Electrical Power and Energy Systems 44 (2013) 816–823

Contents lists available at SciVerse ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A new single ended fault location algorithm for combined transmission line considering fault clearing transients without using line parameters

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ARTICLE INFO

Article history:
Received 14 September 2010
Received in revised form 26 July 2012
Accepted 8 August 2012

Keywords:
Fault location
Fault clearing high-frequency transients
Combined lines
Wavelet transform
Wave speed

ABSTRACT

In this paper a new single ended fault location method is proposed for underground cable combined with overhead lines. In this algorithm fault clearing high frequency transients are used instead of fault-generated transients and the line parameters are not needed. In the proposed algorithm, samples just from voltage transients generated by fault clearing action of circuit breaker are taken from the sending end of the cable line. Applying wavelet transform, the first three inceptions of traveling waves to the fault locator are detected. Using these, the proposed algorithm at first identifies fault section, overhead or cable, and then wave speed is calculated and at last location of fault is determined accurately. Because of using only voltage samples taken from one terminal, it is simple and economic and does not need to GPS and data communication and synchronization. Extensive simulations carried out using SimPowerSystem toolbox of MATLAB, confirm the capabilities and high accuracy of the proposed method under different system and fault conditions.

1. Introduction

Use of cable lines and combined overhead transmission lines with underground power cable are expanding due to safety considerations and enhanced reliability in the distribution and transmission systems [1,2]. Precise fault locating reduces time and costs related to the dispatched crews searching to find the fault location. Providing customers and feeding the consumers with minimal interruption improve the performance of the power system and identifies weak and vulnerable points [3,4]. In addition, accurate fault location improves the availability and reliability of the system [5]. Existing fault location methods, which are used to find location of fault in the overhead lines and underground cables, can be classified into two general categories [6]: impedance-based methods [7–9] and traveling waves-based methods [10–16].

Use of traveling waves-based algorithm is developed because they are more precise compare to impedance-based algorithms and are not influenced by source impedance, fault resistance and power flow [11]. In the majority of traveling waves methods, fault generated high frequency transients are utilized to determine fault location. Theses algorithms, despite the mentioned advantages, are sensitive to noises and faults occurred on the other lines, fault inception angle, reflected waves from other terminals and equipments, which are outside from the relay and fault point [12]. In addition, these methods suffer from faults occurred close to the relay [13]. So, Refs. [12–15] propose utilizing high frequency fault-clearing transients instead of the fault-generated transients to use advantages of the traveling wave methods whilst avoid their problems.

Locating fault point in the combined transmission line due to different wave speeds and different impedance sequences of positive and zero in overhead and cable sections is subject to complexity. Ref. [1] offers a fault location algorithm for locating single phase to ground faults in combined transmission lines using Neuro-Fuzzy approach. In [16] a traveling wave based method, which uses samples from high frequency fault generated voltage transients in two terminals, is introduced. This method is based on the wavelet analysis and is independent of the wave speed. In [17] an algorithm for fault location in combined transmission lines is proposed that uses adaptive network-based fuzzy inference system and samples of voltage and current.

Traveling wave based fault location algorithms for combined transmission lines, which use data sampled only from one terminal, need cable and overhead line parameters. The cable parameters and so, wave speed in cable changes over time, climate and humidity variations [16], therefore, algorithms based on utilizing line and cable parameters will have computational error.

In this paper, a novel single-ended fault location algorithm for combined transmission lines is proposed. The proposed algorithm uses transients caused by opening of circuit breaker instead of using transients generated by fault. In addition, it does not utilize the overhead line and the cable parameters. Suggested algorithm in compare to the double-ended algorithms has the advantage that

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http://dx.doi.org/10.1016/j.ijepes.2012.08.007

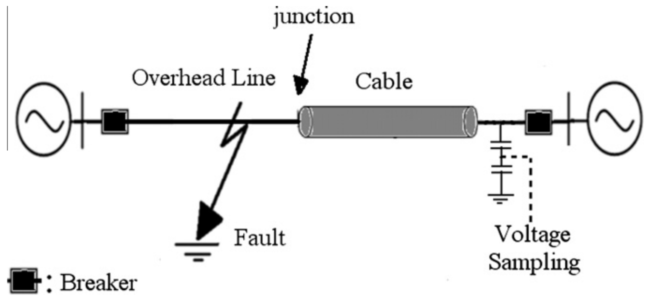

Fig. 1. View of combined line with three-phase to ground fault in the overhead line section.

does not need to communication equipments, Global Positioning System (GPS) and synchronization of data. Because of using fault-clearing transients instead of the fault-generated transients, the common problems of the traveling wave methods are removed. In addition, because of using only voltage samples, it has less instrumental error compare to the algorithms, which use both voltage and current samples.

In the proposed algorithm, using modal transform, three-phase voltages are transformed into a ground and two aerial modes. Then utilizing wavelet transform the first, second and third inceptions of voltage traveling wave to the fault locator are detected and then by comparing the polarities of the inception and incident waves, fault section is identified. After fault section identification, actual speed of traveling wave in the cable and overhead line sections are calculated without using their parameters. Finally, using arrival times of traveling waves the location of fault is calculated accurately. The algorithm is capable to determine the location of fault for different fault types, single-phase, double-phase and three-phase to ground faults and double-phase and three-phase together faults. It should be noted that the accuracy of the proposed algorithm is not sensitive to the fault resistance, the fault inception angle, the fault type, the distance of the fault from the fault locator and the section of fault, cable section or overhead section. In spite of using single terminal data, the accuracy of proposed method is comparable to the double-ended traveling wave-based methods.

