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Wavelet-Based One-Terminal Fault Location Algorithm for Aged Cables without Using Cable Parameters Applying Fault Clearing Voltage Transients

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***Abstract*-- This paper presents a novel fault location algorithm, which in spite of using only voltage samples taken from one terminal, is capable to calculate precise fault location in aged power cables without any need to line parameters. Voltage transients generated after circuit breaker opening action are sampled and using wavelet and traveling wave theorem, first and second inceptions of voltage traveling wave signals are detected. Then wave speed is determined independent of cable parameters and finally precise location of fault is calculated. Because of using one terminal data, algorithm does not need to communication equipments and global positioning system (GPS). Accuracy of algorithm is not affected by aging, climate and temperature variations, which change the wave speed. In addition, fault resistance, fault inception angle and fault distance does not affect accuracy of algorithm. Extent simulations carried out with SimPowerSystem toolbox of MATLAB software, confirm capability and high accuracy of proposed algorithm to calculate fault location in the different faults and system conditions.**

***Index Terms*— cable, fault clearing transients, fault location, wave speed, wavelet transform**

I. Introduction

POWER cables are vital part of transmission and distribution lines, which are used extensively in order to increase system reliability [1]. Power cables utilization with the sake of security considerations is developing [2].

Precise fault location reduces the costs related to excavation crews dispatched to find fault location and provides customers and consumers feeding with minimal interruption, also improves the performance of the power system and diagnoses vulnerable points of system [1], [3]. Fault location methods, which are used in the transmission lines, are divided into two general categories [4], [5]: first group is related to methods, which use fundamental component of voltage and current in order to calculate impedance from the fault locator to the fault point and calculate fault location. The mentioned methods are well known as impedance methods [5], [6]. Second category is related to the algorithms, which utilize traveling wave theorem and analyze high frequency voltage and/or current traveling waves generated by fault occurrence [7]-[9].

Fault location methods based on traveling wave theorem are expanding because the determination of fault location is not affected by fault resistance, load flow and source impedance, in addition, these methods have more accuracy compared to the impedance methods [9]. Most of the traveling wave methods, which are currently used for fault location, utilize fault generated high frequency signals. These algorithms are sensitive to the noises and to the faults occurred in the adjacent lines, the fault inception angle and the traveling waves reflected from other terminals and equipments, which are outside of the distance between the fault locator and the fault point [10]. In order to eliminate the mentioned problems, it is suggested to utilize fault-clearing transients instead of fault-generated transients [10]-[13].

Because the propagation speed of the traveling wave in the cables is changed with time, aging, climate and change of the cable parameters, traveling wave-based fault location algorithms in the power cable have problems. Especially accuracy of the methods, which use only one-terminal data, is strongly dependent to the cable parameters. For example, algorithm proposed in [9], which uses only voltage samples taken from one terminal, is dependent to the wave propagation speed and similarly the accuracy of the proposed algorithm in [14] that utilizes current samples taken from one terminal is dependent to wave speed. The proposed methods in [15], [16] are independent to the line parameters but they use voltage samples and current samples that are taken from the two ends of line. Impedance-traveling wave assembled algorithm presented in the [17] calculates fault location without using wave speed, but this method uses both voltage and current samples which are taken from the one bus.

In this paper, a novel approach is proposed to find the fault location in the aged power cables, which utilizes only high frequency voltage transients, sampled from one terminal and does not need to the cable parameters. Therefore, proposed single-ended method does not need to the communication equipments, global positioning system (GPS) and the data synchronization. Proposed algorithm utilizes fault clearing high frequency transients instead of fault generated transient signals to eliminate mentioned problems of common traveling wave fault location algorithms. In this paper, three-phase components are converted to the two aerial mode and one ground mode signal using modal transform, then using wavelet transform, first and second inceptions of voltage traveling wave signals after circuit breaker opening action are detected. Thereupon, the actual wave speed of the voltage signal is calculated without any need to the cable parameters and then

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the fault location is calculated accurately. Proposed algorithm just requires the cable length to be known and has the capability to locate different single, double and three phase to ground faults as well as double and three phase faults accurately. By the way, algorithm assumes that the lines are fully transposed and uses the distributed cable model. In addition, the accuracy of the algorithm is not sensitive to the fault resistance, fault inception angle, fault location and fault type and also the proposed algorithm has the capability of calculating faults occurred close to fault locator.

