFL method.
- DE_TW_Location is the fault location from the DETWFL method.
- SE_Z-Based_Location is the fault location from the SEZFL method.
- DE_Z-Based_Location is the fault location from the DEZFL method.
- First_TW_Time_Local is the time stamp of the first local TW, compensated for by the CT cable delay.
- First_TW_Time_Remote is the time stamp of the first remote TW, compensated for by the CT cable delay.

Whether or not relay-to-relay communications are available, the arrival time of the initial TW at the local terminal is First_TW_Time_Local.

4.2 Transient Records With 1 MHz Sampling

The MHR IEEE COMTRADE records contain voltages and currents sampled at a rate of 1 MHz with 18 bits of resolution and an effective measurement bandwidth of about 400 kHz. Event analysis software is available that allows the user to open the MHR IEEE COMTRADE record and plot the voltage and current signals. The software makes available the modal TW signals (ground, alpha, and beta Clarke components) and provides time cursors that replicate the interpolation method described in Section 2.3. Therefore, the time stamp of the initial TW at each terminal may be obtained by opening the corresponding MHR IEEE COMTRADE record in the event analysis software, plotting the appropriate modal TW signal for the fault type, and sliding the time cursor to line up with the peak of the initial TW. It is important to note that this time stamp does not include compensation for the CT cable delay. Fig. 3 shows an example of the signals available in the MHR IEEE COMTRADE record from the UHS relay for an internal BG fault in the REE system, and Fig. 6 shows how the alpha-mode B-phase TW signals may be used to obtain the time stamp of the initial TW that arrived at each end of the line.

5 Field Experience

In December 2019, the 220 kV, 61.98 km line between the Casaquemada and Onuba terminals did not have relay-to-relay communications in place, making the DETWFL results unavailable for automatic calculation by the UHS relays.

5.1 Internal BG Fault, December 8, 2019

For this fault event, the pair of UHS relays detected an internal B-phase-to-ground fault while monitoring the line. Both relays were connected to a high-accuracy IRIG-B time source, so the DETWFL results could be obtained using the offline methods described in Section 3. REE calculated the DETWFL result for the Casaquemada terminal to be 27.045 km. This was corroborated by the SEZFL and SETWFL results, which were 24.220 km and 26.728 km, respectively. Fig. 3 shows the voltage and current signals sampled at 1 MHz by the UHS relay at the Casaquemada terminal. As described in Section 4.1, the HDR file of the TDR and MHR IEEE COMTRADE records from the UHS relay contain fault location results for all four available methods. Fig. 4 shows the fault location results from the UHS relay at Casaquemada, and Fig. 5 shows the results from the UHS relay at Onuba. REE calculated the DETWFL results manually using data available in the event records from both terminals. The First_TW_Time_Local value in Fig. 4 and Fig. 5 indicates the arrival time of the initial TW at each end, respectively. These arrival times are compensated for by the TWCPT setting in each relay. The comparison of these arrival times shows that the UHS relay at Casaquemada was the first to detect a TW, which indicates the fault was closer to that terminal. Furthermore, the first TW arrived at Casaquemada 26.798 µs before the first TW arrived at Onuba.

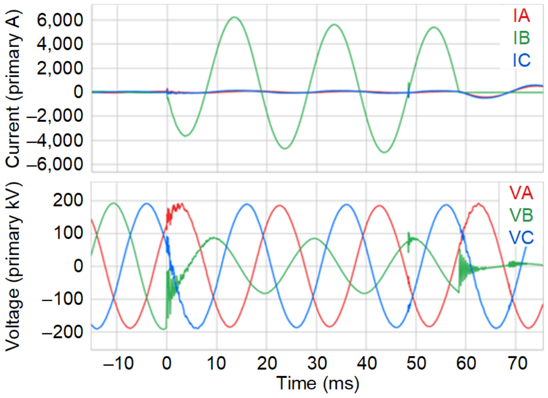

Fig. 3. Casaquemada UHS relay event record data showing a B-phase fault.

```
[Fault_Location]
SE_TW_Location1,"26.728(km)"
SE_TW_Location2,"33.168(km)"
SE_TW_Location3,"$$$$$$$(km)"
SE_TW_Location4,"$$$$$$$(km)"
DE_TW_Location,"$$$$$$$(km)"
SE_Z-Based_Location,"24.220(km)"
DE_Z-Based_Location,"$$$$$$$(km)"
First_TW_Time_Local,"2019/12/08,05:06:48.182811650"
First_TW_Time_Remote,"$$$$$$$$"
```

