Application of a Hybrid Fault Location Technique Combining Impedance and Traveling Waves to Double-Circuit Transmission Line

V.H. Gonzalez-Sanchez, V. Torres-García

***Abstract*—This paper presents a hybrid fault location technique for double-circuit transmission lines that combines impedance-based and traveling wave methods to achieve accurate fault distance estimation. The proposed algorithm operates using single-terminal measurements and applies a correlation technique to determine the time difference between incident waves caused by a fault and their subsequent reflections. To enhance the identification of reflected waves, an impedance-based pre-estimation calculates a time window in which the reflections are expected to occur. The proposed technique is implemented in a real event from the Mexican utility, where voltage and current signals are processed to compare the proposed methodology with existing single- and double-terminal techniques reported in the literature. Finally, the results show that the proposed method achieves fault location errors below 1%.**

***Index Terms*—Fault location, Impedance, Traveling Waves, Transmission Lines**

I. Introduction

Fault location in transmission systems is of critical importance for electric utilities due to the need to maintain reliability and continuity in power system operations. When a fault occurs, accurately estimating its location is essential to minimize repair times and promptly restore normal system operation. Consequently, the development of methods and instruments that can precisely determine fault distances has garnered significant attention from both the industry and the research community. Additionally, if the fault occurs in double-circuit transmission lines it will represent a challenge due to the mutual coupling effects of adjacent circuits and fault resistance.

Over the years, Impedance-based methods, and phasor measurements have been the most widely used techniques for fault location, owing to their simplicity and ease of implementation [1]. Such as in [2] where only the negative-sequence current and voltage phasors during the fault are processed for calculating the fault location in double circuit transmission line. The bi-level and its first level technique is utilized in [3] where the fault location method considers the magnetic coupling between lines and it is also applicable for both transposed and un-transposed lines. Some improvements has been carried out such as in [4] where phasors estimated from variable window size strategies may improve the fault locator performance and in [5], where the distance relay is utilized for the location of simultaneous fault with no comunication channel or the PMUs.

On the other hand, traveling wave-based methods have also gained prominence due to their high precision and rapid response. While the concept of traveling waves has been known for decades, the advent of intelligent electronic devices (IEDs) capable of incorporating these methodologies has significantly advanced their application [6].

Traditionally, fault location methods by using traveling waves can be classified into two categories based on their measurement requirements: single-terminal and double-terminal techniques. Double-terminal methods offer higher precision by utilizing data from both ends of the transmission line, often through communication channels to exchange information. These methods rely on identifying the first wavefronts produced by the fault at both terminals, with the times of wave detection used to calculate the fault distance. However, the effectiveness of double-terminal methods depends on the availability of reliable communication channels and precise measurement synchronization, which can be challenging in certain scenarios. Such as in [7] where the empirical mode decomposition and the variational mode decomposition associated with Teager energy operator is utilized.

In contrast, single-terminal traveling wave-based techniques provide a promising alternative. These methods eliminate the need for communication channels, reducing implementation costs and avoiding synchronization errors, thereby improving reliability. A case in point is [8] where the proposed algorithm uses the three-phase voltages measured through optical sensors at the fault locator installation bus to extract the traveling wave arrival times using two consecutive sliding windows and curve fitting. Some methodologies utilize the maximum wavelet transform modulus to detect the arrival of traveling waves [9], [10]. However, these approaches often require decoupling phase currents and analyzing the zero-sequence mode to ensure accurate fault identification. A fault location method is presented in [11] for Hybrid Parallel HVAC/HVDC Overhead Transmission Lines (HPOTLs) on the same tower using Discrete Wavelet Transform (DWT). Unlike DWT-based techniques, correlation methods can operate with lower sampling rates (in the kHz range), making their implementation more straightforward and computationally efficient. However, the accuracy of these methods depends on selecting an appropriate time window, as the correlation coefficient is sensitive

V. H. Gonzalez-Sanchez is with Universidad Nacional Autónoma de México, Mexico. V. Torres-García is with ITM, Instituto Tecnológio de Morelia, Mexico. (e-mail of corresponding author: v.torres@ieee.org).

Paper submitted to the International Conference on Power Systems Transients (IPST2025) in Guadalajara, Mexico, June 12-15, 2025.

to the width of the chosen window [12], [13]. And other works take advantage of artificial intelligence such as in [14] where the convolution neural network (CNN) is utilized.

The main challenge of single-terminal methods is accurately identifying traveling waves at the measurement terminal, as reflections from discontinuities or adjacent nodes can complicate fault distance calculations.

This paper addresses these challenges with a hybrid fault location method that combines impedance-based and traveling wave-based techniques. It uses a reactance-based impedance method for a preliminary fault distance estimation, which defines a time window for expected wave reflections. This pre-estimation enhances the accuracy of the subsequent correlation-based traveling wave analysis.

The key contribution of this work is a hybrid algorithm that can be applied in double-circuit transmission lines, where coupling effects often hinder conventional methods. By combining impedance and traveling wave techniques, the proposed method mitigates errors from wave misidentification and accurately defines the data window for reflections, improving fault location accuracy under the unique conditions of double-circuit lines.

