Energy Ratio Function-Based Fault Location for Series Compensated Line

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Abstract

The existence of the series compensation capacitor results in the complex fault-travelling wave process of the series compensated lines and the difficulty of the wavefront recognition. From the angle of the traveling wave energy, this paper obtains the fault traveling wave by using the energy ratio function in a specific time window, leading to the realization of the travelling wave fault location of the series compensated lines. The influence of the series compensation capacitor on the energy ratio function is studied; the correctness of the application of the energy ratio function in the fault location of the series compensation lines is verified; and the principle of selecting the width of the time window is analyzed. ATP/EMTP simulation results show that this method can be effectively applied in the fault location of the series compensation lines because of its superiority of high precision, simple calculation and immunity to the series compensation installation position.

Keywords: energy ratio, series compensated line, traveling wave, fault location, time window

1. Introduction

Transmission line series compensation increases power transfer and improves power system stability. Typically, the series compensation equipment comprises either a series capacitor (SC) bank with metal oxide varistor (MOV) protection or a thyristor controlled series capacitor (TCSC) system. The non-linearity of such equipment introduces a great difficulty in computing the voltage drop across the series compensation during the fault period, which accordingly affects the protection and fault location estimation of series compensated transmission lines [1].

For the status, the current algorithms of fault location for series compensated lines are mainly divided into three types, such as algorithms of fault analysis, pattern recognition, and traveling wave.

Based on power frequency, the algorithm of fault analysis makes use of measurements on one terminal or two terminals, such as voltages and currents, to accomplish fault location for series compensated lines through analysis and calculations. Utilizing this algorithm, respectively, and assuming a fault occurs on both sides of the capacitor, two solutions are calculated through establishing the differential equations, and then according to the fault information criterion, the right answer retains while the pseudo root is removed. The algorithm of fault analysis is generally based on the equation of series compensated lines. Not only are the operations complex, but also the problems of the pseudo root exists.

The algorithm of model identification is based on the distance between the fault point and the series compensated capacitor, when single-phase ground fault occurs on series compensated lines. This algorithm is adapted to comparing different dispersions of the line inductance, which is calculated on different models, to identify the location of the fault. Combined with traditional distance protection, fault location for series compensated lines can be achieved by using the algorithm model identification. Similarly, for the realization of the model identification, it is necessary to establish different fault models, and the following problems of pseudo root still exist. What's more, limited by model, the algorithm works only for single-phase ground fault, but not for other types of faults.

The algorithm of traveling wave is based on the traveling wave propagation theory. In accordance with the principle, modern traveling wave algorithms can be divided into four types, which contain A, D, E, F. Type A, E, and F are one-terminal algorithms, making use of only local datas, while type D is two-terminal algorithm, making use of measurements at both terminals. Undeniably, the traveling wave has many advantages in the fault location. However, series compensation device impacts on the traveling wave propagation in the series compensated transmission lines, which may result in some difficulties, such as identification on fault information included in the first wave. Due to the failure of traveling wave being extracted accurately, accurate and reliable fault location will not be achieved.

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Although each algorithm has his own advantages, however, each of them are less than satisfactory in fault location for series compensated transmission lines. Access of a protection device, which is installed to protect the series compensation capacitor, makes the circuit non-linear. Due to the nonlinearity of series compensated lines, the existing algorithms of fault location for general line often can not be directly applied to the series compensated lines. Only if the impact of the non-linear elements is fully considered, we will achieve excellent accuracy and precision. On the one hand, it is the nonlinearity of series compensated lines that results in the nonlinearity of fault signal to a certain extent. Thus, the domain transform method is often unable to process the nonlinear signal effectively. During the research, non-linear methods of signal processing, such as mathematical morphology and Hilbert-Huang Transform, are expected to become new methods of signal processing used in fault location for series compensated lines. On the other hand, bypassing complex composition analysis of nonlinear signal, the function of the energy ratio is used to characterize the fault signal, and possibly becomes new methods of fault location for series compensated lines.

2. Background and Motivation

Despite varieties of difficulties, fault location for the series compensated lines is still one of the focuses by many scholars. More and more results about fault location for the series compensated lines are achieved.

