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Journal of Science and Technology

E-ISSN 2146-7706

Transmission line fault location: Simulation of real faults using wavelet transform based travelling wave methods

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ARTICLE INFO

Article history:
Received 30 November 2019
Received in revised form 12 December 2019
Accepted 12 December 2019

Keywords:
Fault Location
Transmission line
Travelling Wave
Wavelet Transform

ABSTRACT

In this study, High Voltage Transmission Line fault location accuracy of distance relays running impedance algorithm are compared with Travelling Wave (TW) method. Line faults in 154 kV Tatvan – Muş and 154 kV Patnos-Erciş lines in Turkish Electrical Transmission System are analyzed. Real faults in both lines are simulated in MATLAB-SIMULINK. Tower configuration and conductor properties of the lines and the source impedances are included in the simulation to comply with real system. Simulations show that both single-end and double-end Wavelet Transform (WT) based TW methods have better accuracy then the distance relays computing fault location by impedance methods.

1. Introduction

Locating fault in Transmission Lines is vital for reliable, sustainable and efficient delivery of electrical energy. Faults occurred in Transmission lines may cause long power outages. Fault location accuracy in transmission lines affect the consumed time for clearing the fault by maintenance crew. The accuracy in impedance based methods is limited by factors like fault resistance, load flow and compensated lines etc. An example of ±1% error in fault location for a 500 km line means the maintenance crew have to search the fault within 5 km span of the line. This means approximately 30 towers. Percentage error for determining fault location in HV transmission lines can be calculated by using (1).

$$\%Error = \left|\frac{(Actual\ Location - Computed\ Location)}{Total\ Line\ length}\right| \cdot 100 \qquad (1)$$

Common fault location methods can be categorized as Impedance-Based Methods [1] and Travelling Wave(TW)-Based Methods [2]. Also fault location methods can be classified as single-end and double-end [3]. Single-End Methods use data from single end of the line. Double-End Method use data from both side of the line. For this reason, Double-End Methods need time synchronization of both end data. Time synchronization established by means of GPS modules. Impedance-based methods have lower accuracy and less cost compared to TW-based ones. Single-End Methods have lower accuracy and less cost compared to double-end ones. TW-Based Methods need supplemental logic to classify fault type and locate fault for all fault types [4].

Discontinues like faults, lightning strikes, opening or closing the circuit breaker etc. causes high-frequency (10kHz to 600kHz) voltage and current transients moving towards both ends of the line [5]. These transients are called Traveling Waves (TW). TWs propagate along the line with the velocity near the speed of light, 300.000 km/s.

TW propagation initiate at the same time with the discontinuity. This first wave is called incident TW. At every discontinuity point, that is a high impedance point wave is divided three parts: some reflected back, some is transmitted through the point and some is absorbed by the point. In the case of transmission line fault, busbars at each side of the line and fault point are discontinuities (Figure 1).

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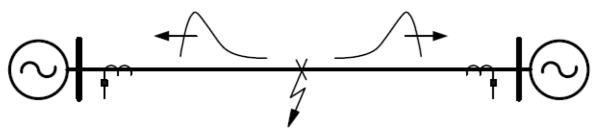


Figure 1. Travelling Waves in case of transmission line fault

For Double-End TW Method, arrival times of incident TWs to each side of the line are extracted from overall fault (current or voltage) signals. For Single-End TW Methods, arrival times of incident TW and first reflected TW at one side of the line are extracted from overall fault (current or voltage) signal. Extraction of these arrival times are made by means of signal processing methods like wavelet transform [6], deviation method [7] or transient spectrum methods[8]–[11]. Difference of these extracted times of each method is used in calculation of fault location. Figure 2 shows how travelling waves be formed due to a fault occurred in the line, also called Bewley's lattice diagram [12].

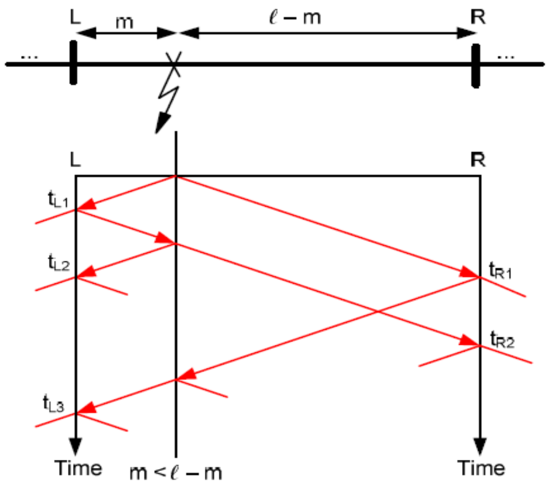


Figure 2. Bewley's lattice diagram showing incident TWs.

This study determines transmission line fault location with both Single-End and Double-End TW Fault Location Method using wavelet transform by means of simulating real faults occurred in the transmission line in MATLAB-SIMULINK.