II. Fault Clearing Transients

Any sudden change in the power system such as fault occurrence generates voltage and current traveling waves, which propagate in two directions from the fault point over the line. Mentioned signals propagate to receive the discontinuity points such as buses, on these points some part of the wave is let through and reminder is reflected, and travels back and this condition is continued to attenuate the wave [12]. Sudden change may be caused by fault clearing action of the circuit breaker, which generates voltage-traveling signals that propagate from circuit breaker to the fault point and remote terminal. In order to distinguish between fault generated transients and fault clearing transients, Fig. 1 illustrates mentioned signals for the fault occurred in the time t = 20 ms and cleared at t = 70 ms. In addition, Fig. 2 illustrates the lattice diagram of the fault clearing signals with the reflected and refracted signals from the fault point and remote bus.

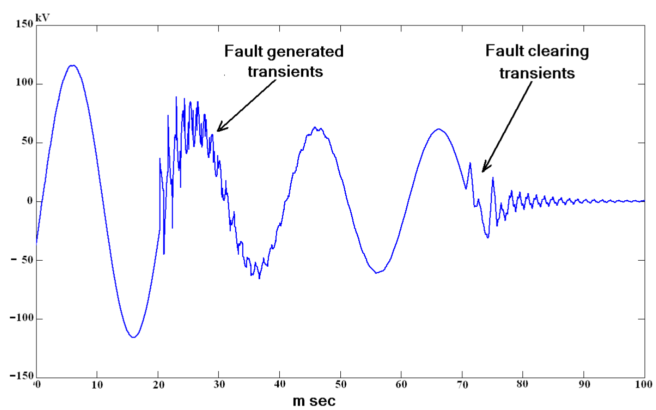

Fig. 1. Fault generated and fault clearing transients

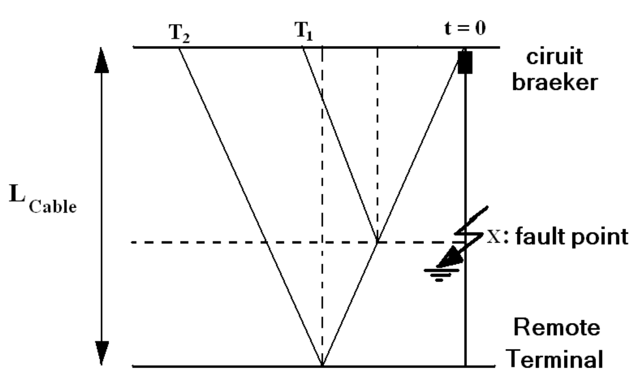

Fig. 2. Lattice diagram of traveling waves generated by circuit breaker opening action

Voltage and current traveling waves in the location x and in the time t in the lossless line can be described as the sum of two forward and backward waves as follow:

$$u(x,t)=f_1\,(x\text{-}vt)+f(x+vt) \tag{1}$$

$$i(x,t)=\frac{1}{Z_c}\,f_1\,(x\text{-}vt)+\frac{1}{Z_c}\,f(x+vt) \tag{2}$$

where f_1 and f are forward and backward waves, respectively; and u and i are the voltage and current; and v is the propagation speed of the wave. And,

$$Z_C=\sqrt{\frac{L}{C}} \tag{3}$$

$$v=\frac{1}{\sqrt{LC}}=\frac{Z_C}{L} \tag{4}$$

where Z_c is the characteristic impedance of the cable and L and C are inductance and capacitance of the cable per unit length. It is clear from (4) that if the wave speed v is calculated from cable parameters, by any change in these parameters wave speed will change. Thus, the accuracy of the algorithms, which are based on the cable parameters, will vary with aging, temperature change and any other factor that causes change in the cable parameters.

A novel fault location approach is presented in this paper, which despite of using only one terminal data, does not require to the cable parameters. Proposed algorithm decomposes three phase voltage signals to the modal components using modal decomposition and then detects the first and second inceptions of the high frequency voltage signals to the fault locator, which are generated by the fault clearing action of the circuit breaker. Then the real-time and accurate wave speed is calculated and precise fault location will be obtained. In the three phase systems the forward and backward equations of the voltage and current are dependent to the voltage and current of the three phases and it should be considered that there is strong coupling between voltages and currents of phases. Therefore, in this paper before any analysis, three phase voltages are decomposed to modal components, which can be analyzed independently as single-phase system. For this purpose, it is possible to use following relation:

$$V_{\text{mod}al}=T^{-1}\times V_{phase} \tag{5}$$

where V is the voltage component and the indices *modal* and *phase* are related to the modal and phase quantities; 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 transient signals [18]:

$$T^{-1}=\frac{1}{\sqrt{3}}\begin{bmatrix}1 & 1 & 1\\ \sqrt{2} & -1/\sqrt{2} & -1/\sqrt{2}\\ 0 & \sqrt{3}/2 & -\sqrt{3}/2\end{bmatrix} \tag{6}$$