II. Fault Location Techniques

A. Impedance-Based Methods

Single-ended impedance-based methods estimate the fault location using voltage and current measurements at a single terminal. These methods are straightforward to implement and do not require communication channels, making them cost-effective solutions for fault location. Among the most common methods are the Simple Reactance, Takagi, Modified Takagi, Eriksson, and Novosel methods. However, their accuracy can be affected by fault resistance, remote infeed, mutual coupling, and non-homogeneous systems [1].

Fig. 1 illustrates the typical configuration of a transmission system used to derive and apply these methods. The system consists of two terminals, each represented by their internal voltage sources (E_G, E_H) and source impedances (Z_G, Z_H), connected through a transmission line with impedance Z_{L1}. The fault occurs at a distance m from terminal G, represented as mZ_{L1}, with a fault resistance R_F. Voltage and current measurements (V_G, I_G) are taken at terminal G to estimate the location of the fault.

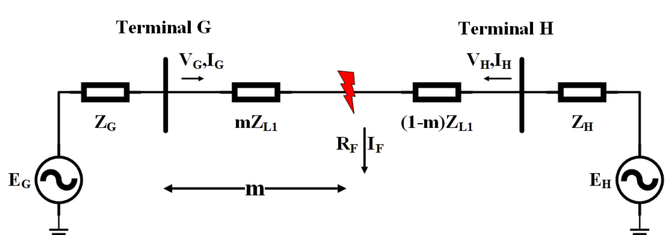

Fig. 1. Schematic representation of the transmission system for one-ended impedance-based fault location methods.

1) Simple Reactance Method: The Simple Reactance method estimates the fault location by considering only the imaginary components of voltage and current measurements. The per-unit distance to the fault, m, is calculated as:

$$m = \frac{\text{imag}\left(\frac{V_G}{I_G}\right)}{\text{imag}(Z_{L1})}, \tag{1}$$

where V_G and I_G are the voltage and current measured at the local terminal, and Z_{L1} is the positive-sequence line impedance. This method assumes that the fault resistance R_F does not introduce significant reactance, which may lead to errors when this assumption is violated.

2) Takagi Method: The Takagi method improves the accuracy of fault location by eliminating the influence of load currents. Using the superposition principle, the faulted network is decomposed into pre-fault and pure fault components. The fault distance is given by:

$$m = \frac{\text{imag}\left(V_G \cdot \Delta I_G^*\right)}{\text{imag}\left(Z_{L1} \cdot I_G \cdot \Delta I_G^*\right)}, \tag{2}$$

where ΔI_G is the change in current caused by the fault, computed as the difference between pre-fault and fault current. This method is effective in homogeneous systems but may introduce errors in non-homogeneous systems.

3) Modified Takagi Method: The Modified Takagi method addresses the unavailability of pre-fault current by using zero-sequence currents in the computation. For single line-to-ground faults, the fault distance is calculated as:

$$m = \frac{\text{imag}\left(V_G \cdot 3I_{G0}^*\right)}{\text{imag}\left(Z_{L1} \cdot I_G \cdot 3I_{G0}^*\right)}, \tag{3}$$

where I_{G0} is the zero-sequence current measured at the local terminal. This method compensates for system non-homogeneity by iteratively correcting the angle mismatch.

4) Eriksson Method: The Eriksson method compensates for fault resistance, load, and non-homogeneity by explicitly incorporating the source impedance parameters into the fault location calculation. The fault distance m is derived by solving the quadratic equation:

$$m^2 - k_1 m + k_2 - k_3 R_F = 0, \tag{4}$$

where k_1, k_2, and k_3 are constants determined by voltage, current, line impedance, and source impedance parameters. The fault resistance R_F can be calculated separately if required.

5) Novosel Method: The Novosel method is a variation of the Eriksson method and is applicable for radial transmission lines. It assumes a constant impedance load model and modifies the constants in the quadratic equation to account for load impedance.

These one-ended methods, while simple and practical, are sensitive to error sources such as remote infeed, fault resistance, and system non-homogeneity [1]. They serve as a baseline for evaluating the performance of more advanced algorithms, such as the hybrid method proposed in this study.

B. Traveling Wave-Based Methods

Traveling wave-based methods are widely recognized for their high precision and fast response in fault location. These methods analyze transient traveling waves generated by faults in transmission lines. A fault creates incident waves that propagate along the line and produce reflected and refracted waves at discontinuities, such as the fault location and line terminals.

Fig. 2 presents a lattice diagram illustrating the propagation of traveling waves. This diagram depicts how incident, reflected, and refracted waves interact with the fault and terminal discontinuities. Voltage and current transients measured at one or both terminals are crucial for estimating the fault distance.

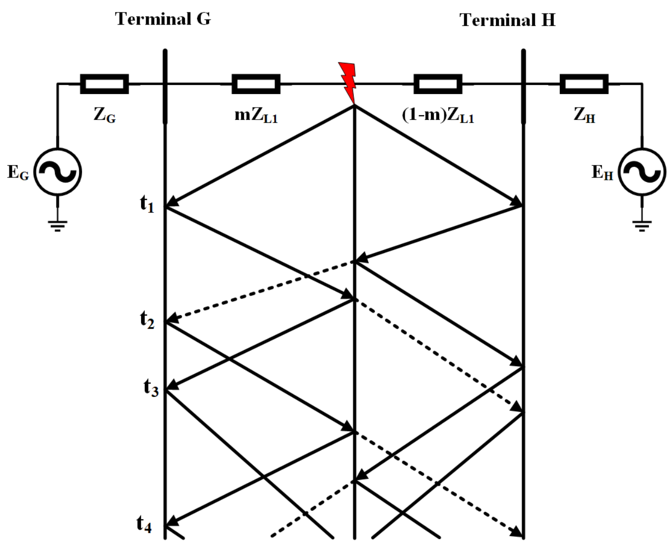

Fig. 2. Lattice diagram illustrating the propagation of traveling waves in a transmission system.