Fig. 4. Fault location information in the HDR file from the UHS relay at Casaquemada.

```
[Fault_Location]
SE_TW_Location1,"3.158(km)"
SE_TW_Location2,"27.738(km)"
SE_TW_Location3,"34.755(km)"
SE_TW_Location4,"38.668(km)"
DE_TW_Location,"$$$$$$$(km)"
SE_Z-Based_Location,"32.081(km)"
DE_Z-Based_Location,"$$$$$$$(km)"
First_TW_Time_Local,"2019/12/08,05:06:48.182838448"
First_TW_Time_Remote,"$$$$$$$$"
```

Fig. 5. Fault location information in the HDR file from the UHS relay at Onuba.

Using (1), REE calculated the DETWFL result for Casaquemada to be 27.045 km, as shown in (2), where $t_L - t_R$ is negative because the fault was closer to Casaquemada.

$$M = \frac{61.98}{2}\left(1 + \frac{-26.798}{210.50}\right) \qquad (2)$$
$$M = 27.045 \text{ km}$$

Similarly, REE used (1) to calculate the fault location from the Onuba terminal. Since the fault was closer to Casaquemada, $t_L - t_R$ is a positive number when performing the calculation with respect to Onuba, and the result is 34.935 km.

Fig. 6 shows the B-phase alpha-mode current TWs captured by the UHS relays (available in the MHR IEEE COMTRADE record) at the local and remote terminals, Casaquemada (black) and Onuba (blue), respectively, and it displays the relative arrival time difference between the first TWs at each end (–27.037 µs). For this application, the TWCPT setting at Casaquemada and Onuba is 0.238 µs and 0.477 µs, respectively. When compensation for TWCPT is applied to the time stamps determined in Fig. 6, the same arrival time difference used in (2) is obtained: (–27.037) – (0.238 – 0.477) µs = –26.798 µs. Fig. 6 also shows that both TWs are in-phase (i.e., both have negative polarity), as expected for an internal (on-the-line) event or fault.

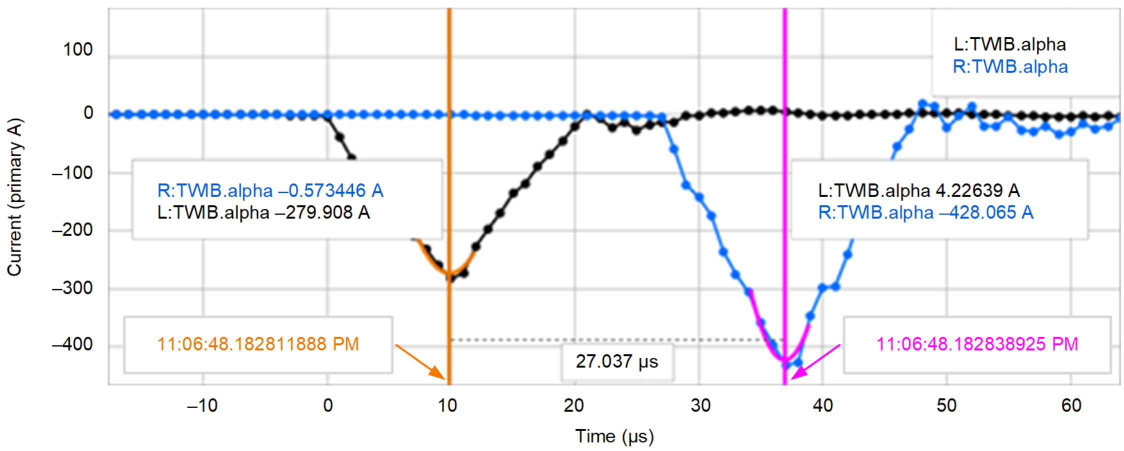

Fig. 6. B-phase alpha-mode current TWs captured by UHS relays at the local and remote terminals, Casaquemada (L, black) and Onuba (R, blue), respectively, including the arrival times of the first TWs at each end.

