Performance Comparison of Impedance-Based Fault Location Methods for Transmission Line

Ngo Minh Khoa, Mai Vu Cuong, Huynh Quoc Cuong, and Nguyen Truong Tan Hieu
Faculty of Engineering and Technology, Quy Nhon University, Quy Nhon City, Binh Dinh, Vietnam
Email: ngominhkhoa@qnu.edu.vn; {vucuongkt06; huynhcuong784; hieunguyentruong20}@gmail.com

Abstract—**Electric transmission lines play a very essential role in transmitting power energy from generation centers to consumption regions. They can be exposed to fault occurrences due to various reasons, such as lightning strikes, malfunction of components, and human errors. Since fault is unpredictable, a fast fault location method is required to minimize the impact of fault in power systems. This paper presents a research work for comparing the performance of the impedance-based fault location methods, in which the impedance parameter of the faulted line section is calculated as a measure of the distance to the fault. To evaluate the capability of the methods for correctly detecting and locating the fault locations, comprehensive simulation results are carried out. This computation is based on modeling and simulating a three-phase 220kV overhead transmission line in the Matlab/Simulink software. Short circuits which occur in various fault resistances and locations along the transmission line are emulated to investigate several case studies and the accuracy of fault location determination is calculated to compare the performance among these fault location methods.**

Index Terms—**Impedance-based method, protection relay, transmission line, distance to fault, location error**

I. INTRODUCTION

Electric power systems growing in size and complexity will be always exposed to failures of their components. In the case of a failure, the faulty element should be disconnected from the rest of the sound system to minimize the damage of the faulty element and to remove the emergency for the entire system [1], [2]. This action should be taken fast and accurately and is accomplished by a set of automatic protective relaying devices. At the same time, when a fault occurs on a line (distribution or transmission), the utility needs to identify the fault location as quickly as possible for improving the service reliability. If a fault location cannot be identified quickly and this produces prolonged line outage during a period of peak load, severe economic losses may occur, and reliability of service may be questioned [3]. All these circumstances have raised the great importance of fault-location research studies and thus the problem has attracted widespread attention among researchers in power system technology in recent years.

Basic algorithms used in fault locators are intended to make the distance to the fault calculation as accurate as possible. The fault locator is mainly associated with protection relays. Distance relays for transmission line protection provide some indication of the general area where a fault occurred, but they are not designed to pinpoint the location. Moreover, both line protection and fault location are fulfilled by processing the same current and voltage signals that are obtained from the instrument transformers and recorded at the substation. Fault-location estimation is a desirable feature in any protection scheme. Locating fault on the transmission line accelerates line restoration and maintains system stability. That is why these two subjects are closely related to each other. There are, however, different demands formulated for protection and fault location. The last function should be made most precisely and with great accuracy. The distance to fault is estimated offline from the recorded data. On the other hand, the relaying function is made online as fast as possible.

In general, the overall process of automatically locating faults in electric transmission lines was described in [4]. Many algorithms have been developed to locate the distance to fault in power transmission lines. Reference [5] reviewed the fault location and detection techniques in electric distribution networks integrated distributed generations. The authors in [6] proposed a new approach to eliminate the influence of mutual reactance on fault location. Barati and Doroudi in [7] developed an algorithm based on a modified impedance-based method for locating faults in electric transmission lines connected to a fault current limiter. In this algorithm, two impedance-based methods are modified to solve the effects of the fault current limiter on the accuracy of traditional fault location methods. Mehrdad and Mehdi in [8] proposed a new algorithm based on an impedance matrix that only uses series impedances of the distribution lines to locate all fault types in distribution networks with and without distributed generations. The authors in [9] developed an accurate fault location approach utilizing synchronized measurements from both terminals of a transmission line with a series compensated capacitor. This approach could also be applied for locating faults in the double-circuit transmission lines. In [10], a new fault location algorithm was proposed for locating faults in a double-circuit transmission line by using voltage and current measurements recorded from a single end of the line.

According to this algorithm, only the negative sequence current and voltage phasors during the fault are utilized to determine the distance to the fault. The novel technique in [11] applied an impedance-based fault location method which utilized both data from the digital fault recorders and the protection relays to estimate the distance to fault in a long electric transmission line.

The impedance-based fault location algorithms were also applied for distribution networks. In [12], Flòrez *et al.* performed the comparison of ten fault location methods based on impedance measurement from the voltage and current signals. Reference [13] proposed an adaptive convolution network for locating faults in distribution networks which can enhance the accuracy of fault classification and decrease the training time. The authors in [14] developed a new single-ended fault location approach based on an iteration scheme of the pre-fault voltage and least square curve fitting to make fast and accurate fault location in distribution grids. Smart distribution grids in [15] were studied for handling fault situations via a fault location technique based on wavelet transform and artificial neural network.

Several modern algorithms based on the traveling wave method and the global positioning system (GPS) were researched in the [16]–[19]. The authors in [16] proposed a new fault location method based on the single-end traveling wave method using a correlation function for estimating the time delay between the fault-induced incident and reflected signals. In [17], Chafi and Afrakhte utilized the GPS for determining the distance to the fault. Khoa and Tung in [18] developed a new method for calculating the apparent impedance at the local end of the transmission line based on the Phasor Measurement Unit (PMU) with the Global Positioning System (GPS). Reference [19] presented a complex wavelet transform-based traveling wave for fault location in a two-end transmission line.