When a fault occurs, traveling waves propagate backward and forward along the transmission line. The telegrapher's equations describe the transient behavior of voltage u and current i as:

$$u(x,t) = f_1(x - vt) + f_2(x + vt), \tag{5}$$

$$i(x,t) = \frac{1}{Z_c}\left[f_1(x - vt) - f_2(x + vt)\right], \tag{6}$$

where v is the propagation speed, and Z_c is the line's characteristic impedance.

For practical purposes, the incremental voltage Δu and current Δi are used to represent the traveling waves:

$$S_1(t) = \Delta u(t) + Z_c \Delta i(t), \tag{7}$$

$$S_2(t) = \Delta u(t) - Z_c \Delta i(t), \tag{8}$$

where S_1 and S_2 are the backward and forward waves, respectively. These signals are used to calculate the fault location by determining their arrival times at the terminals. In multi-phase systems, mutual coupling requires voltage and current signals to be processed using modal transformations to enhance accuracy.

The fault distance m in single-terminal methods is calculated as:

$$m = \frac{v \cdot (t_2 - t_1)}{2}, \tag{9}$$

where t_1 and t_2 are the times of arrival of the incident and reflected waves, and v is the propagation velocity of the traveling wave.

1) Correlation-based Method: Correlation-based methods estimate fault distance by measuring the similarity between the incident and reflected waves. A segment of the forward wave S_2, corresponding to the first wavefront, is stored when a fault is detected. Subsequent portions of the backward wave S_1 are correlated with S_2, and the time difference Δt is identified. The correlation function is expressed as:

$$\Phi_{S_1 S_2}(m\Delta t) = \frac{1}{N}\sum_{k=1}^{N}\left[S_2(k\Delta t) - \overline{S_2}\right]\left[S_1(k\Delta t + m\Delta t) - \overline{S_1}\right], \tag{10}$$

where $\overline{S_1}$ and $\overline{S_2}$ are the mean values of their respective samples.

Based on the maximum correlation value, the fault distance is calculated as:

$$d = \frac{v \cdot m\Delta t}{2}. \tag{11}$$

This method is advantageous as it eliminates the need for time synchronization and line length information, making it suitable for single-terminal configurations.

Traveling wave-based methods are highly effective for fault location due to their precision and rapid response. However, these methods face significant challenges, particularly in identifying reflected waves and multiple reflections caused by discontinuities in the system, such as line terminals, faults, and junctions. This difficulty is exacerbated in complex multi-phase systems, where coupling effects between phases can distort the waveforms and hinder accurate detection.

Moreover, accurately distinguishing the first wavefronts is critical for calculating fault distance but is often complicated by overlapping signals and noise. In these scenarios, errors in wave identification can lead to substantial inaccuracies in fault location. Although advanced signal processing techniques, such as wavelet transforms and correlation analysis, improve the robustness of these methods, they may still require careful parameter tuning and are computationally intensive.

Despite these challenges, traveling wave-based methods remain a valuable benchmark for comparison with hybrid approaches, as they highlight the limitations and areas for improvement in practical fault location scenarios.

III. Proposed Method

The proposed method combines impedance-based fault location algorithms with traveling wave techniques to achieve accurate fault location. The key premise is that most transmission lines are equipped with protection schemes that include impedance-based fault location algorithms. These algorithms provide an initial estimate of the fault distance, which, although simple, may have a significant margin of error due to factors such as fault resistance, remote infeed, and system non-homogeneity.

The methodology begins with the application of Park's transformation to the measured three-phase voltage and current signals. This step decouples the system into direct, quadrature, and zero components, simplifying the transient analysis and enabling effective detection of traveling wave signals [15].

The Park's transformation is applied as follows [16]:

$$\begin{bmatrix} V_0(k) \\ V_d(k) \\ V_q(k) \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & 1 & 1 \\ \cos(\phi) & \cos(\phi - 120^\circ) & \cos(\phi + 120^\circ) \\ -\sin(\phi) & -\sin(\phi - 120^\circ) & -\sin(\phi + 120^\circ) \end{bmatrix} \cdot \begin{bmatrix} V_a(k) \\ V_b(k) \\ V_c(k) \end{bmatrix} \tag{12}$$

where $\phi = \omega t + \theta$, V_a, V_b, and V_c are the three-phase voltage measurements, and V_0, V_d, and V_q represent the zero, direct, and quadrature components, respectively. The same transformation is applied to the current signals, yielding I_0, I_d, and I_q. The V_d and I_d components, being aligned with the fault-induced transients, are used as inputs for subsequent fault location steps.