2. Proposed fault location algorithm for combined lines

Fig. 1 illustrates a schematic view of an overhead line combined with a power cable in which a three-phase fault occurred on the overhead section. In the following subsections, the proposed method is explained based on this figure.

2.1. Modal transform

Every sudden change such as fault occurrence on the power system generates current and voltage traveling waves, which propagate away from the fault point in both directions over the transmission line to arrive discontinuity points such as terminals and junctions. In these points, a part of the wave is let through and a part of the wave is reflected and travels back. This phenomenon continues to wave attenuate and damp. The voltage and current waves in the distance of x, for the time of t in the lossless line can be expressed in two forward and backward waves [18]:

$$u(x,t) = F_1(x - vt) + F_2(x + vt) \tag{1}$$

$$i(x,t) = \frac{1}{Z_0}[F_1(x - vt) - F_2(x + vt)] \tag{2}$$

where Z_0 and v are characteristic impedance and wave speed, respectively and F_1 and F_2 are forward and backward waves.

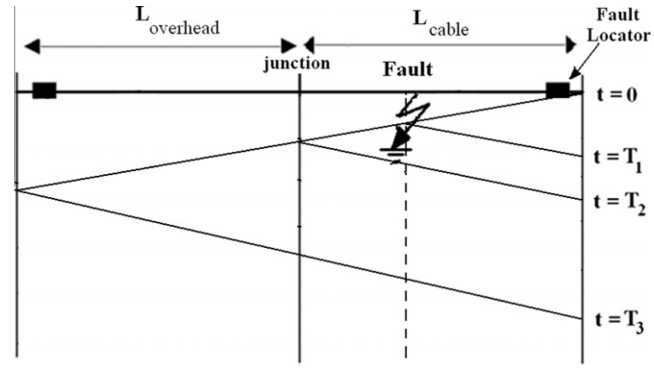

Fig. 2. Lattice diagram for fault occurred in the cable section.

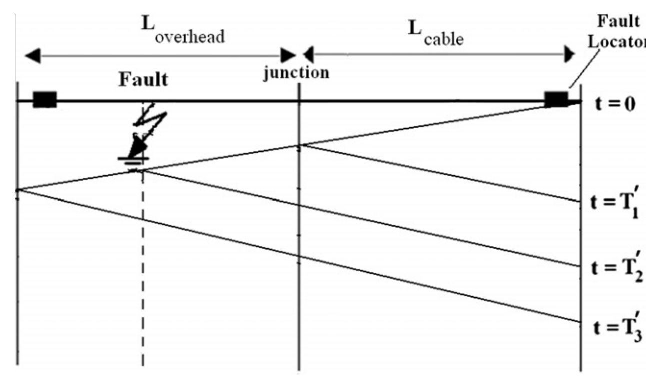

Fig. 3. Lattice diagram for fault occurred in the overhead line section.

Three-phase lines have significant electromagnetic coupling between conductors. By means of modal decomposition, the coupled voltages and currents are decomposed into a new set of modal voltages and currents, which each can be treated independently in a similar manner to the single-phase line. The relation between modal components and phase components of the voltage and current signals are as below:

$$U_m = T^{-1} \times U_p \tag{3}$$

$$I_m = T^{-1} \times I_p \tag{4}$$

where U and I are the voltages and currents and m and p subscripts are related to the modal and phase quantities, respectively, and T is the transformation matrix. For three-phase fully transposed line assumed in this paper, the Clarke's transformation matrix can be used to obtain the ground and aerial mode signals from the three-phase transients [15]:

$$\begin{bmatrix} U_0 \\ U_\alpha \\ U_\beta \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ \sqrt{2} & -1/\sqrt{2} & -1/\sqrt{2} \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \tag{5}$$

where U_0 is the ground mode voltage component, and U_α and U_β are known as the aerial mode voltage components for transposed lines. After transforming the phase voltages to modal components, it is possible to detect the first, second and third inceptions of voltage traveling waves to fault locator point using wavelet transform. In this paper db4 wavelet is used for this purpose [19]. In wavelet decomposition, original signal is decomposed into two approximation and detail, and each part can be decomposed into two others with more resolution. In this paper, details of first decomposition

Table 1
Fault section identification algorithm.

Fault section	Polarities of incident wave and first incepted wave to the fault locator	Polarities of incident wave and second incepted wave to the fault locator
Cable	Reverse	Same
Overhead	Same	Reverse

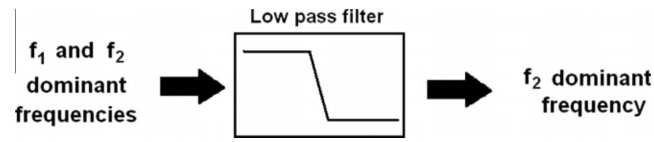

Fig. 5. Proposed filter for extracting f_2.

