International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 14, No. 2, June 2023, pp. 1280~1289
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v14.i2.pp1280-1289

A new algorithm for fault location in multi-end underground cables using traveling waves

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Article Info

Article history:

Received Aug 24, 2022
Revised Jan 19, 2023
Accepted Feb 11, 2023

Keywords:

Fault discrimination
Fault location
Traveling wave
Underground cable
Wavelet de-composition

ABSTRACT

A quick, reliable, and accurate fault location approach is essential in underground power systems protection. Being the most optimistic research topic of electrical power systems, this article presents an optimized algorithm for fault location in multi-end underground cables using travelling waves. Existing algorithms based on wavelet theory have fewer reliability and accuracy issues that raise an error to the power systems in fault location. The proposed layout presents a multiterminal underground cables system where the entire system is segregated into several fault identification sections where this model identifies the faulty section and the faulty half. Voltage and current wave transient at the mid-point of each fault locator are taken into account to eliminate the time-synchronous error. Traveling waves models are modelled using Bewley diagrams. Detecting the first and second traveling wave transient at both ends of each cable keeps the system reliable. Extensive simulations are simulated using the alternative transient program (ATP) to discriminate, identify, and locate several faults, while the system can also validate the faults near the busbar. The model is developed in MATLAB, and the obtained results depict the proposed algorithm's higher accuracy in fault location.

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1. INTRODUCTION

Underground cables play a significant role in power distribution and transmission systems nowadays. Deploying underground lines have restructured the modern power distribution and transmission networks [1]. The power distribution system is continually unearthed to the faults for multiple reasons, including natural disasters, artificial crises, old aged systems, and device failures [2], [3]. These factors affect the power system's continuity and reliability. The deviation from the standard conditions is considered a fault, and a fault must be detected accurately and then located precisely. A fault always leads current to improperly, creating power instability and equipment damages [4]. Current and voltage measurements have all the information to detect the faults, but different feature extraction methods and techniques are still used for better results. Fault detection using the feature extraction method uses the Fourier, wavelet, and S-transform [5]–[7]. These transforms use real-time-frequency parameters in different domains, and the wavelet domain can categorize as discrete and continuous. A transformation method that is widely used is Clarke transformation to detect and classify the faults using discrete wavelet transform (DWT) and back-propagation neural network (BPNN) [8]. Fault classification also has a significant role in power transmission and distribution systems via the protection relay component. Different models and algorithms based on various techniques are used to classify the faults accurately, i.e., the decision tree algorithm has been implemented to identify incipient faults in the UG cable [9].

A tree-like algorithm's logic flow extracts feature in a three-phase power system for a nonlinear statistical model. So, a fault classification analysis using a decision tree is done to quickly and accurately identify the incipient faults occurring in underground distribution cables [10], [11]. An artificial neural network (ANN) is used for classification, and the feedforward neural network (FNN) is deployed for multilayer schemes, where a probabilistic neural network uses the exponential activation function. A Chebyshev neural network (ChNN) is also considered for fault classification and detection. The least-square Levenberg-Marquardt and recursive least-square algorithms with forgetting factors are used as training algorithms [12]. The ChNN has detected the fault accurately and fastly, but it is appropriate for the digital relaying operations [13]–[15]. Usually, the fault location process or method for transmission system is categorized in two ways: impedance-focused and travelling wave-based. On the other hand, multiple methods are used for distribution sides like a single end, double end, various ends, and wide-area ends [16], [17]. Wide-area travelling wave data acquisition method is used in complex power grids. There are smart devices connected to the systems to locate the fault precisely. In such cases, capacitors and metal oxide varistors create trouble in fault locating as these have nonlinear functionality [18].

Similarly, high impedance faults have been discussed in the research, where these are protected by traditional overcurrent relay. Although many solutions have been found in the literature, artificial intelligence (AI) and machine learning-based solutions are the latest ones. These methods are considered for complex systems where various design parameters are part of fault detection. Better reliability and adaptability are the main benefits of these systems [19]. In [20], an optimized fault location method using time-time (TT) and SVM is proposed and obtained high accuracy with various variations in different fault scenarios. It also discriminates the fault accruing time of underground cables' first or second half. The classification accuracy is obtained by tuning the PSO parameters, and Bewley's lattice diagram is considered for locating the faults [20].