2. Materials and Methods

2.1 Single-End TW Fault Location Method

A fault occurred in the point m, in Figure 2, causes TW moving towards both ends of the line. L and R are line ends. t_{Li} and t_{Ri} are successive reflection times of the TWs reaching corresponding end of the line. Fault location can be calculated by using arrival times of indecent TW and the first reflected TW at the same side of the line. Fault location calculated by:

$$m = \left(\frac{t_{L2}-t_{L1}}{2}\right) \cdot v \qquad (2)$$

and

$$v = \frac{1}{\sqrt{L \cdot C}} \qquad (3)$$

where:

m : fault point (km)

t_{L2} , t_{L1} : arrival times of first reflected and incident TW respectively (s)

v : velocity of TW propagation (km/s)

L : Unit line inductance (H/km)

C : Unit line capacitance (F/km)

2.2 Double-End TW Fault Location Method

A fault occurred in the point m, in Figure 2, causes TWs moving towards both ends of the line. L and R are line ends. t_{L1} and t_{R1} are incident times of the TWs reaching corresponding end of the line. Fault location can be computed by using arrival times of indecent TWs to both side of the line. Fault location calculated by:

$$m = \frac{1}{2} \cdot [\ell + (t_{L1} - t_{R1}) \cdot v] \qquad (4)$$

where: ℓ : line length

m : fault point (km)

t_{L1} , t_{R1} : arrival times of Incident TWs respectively (s)

v : velocity of TW propagation (km/s)

2.3 Case Studies

2.3.1 The Fault in 154 kV Patnos-Erciş Line

Real fault data taken from Line Distance Protection Relay at Patnos Substation for 154 kV Patnos-Ercis Line is considered. The fault is modelled in MATLAB-SIMILINK to apply the Single-End TW Method. Phase B to Ground fault (B-G) occurred in December 2, 2016 is examined. Line length is 46,587 km and fully transposed. First 5,281 km is double circuit with 795 MCM DRAKE conductor and the rest is single circuit with 477 MCM HAWK conductor. Fault occurred at 7,31 km from Patnos. The cause was the broken insulator (Figure 3). SEL 421 Distance Relay, is used for line protection in Patnos Substation. The Relay computed distance for the fault as 5,38 km. The output of the relay is given in Figure 4.

Figure 3. The Fault in 154 kV Patnos-Erciş Line

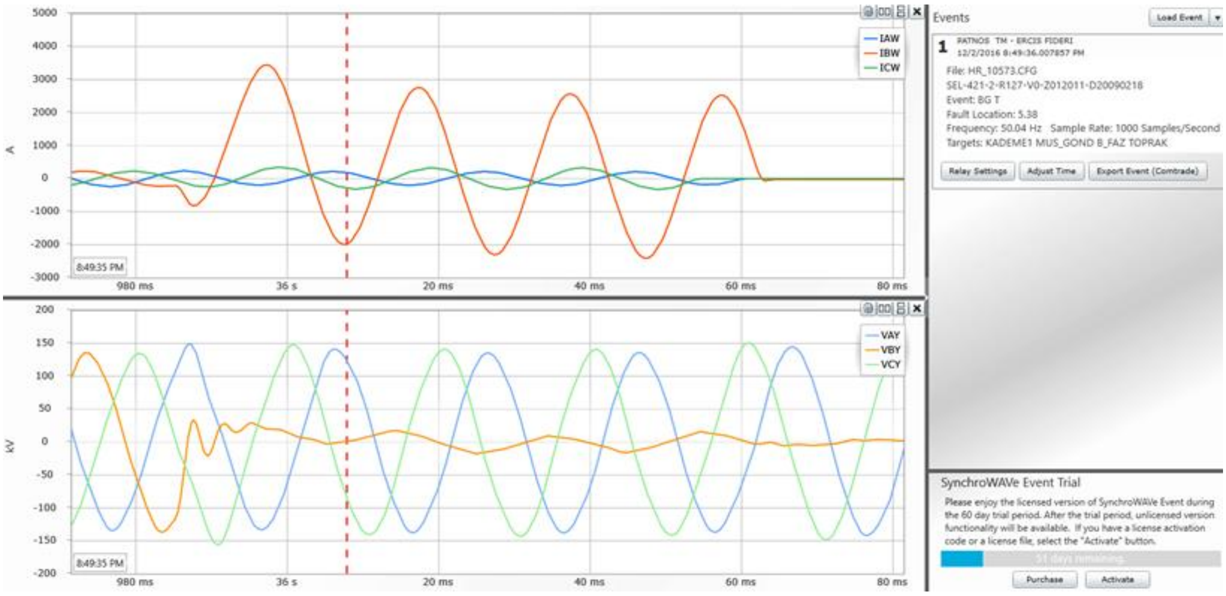


Figure 4. Relay Output for the Fault in 154 kV Patnos-Erciş Line

2.3.2 The Fault in 154 kV Tatvan-Muş Line

Real fault data taken from Line Distance Protection Relays at the both side of 154 kV Tatvan-Muş Line is considered. The fault is modelled in MATLAB-SIMILINK to apply the Double-End TW Method. Phase C to Ground fault (C-G) occurred in March 3, 2017 is examined. Line length is 71,3357 km and fully transposed. The line is single circuit with 477 MCM HAWK conductor. Fault occurred at 9,8157 km from Muş. Stork nest caused short circuit between Phase C and the Tower (Figure 5). Distance Relay at Tatvan Substation gave the fault distance as 62,65 km. Distance Relay at Muş Substation gave the fault distance 10,15 km.

Figure 5. The Fault in 154 kV Tatvan-Muş Line

2.4 Line Parameters

Line parameters are obtained by using 'Powergui Compute RLC Line Parameters Tool' (MATLAB), conductor type and measurements of the tower type. Ground resistivity is neglected. 154 kV Patnos-Erciş Transmission Line parameters are given in Table 1 and 154 kV Tatvan-Muş Transmission Line parameters are given in Table 2.