Once the signals are decoupled, the method utilizes an impedance-based algorithm, such as those described in Section II, to provide a preliminary fault distance estimate, denoted as d_{pre}. This initial estimate serves as the starting point for refining the fault location. Although d_{pre} may contain a significant margin of error due to factors such as fault resistance or system inhomogeneities, it is essential for defining a time window within which the reflections of traveling waves are expected to occur.

The velocity of wave propagation, v, is calculated based on the per-unit-length inductance L' and capacitance C' of the transmission line, as:

$$v = \frac{1}{\sqrt{L' \cdot C'}}. \tag{13}$$

This propagation velocity is critical for determining the arrival times of the traveling waves and refining the fault location through time-domain analysis.

The traveling wave signals are extracted from the voltage and current signals measured at one terminal. The forward (S_1) and backward (S_2) traveling waves are computed as:

$$S_1(t) = V(t) - Z_c \cdot I(t), \tag{14}$$

$$S_2(t) = Z_c \cdot I(t) - V(t), \tag{15}$$

where $V(t)$ and $I(t)$ are the measured voltage and current signals, and Z_c is the characteristic impedance of the line.

To focus on the relevant signal components, a high-pass Butterworth filter is applied to $S_1(t)$ and $S_2(t)$, yielding the filtered signals $S_1^{\text{filtered}}(t)$ and $S_2^{\text{filtered}}(t)$. The Butterworth filter is characterized by its transfer function $H(s)$, defined as:

$$H(s) = \frac{s^n}{s^n + \omega_c^n}, \tag{16}$$

where s is the Laplace transform variable, ω_c is the cutoff angular frequency, and n is the order of the filter.

The filtered signals are obtained by convolving the input signals with the impulse response of the filter:

$$S_1^{\text{filtered}}(t) = h(t) * S_1(t), \quad S_2^{\text{filtered}}(t) = h(t) * S_2(t), \tag{17}$$

where $h(t)$ is the inverse Laplace transform of $H(s)$, representing the impulse response of the Butterworth filter, and $*$ denotes the convolution operation.

The initial estimate d_{pre} is then used to calculate the expected propagation time of the traveling wave to the fault and back. The time window is defined as:

$$t_{\text{start}} = t_0 + \frac{d_{\text{pre}}}{v}, \quad t_{\text{end}} = t_{\text{start}} + \Delta t, \tag{18}$$

where t_0 is the fault initiation time, and Δt is the duration of the window, determined by the assumed uncertainty in d_{pre}.

A template signal is extracted from the backward wave $S_2^{\text{filtered}}(t)$ within this window. This template, $T(t)$, is then cross-correlated with the forward wave $S_1^{\text{filtered}}(t)$ to refine the fault location:

$$R(\tau) = \sum_{k=1}^{N} T(k) \cdot S_1^{\text{filtered}}(k + \tau), \tag{19}$$

where τ is the time lag, N is the length of the template, and $R(\tau)$ is the cross-correlation result.

The maximum value of $R(\tau)$ identifies the time delay between the forward and reflected waves, corresponding to the arrival of the reflections. Let t_1 and t_2 represent the arrival times of the reflected waves at two key points along the line. The fault distance d_f is then calculated as:

$$d_f = L - \frac{(t_2 - t_1) \cdot v}{2}. \tag{20}$$

This process refines the initial estimate d_{pre}, significantly reducing the error introduced by the impedance-based algorithm. By leveraging the traveling wave reflections and focusing the analysis within a well-defined window, the proposed method provides a robust and accurate solution for fault location.

The integration of impedance-based preestimation and traveling wave analysis ensures compatibility with existing protection schemes while enhancing fault location accuracy.

The flowchart in Fig. 3 summarizes the proposed fault location algorithm. The process begins with acquiring three-phase voltage and current signals, followed by an impedance-based preestimation of the fault distance, d_{pre}. Park's transformation is then applied to decouple the signals into direct, quadrature, and zero components, enabling the computation of traveling waves. These waves are filtered using a high-pass Butterworth filter to isolate high-frequency transients, and cross-correlation is performed to determine the time shifts of reflected waves. Finally, the fault distance is refined using the identified time shifts and the propagation velocity of the line.

