Scientific Paper / Artículo Científico

UNIVERSIDAD POLITÉCNICA SALESIANA ECUADOR
INGENIUS
Revista de Ciencia y Tecnología
https://doi.org/10.17163/ings.n30.2023.06
pISSN: 1390-650X / eISSN: 1390-860X

Study for localization of fault in the electrical distribution systems.

Estudio para la localización de fallas en sistemas de distribución eléctrica.

Roberto Gomez [1], Diego Cabrera[1], Pablo Robles[2,*]

Received: 01-02-2023, Received after review: 21-04-2023, Accepted: 22-05-2023, Published: 01-07-2023

Abstract

This article studies the location of faults in the electrical distribution system based on processing short-circuit signals. For this analysis, the simulation of cases using the CYME software is proposed, using the Wavelet transform to study the signal obtained and decomposed. The minimum spanning tree method is proposed so that fault location is optimal and reconnection time is minimal. This analysis considers the reclosers' location in the distribution system that will serve as information repositories. In this investigation, a fault location algorithm was developed to analyse transient phenomena, achieving good precision in time frequency. Applying the proposed method, the signal is broken down into different levels, obtaining the necessary parameters to determine the distance of the fault.

Keywords: Fault detector, Short-circuit impedance, Wavelet transform, Fault location, Fault distance.

Resumen

En este artículo se estudia la localización de fallas en el sistema de distribución eléctrica, basándose en el procesamiento de las señales de cortocircuito. Para este análisis se propone la simulación de casos mediante el software CYME, empleando la transformada wavelet para el estudio de la señal obtenida y descompuesta. Se propone el método del árbol mínimo en expansión para que la localización de las faltas sea óptima y el tiempo de reconexión sea mínimo. Este análisis toma en cuenta la ubicación de los reconectadores en el sistema de distribución que servirán como almacenadores de información. En esta investigación se desarrolló un algoritmo de localización de fallas mediante el análisis de fenómenos transitorios, lográndose buena precisión en tiempo-frecuencia. Aplicando el método propuesto se descompone la señal en diferentes niveles obteniéndose los parámetros necesarios para determinar la distancia de la falla.

Palabras clave: Detector de fallas, Impedancia de cortocircuito, Transformada Wavelet, Localización de fallas, Distancia de fallas.

[1,*]Faculty of Electrical Engineering, Salesian Polytechnic University, Ecuador.
[2]Smart Grid Research Group, Salesian Polytechnic University, Quito, Ecuador.
Corresponding author ✉: probles@ups.edu.ec.

Suggested citation: Gomez, R.; Cabrera, D. and Robles, P. "Study for localization of fault in the electrical distribution systems.," *Ingenius, Revista de Ciencia y Tecnología*, N.° 30, pp. 64-78, 2023, DOI: https://doi.org/10.17163/ings.n30.2023.06.

1. Introduction

Distribution networks are responsible for supplying electric power to consumers using a set of electrical elements such as conductors, transformer equipment, protection, and structures for their fastening. In distribution networks, there are problems due to the location of faults. The faults can interrupt the electricity supply to the end consumer and make the network unstable, thus reducing the electric system's reliability. All these problems can impose economic losses on consumers, power plants, and distributors [1].

According to the study, [2], more than 80 percent of power system outages are due to failures that occur in distribution systems due to various reasons, such as lightning strikes, power system component failures due to aging equipment, and human error [3]. Therefore, distributors try to use efficient technologies, maintenance actions, and corrective procedures to reduce the failure rate and its destructive effects.

Fault location is one of the most critical issues in the electrical power distribution system, so proper location is essential to help electrical maintenance personnel directly locate the correct location and fix the problem quickly. This minimizes outage time, restores power, and reduces operating costs [4].

Despite technological advances and the need to improve performance, today's troubleshooting process still relies on trouble calls from affected customers. When a permanent fault occurs, managers in the operation center identify the feeder and the possible area of occurrence. Maintenance personnel are then sent to patrol that area to identify and isolate. This procedure is ineffective in certain circumstances because the area is sizeable [5].

Generally, methods based on impedance and fundamental frequency components, traveling waves, and knowledge [6] are used to diagnose and locate faults in distribution systems. The first method requires voltage and current measurement data at fundamental frequency to determine the impedance and estimate the fault location using one or several measurement points. This method has the advantage of being implemented at a low cost. Still, it has the disadvantage of estimating multiple fault locations due to the large number of branches that a distribution network may have [7]. The knowledge method encompasses methods based on analysis and statistics, distribution devices, artificial intelligence, and hybrid methods. The application of the knowledge method requires measurements of voltage and current on the feeder, the operating status of the substation and feeder breaker, and data provided by intelligent electronic devices (IED) and protection devices installed on the feeders [8]. The traveling wave method for fault location in distribution systems, which will be used for this work, is based on the transmission and reflection of traveling waves between the line terminals and the fault point. This method requires IED and protection devices capable of storing current and voltage information of the network operation to obtain the transient waveform for the location of the fault occurring in the distribution system [9].

2. Materials and methods

Several methods have been proposed for fault location but are not readily applicable to distribution systems. This is mainly due to short and heterogeneous lines, lateral branches, load taps, and a lower degree of instrumentation in distribution systems.

Currently, the primary methods used to locate the location of single-phase ground faults in distribution networks are impedance, S-injection, traveling wave, and port diagnostic methods [10].

In addition to all the methods mentioned above, employing a FI is the most practical and affordable way for distribution systems, thus providing the best probable fault location [11]. FI in a system does not require sophisticated infrastructures, making it a suitable method in most distribution systems. The assignment of an FI to the networks could restrict the fault area identified by the supervisory control center, so the time required to locate it would decrease substantially. This leads to improved restoration time and service reliability indices. However, using FI in all candidate locations is unnecessary and costly, so cost-effective analysis is needed to determine how many and where FI should be located to get the most out of them [12].

HIF detection may be a protection function in intelligent electronic devices in power distribution networks [13]. HIF can be defined as a fault that draws low currents for conventional protective devices such as overcurrent relays or fuses to trip. Due to the low magnitude of the fault current, HIF does not damage system components but is a public safety hazard because it often involves an electrical arc that increases the fire risk of fire [4].

Several methods have emerged to detect faults in a distribution system over the years. In [14], an algorithm is presented to detect high-impedance faults by feature extraction based on the WT and a Neural Network. The extraction of the most relevant signal features is obtained from WT classification such as Haar, Symlet, Daubechies, Coiflet, and Biorthogonal; for each wavelet mentioned, a decomposition of different levels is performed, which allows the analysis to detect a fault.