Table 1. 154 kV Patnos-Erciş Transmission Line parameters

	Single Circuit Section		Double Circuit Section		
Parameter	**Positive Seq.**	**Zero Seq.**	**Positive Seq.**	**Zero Seq.**	**Zero Seq. Mutual**
R (Ohms/km)	0.12046	0.14231	0.71534	0.8777	0.16236
L (H/km)	0.0013977	0.0022224	0.0012629	0.0038516	0.0022446
C (F/km)	8.5138e-09	6.1677e-09	9.4507e-09	5.534e-09	-1.8159e-09

Table 2. 154 kV Tatvan-Muş Transmission Line parameters

Parameter	Positive Seq.	Zero Seq.
R (Ohms/km)	0.12046	0.14231
L (H/km)	0.0013977	0.0022224
C (F/km)	8.5138e-09	6.1677e-09

2.5. MATLAB-SIMULINK Simulation of Faults

2.5.1 MATLAB-SIMULINK Simulation of the Fault in 154 kV Patnos-Erciş Line

The simulation is created in MATLAB- SIMILINK using Simscape Power Systems Tool. The simulation is shown in Figure 6.

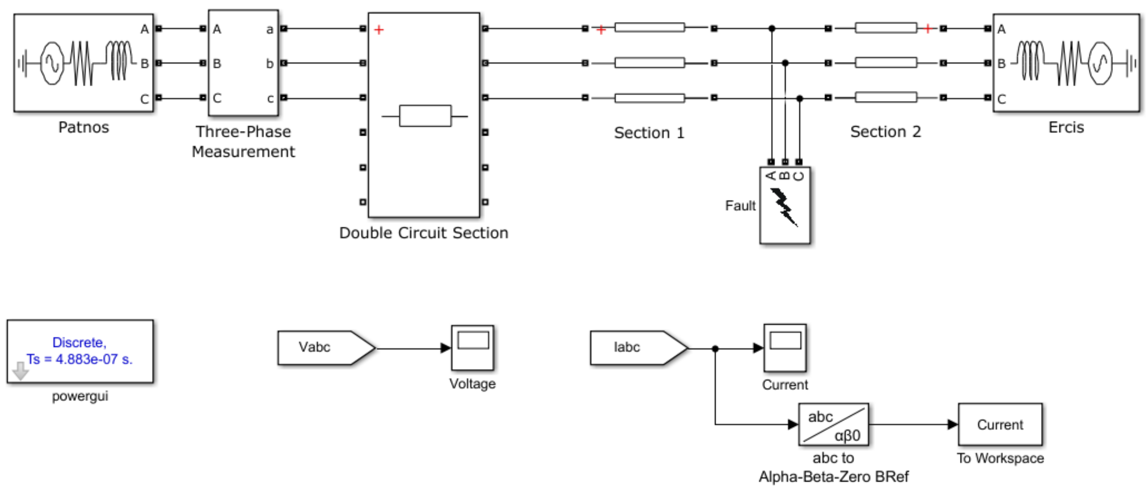


Figure 6. SIMULINK Model of the Fault in 154 kV Patnos-Erciş Line

"Patnos" and "Ercis" sources represent busbars at each side of the line. Source impedance is driven from Three Phase Short Circuit Parameters. The parameters are taken from TEİAŞ (Turkish Electricity Transmission Corporation). The simulation lasts for 200 ms. The fault is programed from 100th ms to 150th ms. Sampling Rate is 2.048 MHz. Fault resistance is chosen as 40 ohms; 20 for arc resistance and 20 for tower resistance and tower footing. Distributed line Model is used. The line divided to sections according to double circuit line section and actual fault location. Base voltage is 154 kV and base power is 100 MVA. In real applications of TW methods Current Transformer (CT) output is used to compute fault location because of their better frequency responses compared to Capacitance Voltage Transformer (CVT) [13]. That is way current waves are chosen for further computations.

Since we do not need load impedance for the method, the load flow is not involved in the SIMULINK model. The method is independent from load flow and that makes the method more useful compered to impedance based ones. Figure 7 shows simulation output for the fault.