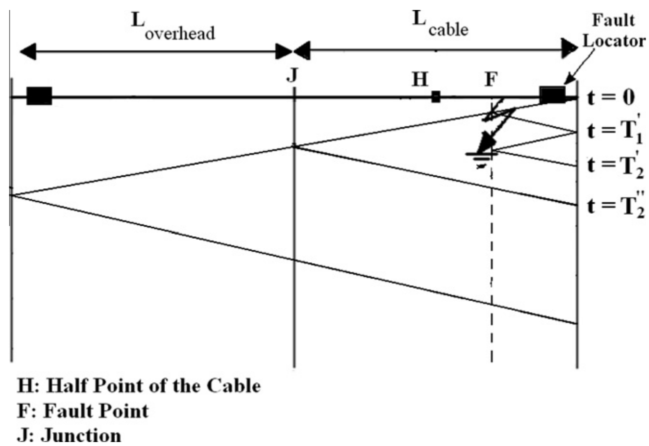

Fig. 4. Lattice diagram of the fault occurred in the first half of the cable.

are used. Therefore, using db4 wavelet, the alpha mode of the voltage signal is transformed and utilizing details of the first decomposition, the first, second and third inceptions of the traveling wave to the fault locator are detected.

2.2. Fault section identification (cable or overhead)

In a combined transmission line fault can be occurred in either the overhead line or cable sections of transmission line. In each case, the wave propagates with different speed and consequently different reflection times will be detected. Figs. 2 and 3 show the lattice diagrams for the faults occurred in cable and overhead line section cases, respectively.

Either fault is occurred on the overhead line or on the cable section, by measuring the inception time of voltage traveling waves to relay point, location of fault can be calculated. The main problem is identification of that the first incepted wave is reflected from fault point or from junction (junction is the point which the overhead line and the cable are combined together). To distinguish between two mentioned cases, it is essential to identify the polarity of the incepted waves in addition to their inception times. Consider the fault is occurred in the cable section; therefore, reflection coefficient in the fault point and in the junction can be obtained by:

$$\rho_{reflection1} = \frac{(R_f||Z_C) - Z_C}{(R_f||Z_C) + Z_C} \quad (6)$$

$$\rho_{reflection2} = \frac{Z_O - Z_C}{Z_O + Z_C} \quad (7)$$

where Z_c, Z_o and R_f are the cable and overhead line characteristic impedances, and fault resistance respectively. Moreover, the refraction coefficient in the fault point can be calculated as:

$$\rho_{refraction1} = \frac{2(R_f||Z_C)}{(R_f||Z_C) + Z_C} = \rho_{reflection1} + 1 \quad (8)$$

In this case the first inception wave is reflected from fault point, and because the $(R_f||Z_c)$ is smaller than Z_c therefore from Eqs. (6) and (8), it is clear that reflection coefficient from fault point is negative and refraction coefficient in the junction is positive. The part of wave, which refracts over the fault point and arrives to the junction, will reflect by positive coefficient on the junction. Because Z_c is smaller than Z_o therefore, according to Eq. (7), the reflection coefficient from the junction will be positive. The reflected wave from junction arrives to the fault point again and propagates with positive refraction coefficient to the fault locator, because the magnitude of the R_f parallel to Z_c is positive therefore, from Eq. (8) it is clear that refraction coefficient in the fault point will be positive. Therefore, it can be concluded that for faults occurred in the cable section, first and second reflections have reverse and same polarity as incident wave, respectively.

If the fault occurs in the overhead section, the first wave inception to the fault locator corresponds to the wave which is reflected from the junction. Since Z_c is smaller than Z_o, therefore considering Eq. (7) it is clear that a part of the wave will be reflected with positive coefficient and another part will be refracted over the junction and will propagate toward fault point. The refraction coefficient in junction can be obtained by:

$$\rho_{refraction2} = \frac{2Z_O}{Z_O + Z_C} \quad (9)$$

Since Z_O is positive, from Eq. (9) it is clear that refraction coefficient in junction is positive. Refracted wave propagates to arrive fault point in overhead line section and at fault point it will be reflected. Reflection coefficient at fault point in overhead line is obtained by:

$$\rho_{reflection3} = \frac{(R_f||Z_C) - Z_O}{(R_f||Z_C) + Z_O} \quad (10)$$

The reflected wave or in other words, backward wave reaches to the junction and some part of it penetrates with positive coefficient, which is obtained by the following equation:

$$\rho_{refraction3} = \frac{2Z_C}{Z_C + Z_O} \quad (11)$$

Therefore, it can be concluded that for faults occurred in overhead line section, first and second reflections have same and reverse polarity as incident wave, respectively.

After operating the circuit breaker, voltage transient signals will be generated which travel along the line toward fault point and junction. If the fault is occurred on the cable section, traveling wave will arrive to the fault point at first and after that it arrives to the junction. Contrary, if the fault is occurred on the overhead section, traveling wave will arrive to the junction at first and after that it arrives to the fault point. In both cases, using the polarity of the first and second waves arrived to the fault locator, which are reflected from fault point, it would be possible to identify the fault section. As expressed in Eqs. (6)–(11), the polarity of the reflected waves in compare to the incident wave can be determined for both faults occurred on the cable section and on the overhead line, after that with a simple comparison between these polarities, fault section can be identified readily as follows:

- If polarity of the first incepted traveling wave to the fault locator is opposite to the polarity of the incident wave, and polarity of the second arrival wave is the same as incident one, it is identified that the fault is in the cable section.