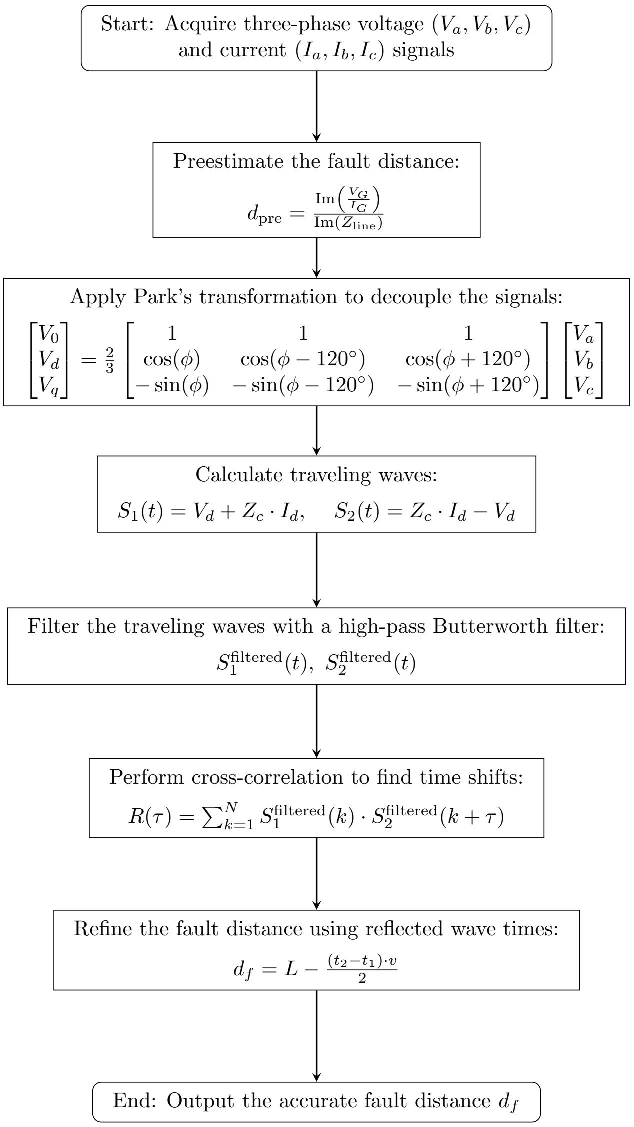

Fig. 3. Flowchart of the proposed algorithm.

IV. Real Fault Event Analysis

The collaboration with the Mexican utility, which provided real-world measurements, offers a unique opportunity to analyze representative data from a specific event on a transmission line. This collaboration enables the evaluation of fault location methods under real operating conditions, validating the accuracy and robustness of the proposed algorithms. Specifically, the acquired data corresponds to an event on a double-circuit transmission line between Terminal G and Terminal H. During this event, the phase B reclosure device failed to operate successfully, leading to the activation of protection systems at the associated substations.

A. Measurements

The performance of fault location algorithms is influenced by the characteristics of the measurement system, including

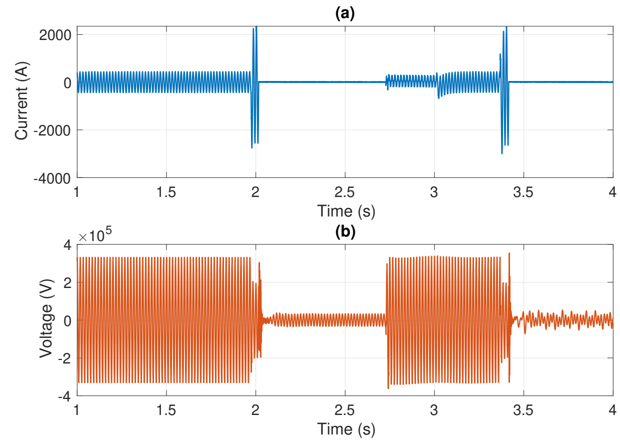

Fig. 4. (a) Current and (b) Voltage of the fault phase during the event on transmission line under study, measured at terminal G.

instrument transformers and signal preprocessing techniques, which can introduce distortions and affect the accuracy of fault distance estimation [17], [18]. In this study, the voltage and current signals were provided directly by the utility; however, detailed information about the specific measurement devices and preprocessing methods used was not provided. Nevertheless, these signals are processed by the fault location algorithms employed by the utility, making them a relevant reference for evaluating the proposed method. While this study focuses on assessing the performance of the hybrid fault location technique, further research is required to assess the impact of measurement instruments on fault location accuracy.

Fig. 4 and Fig. 5 present the three-phase voltage and current recordings obtained at the substations located at Terminals G and H, respectively, during the event. These figures depict the time-domain behavior of the currents and voltages in the fault phase B, providing essential insights into the event's nature and its impact on the electrical system. The data shown in the figures result from real measurements, offering a visual representation of the electrical signals recorded in the transmission line during the event of interest.

The voltage and current signals were recorded using digital fault recorders with a sampling frequency of 1 MHz. This sampling rate ensures sufficient resolution for both impedance-based fault estimation and traveling wave analysis.

B. System Parameters

This section presents the relevant data of the system where the event occurred. These parameters provide essential information for feeding the fault location algorithms. The evaluated transmission line operates at a voltage level of 400 kV in a double-circuit configuration with a total length of 268 km. The line consists of 716 self-supporting steel structures with a vertical arrangement. Each phase has two aluminum conductors with steel reinforcement (ACSR) of size 1113, organized into two independent circuits. Additionally, the line is equipped with two galvanized aluminum-clad guard wires (7#8), which provide protection against lightning and grounding support.

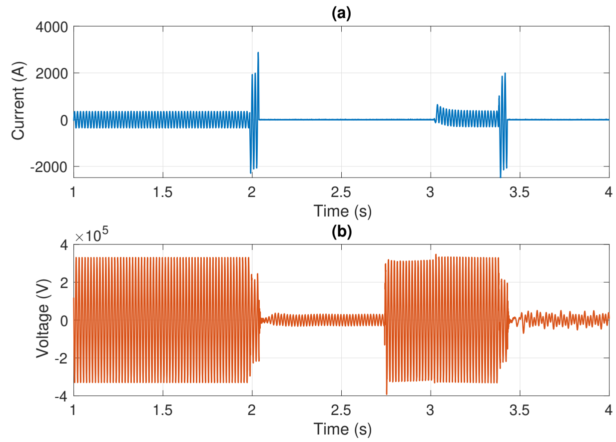

Fig. 5. (a) Current and (b) Voltage of the fault phase during the event on the transmission line under study, measured at terminal H.