Different types of short-circuit faults are generated in distribution networks, so in [15] suggests using the software package CYME that allows the construction of a distribution network and the simulation of several short-circuit faults. Matlab - Simulink uses the wavelet transform that allows decomposing and reconstruction of original signals by decomposing the signal into different levels to improve the speed of fault detection.

Figure 1 represents the structure for this investigation; it sees the scenario when designing the distribution network system, as well as the dynamic analysis when existing a fault in one o more nodes; here is necessary to obtain the short-circuit profile; it is interesting to look at the Wavelet transform process, that allows analyzing what happens in the system and localized the distances and the original node when the system hat a fault o various, therefore the result data allow build the metric whit the critical information about ubication and system behavior.

Transient state analysis requires techniques that exploit the relationship between system parameters, transient frequency, and wave speed. For this reason, it [20] it is suggested to use the Wavelet transform since high frequencies have a better resolution in time.

A high-frequency component can be located with less relative error than a low-frequency component. Conversely, low frequencies have better resolution in the frequency domain than high-frequency components [21]. There are various methods for the location and calculation of the fault distance in electrical power systems, including the traveling wave method, which is applied in most cases for the location of faults in transmission systems.

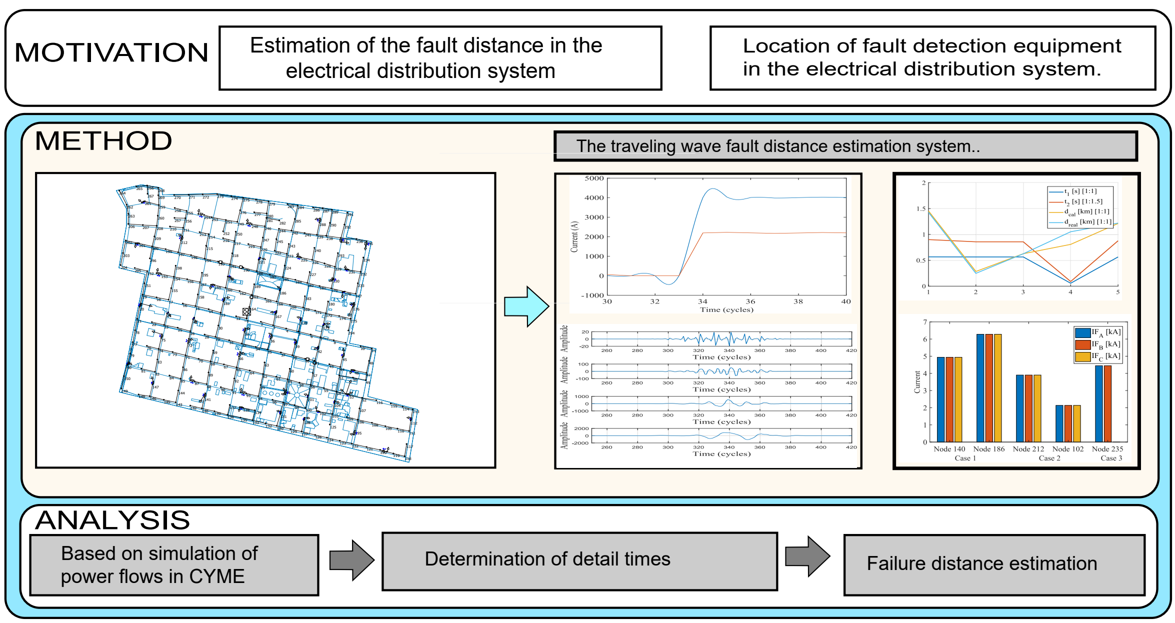

Figure 1. Figure Conceptual & Authors.

The flow diagram, see Figure 2, for obtaining fail signals is necessary to generate a profile obtained of CYME on dynamic analysis; here depends on the original data; if this information is not correct is mandatory interpol; therefore, the analysis Wavelet transform allows thorough a Daubechies and filter of fault to determine the time and the propagation velocity that is a possible estimation of fault distance from the nearest recloser.

In distribution systems, the traveling wave method is implemented, which has low accuracy when the configuration of the lines changes in impedance, so [19] proposes an accurate method of fault location in the distribution network based on the traveling wave with multiple measurement points. To obtain multiple metering points in [17], [22] distribution networks use digital relays at substations, IED along the primary feeders, SCADA sensors on the feeder circuit, and smart meters at customers, all of which have the property of storing information about the operation of the distribution network, thus obtaining multiple metering points.

Table 1 exposes the nomenclature as well as the description of abbreviations that are being used in this investigation; for everything, research is mandatory in creating the state art; this is an excellent tool for the investigator can obtain information about the topic and develop the fundamental structure that through which is the possible analysis and evaluate the mathematics model exposes, see table 2.

There are various methods for the location and calculation of the fault distance in electrical power systems, including the traveling wave method, which is applied in most cases for the location of faults in transmission systems. In distribution systems, the traveling wave method is implemented, which has low accuracy when the configuration of the lines changes impedance, so in [19] proposes an accurate method of fault location in the distribution network based on the traveling wave with multiple measurement points.

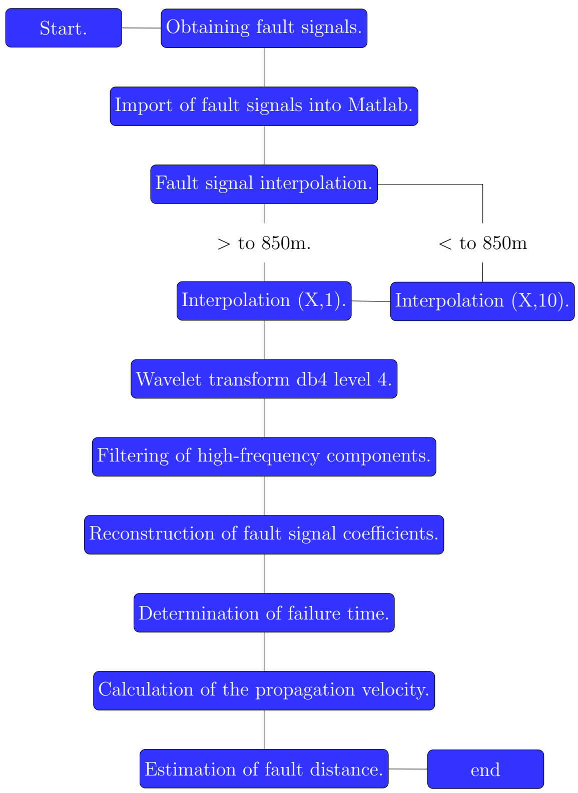

Figure 2. Flow Diagram & Authors.

There are various methods for the location and calculation of the fault distance in electrical power systems, including the traveling wave method, which is applied in most cases for the location of faults in transmission systems. In distribution systems, the traveling wave method is implemented, which has low accuracy when the configuration of the lines changes impedance, so in [19] proposes an accurate method of fault location in the distribution network based on the traveling wave with multiple measurement points.