The faults accrued in the single-end underground cables are easy to detect because the path of travelling wave propagation is more convenient to the characteristic impedance of the particular system. Another ease is to apply the post-fault wave process because there is no interference of reflection and refraction of waves in single-end underground cables [21]. Impedance-based or DWT methods have been tested to overcome the abovementioned problem [22]–[24]. Three ends of the line are observed in [25], where the fault locator is deployed to determine the fault location. These methods are reliable, but high computation time is required for data synchronization of a massive amount. A synchronized phasor has been tested in multi-end lines, where it is also reported that an extra amount of investment is required [26]. The work on the DWT model for fault detection of multi-end lines was published in [27], and offline fault detection model is introduced in [28]. However, AI-based algorithms have difficulties of complexity and extensive memory required for training the data set and implementation of the model. The existing systems have less reliability in fault location because of synchronous time error.

The proposed algorithm not only eliminates this error but also covers more cables of the power system and multiple faults identification with remarkable accuracy. The main contributions of the article are highlighted below:

- The proposed layout presents a multiterminal underground cables system where the entire system is segregated into several fault identification sections. In this regard, the Bewley lattice diagram theory of Wavelet Transform is presented for modelling the fault location approach in two halves of the cables.
- Modelling of fault location Approach for fault near busbar is also carried out.
- Daubechies 4 (db4) wavelet using MATLAB toolbox for the wavelet function is considered for decomposition of Wavelet decomposition for fault location.
- Two transient waves are generated and identified at all busbars used in the proposed power system terminals, while the first and second maxima identify and detect both transients.
- The faulty Section regarding distance in km is identified by deploying the first and second halves models theory.
- Fault discrimination is estimated according to travelling wave theory using reflected wave polarities and initial voltage/current polarities.
- Extensive simulations are made to test the proposed model and obtain the minimal error in fault location.

The rest of the article is organized as follows: Introduction and topic background are present in the section 1. In section 2, the Bewley lattice diagram theory of Wavelet transform is described. Section 3 includes the proposed algorithm framework of fault location, where different models are modelled for fault discrimination, identification, and location. Section 4 validates the proposed model, and the last section concludes the proposed work.

2. THEORY OF PROPOSED METHOD FOR WAVELET TRANSFORM

A fault in underground power cables causes a transient in voltage/current traveling waves while broadband signals are used to asylum the frequency ranges. The frequency waves travel to the power cable until the discontinuity of the power is received. A bus bar is usually considered the destination of the reflection and refraction of the wave. The reason is the generation of additional waves propagating through the power network. These create discontinuity to the cable in the time domain through reflection towards the fault point. According to frequency domain analysis, DWT speed decreases the magnitude of individual frequency signals as its speed increases [29]. The impedance mismatch of the cables reflects the energy to disturbance, and the rest of the energy travels towards power lines. This scenario creates instant fault because a sudden change in the impedance is contingent on the change in voltage [30]. In Figure 1, the fault locator R can record three transient wavefronts at a time of $T_1, 3T_1, and\ 5T_1$. T_1 is used for travelling distances of the wave to A and T_2 denotes the travelling distances of the wave to B. The total length is L, and B becomes:

$$B = (L - A) \tag{1}$$

On the other hand, the fault locator S has to record three transient wavefronts at a time of $T_1, T_1 + 2T_2, and\ T_1 + 4T_2$.