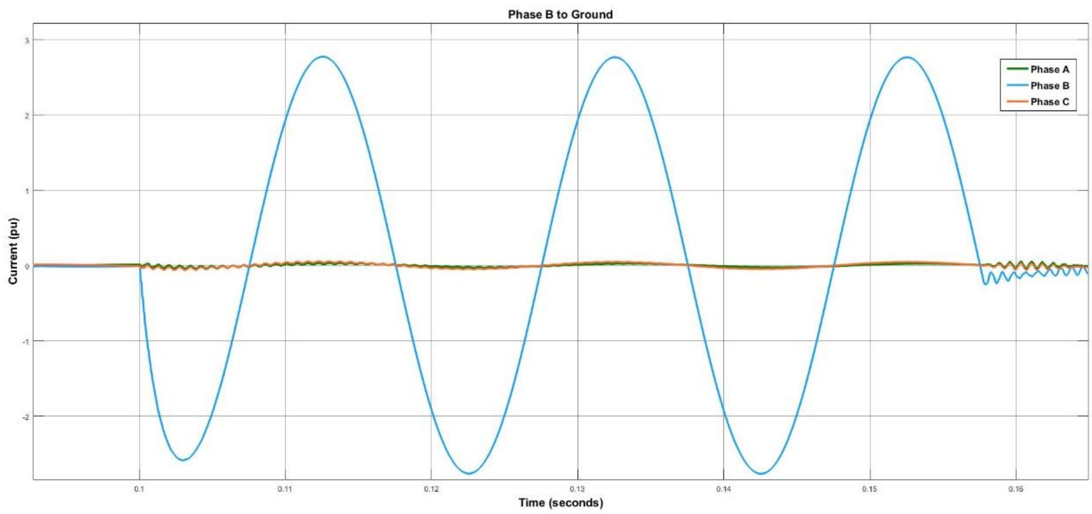


Figure 7. Simulation output for the Fault in 154 kV Patnos-Erciş Line

2.5.2 MATLAB-SIMULINK Simulation of the Fault in 154 kV Tatvan-Muş Line

The simulation is created in MATLAB- SIMILINK using Simscape Power Systems Tool. The simulation is shown in Figure 8.

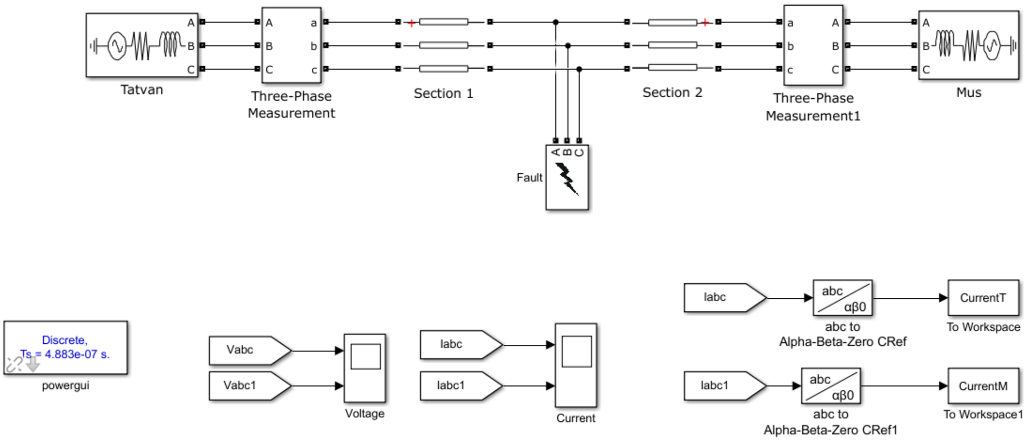


Figure 8. SIMULINK Model of the Fault in 154 kV Tatvan-Muş Line

"Tatvan" and "Mus" sources represent busbars at each side of the line. Source impedance is driven from Three Phase Short Circuit Parameters. The parameters are taken from TEİAŞ (Turkish Electricity Transmission Corporation). The simulation lasts for 200 ms. The fault is programed from 100th ms to 150th ms. Sampling Rate is 2.048 MHz. Fault resistance is chosen as 40 ohms; 20 for arc resistance and 20 for tower resistance and tower footing. Distributed line Model is used. The line divided to section according to actual fault location. Base voltage is 154 kV and base power is 100 MVA. In real applications of TW methods Current Transformer (CT) output is used to compute fault location because of their better frequency responses compared to Capacitance Voltage Transformer (CVT) [13]. That is way current waves are chosen for further computations.

Since we do not need load impedance for the method, the load flow is not involved in the SIMULINK model. The method is independent from load flow and that makes the method more useful compered to impedance based ones. Figure 9 shows simulation output for the fault.

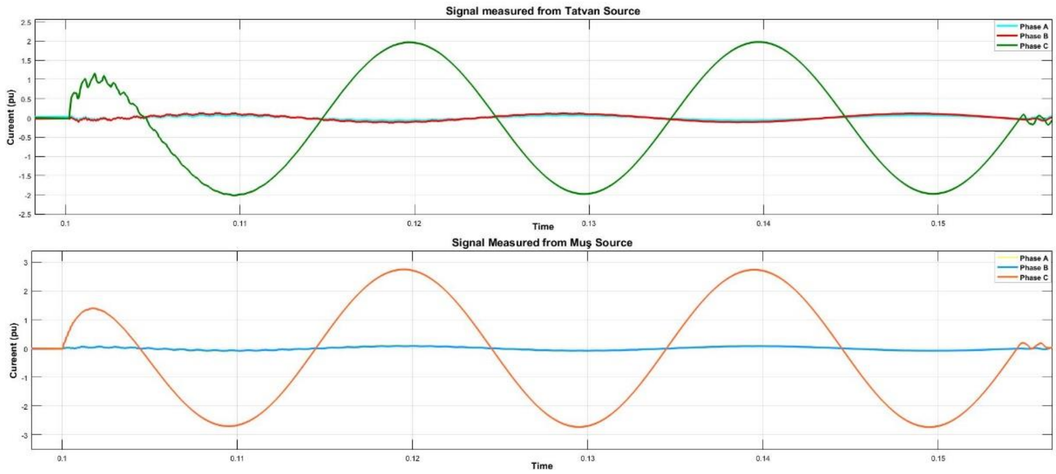


Figure 9. Simulation output for the Fault in 154 kV Tatvan-Muş Line

2.6. Modal Transform

In three phase transmission lines, the travelling waves are coupled and a single wave velocity does not exist. In order to implement methods in three phase systems, the phase domain signals are first decomposed into their modal components using Clarke's Transformation [14]. This transformation is also make simulation more efficient since we do not establish any transposition in models. The Clarke components calculated with reference to Phase A work well for AG and BC faults but will not work optimally for other fault types. In order to cover all fault types, we use three sets of Clarke components with reference to Phase A, Phase B, and Phase C:

$$\begin{bmatrix} I_\alpha^A \\ I_\beta^A \\ I_o^A \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} I_\alpha^B \\ I_\beta^B \\ I_o^B \end{bmatrix} = \frac{1}{3}\begin{bmatrix} -1 & 2 & -1 \\ -\sqrt{3} & 0 & \sqrt{3} \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} I_\alpha^C \\ I_\beta^C \\ I_o^C \end{bmatrix} = \frac{1}{3}\begin{bmatrix} -1 & -1 & 2 \\ \sqrt{3} & -\sqrt{3} & 0 \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad (7)$$