TABLE I
GEOMETRY OF A 400 KV TRANSMISSION LINE WITH TWO CIRCUITS AND TWO CONDUCTORS PER PHASE.

Phase	X (m)	Ytower (m)	Ycl (m)	Separation (cm)	Angle (degrees)	CN
HG1	0.00	48.49	42.99	- - -	- - -	- - -
HG2	20.84	48.49	42.99	- - -	- - -	- - -
A	5.41	25.00	17.50	45.0	30.0	2
B	5.41	33.82	26.32	45.0	30.0	2
C	5.41	42.64	35.14	45.0	30.0	2
A	15.42	25.00	17.50	45.0	30.0	2
B	15.42	33.82	26.32	45.0	30.0	2
C	15.42	42.64	35.14	45.0	30.0	2

The steel structures ensure the physical integrity and support of the conductors and other line components.

Table I summarizes the geometric configuration of the 400 kV transmission line. The vertical arrangement includes two circuits, each consisting of two conductors per phase. This configuration provides the foundational information needed to analyze the electrical behavior of the affected line during the fault event.

The analysis of the mentioned event was validated using data provided by the utility, confirming that the actual fault distance was 114.26 km from terminal G. This information serves as a critical reference to assess the accuracy of the fault location methods applied in this study, enabling a comparison between the calculated results and the precise fault position identified in the field.

V. Results and Analysis

This section presents the results obtained from the implementation of the proposed fault location method. The figures illustrate key aspects of the analysis, including voltage and current data, traveling wave signals before and after filtering, cross-correlation results, and a comparison between the proposed and conventional correlation templates. Additionally, the fault distance estimated by the proposed method is compared with the actual fault distance, providing a comprehensive evaluation of the method's accuracy.

Fig. 6 presents the traveling wave signals. Fig. 6 (a) shows the original traveling wave signals, while Fig. 6 (b) displays the same signals after filtering. Traveling waves are derived from voltage and current components, and the filtering process is applied to eliminate unwanted frequencies. This figure highlights the effectiveness of the filtering process in enhancing the clarity and quality of the traveling wave signals.

Traveling waves play a essential role in accurate fault location, as they propagate along the transmission line at nearly the speed of light and carry critical information about the fault location. A third-order Butterworth filter is applied to reduce noise and improve the detection of high-frequency transients associated with traveling waves.

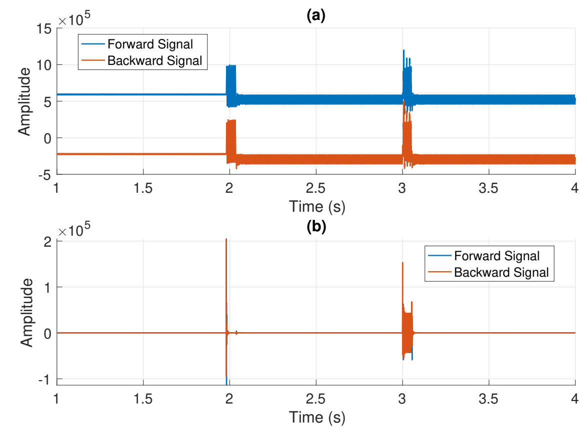

Fig. 6. Forward and backward traveling wave voltage signals along the transmission line.

Fig. 7 presents two key analyses related to the proposed fault location method. The Fig. 7 (a) shows the cross-correlation results between the traveling wave signals and the correlation template, highlighting several key markers: the fault initiation time, the expected arrival time of the first traveling wave, the round-trip time of the traveling wave, and the point of maximum correlation. These markers demonstrate the precision of the proposed method in determining the fault location. Cross-correlation evaluates the similarity between the reference signal (template) and the observed signal at various time shifts, with the maximum correlation point identifying the moment when the traveling wave generated by the fault reaches the measurement terminal, enabling accurate fault distance calculation.

Fig. 7(b) compares the proposed correlation template with the conventional template. The proposed template is adjusted to the estimated fault propagation time, while the conventional template spans the entire propagation time of the line. This comparison illustrates the advantages of the proposed method in reducing noise and improving accuracy. The broader time window used in the conventional template introduces more noise and reduces detection accuracy, whereas the proposed template enhances the detection of relevant transients and increases the method's precision.

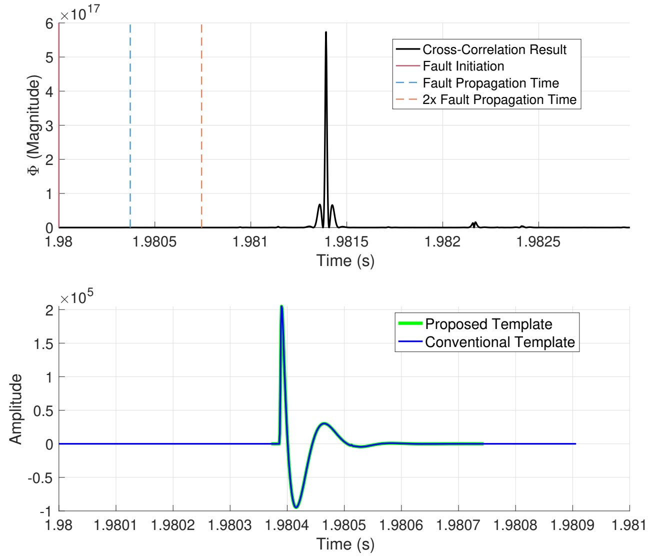

Fig. 7. (a) Cross-correlation results with key markers. (b) Comparison of proposed and conventional correlation templates.