The main contributions of this paper are summarized as follows: (*i*) develop a numerical simulation method based on the Matlab/Simulink software for carrying out a comparative study of four single-end impedance-based fault location methods; (*ii*) calculate the percentage error of the fault location to evaluate the accuracy of the methods, and (*iii*) investigate the impact of the steady state and the fault resistance on the performance of the methods. This paper is organized as follows: Section II presents the theory and method of the impedance-based fault location method. Section III presents the simulation results and discussion for evaluating the performance of the methods by using the simulation method in the Matlab/Simulink. Finally, Section IV concludes the paper.

II. THEORY AND METHOD

Several impedance-based fault location methods have been developed for determining the distance to fault in a transmission line. Each method has specific input data requirements and makes certain assumptions that may or may not hold in a particular fault location scenario. In this paper, we present the theory of single-end impedance-based fault location methods to carry out a comparative study of their performance. The modeling of a two-end transmission line with the positive sequence impedance Z_{L1} as shown in Fig. 1 is used to establish the equation of fault location in this section. It is assumed that a fault occurs on the line at the location m per unit of the line length from the local end. The voltage and current measurements of the local end and the remote end are U_G, I_G, and U_H, I_H, respectively.
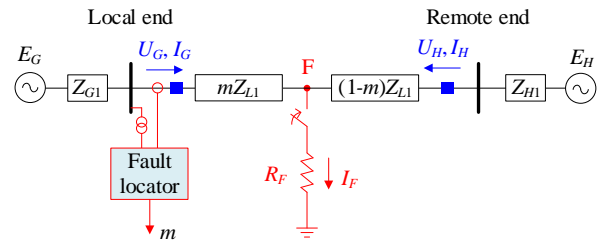

Fig. 1. The positive sequence representation of the transmission line.

The local end voltage U_G shown in Fig. 1 can be defined as follows:

$$U_G = I_G \left(m Z_{L1} \right) + I_F R_F \qquad (1)$$

where m is the distance from the local end to the fault location, Z_{L1} is the positive sequence impedance of the line, R_F is the fault resistance, I_F is the fault current, U_G and I_G are the voltage and current at the local end, respectively. U_G and I_G depend on the fault type and are defined as in [20].

The apparent impedance (Z) from the local end to the fault is measured by using the voltage U_G and the current I_G as follows:

$$Z = \frac{U_G}{I_G} = m Z_{L1} + R_F \frac{I_F}{I_G} \qquad (2)$$

It is clear that (2) is obtained according to (1) and (2) can be seen as a basic equation to develop single-end methods for determining the distance to the fault. There are unknown quantities including m, R_F, and I_F in (2), therefore, to eliminate the impacts of R_F and I_F on the accuracy of fault location result, four single-end impedance-based fault location methods studied in this paper have been developed and are summarized as follows.

A. Simple Reactance Method

This method compares the positive sequence line impedance (Z_{L1}) and the calculated impedance (U_G/I_G) to find the fault location. The accuracy of this method depends on the phase angle of I_G being equal to the phase angle of I_F. If the fault resistance is ignored, the simple form of the distance to fault can be obtained as follows:

$$m = \frac{\text{Im}\left(U_G / I_G \right)}{\text{Im}\left(Z_{L1} \right)} \qquad (3)$$

where U_G and I_G depend on the fault type and are defined as in [20].

B. Takagi Method

The Takagi method [21], [22] requires additionally pre-fault current values. This method improves the simple reactance method by reducing the effect of load flow and minimizing the effect of fault resistance. The distance to fault is given as:

$$m = \frac{\text{Im}\left(U_G \Delta I_G^*\right)}{\text{Im}\left(Z_{L1} I_G \Delta I_G^*\right)} \tag{4}$$

where ΔI_G^* denotes the conjugate of ΔI_G, ΔI_G is the deviation between the fault current and the pre-fault current and it depends on the fault type and is also defined as in [20].

C. Modified Takagi Method

The Modified Takagi method replaces superposition current with the zero-sequence current of the local end. This method is limited to ground faults since zero-sequence current exists for ground faults. Then, the fault distance is calculated as follows:

$$m = \frac{\text{Im}\left(3U_G I_{G0}^*\right)}{\text{Im}\left(3Z_{L1} I_G I_{G0}^*\right)} \tag{5}$$

where I_{G0} is the zero-sequence current of the fault current at the local end.

D. Eriksson Method

The Eriksson method uses the source impedance parameters to estimate the distance to fault [20]:

$$m = \frac{\left(a - \dfrac{eb}{f}\right) \pm \sqrt{\left(a - \dfrac{eb}{f}\right)^2 - 4\left(c - \dfrac{ed}{f}\right)}}{2} \tag{6}$$

where a, b, c, d, e, and f are the real and imaginary components of the complex multiplications of voltage, current, line impedance, and source impedance and are defined as follows:

$$a = \text{Re}\left\{1 + \frac{Z_{H1}}{Z_{L1}} + \frac{U_G}{Z_{L1} I_G}\right\} \tag{7}$$

$$b = \text{Im}\left\{1 + \frac{Z_{H1}}{Z_{L1}} + \frac{U_G}{Z_{L1} I_G}\right\} \tag{8}$$

$$c = \text{Re}\left\{\frac{U_G}{Z_{L1} I_G}\left(1 + \frac{Z_{H1}}{Z_{L1}}\right)\right\} \tag{9}$$

$$d = \text{Im}\left\{\frac{U_G}{Z_{L1} I_G}\left(1 + \frac{Z_{H1}}{Z_{L1}}\right)\right\} \tag{10}$$

$$e = \text{Re}\left\{\frac{\Delta I_G}{Z_{L1} I_G}\left(1 + \frac{Z_{H1} + Z_{G1}}{Z_{L1}}\right)\right\} \tag{11}$$

$$f = \text{Im}\left\{\frac{\Delta I_G}{Z_{L1} I_G}\left(1 + \frac{Z_{H1} + Z_{G1}}{Z_{L1}}\right)\right\} \tag{12}$$

where Z_{G1} and Z_{H1} are the positive sequence impedance of the local and remote sources, respectively.