In addition, an algorithm for fault distance estimation in distribution networks using the transient traveling wave and the Wavelet transform propose in [18], using the current traveling wave signals from the substation bus with the first arrival times of the aerial difference component and zero sequences to calculate the estimated fault distance and the same can be analyzed with the mother wavelet db6 and level 1. However, this is possible only when there are symmetrical faults [23].

Nowadays, GIS geoprocessing computational tools are used to design an electrical distribution network, obtaining a geo-referenced database in which the minimum-spanning algorithm (MST), one of the practical mathematical theories used in electrical network simulation problems, is applied, which can optimize the electrical network [24], [25]. A geo-referenced database also allows applying algorithms such as K-Means and Elbow for a more accurate location of protective devices [26], [27].

In this scenery have been designed an electrical network system and the energy elements how, reclosers, substations, load, and others, ensuring the correct operation of the system is mandatory to execute the power flow and guarantee the voltage profile for the customer in figure 3, observed a short representation in the electrical distribution network, here observing the drop voltage and reclosers load, substation load, among others, this design system is a tool for fault analysis and a priority search the node location, everything is geolocated which allows having a strategy as realistic as possible.

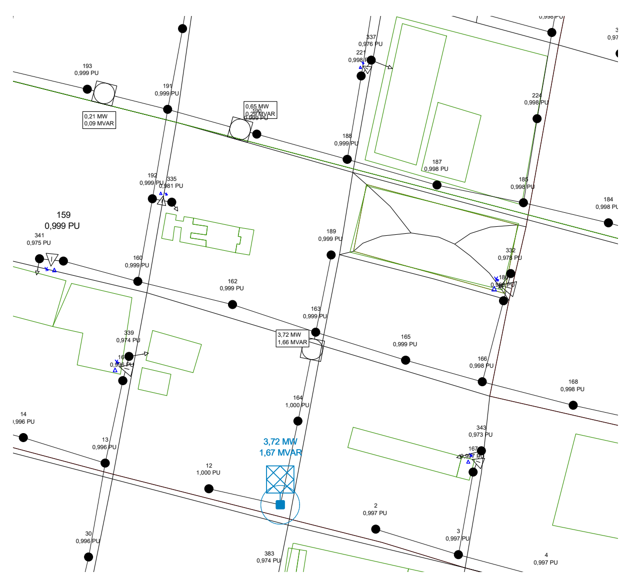

Figure 3. Short representation in the electrical distribution network & CYME.

Table 1. Nomenclature & Description of Abbreviations & Authors

Nomenclature	Description	Nomenclature	Description
$f(t)$	Analysis signal	d_{real}	Actual distance measured from the substation to the fault node.
C	Capacitance	$Wf(\mu, s)$	Continuous-time wavelet transform.
IF	Fault current	d_f	Fault distance measured from the distribution substation to the fault node.
HIF	High impedance faults	FI	Fault indicator.
GIS	Geographic information system	L	Inductance
$IEDs$	Intelligent electronic devices	MST	Minimum spanning tree.
VLN	Phase voltage.		
Δ_F	Sampling frequency	$Z1$	Positive frequency impedance.
s	Scale	I	Rated current.
$STPC$	Simultaneous three-phase short-circuit	S/E	Substation.
SWT	The stationary wavelet transform	$TPSCNS$	Three-phase short-circuit near the substation.
μ	Translation of the wavelet function in the analysis signal domain	WT	Wavelet transform.
$TPSCFS$	Three-phase short-circuit far from substation	$\psi^*\left(\frac{t-\mu}{s}\right)$	Wavelet transform function or wavelet function.
Δ_V	Voltage drop	t	Time.
v	Wave propagation velocity	t_d	Wavelet detail time of the signal.
$Z0$	Zero frequency impedance	$TPSC$	Two-phase short circuit

Table 2. Summary of articles related to flaw detection equipment

		Parameters considered				**Thematic**			
Author, year	Objectives	Voltage	Current	Impedance	Fault Distance	Distribution Network	Short Circuit	Wavelet	Fault Location
[2], 2020	Increased accuracy in fault detection	✠	✠	✠	-	-	-	-	✠
[4], 2019	Fault finding in different locations	✠	✠	✠	✠	-	-	-	✠
[7], 2022	Troubleshooting for four-wire systems	✠	✠	-	✠	✠	-	-	✠
[9], 2020	Short-circuit fault detection	✠	✠	✠	✠	-		-	✠
[10], 2020	Line - ground fault location	✠	✠	✠	✠	-	-	-	✠
[12], 2020	Single-phase fault location	✠	✠	✠	✠	-	-	-	✠
[16], 2019	Minimize distance error	✠	✠	✠	✠	✠	✠	-	✠
[17], 2020	Combining devices in the network	✠	✠	-	✠	✠	-	-	-
[18], 2019	Parameterize short circuit	✠	✠	✠	✠	-	-	✠	✠
[19], 2020	Fault location method	✠	✠	✠	✠	-	-	-	✠
Present work	Fault location	-	✠	✠	✠	✠	✠	✠	✠

2.1. Problem Formulation and Methodology

Case studies are presented on faults in the electrical distribution system, which are identified by the Wavelet transform method; the acquisition of a database describing the operation of the system in a dynamic state is performed in the CYME software, allows simulating transient stability with their respective characteristics acquired by the identification method successively, so the data must contain as a fundamental variable the information of the current fault behavior, which must be interpolated if the distance is less than 850 meters, which is the threshold to have a better sampling of the signal. The traveling wave method calculates the fault distance, considering a system without a change of positive homopolar impedance. Distribution networks are subject to faults due to different types of origin or nature, which affect the electrical network components, generating disturbances in their correct operation and transients in the current and voltage signals. Therefore, it is necessary to identify when a fault occurs using the WT.

The WT is an effective tool for fault identification due to its functionality for processing and analyzing transient signals. WT can be used to obtain simultaneous information about the time and frequency of a signal [14].

The electrical distribution system contains transformers of three phases on medium voltage; its power varies between 30 kVA and 200 kVA, the conductors configuration is 1/0 from phase and 2 for the neutral type ACSR for an overhead line, the reclosers location depends on the system characteristics, but for this investigation was used the failure indicators, other parameter import is the conductors capacity this ensures its changeability; everything scenery is geolocated with the optimal conditions for executed a power flow, see figure 4, the results are exposed in table 3, where the reader can observe the most relevant parameters.