TABLE II
COMPARISON OF CALCULATED DISTANCES WITH REAL DISTANCE (KM)

Method	Calculated Distance (km)	Error (km)
Simple Reactance [19]	116.07	1.81
Takagi [20]	115.07	0.81
Modified Takagi [21]	115.40	1.14
Eriksson [22]	110.92	3.34
Proposed Method	114.29	0.03

To validate the accuracy of the proposed fault location method, the techniques described in Section II.A were applied to the obtained signals. The actual fault distances were compared with the estimated distances obtained using both the impedance-based method and the proposed hybrid method. The results are summarized in Table II.

As shown in Table II, impedance-based methods present certain inaccuracies due to fault resistance, remote infeed, and system non-homogeneities. These factors introduce errors in the initial fault distance estimation. However, by leveraging traveling wave analysis, the proposed hybrid method refines the pre-estimation and effectively reduces these errors, achieving fault location deviations below 1%.

Despite these advantages, there are inherent limitations. The accuracy of the proposed method depends on a precise estimation of the wave propagation velocity, which is influenced by conductor temperature, mechanical tension, and transmission line characteristics [23]. Variations in network topology, such as the presence of distributed generation and changes in load conditions, may also influence the behavior of traveling waves and impact the fault location accuracy. Additionally, the method relies on a high sampling rate and advanced signal processing techniques to properly capture and analyze the traveling wave transients, requiring measurement equipment with a high sampling rate.

Significantly, when evaluated against a broader spectrum of impedance-based methods, the proposed algorithm exhibited consistent and reliable performance. Although the evaluation was conducted on a single real fault event, the algorithm's effectiveness in estimating fault distances remains apparent. This cross-method analysis underscores the algorithm's robustness and its potential to be a valuable asset in real-world fault location applications.

Among the array of impedance-based techniques considered, the proposed algorithm emerged as a dependable solution, consistently delivering accurate calculated distances along with relatively low absolute errors. These results not only validate the algorithm's practical utility but also position it as a promising tool to enhance fault location accuracy within power transmission systems.

VI. CONCLUSIONS

Currently, most transmission systems rely on protection relays with algorithms based on impedance to estimate fault distance. However, the accuracy of these methods is influenced by several factors, including system load, parallel lines, fault resistance, fault incidence angle (DC offset), ground resistivity, line transposition, and other system characteristics.

This study introduced a hybrid method designed to enhance the accuracy of impedance-based approaches by incorporating a traveling wave method based on signal correlation. Unlike traditional methods, this approach does not require communication between terminals or data synchronization. Instead, it uses an impedance-based pre-estimation to approximate the fault distance, which is then refined by defining the appropriate data window size for the traveling wave correlation algorithm.

The proposed algorithm was validated using real-world data from a double-circuit transmission system where a fault occurred. Results demonstrate its capability to accurately locate faults, even in the presence of coupling effects between circuits. This underscores its robustness and suitability for practical applications and it is demonstrated that the proposed technique using traveling waves is immune to coupling effects from double circuits transmission lines.

Although the proposed method enhances fault location accuracy, certain practical considerations must be taken into account. The effectiveness of the correlation-based approach relies on an optimized data window. Large errors in the impedance-based pre-estimation may result in a suboptimal window selection and, consequently, affect the precision of the method. However, in cases where the estimated fault location results in a data window exceeding the expected range, the method inherently adjusts by operating as a standard traveling wave fault location approach, ensuring consistent accuracy and reliability under all conditions.

The hybrid algorithm effectively combines the strengths of impedance-based and traveling wave methods, leveraging impedance pre-estimation to streamline the computational process and improve the definition of the data window for correlation. The independence of the traveling wave method from synchronization and communication channels further enhances its practicality in modern power systems. Future research could explore its performance under diverse fault scenarios, system configurations, and the integration of renewable energy sources, extending its applicability and scalability in evolving grid environments.

Additionally, given that the proposed algorithm has been designed with a data window selection that could be particularly suitable for systems with reduced line lengths, its potential application in distribution networks should also be investigated. In such systems, the presence of tapped lines introduces complexities in wave propagation, potentially affecting the accuracy of the fault location estimate. Furthermore, the variability in impedance, originated by the diversity in conductor sizes, transformer connections, and capacitor banks, introduces changes and phase shifts that influence the method's precision. Future research should evaluate the effectiveness of the proposed method in distribution networks, considering these factors to determine its practical applicability and possible enhancements.

References

[1] S. Das and S. Santoso and A. Gaikwad and M. Patel. Impedance-based fault location in transmission networks: theory and application. *IEEE Access*, 2:537–557, 2014.

[2] M. Nemati, M. Bigdeli, and A. Ghorbani. Impedance-based fault location algorithm for double-circuit transmission lines using single-end data. *Journal of Control, Automation and Electrical Systems*, 31:1267–1277, 2020.