α and **β** components are called **aerial-mode** components, **0** component is called **zero-mode** component. α–mode of the signal is chosen for further computations. The wave velocity of 154 kV Patnos-Erciş and 154 kV Tatvan-Muş Line can be calculated as in (8).

$$v_\alpha = \frac{1}{\sqrt{L_1 \cdot C_1}} = \frac{1}{\sqrt{0.0013977 \cdot 8.5138e{-}09}} = 289888{,}7059 \text{ km/s} \quad (8)$$

where L_1 and C_1 are positive sequence unit inductance (H/km) and the capacitance (F/km) of lines respectively.

2.7. Wavelet Transformation

In signal processing, Wavelet transform helps to obtain frequency-time resolution of any signal. In other words, it gives us which high frequency component at which time period. Since we know that the TWs in the transmission line has relatively high frequencies of 10 kHz to 600 kHz then the system frequency of 50 Hz and we need to estimate arrival times of TWs to end of the lines; wavelet can be a proper choice for our application. We use Discrete Wavelet Transform function (**dwt**) with Daubechies mother wavelet **db2** [15]. DWT decomposes original signal into **approximation coefficients** that is a convolution of the signal with low pass filter and **detail coefficients** that is a convolution of the signal with high pass filter. The sample number of the signal is lowered by ratio of 2 with each filtering operation. This is called **downsampling**. Figure 10 shows block diagram of dwt for first level.

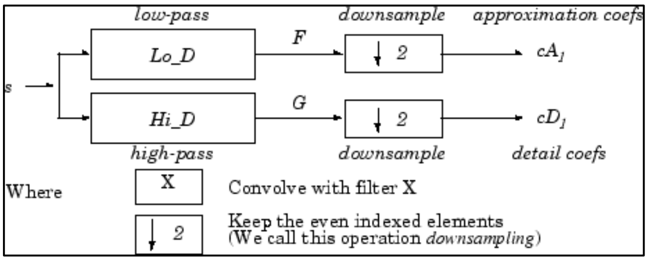


Figure 10. Block diagram of dwt for first level

Mathematical expression for dwt is [16]:

$$W_{\psi,s}(m,n) = 2^{\frac{-m}{2}} \sum_k s(k)\psi(k2^{-m} - n) \quad (9)$$

Where, □ is dwt, □ is scale parameter, □ is time shift parameter, □ is mother wavelet and □ is the signal.

16384 points of the α-mode signal are extracted from overall signals starting just before fault time (100th ms.). This is approximately half period of the current signal. Sampling period is 2,048 MHz. Since 16384 can be written as 2□, where □ is an integer, the signal can be processed for wavelet transform.

Figure 11 shows discrete wavelet transforms of the fault signal measured at Patnos side. First one is α-mode of the signal, second is approximation coefficients, and last one is detail coefficients. Observe that the sudden change in the signal can be seen in the detail coefficients with the exact same time.

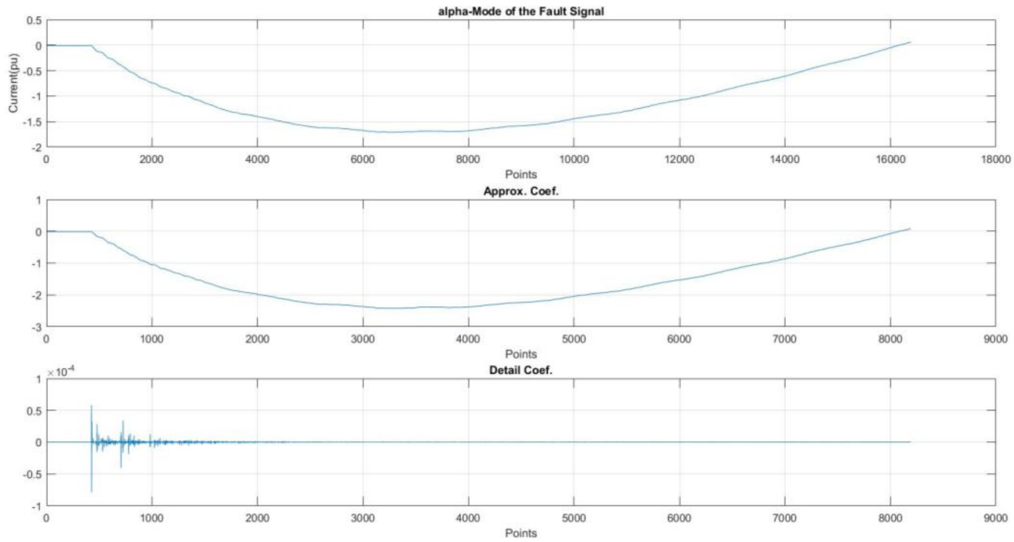


Figure 11. Dwt of the Fault Signal at Patnos Side

Figure 12 and 13 show discrete wavelet transforms of fault signals measured at Muş side and Tatvan side respectively. First one is α-mode of the signal, second is approximation coefficients, and last one is detail coefficients. Observe that the sudden change in the signal can be seen in the detail coefficients with the exact same time.