Table 3. System characteristics in normal state

S/E Capacity	**5 MVA**
Total Load	
Real Power	3.686 MW
Reactive Power	2.325 MVAR
Apparent Power	4.358 MVA
Load Used	
Real Power	3.614 MW
Reactive Power	1,534 MVAR
Apparent Power	3,926 MVA
Total losses	0,823 MVA
Max. ΔV	2,85 %
Length	15899 m

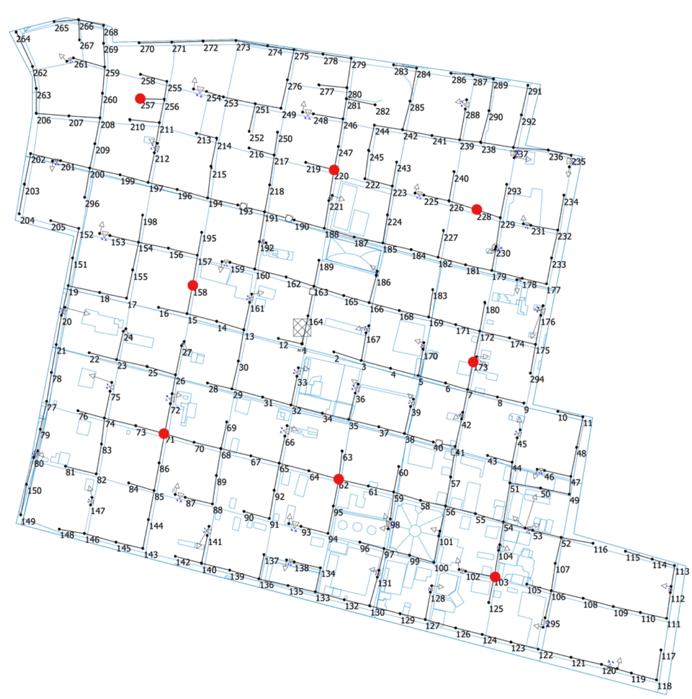

Figure 4. Scenario & Authors.

Signal analysis using WT is based on the dilation and translation of a mother wavelet on the signal. The scaling operation dilates and compresses the mother wavelet, resulting in low and high-frequency signals, respectively [14].

$$W_{f(\mu,s)} = \int_{-\propto}^{\propto} f(t) * \psi_{\mu,s}(t)dt \tag{1}$$

Can define $\psi_{\mu,s}$ as the original Wavelet signal:

$$\psi_{\mu,s}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-\mu}{s}\right) \tag{2}$$

Where:

- s - Scale
- μ - Translation of the wavelet function in the analysis signal domain.
- t - Time.

Different mother wavelets are associated with the family: Daubechies, Coiflets, and Symmlet; for the case studies presented here, we used the Daubechies wavelet level 4 [db4] for the case studies presented.

It is proposed to locate the fault using the traveling wave method, which calculates the wave propagation. It depends on the inductive and capacitive parameters in equation 3 obtained from the positive sequence zero sequence impedance.

$$v = \frac{1}{\sqrt{L * C}} \tag{3}$$

L represents the inductance of the distribution line per unit length. In contrast, C represents the capacitance of the distribution line per unit length. For either case, the parameters can be expressed in kilometers or meters; thus, the calculated velocity will be described in km/s or m/s. The distribution line configurations affect how the traveling waves travel through the network; see table 4.

Table 4. Line Parameters & Authors

Line	L (H/km)	C (F/km)	v (km/s)
Line 139-140	0,0011796	1,0242E-08	287705,1614
Line 166-186	0,0011796	1,0242E-08	287705,1614
Line 102-103	0,0011796	1,0242E-08	287705,1614
Line 197-212	0,0011796	1,0242E-08	287705,1614
Line 235-236	0,0011796	1,0242E-08	287705,1614

To calculate the fault distance, in addition to the velocity, it is necessary to determine the time of the signal utilizing the wavelength and the sampling frequency, which is equal to $3.3kHz$.

$$d_f = \frac{t_d * \Delta_F}{2} * v \tag{4}$$

$$error(\%) = \frac{|d_f - d_{real}|}{d_{real}} * 100 \tag{5}$$

In the location of fault-detecting equipment called FI, the jambu elbow method is implemented to estimate the number of clusters needed. The k-means algorithm allows for a better cluster of the fault indicators within the distribution network presented in the case study (Table 5).

To test the effectiveness of the proposed algorithm, a 22 kV distribution network georeferenced with QGIS, see table 1, is designed. These coordinates are imported to Matlab. The graph is conformed, in which the MST is applied, starting from a root vertex and finding all its linked nodes and the relations that allow connecting them, being the weight considered the smallest distance [28]. A minimum weight spanning tree is an edge-weighted digraph connected to all vertices without the presence of loops [29], [30].

The proposed feeder has 295 nodes, 48 three-phase transformers with two windings whose power in kVA are 30, 50, 75, 112.5, 150, and 200, a single-phase transformer of 75 kVA, 54 concentrated loads, and five reclosers. three-phase resulting in a feeder of 5 MVA installed load; see figure 4, table 3 shows its general data and in table 6 the cases to be studied.

Table 5. Algorithm information

I: Current
T: Time
C, L, Fo: Auxiliary variable
t_d: Wavelet detail time of the signal
v: Velocity
d_f: Fault distance

Steps of the algorithm:
Step 0: Short-circuit current data entry
Step 1: Initialization of variables
Step 2: Data for the calculation of the failure node
C_s = Capacitance [F/km]
L_s = Inductance [H/km]
Step 3: Decomposition and reconstruction of the signal with the Wavelet transform
[C,L] = wavedec(I,4,db4)
Save max(C)
Fo = wrcoef('d',C,L,'db4')
Step 4: Find the two maximum peaks after the failure
Print t_d
Step 5: Calculate v
Step 6: Estimate distance and location of the fault node
Step 7: Estimation of the error percentage
Step 8: Graph the results
Step 9: End

Table 6. Study cases & Authors

Case	Fault Type	Fault Node
Three-phase short-circuit far and near substation	Three-phase	140 - 186
Simultaneous three-phase short-circuit	Three-phase	212 - 102
Two-phase short circuit	Two-phase	235

According to the exposed case study, the starting point is a three-phase short-circuit fault in node 140, 1427 meters from the medium voltage substation. The short-circuit data is generated from the storage of events by the protection and switching device, which is the 41-57 re-closer with a sampling frequency of 3.3 kHz; from the data originates the operation waveform of the distribution system under fault, see figure 5.

Starting from the same case, a three-phase short-circuit fault occurs near the substation at a distance of 274.6 meters. The fault signal is obtained from the storage of events by the protection and switching device, recloser 163-164. As the fault is lower than the threshold, we proceed to interpolate for better sampling; see figure 6.