In (6), the distance to the fault m can take two possible values. However, the fault location must be within the line length, the value of m must be from 0 to 1 per unit. In addition, the local and remote source impedances must be accurately known in (6) to estimate the distance to a fault m.

In general, the single-end impedance-based fault location methods have the flowchart as shown in Fig. 2. Each single-end impedance-based fault location method includes four basic steps as follows [3]:

Step 1: Remove the direct current (DC) offset and sub-harmonics in the voltage and current signals using a high-pass filter.

Step 2: Estimate the voltage and current phasors using the fast Fourier transform (FFT) algorithm.

Step 3: Identify the fault type and select the phases to calculate the fault location.

Step 4: Apply the impedance-based fault location methods to calculate the distance to the fault.
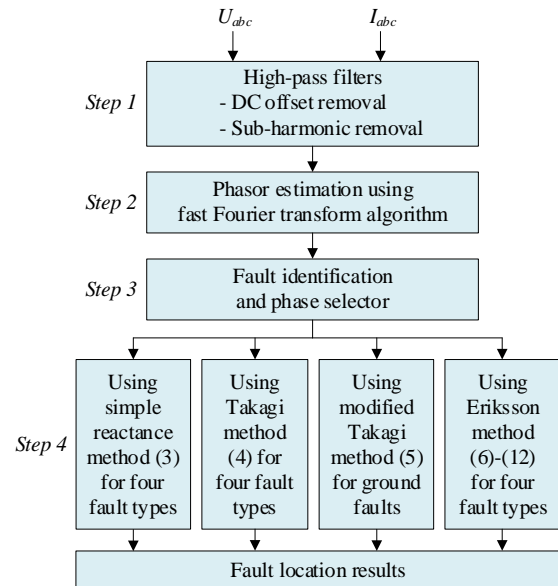

Fig. 2. The flowchart of the single-end impedance-based methods.

III. SIMULATION RESULTS AND DISCUSSION

In this work, to conduct the comparative analysis of four single-end impedance-based fault location methods for power transmission lines, a 220kV three-phase overhead transmission line is modeled and simulated in Matlab/Simulink software. The line has the length $L = 100$km with the positive- and zero-sequence line impedances per unit length $Z_{L1} = 0.42\angle 80.31°\Omega$/km and $Z_{L0} = 1.42\angle 81.10°\Omega$/km, respectively. Additionally, its positive- and zero-sequence shunt capacitance per unit length of $C_{L1} = 0.013\mu$F/km; $C_{L0} = 0.0085\mu$F/km. The line is modeled as a distributed parameter model in the well-known Matlab/Simulink software [23], [24]. The two terminals of the line are connected to two sources which are characterized as an ideal constant voltage source behind its inner equivalent impedance. The nominal frequency of the system is 50Hz and its nominal voltage is 220kV. The voltage source of the local source is $E_G = 1.05\angle 10.0°$pu and its equivalent positive- and

zero-sequence impedances are $Z_{G1} = 3.52\angle72.0°\Omega$ and $Z_{G0} = 12.25\angle64.2°\Omega$, respectively. Similarly, the voltage source of the remote source is $E_H = 1.00\angle0.0°$pu and its equivalent positive- and zero-sequence impedances are $Z_{H1} = 12.0\angle70.0°\Omega$ and $Z_{H0} = 25.0\angle63.0°\Omega$, respectively. The power angle is defined by the angle difference between the local source E_G and the remote source E_H. In this studied power system, the power angle is equal to 10.0° for representing the power flow of steady state served by the electric transmission line.

This paper proposes the simulation process schematic as shown in Fig. 3. This testing process consists of two stages. Firstly, the studied power system is prepared to cover all different situations and network circumstances using the Simulink [25]. For each case, the signals of voltage and current waveforms at the local end of the line are extracted and recorded to be fed into the second stage. The second stage runs the impedance-based fault location methods to estimate the distance to fault. For this task, the required codes for signal processing as well as the associated codes for each method are implemented into the Matlab environment [25]–[27]. The red solid lines in Fig. 3 represent the voltage and current signals from the local end and the red dashed lines represent the voltage and current from the remote end. In the proposed process, the signals from two ends of the line are acquired in a central processing unit, however, only voltage and current signals from the local end are utilized to perform the mentioned impedance-based methods. On the other hand, if the users need to determine the distance to fault from the remote end to the fault location, only voltage and current signals of the remote end will be utilized in this case.
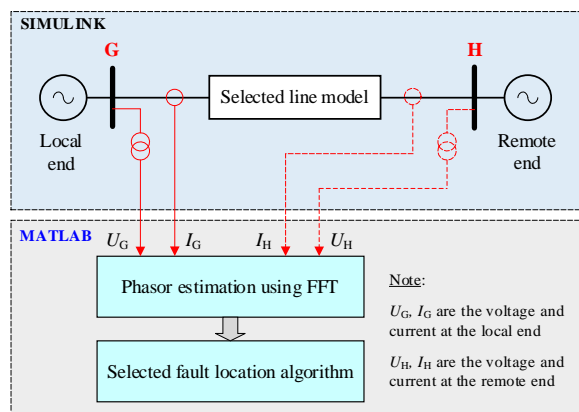

Fig. 3. Simulation process schematic.