Upon phasor components are decomposed to modal components, it is possible to detect the first and second inceptions of traveling wave (generated by fault clearing action of circuit breaker) using wavelet transform. The wavelet analyzes the signal at the different frequency bands with different resolutions by decomposing the signal into an approximation and detail information and again each level can be decomposed more precise as shown in Fig. 3. In this paper, using Db4 as mother wavelet, alpha mode of fault clearing voltage signals are decomposed and only details of first level of decomposition are used to calculate the location of fault.

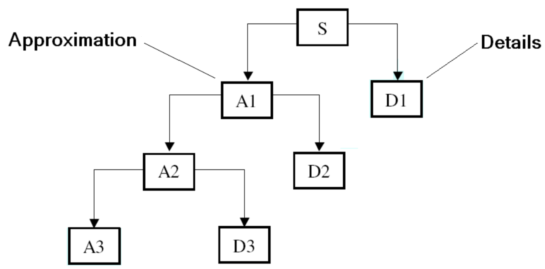

Fig. 3. Approximations and Details in wavelet transform

III. Fault Location Algorithm in the Cables

A new fault location method, which locates fault point without using cable parameters, is presented in this paper. To evaluate the accuracy of the proposed method, a 50 Hz power system including an 80 km length power cable is considered that is illustrated for a symmetrical three-phase fault in Fig. 4.

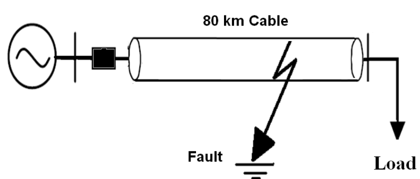

Fig. 4. Cable line with 80 km length

After fault occurrence, circuit breaker opens and deenergizes the line. The opening action is followed by generating the high frequency voltage traveling waves, which propagate from circuit breaker to the fault point and remote bus. Voltage signal arrives to the fault point first and on this point some part of the wave is reflected to the fault locator and the remaining refracts to the behind of the fault and propagates to the remote terminal. Thus, two traveling waves arrive to the fault locator after circuit breaker opening action. It is possible to calculate wave speed and fault location by detecting two mentioned inception waves and measuring the time of inceptions. After opening the circuit breaker, a transient voltage signal is generated and propagates to the fault point. In Fig. 2 the time of generation of the mentioned signals is considered as the reference for time measurement t = 0. In the fault point, a part of wave is reflected and reminder will refract which, reflection and refraction coefficients are obtained by:

$$\rho_{reflection} = \frac{(R_f \parallel Z_C) - Z_C}{(R_f \parallel Z_C) + Z_C} \tag{7}$$

$$\rho_{refraction} = \frac{2(R_f \parallel Z_C)}{(R_f \parallel Z_C) + Z_C} = \rho_{reflection} + 1 \tag{8}$$

where Z_c and R_f are the cable characteristic impedance and fault resistance, respectively.

If fault is occurred in the second half of the transmission line, first inception to the fault locator is related to the voltage-traveling wave reflected from the fault point, and second one is reflected from the remote terminal. In this case, considering lattice diagram provided in Fig. 2, the times T_1 and T_2 are related to the mentioned incepted waves and therefore wave propagation speed is obtained by:

$$v_c = \frac{L_{Cable}}{T_2 / 2} \tag{9}$$

where L_{Cable} is the length of cable. Having the actual and real-time wave speed and considering Fig. 2 it is possible to calculate the fault location as follows:

$$x = v_c \times \frac{T_1}{2} \tag{10}$$

It is clear from (9) that calculated wave speed is independent of cable parameters, so, the accuracy of proposed algorithm will be insensitive to any change in cable parameters caused by aging, humidity and temperature change etc.

If fault is occurred in the first half of the cable line, as illustrated in Fig. 5, second wave incepted to the fault locator does not belong to the wave reflected from the remote terminal, and belongs to the wave, which reflected again from the fault point to the fault locator.