Different algorithms for series compensated lines have been developed in the recent years [3-13]. One-terminal [4, 11, 13] or two-terminal algorithms [5-10, 12] have been proposed, but most of these algorithms have focused on fault analysis based on the available data. In literatures [4-11], two subroutines are adopted to characterize the two hypotheses for locating faults behind and in front of the series compensation. The real fault location is obtained by removing the pseudo root. For the removal of the pseudo root, the method of interval judgment is taken as criterion in literatures [4,5,7,9]; and the criterion of the measured impedance is taken in literatures [6,8]; and a criterion for series compensation voltage across the capacitor deviation is taken in literature [10]; and literature [11] takes the method of model identification as the criterion to identify the exact fault location. The distance protection of series compensated lines is studied in [13], and the least square method is taken to process the data without the need to identify the location of the fault. However, the accuracy of the algorithms is affected by the fault type, the transmission line model employed (e.g. lumped parameters with neglecting shunt capacitance) and the source impedance variation.

Literature [4] is one of the earliest literatures on fault location for series compensated lines. It presents an accurate and robust fault location algorithm for series compensated lines. The algorithm is developed as a one-terminal fundamental frequency based technique, and offsets both the series compensation effect and the reactance effect resulting from the remote end indeed. The algorithm employs two subroutines for estimation of the fault distance - one for faults behind the SCs, and another one for faults in front of the SCs. A special selecting procedure is proposed to pick-up the correct alternative. To simulate the actual situation, source impedances mismatched, MOV diameters mismatched, effect of neglected line capacitances, and accuracy of instrument transformers have been studied, respectively.

Literature [3] is the typical research on fault location for series compensated lines. Distinctly, using the subroutines, the following disadvantages are undoubted:

1). The operation process is very complex, and requires very large amount of computation, which is obviously not conducive to the fault lines ranging;
2). Additional computation will be generated for the process of removing the pseudo root, which improves the complexity of the algorithm.

Consequently, attempts of new algorithms on fault location for the series compensated lines mainly depend on the expansion of non-linear signal processing method.

What's more, after a series of studies on MOVs, the conclusion of “the start time of MOVs is longer than 6ms” has been presented, which demonstrates the feasibility of traveling wave fault location for series compensated lines. For the analysis of MOVs' conduction time, literature [11] laid the foundation of the feasibility. In this paper, the conclusion that there is a certain time before MOVs conduct, has been presented. The certain time is enough for the identification of fault location. Thus, the problems of fault signal obtaining will be avoided. An algorithm based on model identification is proposed in the paper.

Literature [12] have discussed the conduction time of MOVs in series compensated lines and its effect on fault traveling wave of series compensated lines. After the feasibility is demonstrated, a new algorithm based on mathematical morphology morphological gradient technique (MMG) is proposed in the paper. As one of non-linear methods, although the basic operation is simple, the times of operations is too excessive in a certain period. Thus, the efficiency of fault location using the algorithm is so low that the sampling frequency would be limited.

In literature [14], from the viewpoint of the signal energy, the use of the energy ratio function has been successfully used for fault signal processing to achieve fault location for transmission lines. The principle of the method is simple and does not involve complicated internal signal component analysis, and running speed and the energy ratio method are unique advantages. By avoiding the complex composition analysis of signals, as well as simple principle, running speed is quite fast, which is the unique advantage of the algorithm based on energy ratio function. Because of the unique advantages of this algorithm, applied to fault for series compensated lines, it is likely to be a reliable and effective method.

Based on the above analysis, a novel algorithm of fault location for series compensated lines based on energy ratio function is proposed in this paper. From the view of energy, the fault signal energy ratio of adjacent time windows is used to characterize the fault characteristics, and achieve fault location for series compensated line. An equivalent impedance of series compensated capacitor with the transmission lines forms series filters, by which exists a filtering effect to high-frequency signals on the lines. This paper discusses the impact of the filtering effect on the energy ratio function, which demonstrates the feasibility of fault location for series compensated lines based on energy ratio function. Besides, the criterion of selecting the time window has been analyzed in order to ensure reliability of the algorithm.