To carry out the performance comparison of the impedance-based fault location methods in this paper, the percentage location error is given as the following equation:

$$\text{Error}(\%) = \frac{L_{\text{estimated}} - L_{\text{actual}}}{L}100 \qquad (13)$$

where L_{actual} is the actual line segment length from the local end to the remote end, $L_{\text{estimated}} = mL$ is the estimated line segment length from the local end to the fault location, in which L is the line length and m is the distance from the local end to the fault location.

The model for simulating and analyzing faults in the electric transmission line is established in the Matlab/Simulink software. First, the voltage and current signals of the pre-fault and during fault periods at the local end are generated with a sampling rate of 100kHz, and the signals are simulated for ten cycles (0-0.2sec) with fault inception at 0.1sec. The voltage and current signals are then filtered to remove their DC offset and sub-harmonic components via high-pass filters. Next, the fast Fourier transform [14] is applied with a one-cycle window length of the fundamental frequency to extract the voltage and current phasors and this one-cycle window starts at the time after the fault inception 2 cycles (or 0.04sec). Finally, the single-end impedance-based fault location methods utilize these phasors and the transmission line parameters to estimate the distance to the fault. As an example of the fault voltage and current waveform, the phase A to ground fault located at 60% of the line length from the local end occurs at 0.1sec is shown in Fig. 4. In this figure, Fig. 4 (a) shows the three-phase voltage waveform at the local end, in which the phase A voltage slightly decreases after the fault occurs at 0.1sec and the phase B and phase C voltages are still maintained as their pre-fault values. However, Fig. 4 (b) shows the three-phase current waveform, in which the pre-fault current is responsible for the steady state of the line. On the other hand, after the phase A to ground fault occurs at 0.1sec, the phase A current significantly increases while the phase B and phase C currents are unchanged.
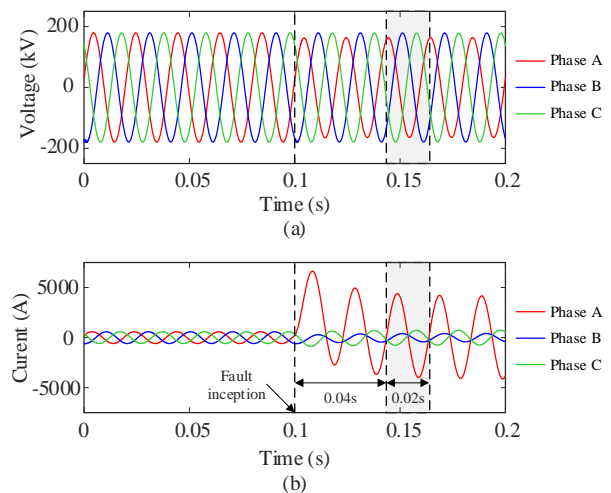

Fig. 4. The voltage and current waveforms at the local end for the phase A to ground fault at 60% of the line length.

The simulation case studies are performed in this work by varying the fault location along the transmission line with various fault resistances to get the voltage and current measurements at the local end. The voltage and current phasors are then calculated for the measurements to determine the distance to the fault according to the impedance-based fault location methods mentioned in this paper. Single-phase to ground faults with various fault resistances are created at the locations along the power transmission line. The simulation results of this case study are clearly shown in Fig. 5. Observing this

figure, the percentage location error of the single-end impedance-based methods depends on the fault location and resistance. The percentage location error of each method is proportional to the actual fault location on the transmission line because of the line capacitance. Besides, the fault resistance is an impact factor on the accuracy of single-end impedance-based fault location methods as shown in Fig. 5. The percentage location error for the single-phase to ground faults with the fault resistance R_F = 0Ω, which is shown in Fig. 5 (a), is the smallest one among the case studies.
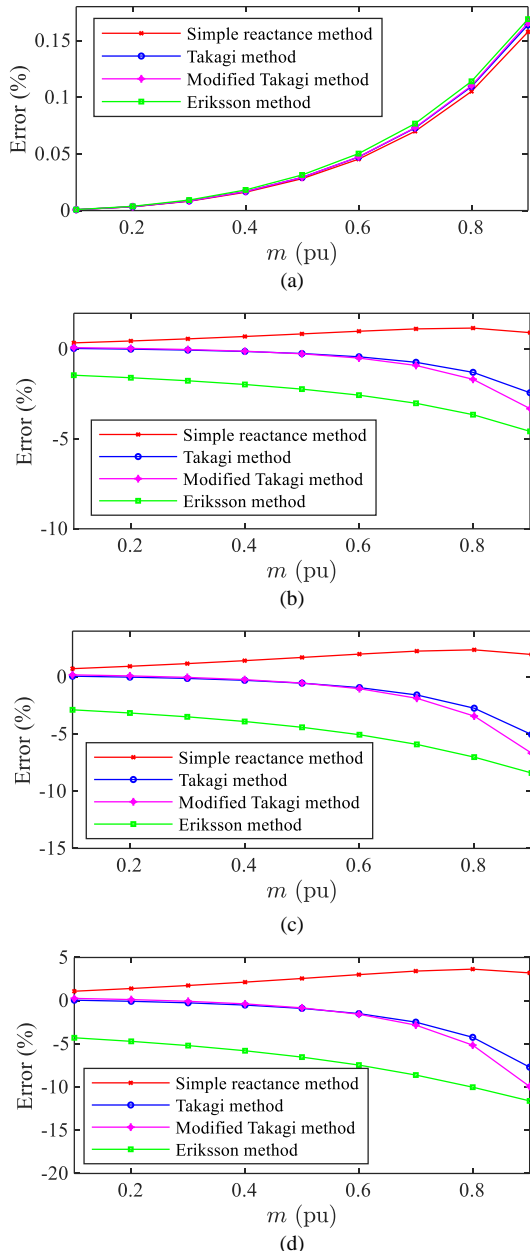

Fig. 5. The percentage location error of four methods for various fault resistances: (a) R_F = 0Ω, (b) R_F = 5Ω, (c) R_F = 10Ω, and (d) R_F = 15Ω.