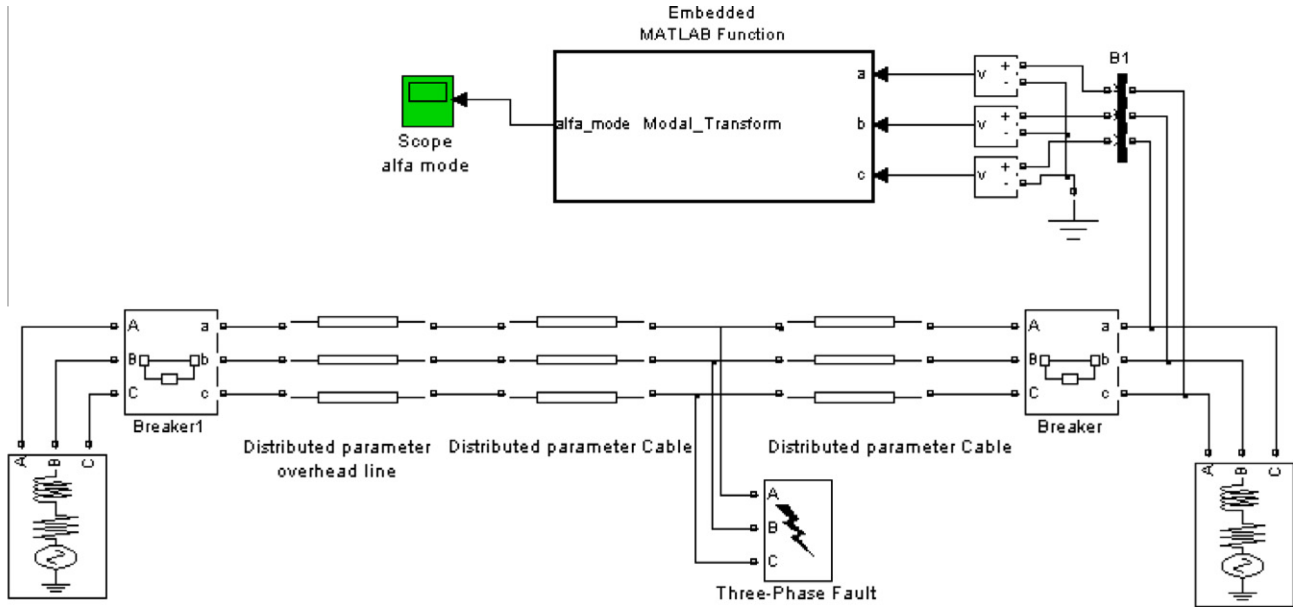

Fig. 6. Schematic diagram of the simulated system in the MATLAB software for three-phase to ground fault in the cable section.