3. Princinple of Fault Location for Series Compensated Lines

3.1 Energy ratio function

The leading edge of the fault signal is obtained by the ratio of the signal energy to the noise energy. Essentially, energy ratio function amplifies the signal level of mutation, which makes it easier to identify. Compared to the transform based on integration, such as wavelet transform, the algorithm based on energy ratio function avoids the complicated analysis of the signal component. The ratio of signal energy in the rear part of time window to energy in the front part is taken as an expression of the change of signal singularity for the detection signal singularity.

Assume that the valid value x_R of the signal *x* (*t*) in the time period [*0, T*] on the definition is shown as follows:

$$x_R = \sqrt{\frac{1}{T}\int_0^T x^2(t)dt} \tag{1}$$

The ratio of signal energy to parts of time window is taken to indicate the mutation. The time window is a certain period, which can be transformed into the sampling points. Energy ratio function is expressed as follow:

$$P = \left[\sum_{t=T_0+T/2}^{T_0+T} x^2(t)\right]^{1/2} / \left[\sum_{t=T_0}^{T_0+T/2} x^2(t)\right]^{1/2} \tag{2}$$

Where, *T* is the time window, while *P* shows the value of the energy ratio function. T_0 is the start of the time window. From the beginning, the window moves point by point on the signal line until the end, and the signal energy ratio conversion is completed.

It is critical to select the time window when using energy ratio function for obtaining fault information. Typically, the smaller *T* is, the more precise mutations moment is, and the smaller P-value is. And because of the small *P*-value, which shows mutant of signal, the mutation information may be submerged in the noise. Conversely, the larger T is, the larger the value of the energy ratio P is, but the energy ratio curve is not sharp, which may cause inaccurate positioning of signal mutation moment. Consequently, various factors should be taken into account to select a suitable time window.

3.2 The effect of series compensated capacitor on energy ratio function

The combination of series compensated capacitor and distributed impedance on line, which forms a series filter, filters the high-frequency signals. Assume that the fault occurs in the left of the capacitor, and take it as a case to explain the effect of filtering. The schematic circuit is shown in Figure.1.

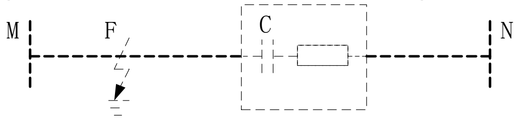
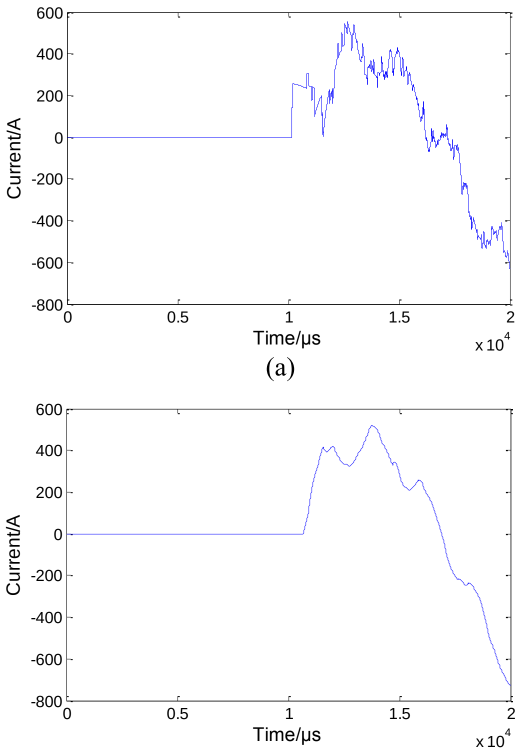


Figure 1: Equivalent circuit of the series filter



(a)

(b)

Figure 2: Filtering effect of series capacitor: (a)Waveform of current at the left side of capacitor; (b) Waveform of current at N end