[3] M. K. Arpanahi, M. H. Fini, M. Khoshnam and A. Ghorbani. A fast and accurate Bi-level fault location method for transmission system using single ended phasor measurements. *Electric Power Systems Research*, 210:108110, 2022.

[4] R. L. A. Reis, F. V. Lopes, E. J. S. Leite Jr., G. Zat, J. V. Souza, A. Scheid, and T. G. Jahn. Evaluation of single-ended impedance-based transmission fault location using fixed and variable window phasor estimation approaches. *IPST International Power System Transients*, 1(1):1–7, 2023.

[5] H. Abdollahzadeh. A distance Protection/Fault location algorithm for Double-Circuit transmission lines with asymmetrical circuits during Cross-Country faults. *Intl Journal of Electr Power and Energy Syst*, 148:108943, 2023.

[6] F. B. Costa, A. Monti, F. V. Lopes, K. M. Silva, P. Jamborsalamati, and A. Sadu. Two-terminal traveling-wave-based transmission-line protection. *IEEE Transactions on Power Delivery*, 32(3):1382–1393, 2017.

[7] A. F. Picanço A. P. Oliveira, F. A. Moreira. Accuracy analysis using the emd and vmd for two-terminal transmission line fault location based on traveling wave theory. *IPST International Power System Transients*, 1(1):1–7, 2023.

[8] Farzad Parvaresh Davod Rezaei, Mehdi Gholipour. A single-ended traveling-wave-based fault location for a hybrid transmission line using detected arrival times and tws polarity. *Electric Power Systems Research*, 210(1):1–7, 2022.

[9] Vishal Kumar Gaur and Bhavesh R. Bhalja. Wavelet transform modulus maxima-based fault location method for three-terminal transmission line. In *2019 8th International Conference on Power Systems (ICPS)*, pages 1–5, 2019.

[10] Chenhao Zhang, Guobing Song, Ting Wang, and Liming Yang. Single-ended traveling wave fault location method in dc transmission line based on wave front information. *IEEE Transactions on Power Delivery*, 34(5):2028–2038, 2019.

[11] Mohammad Fayazi, Mahmood Joorabian, Alireza Saffarian, and Mehdi Monadi. A single-ended traveling-wave-based fault location for a hybrid transmission line using detected arrival times and tws polarity. *Electric Power Systems Research*, 220(1):1–7, 2023.

[12] P.F. Gale, P.A. Crossley, Xu Bingyin, Ge Yaozhong, B.J. Cory, and J.R.G. Barker. Fault location based on travelling waves. In *1993 Fifth International Conference on Developments in Power System Protection*, pages 54–59, 1993.

[13] V.H. Gonzalez-Sanchez, V. Torres-García, and D. Guillen. Fault location on transmission lines based on travelling waves using correlation and modwt. *Electric Power Systems Research*, 197:107308, 2021.

[14] Feng Deng, Yihan Zhong, Zhe Zeng, Yarui Zu, Zhen Zhang, Yifei Huang, Sixu Feng, and Xiangjun Zeng. A single-ended fault location method for transmission line based on full waveform features extractions of traveling waves. *IEEE Transactions on Power Delivery*, 38(4):2585–2595, 2023.

[15] R.L.A. Reis, F.V. Lopes, W.L.A. Neves, D. Fernandes Jr., C.M.S. Ribeiro, and G.A. Cunha. An improved single-ended correlation-based fault location technique using traveling waves. *International Journal of Electrical Power and Energy Systems*, 132:107167, 2021.

[16] R. H. Park. Two-reaction theory of synchronous machines generalized method of analysis-part i. *Transactions of the American Institute of Electrical Engineers*, 48(3):716–727, 1929.

[17] R. L. A. Reis, F. V. Lopes, W. L. A. Neves, and D. Fernandes Jr. Influence of coupling capacitor voltage transformers on travelling wave-based fault locators. In *International Conference on Power Systems Transients (IPST2015)*, Cavtat, Croatia, June 15-18 2015.

[18] Raphael L.A. Reis, Washington L.A. Neves, and Damásio Fernandes. Influence of instrument transformers and anti-aliasing filters on the performance of fault locators. *Electric Power Systems Research*, 162:142–149, 2018.

[19] Stanley H. Horowitz and Arun G. Phadke. *Power System Relaying*. Wiley, 2013.

[20] T. Takagi, Y. Yamakoshi, M. Yamaura, R. Kondow, and T. Matsushima. Development of a new type fault locator using the one-terminal voltage and current data. *IEEE Transactions on Power Apparatus and Systems*, 101(8):2892–2898, 1982.

[21] M. M. Saha, J. Izykowski, and E. Rosolowski. *One-end Impedance-based Fault-location Algorithms*, pages 187–262. Springer London, London, 2010.

[22] L. Eriksson, M. M. Saha, and G. D. Rockefeller. An accurate fault locator with compensation for apparent reactance in the fault resistance resulting from remote-end infeed. *IEEE Transactions on Power Apparatus and Systems*, 104(2):424–436, 1985.

[23] Overhead line conductor and technical specifications. In C.R. Bayliss and B.J. Hardy, editors, *Transmission and Distribution Electrical Engineering (Third Edition)*, pages 630–692. Newnes, Oxford, third edition edition, 2007.