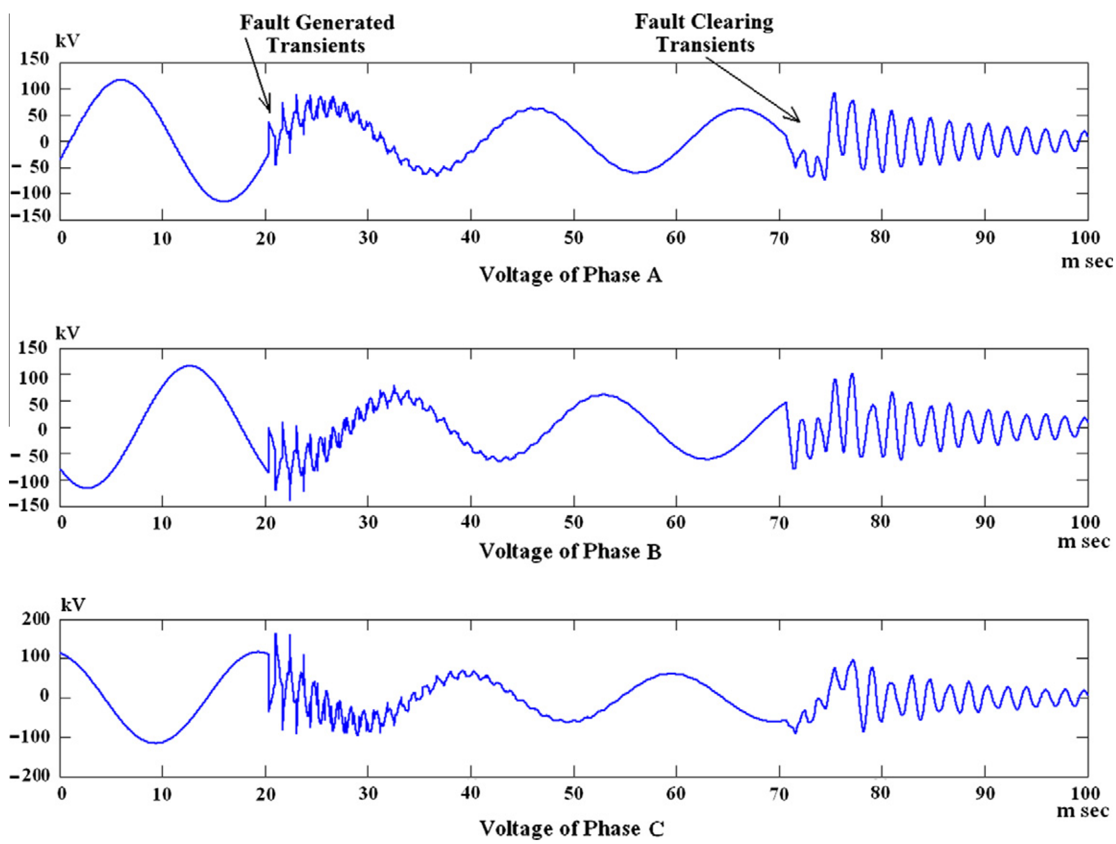

Fig. 7. Three phase voltages for double-phase fault occurred at distance 23 km in the cable section.

- Else, if the first incepted wave to the fault locator has polarity the same as incident wave, and the second one has opposite polarity, the overhead line is identified as fault section.

The proposed algorithm for fault section identification is described briefly as indicated in Table 1.

2.3. Accurate calculation of wave speed in cable section and overhead line

As mentioned previously, using db4 wavelet transform, alpha mode of the voltage signal is analyzed and utilizing details of the first level of the decomposition, the first, second and third incep-

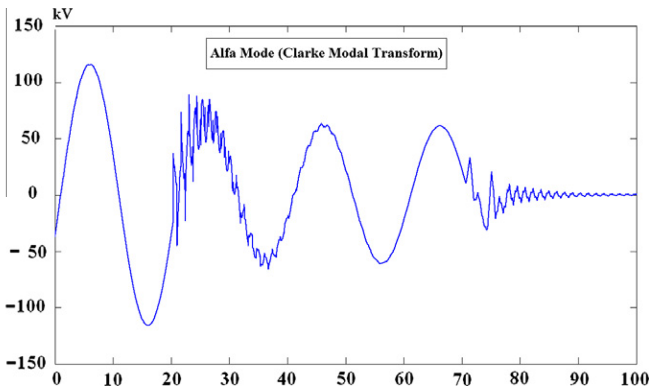

Fig. 8. Alpha mode of voltage signal in modal transform for double-phase fault at distance 23 km in the cable section.

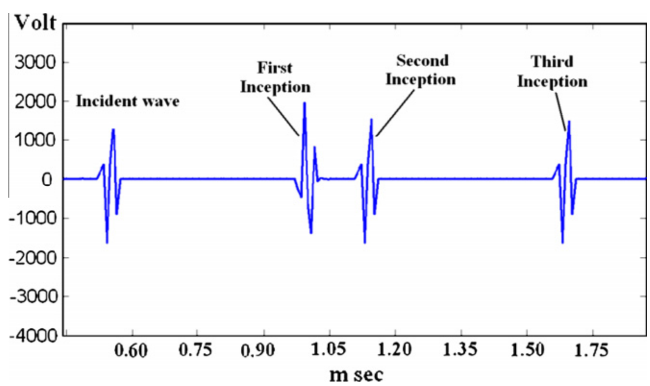

Fig. 9. Detail level of the voltage signal in the wavelet transform for double-phase fault occurred in the cable section.

tions of the traveling waves to the fault locator, after opening the circuit breaker, are detected. Either fault has occurred in the cable section or in the overhead line, the third wave arrived to the fault locator is the wave, which has reached to the far end and reflected backward. If the fault is occurred in the cable section, the first inception of the traveling wave is a wave which is reflected from the fault point and the second one is the reflection from the junction. Moreover, for the fault occurred in the overhead line the first and the second waves are reflected from the junction and the fault point, respectively. The elapsed time for the wave to travel from fault locator to the junction is assumed to be τ_1, and similarly elapsed time for the wave to travel from fault locator to the far end of the line assumed to be τ_2, therefore wave speed in the cable section and the overhead line can be calculated from the following equations:

$$v_C = \frac{L_{Cable}}{\tau_1} \tag{12}$$

$$v_O = \frac{L_{Overhead}}{\tau_2 - \tau_1} \tag{13}$$

where v_c and v_o are the wave speeds in cable and overhead sections, respectively and L_{Cable} and $L_{Overhead}$ are cable and overhead transmission line lengths. It is clear from Eqs. (12) and (13) that in the process of the calculation of the actual (real-time) speed of the wave in the lines, there is no need to the parameters of the overhead and cable lines. Therefore, it is obvious that any changes in the line parameters caused by aging, thermal variations, humidity changes, etc. do not affect the accuracy of the algorithm because the wave speeds are calculated independent of the line parameters.

2.4. Fault location calculation

Once the fault section is identified using the polarity of the inception waves to the fault locator, it is possible to calculate accurate fault location using wave speeds obtained by Eqs. (12) and (13) and the inception times of traveling waves to the fault locator. This step is divided into two states: the first state relates to fault locating for faults occurred in the cable section and the second state is related to faults occurred in the overhead transmission line section.