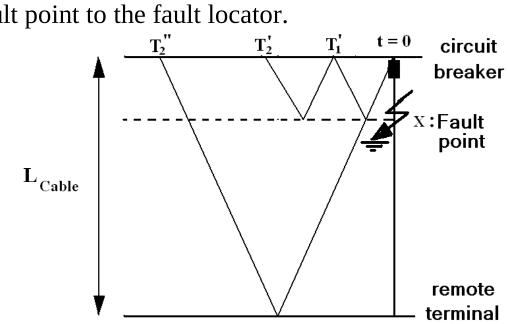

Fig. 5. Lattice diagram for fault occurred in the first half of the cable

In this case T_1' belongs to wave reflected from fault point and T_2' belongs to this wave which is reflected again from fault point. Therefore, it is essential to recognize between this wave which is illustrated in Fig. 5 with T_2' and the reflection from remote terminal which is illustrated with T_2''. It is possible to recognize mentioned state using a low pass filter. For fault occurred in the first half of the cable, frequency of the wave reflected from fault point, will be greater than twice of the frequency of the wave reflected from remote terminal. The reason is that for faults occurred in the first half of the cable, the distance traveled by the wave to arrive to remote terminal and reflect to the fault locator is at least twice the distance to travel from fault locator to the fault location; therefore, mentioned frequencies are as follow:

$$f_1 = \frac{1}{T_1'} = \frac{v_c}{x} \tag{11}$$

$$f_2 = \frac{1}{T_2''} = \frac{v_c}{L_{Cable}} \tag{12}$$

where x is the distance of fault from the fault locator and T_1' is required time for traveling wave to arrive to the fault point and reflect and T_2'' is the elapsed time to arrive to the remote terminal and reflect, respectively; and f_1 and f_2 are related frequencies, respectively. For the fault occurred in the first half of the cable, it is clear that $x < \frac{1}{2} L_{Cable}$ and thus considering (11) and (12), it is clear that $f_1 \geq 2\times f_2$. Now using a low pass filter, it is possible to eliminate f_1 , therefore the existent dominant frequency merely will be f_2, thus, simply T_2'' is calculated and wave propagation speed will be specified. For the fault occurred exactly in the half point, algorithm is similar to faults occurred in the first half of the cable. Fig. 6 shows proposed filtering system.

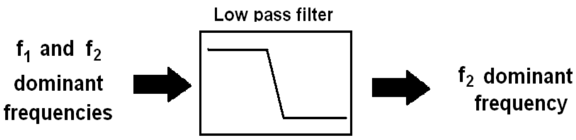

Fig. 6. Proposed filter for extracting f_2

Computational error for the distance calculated as fault location can be obtained by:

$$\%error = \frac{x_{calculated} - x_{actual}}{L_{Cable}} \times 100 \quad (13)$$

where x_{actual} is actual distance of the fault point from the locator and $x_{calculated}$ is calculated fault location.

IV. Evaluation of The Proposed Algorithm

To evaluate performance of proposed algorithm, extensive simulations have been carried out using SimPowerSystem toolbox of MATLAB software. For this purpose a 132 kV, three-phase system similar to the system shown in Fig. 4 with 80 km cable length is considered. Simulations for different single, double and three phases to ground faults and similarly for double and three phases faults occurred in different distances from fault locator are performed. Fault resistances between zero and 5 Ω and fault inception angles between zero and 90° are considered.

As an example, if a double-phase to ground fault with resistance of 2 Ω and 30° fault inception angle occurs in distance 63 km far from fault locator, three phase voltage signals and their modal decomposition are shown in Figs. 7 and 8, respectively (the time of fault occurrence assumed 30 ms and cleared at 70 ms). In addition, wavelet transform of alpha component of the decomposed signal is shown in Fig. 9.

If the time which incident wave is generated by the fault clearing action assumed to be origin of time t = 0, thus using Fig. 9 T_1 and T_2 will be 1383 and 1754 microsecond, respectively. Now using (9), wave speed will be determined 91,220.068 km/sec and using (10), fault location can be determined 63.079 km, which has 0.098% computational error.