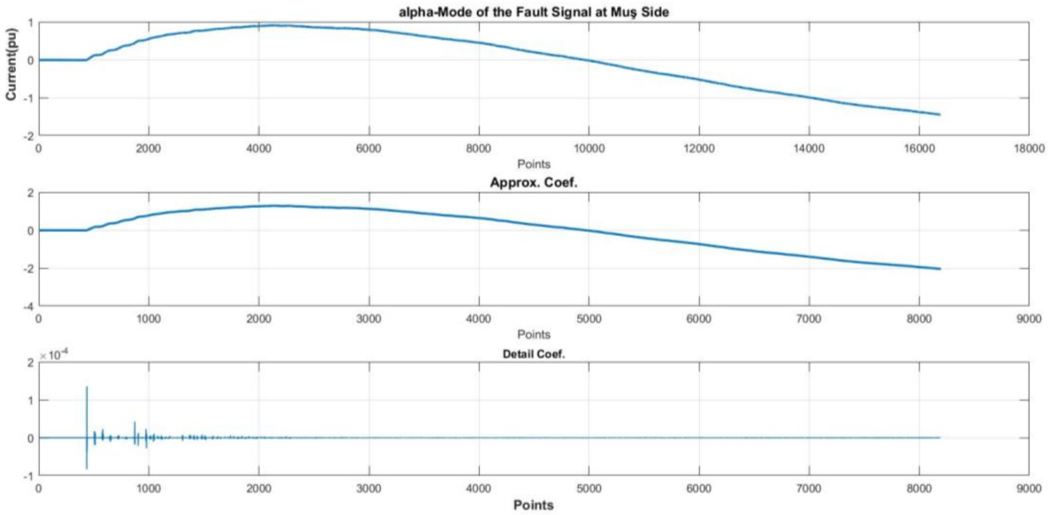


Figure 12. Dwt of the Fault Signal at Muş Side

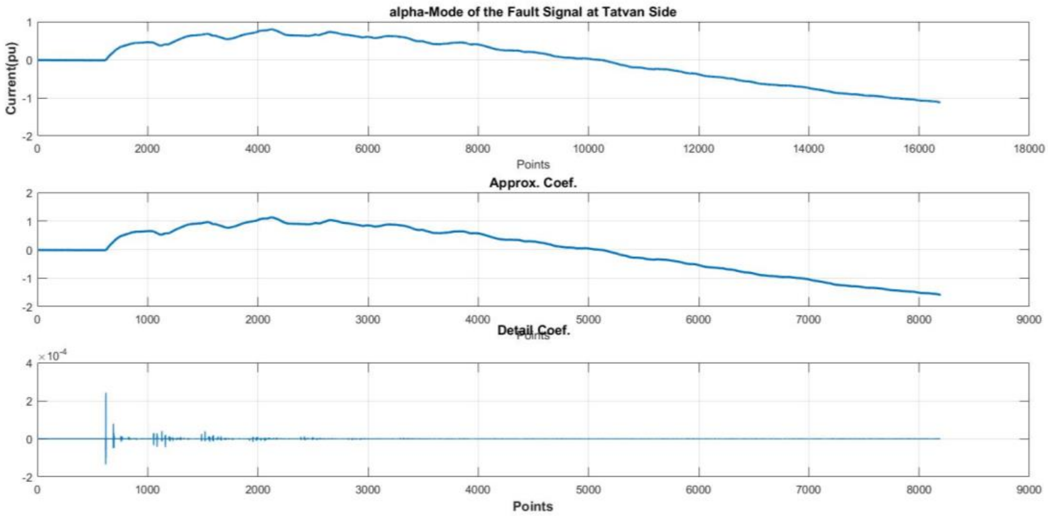


Figure 13. Dwt of the Fault Signal at Tatvan Side

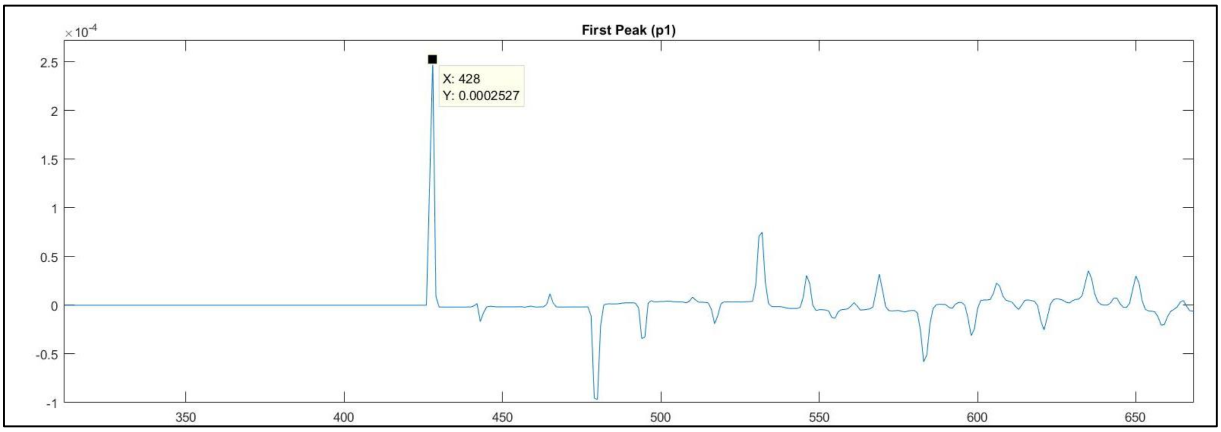
3. Results

3.1. Simulation Results of the Fault in 154 kV Patnos-Erciş Line with Single-End Method

By wavelet transform the difference of arrival times of incident TW and first reflected TW can be obtained. Peaks in Detail Coefficients of first level DWT represent sudden changes in the signal. The difference of sample number of first peak and second opposite polarity peak gives us the time difference of arrival times of incident TW and first reflected TW. The fault location expression with α-mode velocity for downsampled detail coefficients:

$$m = (p_2 - p_1) \cdot \frac{v_\alpha}{f_s} \tag{10}$$

where m is fault location, p_1 is sample number of first peak with highest amplitude, p_2 is sample number of second peak with opposite polarity than p_1, v_α is wave propagation velocity in km/s and f_s is sampling rate in Hz. Figure 14 shows first peaks with sample numbers at each side.