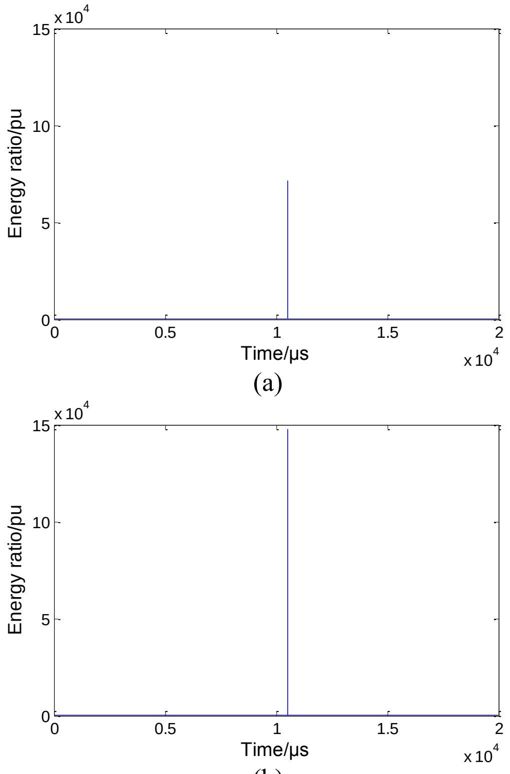
The waveform of current traveling wave on both sides of the capacitor, which is measured in simulation experiments, is shown in Figure 2. In the figure, each refracted wave and reflected wave are superimposed together to compose the measured current traveling wave. Filtering effects of the filters may cause the loss or attenuation of a component, which carries fault massages. Because of the distortion of information, accurate fault location for series compensated lines will not be achieved. By the transforms based on domain, such as Fourier transform and wavelet transform, the fault information at both ends of series compensated lines can not be effectively extracted. However, from the perspective of energy, mutations of energy that consist of the two parts of the signal are studied. Avoiding the internal complexity of the signal components, the possibility of fault location for series compensated lines based on energy ratio function theoretically exists.

By the Eq. (1), the signal mutation is characterized by the ratio of energy of the mutant signal to energy of the noise. Assuming fault occurs at point F, fault signal is *s*(*t*), the noise signal is *n* (*t*), and the detected signal is *x* (*t*). Then the definition of energy ratio function is written as:

$$x(t) = \begin{cases} n(t) & t < T_0 \\ n(t) + s(t) & t \geq T_0 \end{cases} \tag{3}$$

From the function of the energy ratio, what's reflected in the energy function is the energy ratio of the last half to the first half of the time window. Taking the fault time as the middle point of the time window, energy of the last half of the time window is energy of fault travelling wave, while energy of the first half is energy of noise.

Typically, there are series compensated lines relative to line noise interference fault current. Generally, line fault current is much greater than the value of the interference noise. Because of the effect of filtering on series compensated lines, both the fault current and the interference noise are filtered by the series compensated capacitor. Thus, the value of noise energy becomes much smaller than before. However, amplitude of fault travelling wave is so large compared to the noise that only the high-frequency glitches are filtered. The denominator becomes smaller, and the molecule nearly keeps constant. From the above analysis, energy ratio of the filtered wave becomes bigger than before; that is to say, the effect of series compensated capacitor makes the characteristic of fault signal more obvious, and the fault time is easier to be identified and ensured.



(a)

(b)

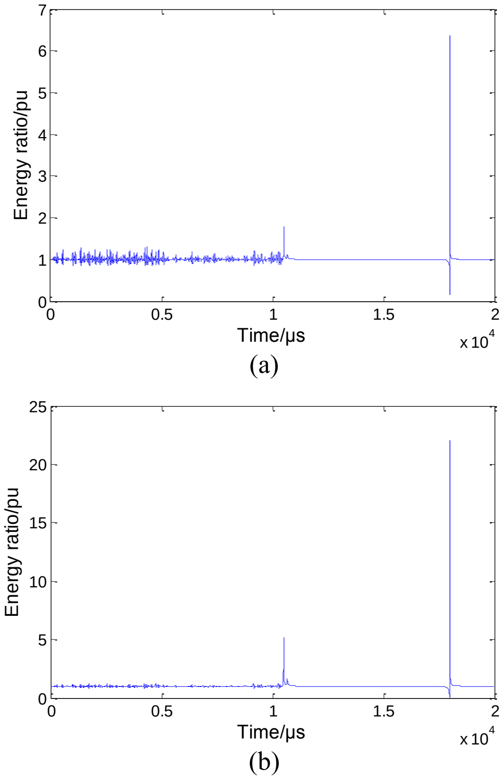
Figure 3: The effect of series capacitor to energy ratio: (a) The energy ratio at the end of M; (b) The energy ratio at the end of N

Figure 3 shows the waveforms of energy ratio function without noise when the fault occurs on the left of the series compensated capacitor in the middle of the line. The energy ratio of fault traveling wave filtered by series compensated capacitor is significantly greater than the unfiltered fault traveling wave energy ratio. In summary, the energy ratio function reflects information of fault traveling wave on series compensated lines, and the characteristics of the fault lines are more obvious; it is easier to achieve fault location for series compensated lines. Theoretically, the energy ratio function can not only be applied to traveling wave fault location for series compensated lines, but also get a high reliability.