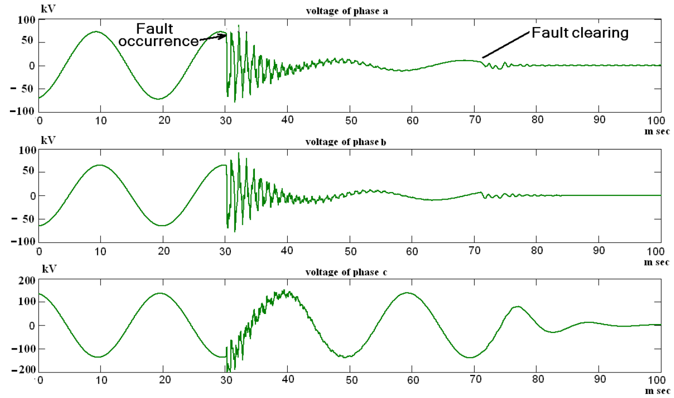

Fig. 7. Three phase voltage signals for double phase to ground fault occurred in 63 km

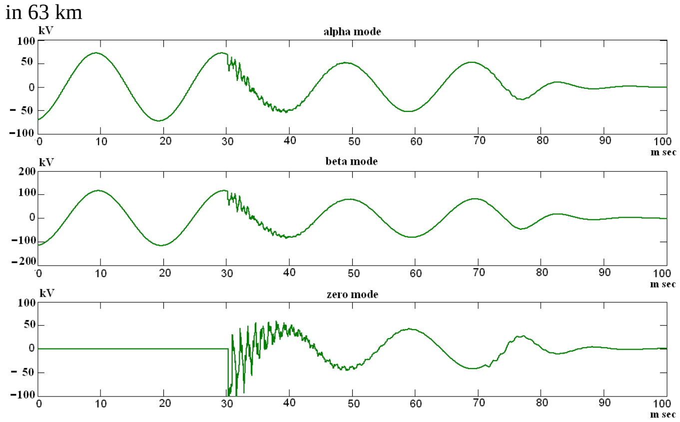

Fig. 8. Modal component voltage signals for double phase to ground fault occurred in 63 km with

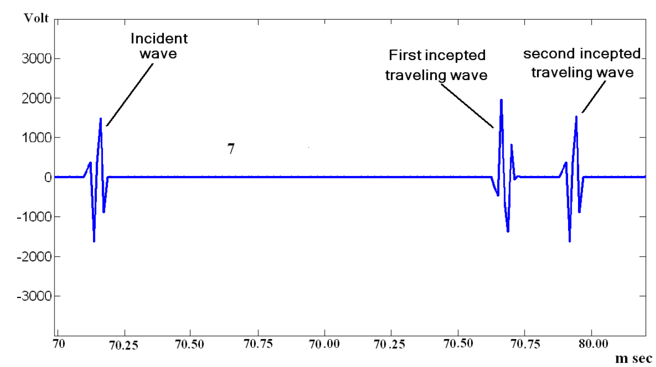

Fig. 9. Wavelet transform of alpha mode signal and detection of first and second inceptions of traveling wave to the fault locator

As another example, for three-phase fault occurred in distance 34 km from locator with zero fault inception angle, wavelet transform of the alpha mode signal is shown in Fig. 10 and so, T_1' and T_2' are 745 and 1490 microsecond. Since T_2' = $2\times T_1'$ it is identified that the fault has been occurred in the first half of the cable and therefore, first and second inception waves are related to reflections from fault point. In this case, using a low pass filter it is possible to eliminate this inception waves and reach to the wave reflected from remote terminal. This process is shown in Fig. 11 and the resultant signal presented in Fig. 12.

Therefore, it is possible to specify the time of reflection from remote terminal. Therefore, for mentioned example, this time will be 1754 microsecond. Using (9), wave speed is

91,220.068 km/s and using (10), fault location is determined 33.979 km, which has 0.026% computational error.

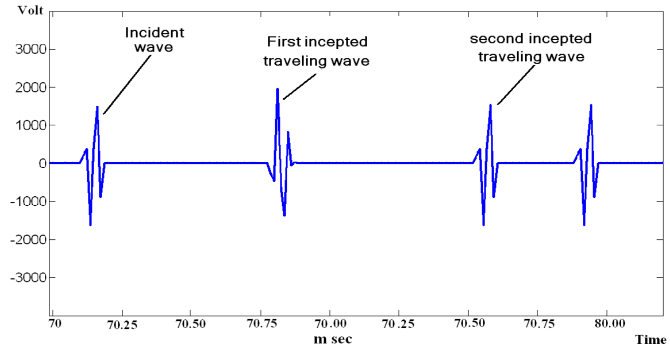

Fig. 10. Wavelet transform of alpha mode signal for fault occurred in the first half of the cable