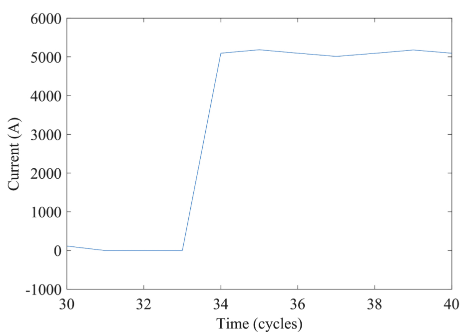

Figure 5. Three-phase short-circuit far from the substation & Authors.

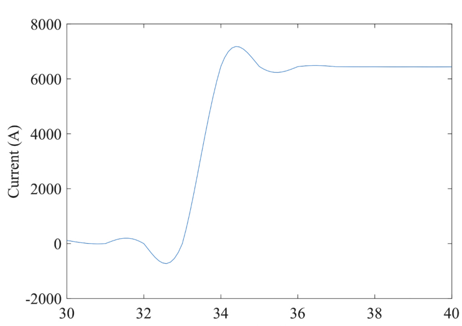

Figure 6. Three-phase short-circuit near the substation & CYME.

A second case is that of a simultaneous three-phase short circuit. Therefore, we have two distances, the first at 625.8 meters, lower than the threshold we must interpolate, and the second at 1051.7 meters, taken from the substation. The signals are obtained from reclosers 41-57 and 191-193; see figure 7.

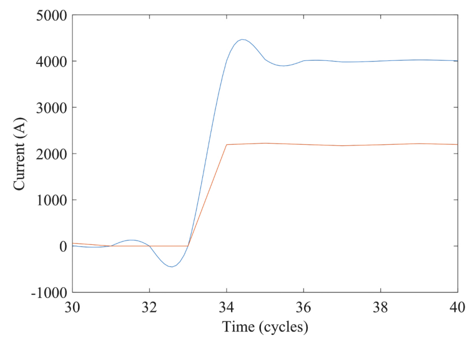

Figure 7. Simultaneous three-phase short-circuit in two nodes of electrical distribution system & CYME.

A two-phase fault occurs within the 190-191 recloser zone 1219 meters from the substation. In this case, the fault currents are symmetrical because there is no impedance change in the distribution lines; see figure 8.

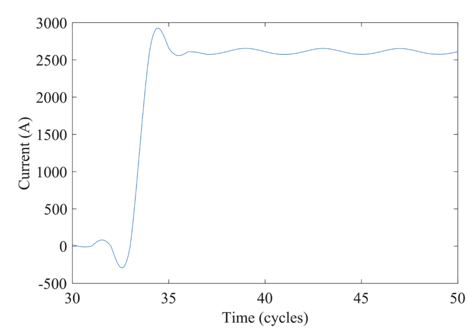

Figure 8. Two-phase short circuit & CYME.

3. Results and discussion

A WT of family Db4 and order 4 is used from the fault signals obtained from each case. The signal is reconstructed using the maximum level based on the wavelet decomposition structure.

The detail signals for all cases are similar with the variation in their amplitude due to the number of calculated coefficients. One of the essential variables to apply the traveling wave method and subsequent location of the fault is the exact time (td), which results from the difference between the two consecutive peaks called rms value at the instant of the fault, which is calculated for each case.

For the application of the fault location and identification algorithm, it is necessary to determine the time TD for each case, which will be similar for each type of fault and can be obtained from the signal presented in Figure 9, which corresponds to the analysis of the identification of the distant fault of the substation located at node 140.

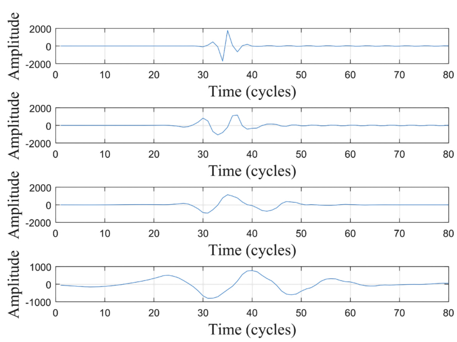

Figure 9. Wavelet detail signal to calculate the fault detail time away from the substation, amplitude on amperes vs WT of the order 4.

Now, as the fault occurs at node 186, located near the substation, the information from the database obtained by the recloser is interpolated due to the small amount of data. This allows a better signal for fault identification and determination of time td, figure 10.

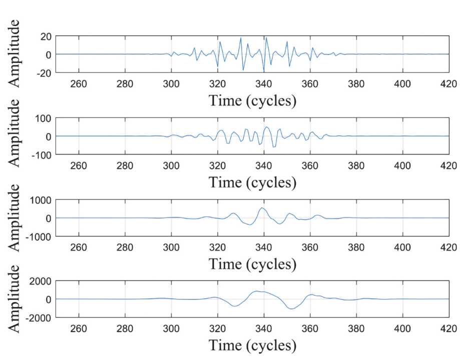

Figure 10. Wavelet detail signal to calculate fault detail time near the substation, amplitude on amperes vs WT of the order 4.

When two simultaneous faults occur, one located at node 212 and the second at node 102, which belong to recloser zone 41-57 and 191-193, respectively, two different databases were obtained in which an independent analysis of each signal was performed to identify the fault occurred and determine the td times of each fault signal, which are presented in Figure 11 and 12.

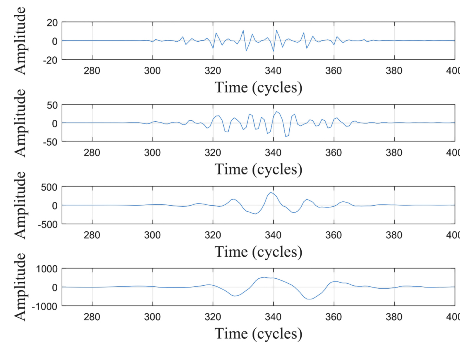

Figure 11. Wavelet detail signal for fault detail time calculation 1, amplitude on amperes vs. WT of the order 4.

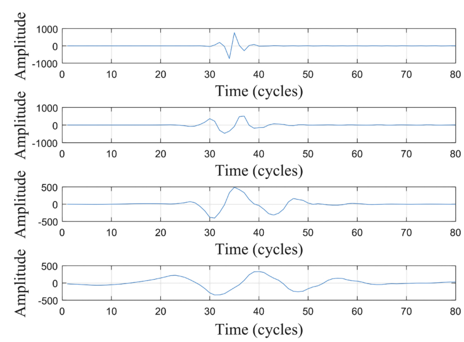

Figure 12. Wavelet detail signal for fault detail time calculation 2, amplitude on amperes vs. WT of the order 4.

Figure 13 shows the wavelet detail signal to obtain the time *td* for calculating the distance of the two-phase fault case occurring in the recloser 190-191 zone.