3.3 Selection of time window

Selecting the width of the time window plays a decisive role in accurate traveling wave fault location for series compensated lines.

Assumed that the single-phase ground fault occurs in locations at 50km from M-terminal, the window width of 6 μs, 30 μs and 200 μs were selected to study the impact of different widths on energy ratio function.



(a)

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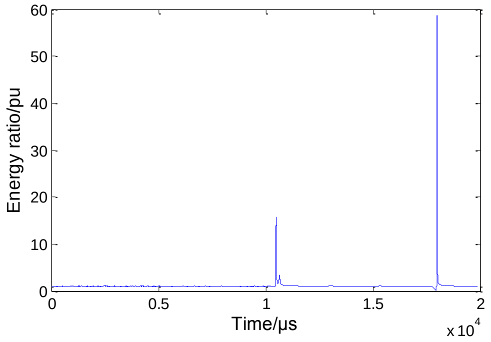


(c)

Figure 4: Energy ratio under different time windows: (a) Energy ratio when time window of 6 μs; (b)Energy ratio when time window of 30 μs; (c)Energy ratio when time window of 100 μs

As figure 4 shows, if the window width is too narrow, such as (a) below, the fault information in the peak of energy ratio function is almost submerged in interference noise; if the window is too wide, such as (c), the waveform of energy ratio, which carries fault information, is not sharp enough, and the fault time is not accurately obtained. Big errors are produced when an improper time window is selected, and we can not achieve accurate fault location.

Integrated into account, after repeated tests, the time window of 30μs is found to be appropriate. So, in this paper, the time window of 30μs is selected for the fault location.

3.4 Selection of fault location algorithm

One-terminal and two-terminal algorithms are included in the algorithms of raveling wave fault location or series compensated lines.

Taking one-terminal algorithms, if the line is too long, the wave generated by the conduction of MOVs may arrive at in the detection point earlier than the initial wave or the reflected wave from the other end. As the result of the one-terminal algorithms may lead to failure of location, the D-type two-terminal algorithm is taken in this paper. The formula is as follows:

$$d_M = \frac{l + (t_{1M} - t_{1N})v}{2} \tag{4}$$

$$d_N = \frac{l + (t_{1N} - t_{1M})v}{2} \tag{5}$$

Where, t_{1M} is the arriving time of the first wave head from the M end, and t_{1N} is the arriving time from the N end. l is the length of the line, and v is the speed of the wave.

4. Experiment and Analysis

4.1 Model for simulation

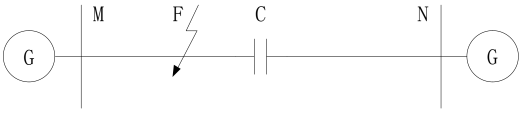


Figure 5: Model of series compensated line

The model of series compensated line is established in Figure 5 to simulate the waveforms. The parameters are:

The Line is voltage classes of 500kV; the length of line is 300km; the series compensation degree is 40%; the series compensation capacitor is C = 95.74μF; the grounded resistor is 10Ω. The system impedance of M-side is $Z_{M1} = 6.139 + j529.8\Omega$,and $Z_{M0} = j130.6\Omega$; the system impedance of N-side is $Z_{N1} = 17.56 + j46.11\Omega$, and $Z_{N0} = 1.6 + j65.13\Omega$. The parameters of line are: $r_1 = 0.0279\Omega / km$, $r_0 = 0.253\Omega / km$, $l_1 = 0.882mH / km$, $l_0 = 2.33mH / km$, $c_1 = 0.01306\mu F / km$, $c_0 = 0.0085\mu F / km$.