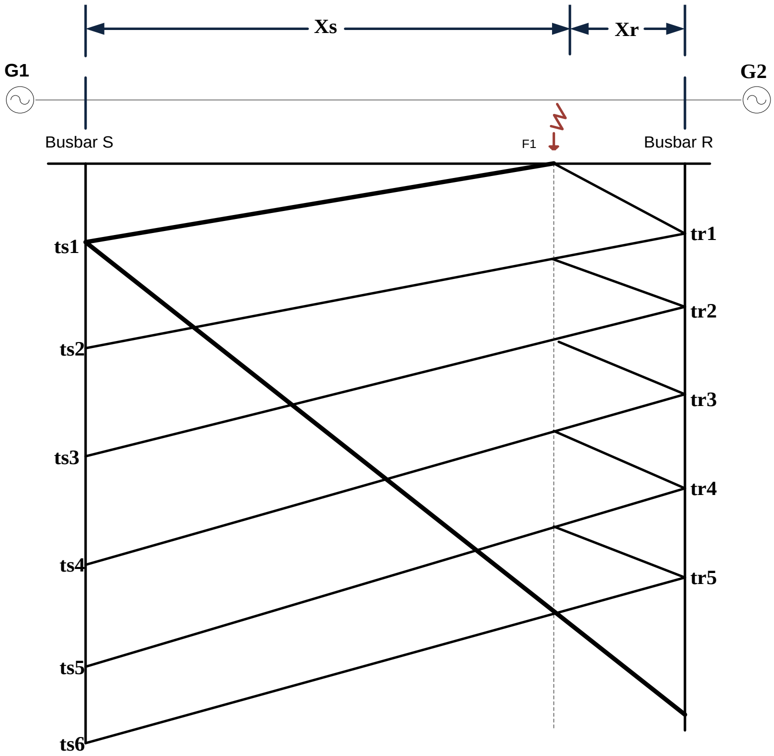

Figure. 1 Bewley lattice diagram theory of wavelet transforms

3. METHOD

This section describes the proposed framework of the fault location approach where the followings are the steps:

3.1. Modelling of fault location approach in two halves of the cables

The phenomenon of a fault occurring in underground cables defines that the transient wave (voltage/current) propagates away from the faulty point. The discontinuity of wave propagation happens when the wave passes through the fault locator and reflects back towards the fault location. This algorithm is based on the high-frequency transient analysis to determine the faulty line and exact location, as shown in Figure 2. where "+" and "-" define the polarities of transient sequences of the waves. Moreover, the remote busbar considers the reflected waves as opposite polarity, and the first forward wave has the opposite polarity, similar to the reverse fault [31].

$$t_{12} = T_{s2} - T_{s1} = 2\left(\frac{X_s}{v}\right) \tag{2}$$

$$t_{21} = 2\left(\frac{L_{ST}}{v}\right) - T_{s2} \tag{3}$$

$$L_{ST} = X_s + X_t \tag{4}$$

$$X_s = \frac{1}{2}\left(\frac{L_{ST}}{1+t_{12}/t_{21}}\right) \tag{5}$$

Where: t_{12} : The first two transient waves are in the first half of the cable; t_{21}: Time arrival of the first two transient waves at both ends of the cable; T_{s2}: Second transient wave; T_{s1} : First transient wave; L_{ST}: Total length; X_s: Length of the first half; X_t : Length of the second half; v: Velocity of the traveling waves;

$$t_{12} = T_{t2} - T_{t1} = 2\left(\frac{X_T}{v}\right) \tag{6}$$

$$t_{21} = 2\left(\frac{L_{ST}}{v}\right) - T_{t2} \tag{7}$$

$$X_s = \frac{1}{2}\left(L_{ST} - \frac{L_{ST}}{1+t_{21}/t_{12}}\right) \tag{8}$$

Where: t_{12} : The first two transient waves are in the first half of the cable; t_{21} : Time arrival of the first two transient waves at both ends of the cable; T_{t2}: Second transient wave; T_{t1}: First transient wave.

3.2. Modelling of fault location approach for fault near busbar

In the previous Section, the mathematical models presented are used for only the fault discrimination of two halves. This Section has the same parameters as section 3.1, but it is modelled for fault accrued near the busbar, and the models are:

$$t_{12} = T_{s2} - T_{s1} = 2\left(\frac{X_S}{v}\right) \tag{9}$$

$$t_{21} = \left(\frac{X_T}{v}\right) - \left(\frac{X_s}{v}\right) \tag{10}$$

$$X_s = \frac{1}{2}\left(L_{ST} - \frac{L_{ST}(t_{21}/t_{12})}{1-t_{21}/t_{12}}\right) \tag{11}$$

$$t_{12} = T_{t2} - T_{t1} = 2\left(\frac{X_S}{v}\right) \tag{12}$$

$$t_{21} = \left(\frac{X_S}{v}\right) - \left(\frac{X_T}{v}\right) \tag{13}$$

$$X_s = \frac{1}{2}\left(\frac{L_{ST}}{1+t_{21}/t_{12}}\right) \tag{14}$$

3.3. Data collection of three-phase voltages signals

This proposed model considers voltage signals of all three waves at different cable terminals. In previous models, CVTs have been used for capturing the fault transient, whereas limited bandwidth of less than 1kHZ is provided [32]. Here, a specific transient voltage detector of 500 KHZ is deployed to capture the fault waves speedily instead of CVTs [33].