In the pre-fault stage, the power transmission line is operating under a steady state which is represented by the power angle difference between the local end source and the remote end source. The pre-fault current and power flow of the transmission line depend on the power angle. To investigate the impact of the power angle on the

accuracy of four single-end impedance-based fault location methods above, three values of the power angles including +10°, 0°, and −10° are established in the simulation system in this paper. Besides, for every operating mode according to each power angle, a single-phase to ground fault (LG) is emulated along the line length with a constant fault resistance R_F = 10Ω. The distance to fault of each impedance-based method is estimated and compared with the actual location to calculate the percentage location error as shown in Fig. 6. From this figure, the power angle strongly impacts the accuracy of the simple reactance method as shown in Fig. 6(a). However, the three methods consisting of the Takagi, modified Takagi, and Eriksson methods almost have no impact by the power angle at the steady state of the transmission line.
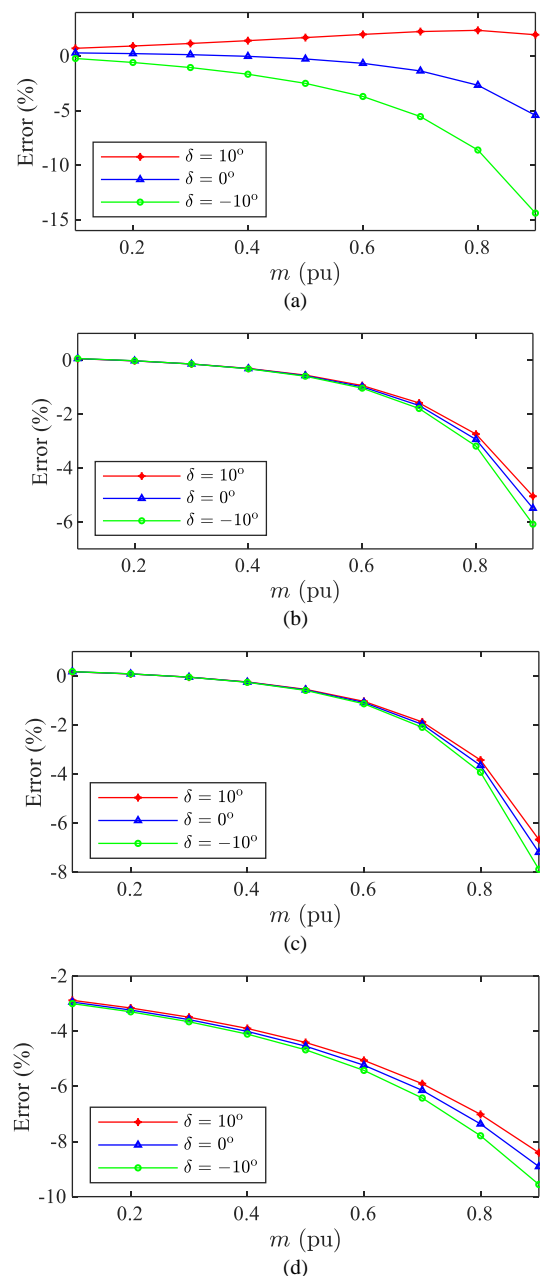

Fig. 6. The impact of the steady state on the accuracy of the methods: (a) Simple reactance method, (b) Takagi method, (c) Modified Takagi method, and (d) Eriksson method.

In addition, to compare the performance of all single-end impedance-based fault location methods for each power angle, the simulation results of percentage location error are shown in Fig. 7. The fault resistance is also set at $R_F = 10\Omega$. Fig. 7(a), Fig. 7(b), and Fig. 7(c) show the fault location performance for the power angle $\delta = +10^o$, $\delta = 0^o$, and $\delta = -10^o$, respectively. In these figures, the absolute values of the error percentages are used to plot these bar charts. Therefore, the performance of impedance-based methods is compared together for each power angle. In this simulation, the power angle is the angle between the local source's voltage (U_G) and the remote source's voltage (U_H). In a practical power system, this power angle in the transmission line depends on a variety of factors such as loads, network parameters, line impedance, etc. However, the authors selected the power angles including $\delta = +10^o$, $\delta = 0^o$, and $\delta = -10^o$ for representing the power flow on the line at the steady state before the time of fault inception $t = 0.1\text{sec}$. These power angles will affect the pre-fault current as shown in Fig. 4b and to the fault location performance of the impedance-based methods. Fig. 7 clearly shows the comparison results between four methods for each power angle.
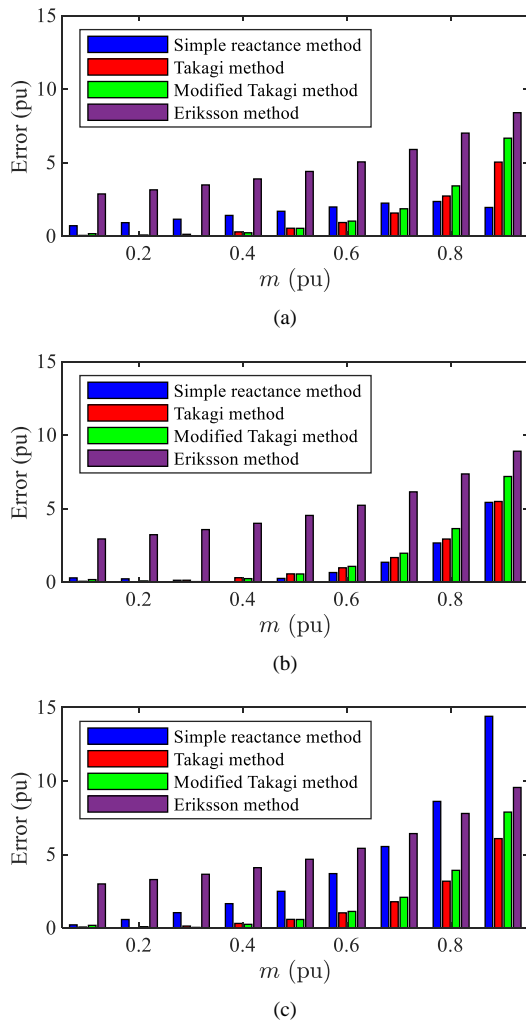