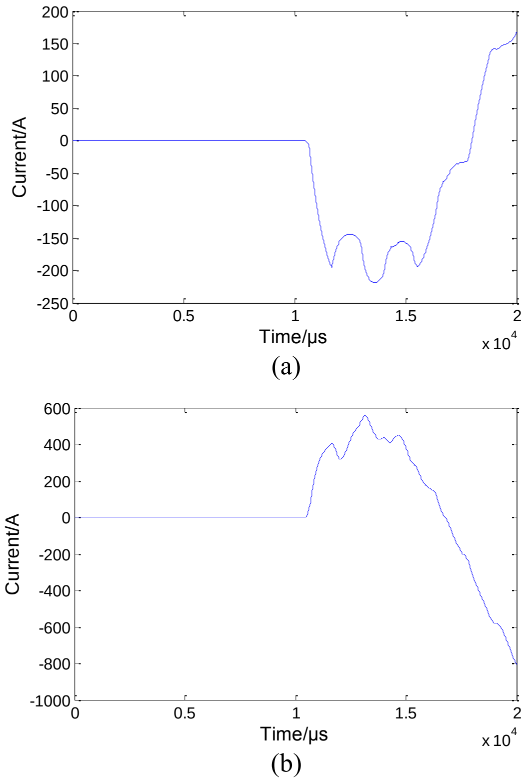
Establishing the above models, simulation time is 0.05s, while the fault occurs at 0.03s, and the sampling frequency is 1MHz. Since the voltage between the two sides of the series compensated capacitor can not change suddenly, the traveling wave voltage can not spread immediately through the series compensated capacitor. And the bandwidth requirements of the capacitive TV can not be met to traveling wave. Thus, the travelling wave current is adopted in this paper.

To decouple the three-phase system, the Clarke of modal transformation is used to make the fault signal of each phase independent, and the modal 1 is adopted for fault location.

4.2 The waveform of noise simulation in consideration

Essentially, energy ratio function is defined by energy ratio in two halves of the time window, respectively. When the fault occurs at the middle of the time window, there is only noise in the former half of time window, while both of fault information and noise are included in the latter. Thus, by taking the noise into account and filtering it, the accuracy and reliability are improved quiet a lot.

Filtering the noise in signals utilizing wavelet transform, the key is the selection of threshold. Pursuing great effect of filtering unduly, the distortion of fault signals comes out, which causes error filling out. Being conservative to select a threshold, the effect of filtering is not good enough. Figure 6 shows the waveform of the fault travelling wave, which is mixed with the noise of SNR (Signal to Noise Ratio) 20 dB and filtered by wavelet transform.



(a)

(b)

Figure 6: The filtered fault current waveform: (a)The waveform of fault current at the terminal of M; (b) The waveform of current at the terminal of N

4.3 Analysis of the simulation results

To demonstrate the algorithm, taking the noise into account, two-terminal algorithm is adopted to simulate the above algorithm for fault location of series compensated lines. The model is shown in figure 4, and the noise is added to the fault signals, and wavelet transform is used to filter the noise. The width of time window is 30 μs.

For the series compensated devices are installed at the terminals of lines in China, the series compensated devices both at middle-line and at terminals are simulated in this paper as follow. The results of simulation are shown in Table 1 and Table 2.

Table 1: Fault location results by series capacitor at middle-line

Fault type	50 (km)	149 (km)	151 (km)	290 (km)
AG	50.117	148.6741	151.0312	290.8379
AC	50.4117	149.4107	151.3259	290.9852
ACG	50.1170	148.9688	151.1786	290.2486
ABC	50.1170	148.6741	151.0312	290.3960
ABCG	49.6751	148.6741	150.8839	290.2486

Table 2: Fault location results by series capacitor at the terminal

Fault type	50 (km)	150 (km)	200 (km)	290 (km)
AG	49.6751	150.1473	200.5308	290.2487
AC	50.1170	150.5893	200.0888	290.8379
ACG	49.6751	150.0000	200.8254	290.8379
ABC	49.9697	150.2946	200.8254	290.1013
ABCG	49.5278	150.4420	200.0888	290.3960

From the analysis of the above results, the algorithm based on energy ratio function is applied to any case for different fault types under the effect of noise. What's more, the accuracy of fault location for series compensated lines is high, and reliability is great.