3.4. Modelling of wavelet transform for fault location

As a three-phase system is considered, each phase's electromagnetic coupling can affect the accuracy in fault location. There is a need for such transformation that three-phase non-independent components convert into mutually independent mode components as per Clarke transformation matrices [34]. The proposed model transformation is formulated as (15).

$$\begin{matrix} V_\alpha \\ V_\beta \\ V_\gamma \end{matrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ 1 & 1 & 1 \\ 0 & \sqrt{3} & \sqrt{3} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{15}$$

V_α, V_β, and V_γ are mutually independent mode components of three-phase voltages V_a, V_b, and V_c. Similarly, I_α, I_β, and I are mutually independent mode components of three-phase currents I_a, I_b, and I_c. As earlier discussed, there is a need for different time frames and frequency bands for high frequency and high resolution.

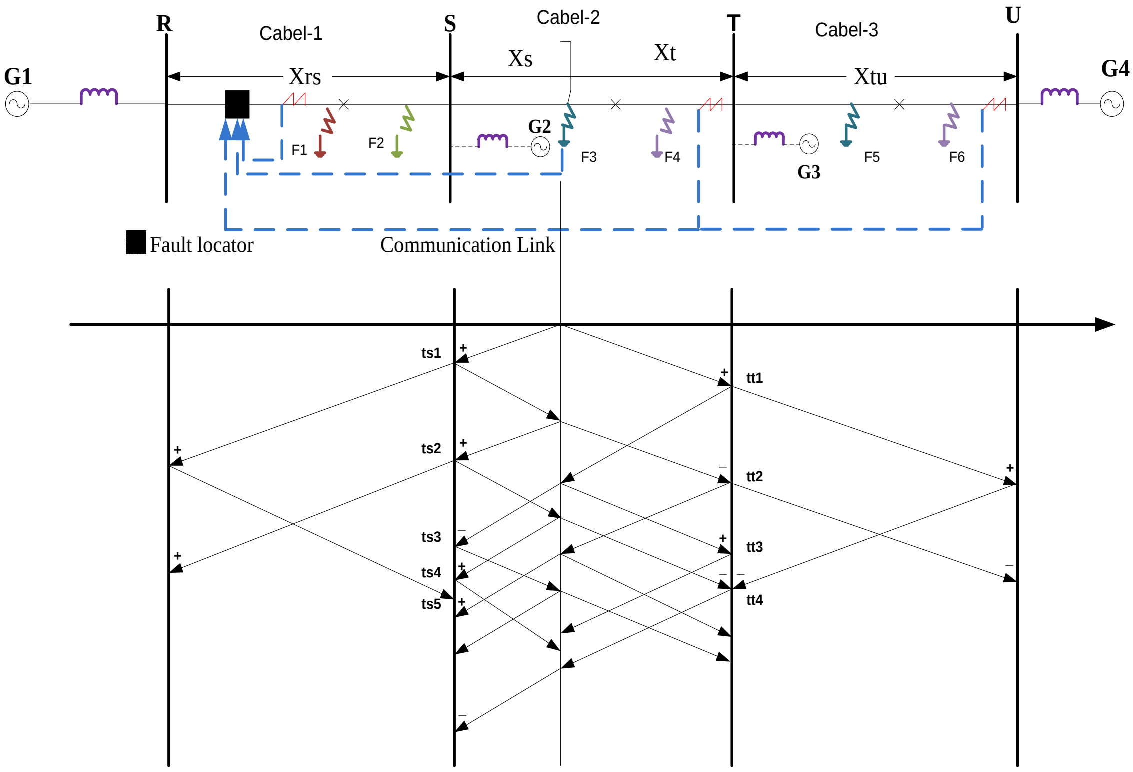

Figure 2. Proposed system configuration

3.5. Wavelet decomposition for fault location

Travelling wave signals are nonperiodic and have high-frequency oscillation, superimposed on the power system in the form of harmonics. Proposed wavelet decomposition for fault location considers Daubechies 4 (db4) wavelet using MATLAB toolbox for the wavelet function. The number 4 defines the wavelet coefficients. It is normally considered the frequency of 40 to 80 KHZ to extract the transient in the wavelet method, whereas the original signal is divided into further frequency bands for wavelet transformation [35].