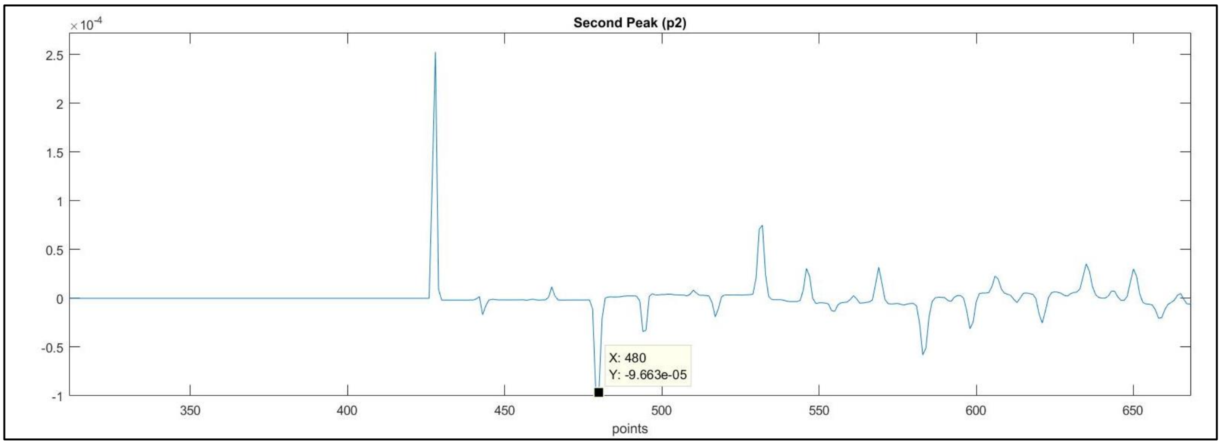


Figure 14. p_1 and p_2 and their sample numbers in detail coefficients

The fault distance can be computed as:

$$m = (p_2 - p_1) \cdot \frac{v_\alpha}{f_s} = (480 - 428) \cdot \frac{289888{,}7059}{2048000} = 7{,}36\ km$$

Since the fault occurred at the tower, the actual location can be obtained by construction list of the line. Actual fault location is 7,31 km from Patnos Substation. The percentage error of the computed location is:

$$\%\ Error_{computed} = \left|\frac{(7{,}36 - 7{,}31)}{46{,}587}\right| \cdot 100 = 0{,}1\%$$

And the percentage error of Distance Relays:

$$\%\ Error_{Relay(Patnos)} = \left|\frac{(7{,}31 - 5{,}38)}{46{,}587}\right| \cdot 100 = 4{,}14\%$$

Maximum error with the Single-End TW Method:

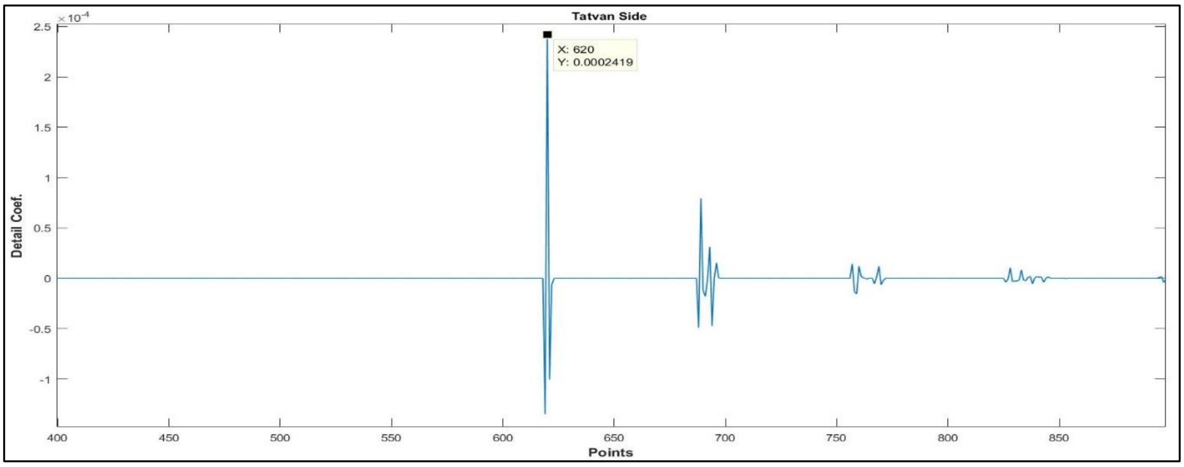
$$\%Error_{max} = \frac{v_\alpha}{2 f_s} \cdot \frac{100}{line\ lenght} \approx 0{,}15\% \Rightarrow 70\ meters$$