The Bewley diagram in Fig. 7 shows the time and distance relationship of the measured B-phase alpha-mode current TWs for the local and remote terminals, Casaquemada (black) and Onuba (blue), respectively, and it shows the first TW that arrived at each terminal, along with the subsequent reflections. This view is obtained after aligning the time cursors to the initial TW peaks for each end (green and red, respectively). The fault location provided by the software in the information pane on the left side of Fig. 7 matches the result of the manual calculations shown in (2).

The offline DETWFL results calculated by REE differed from the SETWFL results in Fig. 4 and Fig. 5 by 317 m and 180 m, respectively. The SETWFL and SEZFL results corroborated the DETWFL results REE obtained from the Bewley diagram and by manual calculation. Using the results of this analysis, REE's maintenance team inspected the circuit and found evidence of the fault at a tower located 26.943 km from Casaquemada (35.009 km from Onuba). Identification of the true fault location confirmed that the results obtained from the Bewley diagram in Fig. 7 and from manual calculations were within one tower span from either end: 102 m from Casaquemada and 74 m from Onuba.

5.2 *Summary of Results*

A summary of five fault events, including the event described in Section 5.1, is provided in Table 1. It includes fault location results on the Casaquemada-to-Onuba line while relay-to-relay communications were unavailable. The tabulated results include the following:

- SEZFL, provided by the distance relays protecting the line.
- SETWFL, provided by the UHS relays monitoring the line.
- DETWFL, obtained from UHS relays using the offline calculation methods explained in this paper.
- The location of the tower where the fault was confirmed.

Table 1 shows that the offline DETWFL method provided results that were accurate to within one tower span for all five faults that occurred on this line while relay-to-relay communications were unavailable. Having these accurate results allowed line crews to quickly identify the cause of the fault and restore the line to service. Fig. 8 shows an example in which evidence of the December 17, 2019, fault was found, confirming the fault location and showing that bird contamination was the likely cause.