Fig. 7. The performance comparison of the methods for each power angle: (a) $\delta = +10^o$, (b) $\delta = 0^o$, (c) $\delta = -10^o$.

The pre-fault load flow is a factor that affects the performance of the single-end impedance-based fault location methods. The condition of the pre-fault load flow is, therefore, investigated in the studied system. Two situations including no loading and full loading cases are established for the transmission line. For these cases, the phase A to ground fault is assumed that it occurs at 80% of the line length with the fault resistance of 20Ω. The simulation results related to this condition are illustrated in Fig. 8. This figure shows clearly that the Takagi method has the smallest error percentage compared to other methods. The error percentages of the Takagi method are 5.49% and 6.08% for the no loading and full loading cases, respectively. On the other hand, the simple reactance method has the largest error percentage of 13.43% and 14.40% for the no loading and full loading cases, respectively. In addition, these simulation results in Fig. 8 show that the location error difference between the two cases (the no loading and full loading cases) is small, therefore, the loading on the line has almost no impact on the fault location results of the methods.
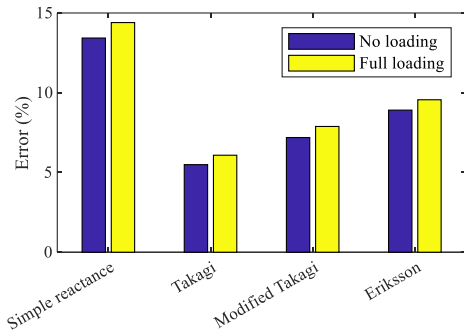

Fig. 8. The fault location performance for the phase A to ground fault at 80% of the line length with the fault resistance of 20Ω.

The performance of the single-end impedance-based fault location methods was studied by other fault types such as phase-to-phase to ground fault (LLG), phase-to-phase fault (LL), and three-phase to ground fault (LLLG). The percentage location errors for different types with the fault resistances $R_F = 0\Omega$ and $R_F = 10\Omega$ are shown in Table I and Table II, respectively. In these tables, the estimated location in per unit and the location error in percent of three methods including the simple reactance, Takagi, and Eriksson methods are presented.

TABLE I: THE PERCENTAGE LOCATION ERRORS FOR DIFFERENT FAULT TYPES WITH THE FAULT RESISTANCE $R_F = 0\Omega$

Fault type	m_{actual} (pu)	Simple reactance method		Takagi method		Eriksson method	
		$m_{estimated}$ (pu)	Error (%)	$m_{estimated}$ (pu)	Error (%)	$m_{estimated}$ (pu)	Error (%)
	0.1	0.100	-0.001	0.100	-0.001	0.100	-0.001
	0.3	0.300	-0.013	0.300	-0.013	0.300	-0.013
LLG	0.5	0.501	-0.058	0.501	-0.059	0.501	-0.060
	0.7	0.702	-0.159	0.702	-0.162	0.702	-0.166
	0.9	0.903	-0.340	0.904	-0.347	0.904	-0.353
	0.1	0.100	-0.001	0.100	-0.001	0.100	-0.001
	0.3	0.300	-0.013	0.300	-0.013	0.300	-0.013
LL	0.5	0.501	-0.058	0.501	-0.059	0.501	-0.060
	0.7	0.702	-0.159	0.702	-0.162	0.702	-0.166
	0.9	0.903	-0.340	0.904	-0.347	0.904	-0.353
	0.1	0.100	0.000	0.100	0.000	0.100	0.000
	0.3	0.300	-0.004	0.300	-0.004	0.300	-0.004
LLLG	0.5	0.500	-0.021	0.500	-0.021	0.500	-0.022
	0.7	0.701	-0.057	0.701	-0.057	0.701	-0.058
	0.9	0.901	-0.103	0.901	-0.106	0.901	-0.107