3.2. Simulation Results of the Fault in 154 kV Tatvan-Muş Line with Single-End Method

By wavelet transform we can obtain the difference of arrival times of incident TWs. The peaks in Detail Coefficients of first level DWTs represent sudden changes in the signal. The difference of sample numbers of first peaks gives us the difference of arrival times of incident TWs. The fault location expression with α-mode velocity for downsampled detail coefficients:

$$m = \frac{\ell}{2} + (p_L - p_R) \cdot \frac{v_\alpha}{f_s} \quad (11)$$

where ℓ is line length, m is fault location, p_L is sample number of first peak for the L side signal p_R is sample number of first peak for the R side signal v_α is wave propagation velocity in km/s and f_s is sampling rate in Hz. Figure 15 shows first peaks with sample numbers at each side.



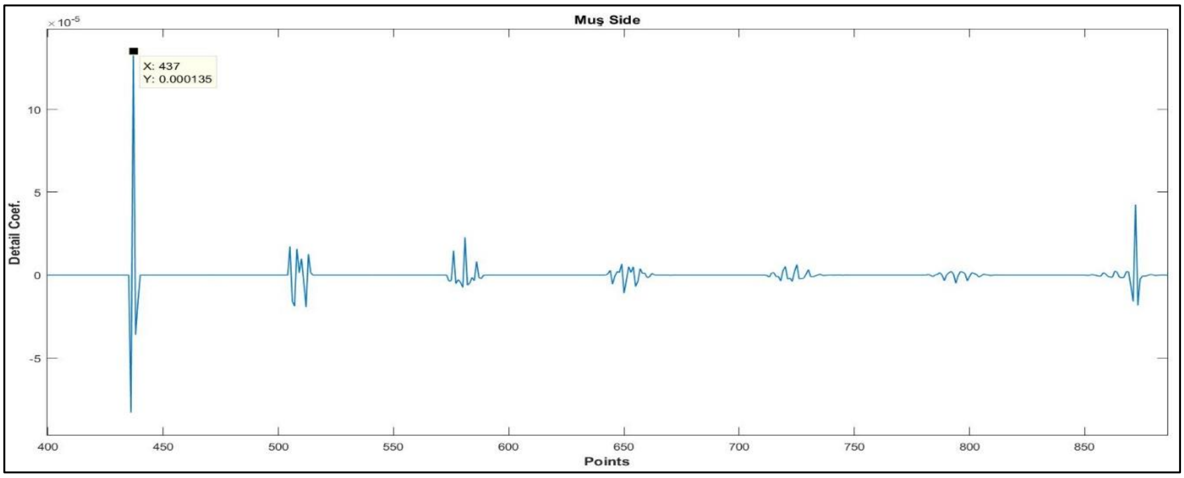


Figure 15. First peaks with sample numbers in detail coefficients

The fault distance can be computed as:

$$m = \frac{\ell}{2} + (p_L - p_R) \cdot \frac{v_\alpha}{f_s} = \frac{71,3357}{2} + (620 - 437) \cdot \frac{289888,7059}{2048000} =$$

61,57 km from Tatvan

and

$$m = \frac{\ell}{2} + (p_L - p_R) \cdot \frac{v_\alpha}{f_s} = \frac{71,3357}{2} + (437 - 620) \cdot \frac{289888,7059}{2048000} =$$

9,76 km from Muş.

Since the fault occurred at the tower, the actual location can be obtained by construction list of the line. Actual fault location is 61,52 km from Tatvan Substation. The percentage error of the computed location is:

$$\%\ Error_{computed} = \left|\frac{(61,57 - 61,52)}{71,3357}\right| \cdot 100 = 0,07\%$$

And the percentage error of Distance Relays:

$$\%\ Error_{Relay(Muş)} = \left|\frac{(10,15 - 9,76)}{71,3357}\right| \cdot 100 = 0,54\%$$

$$\%\ Error_{Relay(Tatvan)} = \left|\frac{(62,65 - 61,52)}{71,3357}\right| \cdot 100 = 1,58\%$$

Maximum error with Double-End TW Method:

$$\%Error_{max} = \frac{v_\alpha}{2f_s} \cdot \frac{100}{line\ lenght} \approx 0,1\% \ \Rightarrow 70\ meters$$

4. Conclusion

The error of distance relay is 1930 meters with the relay located at Patnos Substation, where the error of simulating same fault with Single-End TW Method is 50 meters. Although Patnos-Erciş HV Transmission line is a short line, 46,587 km, the method has significantly better accuracy than the Distance Relay.

The minimum error of distance relays is 390 meters (relay located at Muş Substation), where the error of simulating same fault with Double-End TW Method is 50 meters. Although, the benefits of the method may not be seen with short lines like Tatvan-Muş line, it can be seen that the method has a considerable benefit with long lines over 250 km.

It can be concluded by the work that both TW Fault Location Methods are significantly more accurate than the Impedance Based Method.

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