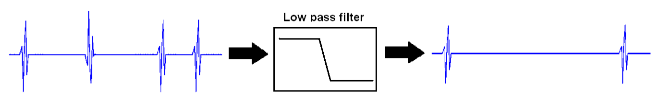

Fig. 11. Proposed filtering algorithm

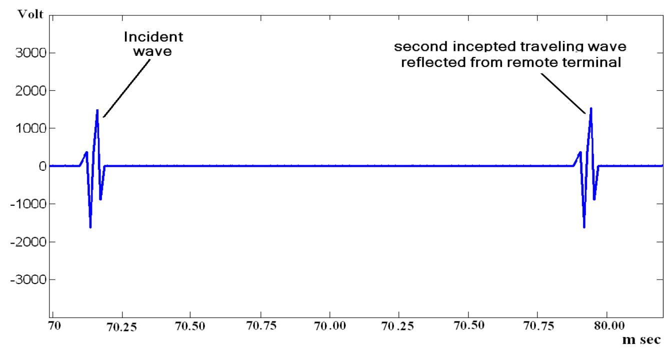

Fig. 12. Resultant signal after filtering

To demonstrate the effect of different parameters on the accuracy of the proposed algorithm, the following subsections will discuss about the influence of fault resistance, fault inception angle, fault location and fault type on the accuracy.

A. Influence of fault resistance

In majority of cable fault location studies, fault resistance is considered between zero and 5 Ω. In this section faults with different resistances are included. Simulation results for single, double and three phases to ground faults in distance 78 km with different fault resistances are presented in Table I.

Table I
Single, double and three phases to ground faults with 24° fault inception angle occurred at 78 km and different fault resistances

Fault type	Fault resistance (Ω)	Calculated distance	error %
Single phase to ground	0	78.083	0.103
	2	78.102	0.128
	5	78.074	0.091
Double phase to ground	0	78.125	0.156
	2	77.967	-0.042
	5	77.943	-0.071
Three phase to ground	0	78.065	0.081
	2	78.043	0.054
	5	77.974	-0.032

Based on the results presented in Table I, it is clear that fault resistance doesn't have influence on the accuracy of proposed algorithm.

B. Influence of fault inception angle

Most of traditional traveling wave methods used to find fault location are sensitive to fault inception angle. In this section influence of fault inception angle on the accuracy of the algorithm is evaluated. Simulation results for double and three phase faults occurred in distance 2 km with different fault inception angles are presented in Table II.

Table II
Double and three phase faults with different fault inception angle occurred in 2 km

Fault type	fault inception angle (degree)	Calculated distance	error %
Double-phase fault	5	2.056	0.070
	45	1.963	- 0.046
	90	1.959	- 0.051
Three-phase fault	5	2.073	0.091
	45	2.083	0.103
	90	2.025	0.031

It is observed from Table II that fault inception angle does not affect the accuracy of proposed algorithm. Because of using fault clearing voltage transients, when current become zero, voltage is in maximum amplitude and so fault inception angle does not affect on algorithm.

C. Influence of fault distance

Some of fault location algorithms are influenced by fault distance and so in this subsection it is aimed to investigate the effect of fault distance from fault locator on the accuracy of the algorithm. For this purpose, simulations were carried out for double and three phase faults with zero fault inception angle occurred at different distances from locator point. The obtained results are shown in Table III.

Table III
Faults occurred with zero inception angle at different distances

Fault type	fault distance (km)	Calculated distance	error %
Double phase fault	14	14.079	0.099
	48	48.034	0.043
	77	76.984	0.033
Three-phase fault	14	13.075	0.094
	48	47.096	0.005
	77	77.055	0.069

From provided results of Table III, it is obvious that the distance of fault from fault locator does not affect the accuracy of proposed method.

D. Influence of fault type

From previous sections, for example by comparison between Tables I and II it is clear that the fault type does not affect the accuracy of proposed method. Proposed method is capable to locate different types of fault occurred on the power cable with high accuracy.

V. Conclusion

In this paper, a novel fault location algorithm is presented which uses only voltage samples taken from one-terminal. The wavelet-based algorithm utilizes high frequency fault clearing voltage transients and detects first and second inceptions of traveling waves after circuit breaker opening action to the locator point. Thereafter, actual wave speed is calculated and fault location is determined. Extensive simulations performed using SimPowerSystem toolbox of MATLAB software, for different fault types and conditions confirm the capability and accuracy of the proposed algorithm. The presented results show that fault inception angle, fault resistance, fault type and distance of fault do not affect the accuracy of the proposed algorithm. Presented method despite of using only one terminal data provides accurate results, such that in the worst case, computational error does not exceed 0.2 %, in addition, does not need to the communication systems and data synchronization.

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