TABLE II: THE PERCENTAGE LOCATION ERRORS FOR DIFFERENT FAULT TYPES WITH THE FAULT RESISTANCE $R_F = 10\Omega$

Fault type	m_{actual} (pu)	Simple reactance method		Takagi method		Eriksson method	
		$m_{estimated}$ (pu)	Error (%)	$m_{estimated}$ (pu)	Error (%)	$m_{estimated}$ (pu)	Error (%)
LLG	0.1	0.089	1.083	0.098	0.238	0.149	-4.911
	0.3	0.281	1.925	0.300	0.006	0.358	-5.798
	0.5	0.470	3.008	0.505	-0.524	0.571	-7.056
	0.7	0.656	4.402	0.718	-1.834	0.788	-8.801
	0.9	0.841	5.927	0.958	-5.798	0.989	-8.912
LL	0.1	0.089	1.083	0.098	0.098	0.149	-4.911
	0.3	0.281	1.925	0.300	0.300	0.358	-5.798
	0.5	0.470	3.008	0.505	0.505	0.571	-7.056
	0.7	0.656	4.402	0.718	0.718	0.788	-8.801
	0.9	0.841	5.927	0.958	0.958	0.989	-8.870
LLL	0.1	0.090	1.005	0.098	0.157	0.150	-4.987
	0.3	0.282	1.814	0.301	-0.106	0.359	-5.896
	0.5	0.472	2.850	0.507	-0.676	0.572	-7.176
	0.7	0.658	4.156	0.721	-2.050	0.790	-8.955
	0.9	0.846	5.434	0.962	-6.199	0.995	-9.954

The simulation results in this section confirm that the impedance-base fault location methods can be applied to determine the distance to fault in the transmission line, however, their fault location performance depends on the factors including the fault resistance, the fault location, the power angle, and the loading mode. In addition, the input data requirements depend on each method. Because they are all impedance-based fault location methods, the line parameters including the line length, positive- and zero- sequence impedance are required to determine the distance to fault. Besides, all methods also require the fault parameters such as the fault type, fault voltage, and current phasors at the local end of the line. On the other hand, the pre-fault current phasor at the local end is utilized to apply three methods: the Takagi, modified Takagi, and Erikson methods, but it is not necessary for the simple reactance method.

IV. CONCLUSION

A comparative study of the fault location techniques based on single-end impedance-based methods, used in electric transmission lines, has been reviewed in this paper. The numerical simulation case studies are carried out to evaluate the performance of the methods. All single-end impedance-based methods use the fault type, the fault voltage phasor, and the fault current phasor at the local end to calculate the distance to the fault. In addition, the Takagi and Eriksson methods utilize the pre-fault current phasor to compute the fault location. The transmission line parameters including the line length, the positive- and zero-sequence line impedance are utilized by all methods mentioned in this paper. The simulation results show that the simple reactance method is the simplest method of all the fault location methods mentioned in this paper. The fault location accuracy of this method, however, dramatically depends on the fault resistance and location. The performance of the simple reactance method is varied by the power angle at the steady state of the power transmission line. The performance comparisons between the impedance-based fault location methods are studied in the simulation cases, including the pre-fault different power angles and power

flow conditions in the transmission line. It can be concluded that the pre-fault conditions (no loading and full loading) have almost no impact on the fault location results of the methods. Moreover, the Takagi method utilizes the pre-fault current phasor to minimize any reactance error caused by the system load while the modified Takagi and Eriksson methods use the source impedance data to remove any error caused by load and remote source. Therefore, data availability is one of the most key conditions for selecting the most suitable method for fault location in power transmission lines. Finally, the fault data recorded at the fault locator can also be used to determine the fault resistance and current, which are necessary information to identify the root cause of the fault as well as to validate the system modeling parameters.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All authors conducted the research; Mai Vu Cuong, Huynh Quoc Cuong, and Nguyen Truong Tan Hieu conducted the simulation results. Ngo Minh Khoa wrote the paper; all authors had approved the final version.

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REFERENCES

[1] S. A. Daza, *Electric Power System Fundamentals*, Artech House, 2016.

[2] S. W. Blume, *Electric Power System Basics for the Nonelectrical Professional*, John Wiley & Sons, 2016.

[3] C37.114-2014 - IEEE Guide for Determining Fault Location on AC Transmission and Distribution Lines, IEEE Standard, 2014.

[4] S. S. Gururajapathy, H. Mokhlis, and H. A. Illias, "Fault location and detection techniques in power distribution systems with distributed generation: A review," *Renewable and Sustainable Energy Reviews*, vol. 74, pp. 949–958, July 2017.

[5] M. M. Saha, J. J. Izykowski, and E. Rosolowski, *Fault Location on Power Networks*, Springer Science & Business Media, 2009.

[6] Z. Han, S. Li, S. Liu, and S. Gao, "A reactance-based fault location method for overhead lines of AC electrified railway," *IEEE Trans. Power Delivery*, vol. 35, no. 5, pp. 2558–2560, 2020.

[7] J. Barati and A. Doroudi, "Novel modified impedance-based methods for fault location in the presence of a fault current limiter," *Turkish Journal of Electrical Engineering & Computer Sciences*, vol. 26, no. 4, pp. 1881–1893, 2018.

[8] M. Majidi and M. Etezadi-Amoli, "A new fault location technique in smart distribution networks using synchronized/ nonsynchronized measurements," *IEEE Trans. Power Delivery*, vol. 33, no. 3, pp. 1358–1368, 2017.

[9] T. P. S. Bains, T. S. Sidhu, Z. Xu, I. Voloh, and M. R. D. Zadeh, "Impedance-based fault location algorithm for ground faults in series-capacitor-compensated transmission lines," *IEEE Trans. Power Delivery*, vol. 33, no. 1, pp. 189–199, 2017.

[10] M. Nemati, M. Bigdeli, and A. Ghorbani, "Impedance-based fault location algorithm for double-circuit transmission lines using

single-end data," *Journal of Control, Automation and Electrical Systems*, vol. 31, no. 5, pp. 1267–1277, 2020.

[11] S. Roostaee, M. S. Thomas, and S. Mehfuz, "Experimental studies on impedance based fault location for long transmission lines," *Protection and Control of Modern Power Systems*, vol. 2, no. 1, pp. 1–9, 2017.