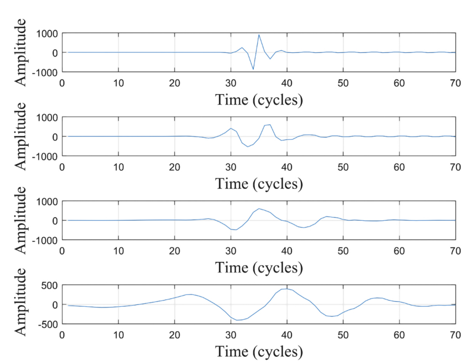

Figure 13. Wavelet detail signal for calculating the detailed time for the two-phase short circuit, amplitude on amperes vs. WT of the order 4.

Once the fault occurrence and the estimated distance from its origin are identified, the jambu elbow method is implemented to determine the required number of IF installed in the distribution network. The sult of the elbow method is presented in Figure 14.

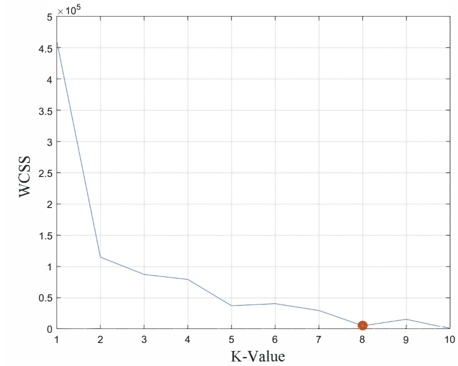

Figure 14. Elbow method for locating fault detection equipment.

The k-means method obtains the optimum location where each fault indicator should be installed, Figure 5 the optimum location of the 8 fault indicators, represented by red dots.

To verify that the developed algorithm estimates the fault distance correctly, Table 7 shows the results obtained in the tests of each case, in which it can be seen that the calculated values of fault distance are satisfactory with a margin of error of less than 30%.

The distance calculation depends directly on the exact time, Figure 15, i.e., the calculated distance curve also varies by varying the time curves t1 and t2. The same graph shows that the calculated distance curve is similar to the actual distance curve, i.e., satisfactory results.

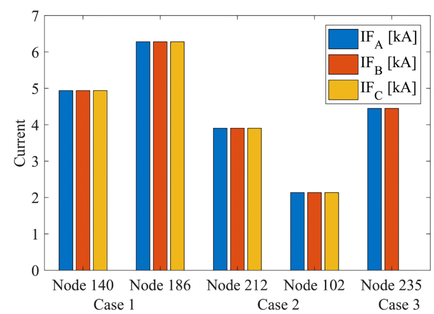

Figure 15. Node fault current.

Table 7. Results obtained after the occurrence of the failure.

Cases	Type of fault	t_1(s)	t_2(s)	d_{cal}(km)	d_{real}(km)	$error$(%)	$Node$
Case 1	TPSCFS	0,5667	0,6	1,4531	1,427	1,8626	140
	TPSCNS	0,5649	0,5715	0,28413	0,2476	3,4701	186
Case 2	STPC	0,5649	0, 0,5715	0,62706	0,6258	0,2	212
	STPC	0,0567	0,06	0,80768	1,0517	23,202	102
Case 3	TPSC	0,5649	0,5849	1,2117	1,219	0,5963	235

For each node where the fault occurs, the rated current and short-circuit current, Table 9, are shown in the fault current in Figure 14 and the rated current in Figure 17.

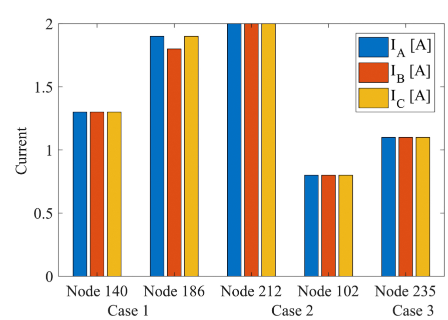

Figure 16. Nominal current of the node.

In figure 16, node 212, distant from the substation, presents the maximum rated current of the system due to a more significant amount of connected load. In contrast, node 102 presents the minimum rated current within the system and is connected to a small load. For the case of figure 15, it is observed that the maximum fault current occurs at node 186 near the substation due to a large amount of connected load, while node 102 again presents the minimum fault current for the same reason of having a smaller load.

The voltages at the nodes of the electrical distribution system vary depending on the distance at which they are located because the greater the distance, the more significant the voltage drop (Table 8), where the nominal and fault voltage values are shown.

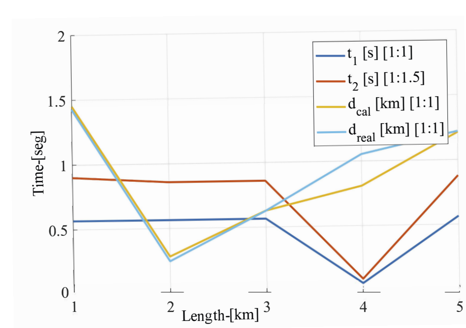

Figure 17. Detail time and actual and calculated distance.

Table 8. Nominal voltage and fault voltage.

		Nominal phase voltage			Fault phase voltage		
		$VLNA$ (kV)	$VLNB$ (kV)	$VLNC$ (kV)	$VLNA$ (kV)	$VLNB$ (kV)	$VLNC$ (kV)
Case 1	140	12.671717	12.671717	12.671717	0.0017369	0.0017369	0.0017369
	186	12.692277	12.692277	12.692277	0.0002725	0.0002725	0.0002725
Case 2	212	12.692948	12.692948	12.692948	0.0016125	0.0016125	0.0016125
	102	12.673058	12.673058	12.673058	0.0007874	0.0007874	0.0007874
Case 3	235	12.691229	12.691229	12.691229	6.3432678	6.3432678	12.709157

Figure 18 analyzes the phase voltage values that vary depending on the distance at which any node belonging to the distribution system is located, far or near the substation. Figure 19 shows that each phase varies according to the fault type for the fault voltages (Table 9).

Table 9. Fault and rated current.

Cases	**Nodes**	IF_A**(kA)**	IF_B**(kA)**	IF_C**(kA)**	I_A **(A)**	I_B **(A)**	I_C **(A)**
Case 1	140	4,9372	4,9372	4,9372	1,3	1,3	1,3
	186	6,2784	6,2784	6,2784	1,9	1,8	1,9
Case 2	212	3,9035	3,9035	3,9035	2	2	2
	102	2,1351	2,1351	2,1351	0,8	0,8	0,8
Case 3	235	4,4482	4,4482	0	1,1	1,1	1,1

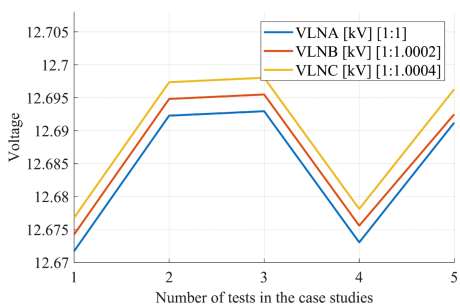

Figure 18. Nominal voltage of the node.