4.4 Fault location performance evaluation studies

When the fault inception angle takes some certain value, affected by the initial value, the mutation of the travelling wave at fault time will be crippled, which is detrimental to the obtaining of fault travelling wave. To investigate the algorithm of energy ratio function, the effect of fault inception angle should be taken into account by changing different fault inception angles.

Changing different fault inception angles, the results of simulation are shown in Table 3.

Table 3: Effect of fault inception angle to fault location results

Fault inception angle(dgree)	Results (km)	Errors (km)	Error ratio(%)	Accuracy (%)
0	50.5590	0.5590	1.1180	98.8820
45	49.2331	0.7669	1.5338	98.4662
90	49.9697	0.0303	0.0606	99.9394
135	50.1170	0.1170	0.2341	99.7659
180	49.5278	-0.4722	0.9445	99.0555
225	50.4117	0.4117	0.8234	99.1766
270	49.8224	-0.1776	0.3552	99.6448
315	50.8536	0.8536	1.7073	98.2927

By Table 3, the mutation of fault currents under different fault inception angles is rather obvious, and the characteristic of energy ratio function is distinct. Thus, the effect of fault inception angle on fault location results is week to the fault location for series compensated lines.

Except for the fault inception angle, the fault resistances, source impedances and the compensation level are the factors, which affect the final results of fault location. The effect of the compensation level and the fault resistance are shown in Table 4 and Table 5, respectively.

Table 4: Effect of the compensation level to fault location results

Compensated Level (%)	Fault (km)	Results (km)	Errors (%)	Accuracy (%)
20	50	49.8224	0.3552	99.6448
	149	148.5268	0.3176	99.6824
30	50	49.8224	0.3552	99.6448
	149	148.5268	0.3176	99.6824
40	50	49.8224	0.3552	99.6448
	149	148.5268	0.3176	99.6824
50	50	49.8224	0.3552	99.6448
	149	148.5268	0.3176	99.6824
60	50	49.8224	0.3552	99.6448
	149	148.5268	0.3176	99.6824

Table 5: Effect of the fault resistance to fault location results

Fault (km)	Fault Resistance(Ω)	Location Results(km)	Errors (%)	Accuracy (%)
50	0.1	50.5590	0.0112	98.8820
	10	49.0858	0.0183	98.1716
	50	49.8224	0.0036	99.6448
	100	49.8224	0.0036	99.6448
100	0.1	100.6478	0.0065	99.3522
	10	99.9112	0.0009	99.9112
	50	100.6478	0.0065	99.3522
	100	100.6478	0.0065	99.3522
149	0.1	149.2634	0.0018	99.8232
	10	148.5268	0.0032	99.6824
	50	148.5268	0.0032	99.6824
	100	149.2634	0.0018	99.8232
200	0.1	200.0888	0.0004	99.9556
	10	200.0888	0.0004	99.9556
	50	200.8254	0.0041	99.5873
	100	200.0888	0.0004	99.9556
250	0.1	250.1776	0.0007	99.9290
	10	250.1776	0.0007	99.9290
	50	250.9142	0.0037	99.6343
	100	250.9142	0.0037	99.6343

By a variety of simulations, the algorithms is insensitive to fault resistances, fault inception angles, source impedances and the compensation level provided by the series compensator.

5. Conclusions

A new algorithm for locating faults on series compensated lines utilizing current measurements from both ends of the line has been presented. The algorithm is based on a distributed parameter line model with use of Clarke modal transformation, which decouples the mutually coupled zero-sequence networks. Thus, it achieves superior accuracy especially for long transmission lines. The algorithm can deal effectively with all possible fault types encountered in series compensated lines arrangements, including both faults among phases and varieties of grounding faults. Moreover, the algorithm is insensitive to fault resistances, fault inception angles, source impedances and the compensation level provided by the series compensator. The validity of the algorithm has been verified by extended EMTP simulations. All applied tests reveal a high accuracy and promising performance for all situations.

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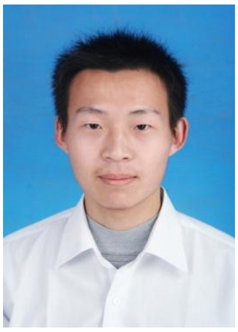

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