Suppose the system has a transient wave at the terminal of first busbar, then in (2) and (3) can estimate the location of the fault using the time of the first two transient waves. Further, one step ahead, the transient time at S and (4), and (5) are used to estimate the location of the fault in kilometers. If the system has a transient wave at the terminal of second busbar S, then (6) and (7) can estimate the location of the fault using the time of the first two transient waves. Further, one step ahead, the transient time at S and (8) are used to estimate the location of this fault in kilometers. The faults 1-6 can be estimated as explained in the scenarios mentioned above. Suppose the faults accrued near to busbar, then (9)-(14) are used for estimation.

4. RESULTS AND DISCUSSION

This subsection includes the main implementation of a novel fault location method for multiterminal underground cables. The model is applied to 4 terminals of the transmission line, as shown in the Figure 2, i.e. Point R, point S, point T, and point U. In the first step, two transient waves are generated and identified at all four terminals of the proposed power system. The first and second maxima define both transients, respectively, and this continues so on. The detail is following:

Maxima estimation detail coefficient $[J_i]$ that adopt the approach as $[J_i] > [J_{i-1}]$ and $[J_i] > [J_{i+1}]$ whereas $[K_i]$ defines a set of maximum points. The local maxima can verify by $[K_i] > [K_{i-1}]$ and $[K_i] >$

$[K_{i+1}]$. In the second step, the faulty section is identified by locating the fault in terms of distance. The sequences describe as:

- Suppose the system has succeeded in detecting the transient wave the terminal of busbar R, then the proposed fault locator discriminates it F-1 (fault-1) as the first half of the cable 1.
- Suppose the system has succeeded in detecting the transient wave the terminal of busbar U, then the proposed fault locator discriminates it F-6 (fault-6) as the second half of the cable 3.
- Suppose the system has succeeded in detecting the transient wave the terminal of busbar S, then the proposed fault locator discriminates it F-2 (fault-2) as the second half of the cable 3 or F-3 (fault-3) as the first half of the cable 2.
- Suppose the system has succeeded in detecting the transient wave at the terminal of busbar T, then the proposed fault locator discriminates it F-4 (fault-4) as the second half of the cable.2 or F-5 (fault-5) as the first half of the cable 3.

In the third stage, fault discrimination is estimated according to traveling wave theory; reflected wave polarities and initial voltage/current polarities are considered a solution to discriminate the fault 2,3. In this regard, the polarity of reflected waves at the fault location has the same polarity, whether for voltage or current. At the time of fault, the transient wave of voltage/current has the same polarity in the first few cycles. So, following faults are discriminated as:

- It has to be discriminated whether it is F2 or F3; if the system has succeeded in detecting the transient wave the terminal of busbar S. So, if the transient wave signal is of the same polarity at buses R and S, then the fault is considered F3. Meanwhile, if the transient wave signal of the same polarity at buses S and T is detected, the fault is considered F2.
- Similarly, it has to be discriminated whether it is F4 or F5; if the system has succeeded in detecting the transient wave a the terminal of busbar T. So, if the transient wave signal is of the same polarity at buses S and T, then the fault is considered F5. Meanwhile, if the transient wave signal of the same polarity at buses T and U is detected, the fault is considered F4.

As earlier discussed, fault discrimination is estimated according to traveling wave theory. In this regard, F-2 and F-3 are discriminated by the polarities of the second transient wave, as shown in Figure 3 and Figure 4. Numbers of samples and voltages at the time of fault can also be observed. Similarly, the same approach is adapted for the discrimination of F-4 and F-5.

In the final stages, fault location is estimated, which is described as:

- Scenario 1: F-1 (fault-1). Suppose the system has a transient wave at the terminal of busbar R, then (2) and (3) can estimate the location of the fault using the time of the first two transient waves. Further, one step ahead, the transient time at S and (4), and (5) are used to estimate the location of the fault (F-1) in kilometers.
- Scenario 2: F-2 (fault-2). Suppose the system has a transient wave at the terminal of busbar S, then (6) and (7) can estimate the location of the fault using the time of the first two transient waves. Further, one step ahead, the transient time at S and (8) are used to estimate the location of the fault (F-2) in kilometers.
- Scenario 3: F-3 (fault-3). Suppose the system has a transient wave at the terminal of busbar S, then (2) and (3) can estimate the location of the fault using the time of the first two transient waves. Further, one step ahead, the transient time at T and (4), and (5) are used to estimate the location of the fault (F-3) in kilometers.
- Scenario 4: F-4 (fault-4). Suppose the system has a transient wave at the terminal of busbar T, then equations (6) and (7) can estimate the location of the fault using the time of the first two transient waves. Further, one step ahead, the transient time at T and (8) are used to estimate the location of the fault (F-4) in kilometers.
- Scenario 5: F-5 (fault-5). Suppose the system has a transient wave at the terminal of busbar T, then (2) and (3) can estimate the location of the fault using the time of the first two transient waves. Further, one step ahead, the transient time at U and (4) and (5) are used to estimate the location of the fault (F-5) in kilometers.
- Scenario 6: F-6 (fault-6). Suppose the system has a transient wave at the terminal of busbar U, then (6) and (7) can estimate the location of the fault using the time of the first two transient waves. Further, one step ahead, the transient time at U and (8) are used to estimate the location of the fault (F-6) in kilometers.
- Scenario 7: fault near busbar. The faults 1-6 can be estimated as explained in the scenarios mentioned earlier. Suppose the faults accrued near to busbar, then (9-14) are used for estimation.

4.1. Model validation

The proposed configuration has $11\ \mathrm{kV}, 60\ \mathrm{HZ}$ underground power system where three underground cables are taken into account. Cable-1 is from busbar R to S, Cable-2 is from busbar S to U, and Cable-3 is from busbar U to T. Each cable has an equal length of 100 km, as shown in Figure 3. Generator's specifications are considered as G_1 has 15 MVA, G_2 has 20 MVA, G_3 has 25 MVA, and G_4 has 30 MVA. Extensive simulations are simulated using the Alternative transient program (ATP), validating the proposed model at each underground cable. The results estimated in Table 1 are remarkable where the error is nominal. The given formula calculates the error.

$$\text{error}\ \% = \frac{|\text{Actual location of fault in km} - \text{Estimated location of fault in km}|}{\text{Total Length of the entire power system}} \times 100$$

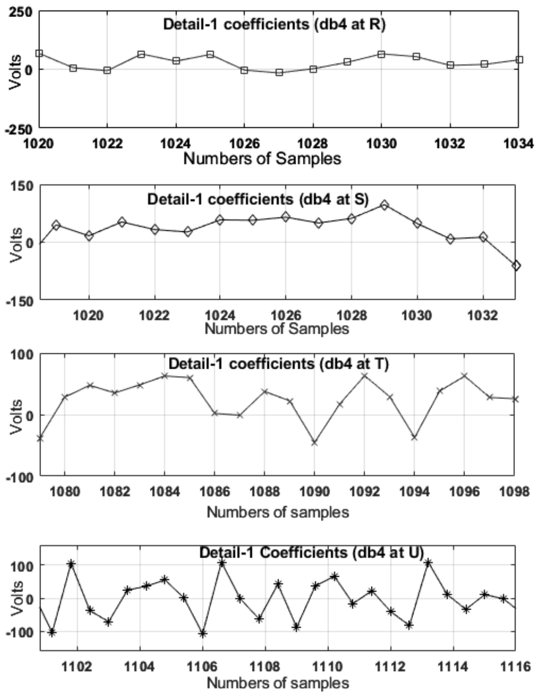

Figure 3. Detail-1 coefficients at end terminal of busbar R, S, T, and U for F2 (fault-2)