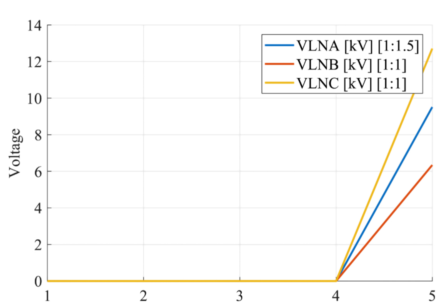

Figure 19. Node fault voltage.

3.1. Discussion

The performance of the fault location algorithm based on WT and traveling wave propagation speed depends on the configuration of the distribution system lines and the fault location. When the design of the lines does not present impedance change, the algorithm shows excellent performance in calculating the fault distance, so the location of the fault point is more accurate. When the configuration of the lines presents impedance changes, it is necessary that the feeder has IED and protection equipment installed in multiple topics to have more information about the occurrence of faults, which allows the algorithm to present a high performance.

Several simulations were performed far and near the substation; faults greater than 850 m should not interpolate the data, and more minor faults should be interpolated. Given this hypothesis, it was determined that the interpolation threshold is 850m.

The precise location analysis is necessary because there may be equal distances in the distribution network; it performs based on the protection and switching equipment, such as reclosers, which allows zoning and reduces the fault location error. Although the analysis is performed by recloser zone, there are still equal distances to the point of failure. The location of FI is proposed to achieve a precise fault location. They can visually indicate which section of the distribution line is at fault.

4. Conclusions

Fault location in electrical distribution systems is essential to improve their reliability and reduce the interruption time of electrical service; in this article, the wavelet transform is related to the traveling wave to propose a fault location method.

The distribution system characterization shows that the line parameters' variation influences the velocity calculation through the traveling wave and the different protection equipment installed in the feeder, whose sampling frequency varies depending on the make and model.

For the calculation of the fault distance, it is necessary to correctly choose the mother wavelet, which will allow identifying in a better way the two maximum peaks after the fault being this approximate, which can have up to 30% of permissible error.

The fault signal obtained by the network's protection equipment can be acquired from equipment far or near the substation. It should be noted that if the data for constructing the fault signal are insufficient to obtain a smoothed signal, they should be interpolated to have a broader database and better approximate the fault; tests have been conducted showing in this work that the optimal distance is 850 m.

The methodology implemented in this case study was able to locate the faults in the distribution system through the short circuit current signals visualized by the reclosers near the fault. Finding the correct detail coefficients since these coefficients directly influence the distance calculation. This being the duration time of the fault, it should be noted that the proposed methodology can only be used in scenarios where there is no impedance change in the distribution lines.

For the quantification of the fault-detecting equipment, the jambu elbow method was used, which is used to implement within the k means algorithm that will place the fault-detecting equipment at strategic nodes.

References

[1] R. Dashti, M. Daisy, H. R. Shaker, and M. Tahavori, "Impedance-based fault location method for four-wire power distribution networks," *IEEE Access*, vol. 6, pp. 1342–1349, 11 2017. [Online]. Available: https://doi.org/10.1109/ACCESS.2017.2778427

[2] M. Gholami, A. Abbaspour, M. Moeini-Aghtaie, M. Fotuhi-Firuzabad, and M. Lehtonen, "Detecting the location of short-circuit faults in active distribution network using pmu-based state estimation," *IEEE Transactions on Smart Grid*, vol. 11, pp. 1396–1406, 3 2020. [Online]. Available: https://doi.org/10.1109/TSG.2019.2937944

[3] S. Gururajapathy, H. Mokhlis, and H. Illias, "Fault location and detection techniques in power distribution systems with distributed generation: A review," *Renewable and Sustainable Energy Reviews*, vol. 74, pp. 949–958, 2017. [Online]. Available: https://doi.org/10.1016/j.rser.2017.03.021

[4] S. H. Mortazavi, Z. Moravej, and S. M. Shahrtash, "A searching based method for locating high impedance arcing fault in distribution networks," *IEEE Transactions on Power Delivery*, vol. 34, pp. 438–447, 4 2019. [Online]. Available: https://doi.org/10.1109/TPWRD.2018.2874879

[5] R. Dashti, M. Daisy, H. Mirshekali, H. R. Shaker, and M. Hosseini Aliabadi, "A survey of fault prediction and location methods in electrical energy distribution networks," *Measurement*, vol. 184, p. 109947, 2021. [Online]. Available: https://doi.org/10.1016/j.measurement.2021.109947

[6] M. Dashtdar, "Fault location in distribution network based on fault current analysis using artificial neural network," *International Journal of Electrical and Computer Sciences (IJECS)*, vol. 1, pp. 18–32, 10 2018. [Online]. Available: https://doi.org/10.33544/MJECE.V1I2.75

[7] J. Tavoosi, M. Shirkhani, A. Azizi, S. Ud Din, A. Mohammadzadeh, and S. Mobayen, "A hybrid approach for fault location in power distributed networks: Impedance-based and machine learning technique," *Electric Power Systems Research*, vol. 210, p. 108073, 2022. [Online]. Available: https://doi.org/10.1016/j.epsr.2022.108073

[8] M. Azeroual, Y. Boujoudar, K. Bhagat, L. El Iysaouy, A. Aljarbouh, A. Knyazkov, M. Fayaz, M. S. Qureshi, F. Rabbi, and H. EL Markhi, "Fault location and detection techniques in power distribution systems with distributed generation: Kenitra city (morocco) as a case study," *Electric Power Systems Research*, vol. 209, p. 108026, 2022. [Online]. Available: https://doi.org/10.1016/j.epsr.2022.108026

[9] Z. Jianwen, H. Hui, G. Yu, H. Yongping, G. Shuping, and L. Jianan, "Single-phase ground fault location method for distribution network based on traveling wave time-frequency characteristics," *Electric Power Systems Research*, vol. 186, p. 106401, 2020. [Online]. Available: https://doi.org/10.1016/j.epsr.2020.106401

[10] J. Liang, T. Jing, H. Niu, and J. Wang, "Two-terminal fault location method of distribution network based on adaptive convolution neural network," *IEEE Access*, vol. 8, pp. 54 035–54 043, 2020. [Online]. Available: https://doi.org/10.1109/ACCESS.2020.2980573