2.4.1. Fault location in cable section

For faults occurred in the second half of the cable section, considering Fig. 2 and using wave speed obtained by Eq. (12), fault location is calculated by the following formula:

$$x = v_C \times \frac{T_1}{2} \tag{14}$$

where T_1 is the elapsed time for wave to travel from breaker to the fault point in cable section and reflect to the breaker point again, and x is fault distance from fault locator.

For faults occurred in the first half of the cable, the analysis is different and more complicated. Fig. 4 shows lattice diagram for fault occurred in the first half of the cable. The fault point, the junction and the middle point of the cable are illustrated with points F, J and H, respectively. For fault in the first half of the cable, the first inception of traveling wave to the fault locator is related to reflection from point F. In this case, the second inception is not related to reflection from junction, but it is reflection from point F, again. Therefore, T_1'', inception time of second wave is exactly twice the first inception time T_1'. By this, it can be identified easily that fault is occurred in the first half of the cable.

It is clear from Fig. 4 that the distance between fault locator and point J is at least twice of the distance between fault locator and point F. Required time for wave to reach to the point J is at least twice of required time to reach to the point F. Therefore, the frequency of wave reflected from point F illustrated by f_1 will be at least twice of the frequency of wave reflected from point J illustrated by f_2. Using a low pass filter, it is possible to eliminate consecutive reflections from point F with frequency of f_1, and then the existent dominant frequency merely will be f_2 and simply time of reflection from point J, $T_2''$is detected. Now wave propagation speed can be calculated. For the fault occurred exactly in the middle point of the cable, algorithm is similar to faults occurred in the first half of the cable. Fig. 5 shows proposed filtering system.

2.4.2. Fault location in overhead line section

For faults occurred in the overhead line section, referring to Fig. 3 and using wave speed obtained by Eq. (13) fault location can be calculated as follows:

$$x = L_{Cable} + \left(v_O \times \frac{T_2' - T_1'}{2} \right) \tag{15}$$

where $T_2'$is elapsed time for traveling wave to go from breaker to junction and come back, and T_1' is elapsed time for wave to travel from breaker to fault point in overhead line section and reflect to breaker point again.

Computational error for calculated distance as fault location can be obtained by the following relation [20]:

$$\%\text{error} = \frac{\text{Calculated Fault Location} - \text{Actual Fault Location}}{\text{Total Fault Section Length}} \tag{16}$$

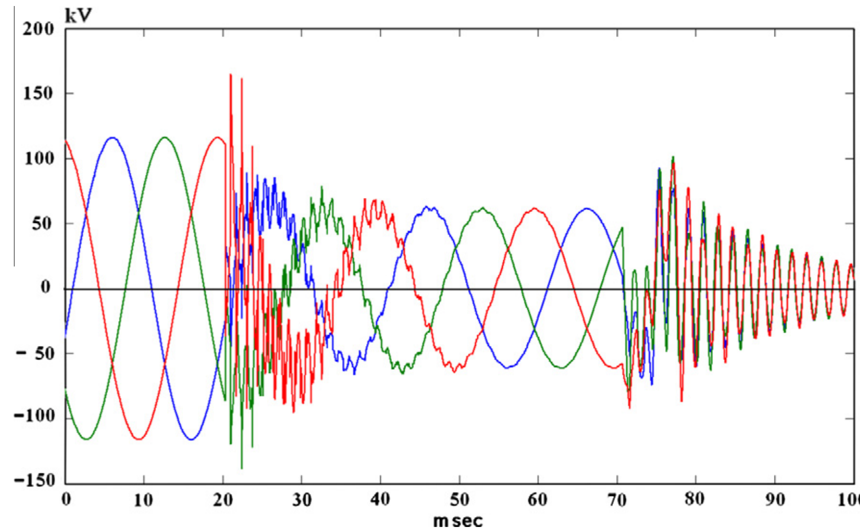

Fig. 10. Three phase voltages for single phase to ground fault occurred at 74 km distance in the overhead line.

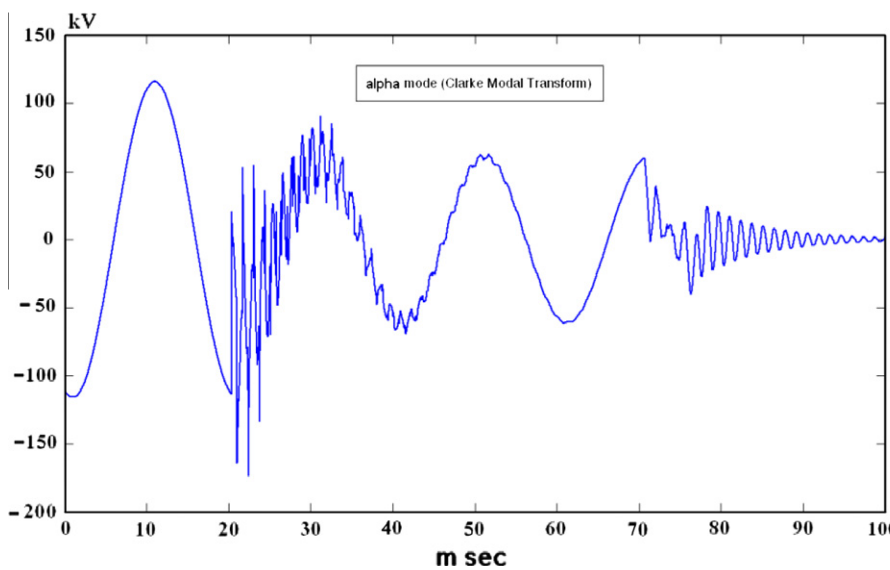

Fig. 11. Alpha mode signal for single phase to ground fault occurred at 74 km distance in the overhead line section.