[12] J. Mora-Florez, J. Meléndez, and G. Carrillo-Caicedo, "Comparison of impedance based fault location methods for power distribution systems," *Electric Power Systems Research*, vol. 78, no. 4, pp. 657–666, 2008.

[13] J. Liang, T. Jing, H. Niu, and J. Wang, "Two-terminal fault location method of distribution network based on adaptive convolution neural network," *IEEE Access*, vol. 8, pp. 54035–54043, Mar. 2020.

[14] K. Jia, D. Thomas, and M. Sumner, "A new single-ended fault-location scheme for utilization in an integrated power system," *IEEE Trans. Power Delivery*, vol. 28, no. 1, pp. 38–46, 2012.

[15] M. R. Mosavi and A. Tabatabaei, "Traveling-wave fault location techniques in power system based on wavelet analysis and neural network using GPS timing," *Wireless Personal Communications*, vol. 86, no. 2, pp. 835–850, 2016.

[16] R. L. A. Reis, F. V. Lopes, W. L. A. Neves, D. Fernandes Jr, C. M. S. Ribeiro, and G. A. Cunha, "An improved single-ended correlation-based fault location technique using traveling waves," *International Journal of Electrical Power & Energy Systems*, vol. 132, Nov. 2021.

[17] Z. S. Chafi and H. Afrakhte, "Wide area fault location on transmission systems using synchronized/unsynchronized voltage/current measurements," *Electric Power Systems Research*, vol. 197, Aug. 2021.

[18] N. M. Khoa and D. D. Tung, "Locating fault on transmission line with static var compensator based on phasor measurement unit," *Energies*, vol. 11, no. 9, p. 2380, 2018.

[19] S. Sawai, R. N. Gore, and O. D. Naidu, "Novel traveling wave phase component-based fault location of transmission lines," presented at 2020 IEEE International Conference on Power Electronics, Drives and Energy Systems, Jaipur, India, March 2021.

[20] S. Das, S. Santoso, A. Gaikwad, and M. Patel, "Impedance-based fault location in transmission networks: Theory and application," *IEEE Access*, vol. 2, pp. 537–557, May 2014.

[21] T. Takagi, Y. Yamakoshi, J. Baba, K. Uemura, and T. Sakaguchi, "A new algorithm of an accurate fault location for EHV/UHV transmission lines: Part I - Fourier transformation method," *IEEE Trans. Power Apparatus and Systems*, PAS-100, no. 3, pp. 1316–1323, 1981.

[22] T. Takagi, Y. Yamakoshi, M. Yamaura, R. Kondow, and T. Matsushima, "Development of a new type fault locator using the one-terminal voltage and current data," *IEEE Trans. Power Apparatus and Systems*, vol. PAS-101, no. 8, pp. 2892–2898, 1982.

[23] A. Gopalakrishnan, M. Kezunovic, S. M. McKenna, and D. M. Hamai, "Fault location using the distributed parameter transmission line model," *IEEE Trans. Power Delivery*, vol. 15, no. 4, pp. 1169–1174, 2000.

[24] N. M. Khoa and D. D. Tung, "Modeling for development of simulation tool: Impact of TCSC on apparent impedance seen by distance relay," *Engineering, Technology & Applied Science Research*, vol. 8, no. 5, pp. 3332–3337, 2018.

[25] G. Ren, "MATLAB/Simulink-based simulation and experimental validation of a novel energy storage system to a new type of linear engine for alternative energy vehicle applications," *IEEE Trans. Power Electronics*, vol. 33, no. 10, pp. 8683–8694, 2018.

[26] V. F. Pires, L. S. Martins, T. G. Amaral, R. Marcal, R. Rodrigues, and M. M. Crisostomo, "Distance-Learning power-system protection based on testing protective relays," *IEEE Trans. Industrial Electronics*, vol. 55, no. 6, pp. 2433–2438, 2008.

[27] D. K. Ibrahim, G. M. Abo-Hamad, E. E. M. A. Zahab, and A.F. Zobaa, "Comprehensive analysis of the impact of the TCSC on distance relays in interconnected transmission networks," *IEEE Access*, vol. 8, pp. 228315–228325, Dec. 2020.

Ngo Minh Khoa was born in Binh Dinh, Vietnam in 1983. He received both the M.Sc. degree and the Ph.D. degree in Electrical Engineering from The University of Danang - University of Science and Technology, Vietnam, in 2010 and 2017, respectively. He is currently a lecturer in the Faculty of Engineering and Technology, Quy Nhon University, Binh Dinh, Vietnam. His current research interests include power system stability, protection relay, power quality improvement, renewable energy, and smart grid.

Mai Vu Cuong was born in Kon Tum, Vietnam in 2000. He is currently an undergraduate student in Electrical Engineering at the Faculty of Engineering and Technology, Quy Nhon University, Quy Nhon City, Binh Dinh, Vietnam. His current research interests include protection relay, smart grid, renewable energy resources, and voltage stability.

Huynh Quoc Cuong was born in Binh Dinh, Vietnam in 2000. He is currently an undergraduate student Electrical Engineering at the Faculty of Engineering and Technology, Quy Nhon University, Quy Nhon City, Binh Dinh, Vietnam. His current research interests include protection relay, power system stability, and volt/var control and optimization.

Nguyen Truong Tan Hieu was born in Binh Dinh, Vietnam in 1999. He is currently an undergraduate student Electrical Engineering at the Faculty of Engineering and Technology, Quy Nhon University, Quy Nhon City, Binh Dinh, Vietnam. His current research interests include protection relay, renewable energy, smart grid, and Internet of Things.