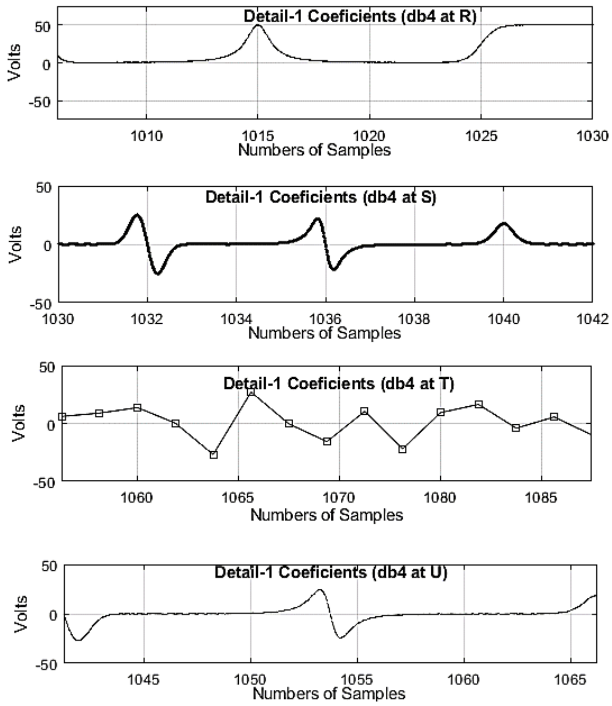

Figure 4. Detail-1 coefficients at end terminal of busbar R, S, T, and U for F3 (fault-3)

Table 1. Algorithm validation at the different fault locations

Cable	Fault Identification	Location of Faults in (KM) (Actual Location)	Location of Faults in (KM) (Estimated Location)	Error %
Cable-1 is from busbar R to S	F1	3.3	3.4848	0.051615
	F1	8.3	7.6846	0.213453
	F1	15.0	16.6503	0.555111
	F1	24.0	22.0709	0.635031
	F2	54.9	56.4235	0.49284
	F2	69.9	69.6969	0.0777
	F2	85.6	86.2770	0.23199
	F2	98.2	99.8834	0.54945
Cable-2 is from busbar S to U	F3	7.5	7.8125	0.104166667
	F3	25.0	23.8463	0.384583333
	F3	40.5	39.0375	0.4875
	F3	46.3	47.5600	0.436666667
	F4	55.5	54.7625	0.245833333
	F4	68.8	70.0000	0.416666667
	F4	80.0	80.2350	0.078333333
	F4	97.5	99.0125	0.504166667
Cable-3 is from busbar U to T	F5	6.0	6.2500	0.083333333
	F5	20.0	19.0770	0.307666667
	F5	32.4	31.2300	0.39
	F5	37.0	38.0480	0.349333333
	F6	44.4	43.8100	0.196666667
	F6	55.0	56.0000	0.333333333
	F6	64.0	64.1880	0.062666667
	F6	78.0	79.2100	0.403333333

In the end, to check more validation of the proposed system, the resistance of the fault is also estimated and compute the error rate in percentage. The range of fault resistance is observed from 20Ω to 200Ω, showing the increase in resistance with the distance of the fault as shown in Table 2. The model has the property of unchanged behavior in the characteristics of the wavelet by changing the resistance. At the distance of 50 km, between busbar S and T (Cable-2), the resistance is observed and estimated, then compute the percentage error as shown in Table 2. Maximum error is minimal of 0.305%, which indicates the excellent performance of the proposed system.

Table 2. Algorithm validation at the different fault resistance

Sr. No	Resistance of faults (Ω)	Fault distance (km)	Error (%)
1	20	49.495	0.2525
2	30	49.495	0.2525
3	40	49.495	0.2525
4	80	49.406	0.297
5	100	49.406	0.297
6	120	49.406	0.297
7	140	49.39	0.305
8	160	49.39	0.305
9	200	49.39	0.305

5. CONCLUSION

This paper presents a novel fault location algorithm for multiterminal underground cables of the electrical power system. The proposed model eliminates the synchronous time error by deploying a fault locator at each midpoint of the cable. The Bewley lattice diagram theory of Wavelet Transform is presented for modeling the fault location approach in two halves of the cables. The article is based on the detection of the first and second traveling wave transient at each end of the busbar where the system not only discriminates the faults but also identifies the fault's location in km. Alternative transient programs (ATP) to discriminate the waves transient and Daubechies 4 (db4) wavelet using MATLAB toolbox for the wavelet function are considered for decomposition of Wavelet decomposition for fault location. The main focus points of this research are detection of voltage/current wave transient on the end terminal of each busbar, discrimination of faults, and fault location with high accuracy and reliability. The model also validates the fault near the busbar. The model validation at different fault locations and faults resistance is obtained in an error percentage that is not greater than 0.7% in fault location and 0.4% in fault resistance. The mentioned points prove that our underground cables' multiterminal fault location algorithm is more robust and accurate than other algorithms. In the future, this model can be tested for fault location of shunt and series fault conditions.

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