3. Evaluation of the proposed algorithm

To evaluate the performance and capability of the proposed algorithm, extensive simulations have been performed. For this purpose a 132 kV three-phase system, which includes overhead transmission line in combination with power cable as shown in Fig. 1, is simulated by the SimPowerSystems toolbox, which is one of the powerful and useful toolboxes of MATLAB software. In this study, the overhead line length used in simulations is 80 km and cable section is 30 km long, which their characteristics are presented in Table A of Appendix.

Fig. 6 shows schematic diagram of the study system in the MATLAB software. A variety of simulations have been performed for single-phase, double-phase and three-phase to ground faults as well as for double-phase and three-phase faults. Fault resistances considered between 0 and 100 Ω and different cases for fault inception angles between 0° and 90° are applied. The voltage source and lines parameters are provided in Appendix.

As an example, if a double-phase fault is occurred at distance 23 km away from the fault locator in the cable section with 34°

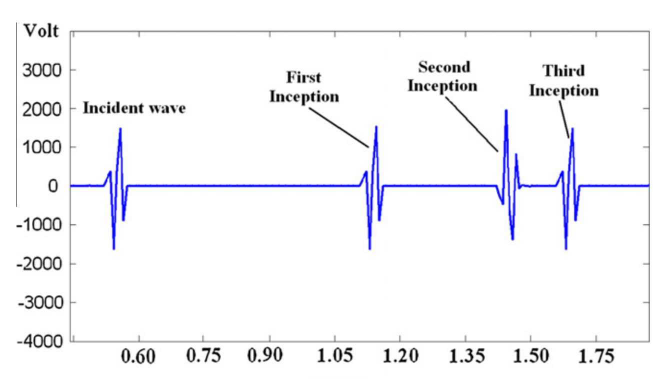

Fig. 12. Detail level of the voltage signal in the wavelet transform for single phase fault occurred in the overhead line.

inception angle, three phase voltages are shown in Fig. 7 and applying modal transformation, alpha mode signal is shown in

Fig. 8. Fig. 9 shows the detail level in wavelet decomposition of mentioned alpha mode voltage signal. It is clear from Fig. 9 that the first wave arrived to the fault locator has polarity reverse to incident wave and second one has the same polarity as incident wave. Therefore, using Table 1, fault is identified in cable section. If $t = 0$ assumed the time which incident wave is generated, therefore first, second and third waves are detected in 404, 658 and 1193 µs, respectively. Then using Eq. (12) wave speed is calculated 91,185.410 km/s and using Eq. (14) fault location is determined in 23.047 km, which has% 0.156 error.

As another example, if a single phase to ground fault occurs at distance 74 km in the overhead line section, with 67 Ω fault resistance and fault inception angle of 12°, three phase voltages are shown in Fig. 10 and alpha mode signal is depicted in Fig. 11, also wavelet transform of the alpha mode signal is shown in Fig. 12. It is obvious from Fig. 12 that the polarity of first reflected wave is the same as incident wave one and the second one has reverse polarity. Using Table 1, it is clear that fault is occurred in the overhead section and so, fault section is identified correctly. With respect to time of first, second and third arrivals of traveling waves that are measured as 650, 952 and 1193 µs, using Eqs. (12) and (13) wave speeds in the cable and overhead line will be 91,185.410 and 294,659.323 km/s and using Eq. (15) fault location is calculated 73.986 km that has% −0.0175 error.

In the following sections, influence of different parameters such as fault resistance, fault inception angle, fault type, fault distance and fault section on the accuracy of the proposed algorithm is analyzed.

3.1. Effect of fault resistance

About 80% of the transmission line faults are single phase to ground fault [21] which one of the conductors is short circuited to the ground without or via a fault resistance. Majority of the fault location algorithms are influenced by the fault resistance, therefore it is essential to study the effect of fault resistance on the accuracy of the proposed algorithm. To evaluate the influence of the fault resistance, simulation results for single and double-phase to ground faults occurred in overhead line with different fault resistances are presented in Table 2.

Based on the results presented in Table 2, it is clear that the fault resistance does not have undesirable effect on the accuracy of the proposed algorithm.

3.2. Effect of fault inception angle

Many traveling wave-based fault location algorithms suffer from the fault inception angle [22]. To evaluate the influence of the fault inception angle on the accuracy of the proposed algorithm, simulations for double-phase and three-phase faults that are occurred in 5 km distance from fault locator in cable section with different fault inception angles are carried out and the obtained results are shown in Table 3.

From Table 3, it is clear that the inception angle of the fault has no significant effect on the accuracy of the algorithm and the accuracy is not influenced by the variations of the fault inception angle.

Table 2
Results for single and double-phase to ground faults at 75 km on the overhead line with different fault resistances.