[11] P. Mršić, v. Zeljković, D. Lekić, B. Erceg, P. Matić, S. Zubić, and P. Balcerek, "Minimization of power interruption time in mv distribution networks with fault locators based on optimal placement of fault passage indicators," in *2018 International Symposium on Industrial Electronics (INDEL)*, Nov 2018, pp. 1–7. [Online]. Available: https://doi.org/10.1109/INDEL.2018.8637620

[12] X. Wang, H. Zhang, F. Shi, Q. Wu, V. Terzija, W. Xie, and C. Fang, "Location of single phase to ground faults in distribution networks based on synchronous transients energy analysis," *IEEE Transactions on Smart Grid*, vol. 11, pp. 774–785, 1 2020. [Online]. Available: https://doi.org/10.1109/TSG.2019.2938667

[13] W. C. Santos, F. V. Lopes, N. S. Brito, and B. A. Souza, "High-impedance fault identification on distribution networks," *IEEE Transactions on Power Delivery*, vol. 32, pp. 23–32, 2 2017. [Online]. Available: https://doi.org/10.1109/TPWRD.2016.2548942

[14] S. Silva, P. Costa, M. Gouvea, A. Lacerda, F. Alves, and D. Leite, "High impedance fault detection in power distribution systems using wavelet transform and evolving neural network," *Electric Power Systems Research*, vol. 154, pp. 474–483, 1 2018. [Online]. Available: https://doi.org/10.1016/J.EPSR.2017.08.039

[15] M. F. Guo, N. C. Yang, and L. X. You, "Wavelet-transform based early detection method for short-circuit faults in power distribution networks," *International Journal of Electrical Power & Energy Systems*, vol. 99, pp. 706–721, 7 2018. [Online]. Available: https://doi.org/10.1016/J.IJEPES.2018.01.013

[16] F. M. Aboshady, D. W. Thomas, and M. Sumner, "A new single end wideband impedance based fault location scheme for distribution systems," *Electric Power Systems Research*, vol. 173, pp. 263–270, 8 2019. [Online]. Available: https://doi.org/10.1016/J.EPSR.2019.04.034

[17] A. Silos-Sanchez, R. Villafafila-Robles, and P. Lloret-Gallego, "Novel fault location algorithm for meshed distribution networks with ders," *Electric Power Systems Research*, vol. 181, p. 106182, 4 2020. [Online]. Available: https://doi.org/10.1016/J.EPSR.2019.106182

[18] S. Myint and W. Wichakool, "A traveling wave-based fault section and fault distance estimation algorithm for grounded distribution systems," *2019 IEEE PES GTD Grand International Conference and Exposition Asia, GTD Asia 2019*, pp. 472–477, 5 2019. [Online]. Available: https://doi.org/10.1109/GTDASIA.2019.8715933

[19] P. Li, X. Liu, Z. Yuan, W. Chen, L. Yu, Q. Xu, and Y. Lin, "Precise fault location method of traveling wave in distribution grid based on multiple measuring point," *2020 IEEE 4th Conference on Energy Internet and Energy System Integration: Connecting the Grids Towards a Low-Carbon High-Efficiency Energy System, EI2 2020*, pp. 1867–1872, 10 2020. [Online]. Available: https://doi.org/10.1109/EI250167.2020.9346873

[20] X. G. Magagula, Y. Hamam, J. A. Jordaan, and A. A. Yusuff, "A fault classification and localization method in a power distribution network," *2017 IEEE AFRICON: Science, Technology and Innovation for Africa, AFRICON 2017*, pp. 1337–1343, 11 2017. [Online]. Available: https://doi.org/10.1109/AFRCON.2017.8095676

[21] Z. Jianwen and D. Jiaxin, "Traveling wave fault location for lines combined with overhead-lines and cables based on empirical wavelet transform," *2019 IEEE 2nd International Conference on Electronics and Communication Engineering, ICECE 2019*, pp. 285–289, 12 2019. [Online]. Available: https://doi.org/10.1109/ICECE48499.2019.9058522

[22] Y. Jiang, "Data-driven probabilistic fault location of electric power distribution systems incorporating data uncertainties," *IEEE Transactions on Smart Grid*, vol. 12, pp. 4522–4534, 9 2021. [Online]. Available: https://doi.org/10.1109/TSG.2021.3070550

[23] C. Zhang, G. Song, T. Wang, and L. Yang, "Single-ended traveling wave fault location method in dc transmission line based on wave front information," *IEEE Transactions on Power Delivery*, vol. 34, pp. 2028–2038, 10 2019. [Online]. Available: https://doi.org/10.1109/TPWRD.2019.2922654

[24] W. Pavón, E. Inga, and S. Simani, "Optimal routing an ungrounded electrical distribution system based on heuristic method with micro grids integration," *Sustainability*, vol. 11, no. 6, 2019. [Online]. Available: https://doi.org/10.3390/su11061607

[25] M. A. Alotaibi and M. M. A. Salama, "An incentive-based multistage expansion planning model for smart distribution systems," *IEEE Transactions on Power Systems*, vol. 33, no. 5, pp. 5469–5485, Sep. 2018. [Online]. Available: https://doi.org/10.1109/TPWRS.2018.2805322

[26] A. Valenzuela, E. Inga, and S. Simani, "Planning of a resilient underground distribution

network using georeferenced data," *Energies*, vol. 12, p. 644, 2 2019. [Online]. Available: https://doi.org/10.3390/EN12040644

[27] M. A. Syakur, B. K. Khotimah, E. M. S. Rochman, and B. D. Satoto, "Integration k-means clustering method and elbow method for identification of the best customer profile cluster," *IOP Conference Series: Materials Science and Engineering*, vol. 336, p. 012017, apr 2018. [Online]. Available: https://doi.org/10.1088/1757-899x/336/1/012017

[28] M. Mosbah, S. Arif, R. D. Mohammedi, and A. Hellal, "Optimum dynamic distribution network reconfiguration using minimum spanning tree algorithm," in *2017 5th International Conference on Electrical Engineering - Boumerdes (ICEE-B)*, Oct 2017, pp. 1–6. [Online]. Available: https://doi.org/10.1109/ICEE-B.2017.8192170

[29] A. Guamán and A. Valenzuela, "Distribution network reconfiguration applied to multiple faulty branches based on spanning tree and genetic algorithms," *Energies*, vol. 14, no. 20, 2021. [Online]. Available: https://doi.org/10.3390/en14206699

[30] G. Michau, N. Pustelnik, P. Borgnat, P. Abry, A. Nantes, A. Bhaskar, and E. Chung, "A primal-dual algorithm for link dependent origin destination matrix estimation," *IEEE Transactions on Signal and Information Processing over Networks*, vol. 3, no. 1, pp. 104–113, March 2017. [Online]. Available: https://doi.org/10.1109/TSIPN.2016.2623094