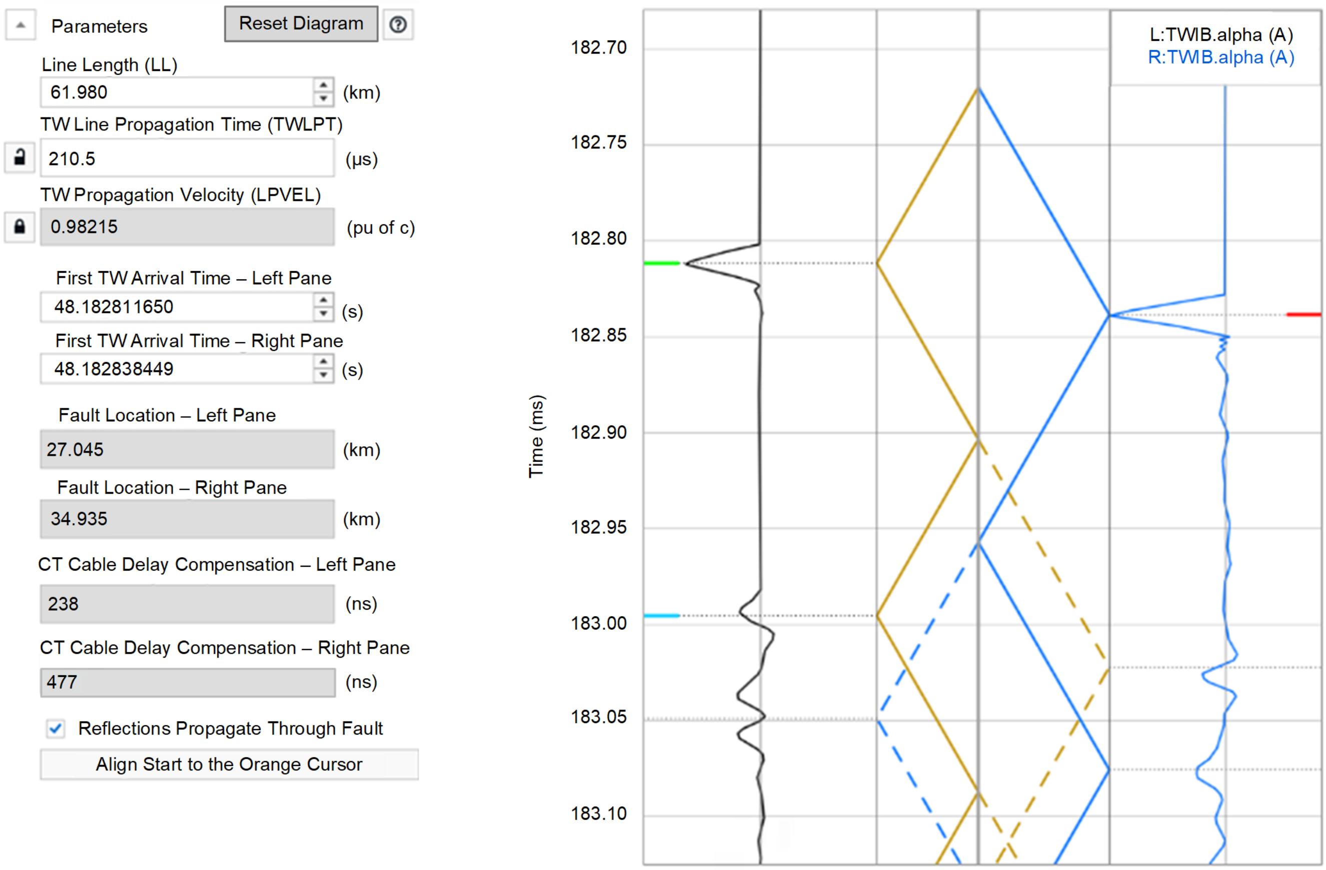

Fig. 7. Bewley diagram showing B-phase alpha-mode current TWs for the local and remote terminals, Casaquemada (L, black) and Onuba (R, blue), respectively.

Table 1 Summary of fault location results for the 220 kV, 61.98 km overhead transmission line between the Casaquemada and Onuba terminals.

Event date	Fault type	Terminal	SEZFL		SETWFL		DETWFL		Tower location (km)
			Result (km)	Error (km)	Result (km)	Error (km)	Result (km)	Error (km)	
Nov. 29, 2019	BG	Casaquemada	30.573	3.294	33.449	0.418	33.872	0.005	33.867
		Onuba	25.332	2.753	28.212	0.127	28.108	0.023	28.085
Dec. 8, 2019	BG	Casaquemada	24.220	2.723	26.728	0.215	27.045	0.102	26.943
		Onuba	32.081	2.928	34.755	0.254	34.935	0.074	35.009
Dec. 17, 2019	BG	Casaquemada	25.922	3.115	28.758	0.279	29.138	0.101	29.036
		Onuba	29.825	3.091	32.714	0.202	32.842	0.074	32.916
Dec. 26, 2019	BG	Casaquemada	55.398	4.033	33.153	26.278	59.210	0.221	59.431
		Onuba	2.154	0.367	2.505	0.016	2.770	0.249	2.521
Jan. 1, 2020	BG	Casaquemada	30.447	3.420	33.343	0.524	33.908	0.041	33.867
		Onuba	25.162	2.923	27.918	0.167	28.072	0.013	28.085

Fig. 8. Evidence found of the December 17, 2019, fault, showing bird contamination and arcing across the insulators.

6 Conclusion

UHS transmission line protective relays include built-in TW-based fault-locating methods that are accurate to within a tower span (300 m; 1,000 ft), regardless of the line length. Having accurate fault location results allows for improved system operations by reducing patrol and repair time. Furthermore, these accurate results help minimize costs by aiding in the detection of problematic areas of the line so reoccurring faults can be reduced.

Since 2019, REE has been gaining experience with UHS relays for TW-based fault locating and adaptive autoreclosing on hybrid lines with relay-to-relay communications. This paper presented REE's experience with performing offline calculations using the DETWFL method when relay-to-relay communications were not yet available on one of the lines where the new technology was being evaluated. Analysis of the results verified that the accuracy was within one tower span for this line, providing confidence for REE to continue moving forward with evaluation of UHS relays.

Methods for obtaining DETWFL results using offline calculations and software tools (such as the Bewley diagram available in event analysis software) were described, as well as requirements for time-stamping TWs and options for obtaining the time stamps using manual methods. Fault location data recorded during five faults on an REE transmission line confirmed that DETWFL results could be obtained using an offline methodology when relay-to-relay communications were unavailable, providing REE with results that were accurate to within a tower span.

The offline calculated DETWFL result can be used to confirm the SETWFL result(s), help select the correct alternative result, or provide a TW-based result when the results from other fault-locating methods are unavailable.

7 References

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