Fault type	Fault resistance (Ω)	Calculated distance	Error (%)
Single-phase to ground	0	74.941	−0.074
	40	75.161	0.201
	80	75.037	0.046
Double-phase to ground	0	75.108	0.135
	40	74.899	−0.126
	80	75.173	0.216

Table 3
Results for fault occurred in 5 km on the cable section with different fault inception angles.

Fault type	Fault inception angle (°)	Calculated distance	Error (%)
Double-phase fault	0	5.014	0.047
	30	5.056	0.186
	60	4.959	−0.137
	90	5.028	0.094
Three-phase fault	0	5.073	0.243
	30	5.061	0.203
	60	4.973	−0.090
	90	5.045	0.150

Table 4
Effect of fault type on the accuracy of the proposed method for faults on the overhead line.

Fault type	Actual fault distance	Calculated distance	Error (%)
Single-phase to ground	2.34	2.367	0.090
	17.95	17893	−0.190
	29	29.012	0.040
Double-phase to ground	2.34	2.416	0.250
	17.95	17.912	−0.126
	29	29.021	0.070
Three-phase to ground	2.34	2.393	0.176
	17.95	17.978	0.094
	29	29.066	0.220

3.3. Effect of fault type

The proposed algorithm in this paper is capable to find the location of the various types of the faults occurred in the overhead line and cable section. To understand the effect of the fault type on the accuracy of the method, simulation results for single, double- and three-phase to ground faults that are occurred on the overhead section with 34° fault inception angle and 63 Ω fault resistance are presented in Table 4.

In addition, results for double- and three-phase faults with zero fault inception angle and 1 Ω fault resistance occurred in the cable section are presented in Table 5.

Presented results in Tables 4 and 5 confirm that the accuracy of the proposed algorithm is similar for different types of the faults occurred on the transmission line.

Table 5
Effect of fault type on the accuracy of the proposed method for faults on the cable section.

Fault type	Actual fault distance	Calculated distance	Error (%)
Single-phase fault	3	2.933	−0.223
	8.75	8.761	0.037
	28.5	28.531	0.1033
Double-phase fault	3	2.973	−0.090
	8.75	8.773	0.077
	28.5	28.488	−0.040
Three-phase fault	3	3.011	0.036
	8.75	8.769	0.063
	28.5	28.472	−0.093

Table 6
Result for faults in different distances in overhead line with zero fault inception angle and 100 Ω fault resistance.

Fault type	Actual fault distance	Calculated distance	Error (%)
Single-phase to ground	32.47	32.495	0.031
	85	85.098	0.122
	108	108.066	0.083
Double-phase to ground	32.47	32.397	−0.091
	85	84.966	−0.042
	108	108.123	0.153
Three-phase to ground	32.47	32.785	0.039
	85	85.102	0.127
	108	108.114	0.142

Table 7
Result for faults in different distances in cable with 10° fault inception angle and 3 Ω fault resistance.

Fault type	Actual fault distance	Calculated distance	Error (%)
Single-phase to ground	2.34	2.393	0.176
	17.95	17.912	−0.126
	29	29.021	0.070
Double-phase to ground	2.34	2.397	0.190
	17.95	17.966	0.053
	29	28.973	−0.090
Three-phase to ground	2.34	2.333	0.023
	17.95	17.966	0.053
	29	28.978	−0.073

3.4. Effect of fault distance and fault section

To investigate the effect of fault distance and fault section on the accuracy of proposed method, results for single-, double- and three-phase to ground faults occurred in different distances on the overhead line with zero fault inception angle and 100 Ω fault resistance are shown in Table 6. Moreover, results for single-, double- and three-phase to ground faults occurred in different distances on the cable section are presented in Table 7.

From above tables, it is clear that the accuracy of the algorithm for faults occurred in different distances and different sections is similar and has no obvious variations.

4. Conclusion

In this paper, a new single-ended method for determination of fault section and fault location in the combined lines (overhead/cable) is presented. In the proposed method unlike all single-ended traveling waves-based algorithms, the line parameters are not used and the fault-clearing transients instead of fault-generated transients are utilized. So, the effect of phase inception angle on the accuracy of traveling wave-based algorithms is mitigated. In addition, the accuracy of the proposed algorithm is not influenced by reflected waves from other terminals. Extensive simulations performed by MATLAB software, shows that it has nearly similar accuracy to the double-ended methods. Also, the accuracy of the proposed method is insensitive to the fault type, fault resistance, fault inception angle and fault location. Since the wave speed is calculated independent of the line parameters, accuracy of the algorithm does not change with aging, climate and humidity variations. The accuracy of proposed algorithm is very high in almost all conditions and the error is kept below 0.3%.

Appendix A

See Tables A and B.

Table A
Overhead and cable line parameters.

Line section	Parameter	Positive and negative sequences	Zero sequence
Overhead line	R (Ω/km)	0.3317	0.4817
	L (mH/km)	1.326	4.595
	C (μF/km)	0.008688	0.00476
Cable line	R (Ω/km)	0.024	0.412
	L (mH/km)	0.4278	1.5338
	C (μF/km)	0.2811	0.1529

Table B
Voltage source parameters.

Voltage (kV)	Short circuit capacity (MVA)	Inductance (H)		Resistance (Ω)	
		Zero sequence	Positive and negative sequences	Zero sequence	Positive and negative sequences
132	250/500	0.48	0.35	20.73	13.96

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