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Advances in Transmission Network Fault Location in Modern Power Systems: Review, Outlook and Future Works

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ABSTRACT Faults in the power system need appropriate maintenance actions at the fault point to fix the problem immediately. A high percentage of the short circuit faults in power systems occur on the transmission system where the lines pass through different harsh climates and experience outdoor environmental conditions. The repairing procedure of the faulty line requires determining the accurate fault location. Fast and accurate fault location of transmission networks play an important role in modern power systems to improve the system reliability and stability. A fault locator is an apparatus that determines the location of the fault in the transmission system by acquiring the proper measured quantities, i.e. the voltages and currents at the lines terminals. As such, the utilities can repair and fix the problem rapidly after determining the location of the fault using the analytical and numerical methods provided in fault locators. This research explores various fault location techniques of transmission networks in detail as a vital requirement for operating the modern power system more secure and reliable. In this survey, different new methods of fault location such as i) distance relay algorithm, ii) traveling wave, iii) artificial intelligence, iv) wide-area, v) time reversal theory, vi) differential equations, and vii) impedance calculation methods are reviewed and investigated to illustrate their pros and cons inaccurate fault location for complex modern power networks. In addition, these methods are assessed to compare their requirements, abilities and shortcomings. Moreover, using the provided extensive analysis in the paper, and based on the useful experiences of the authors, some beneficial topics and suggestions are proposed for future works and improved algorithms in the field of fault location.

INDEX TERMS Fault location, impedance-based method, transmission lines, traveling-wave.

I. INTRODUCTION

Generally, rapid and accurate fault location of transmission networks play a crucial role in modern power systems for two main reasons. Firstly, the tear and wear of the power system lines which are constantly in the operation mode. Their prolonged maintenance leads to partial load shedding and may direct the system to a blackout. In second, the effects of fault occurrence in a part of the system are not limited and bounded to a specific area of the system and other parts are

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also affected during this event. Therefore, if a fault occurs on the transmission system and is not located and repaired fast, the whole system will be threatened and may even fail due to facing serious problems for the entire network [1].

One of the challenging events that threatens the power system is short circuit fault that may occur for any equipment. During the occurrence of a short circuit fault in equipment, in order to prevent extra damage to it and to stop spreading the fault to other devices, the protective relays are responsible for fault detection and identification. After detecting the fault, the associated relay issues the trip command to the breakers of the faulty section and that section will be disconnected

from the network. If the protection system does not operate correctly, the faulty zone can be expanded and this may even result in a system instability and blackout [2]. After removing and isolating the faulty part from the rest of the system, it should be located and repaired quickly.

The power transmission system constitutes a considerable part of the power system. Since transmission lines pass through different climatic conditions, the short circuit fault rate is higher in the lines than that in other power system equipment and components. In [3] the transmission system faults rates are investigated considering various factors. Transmission lines short circuit faults have different causes; some of them can be listed as [4]: i) lightning strike, ii) snow and ice on the line, iii) inappropriate insulation, iv) falling trees on the lines, v) birds' collision with the lines, vi) severe wind (storm), vii) fog, viii) falling power towers and ix) wire ripping.

Transmission lines short circuit faults can be divided into two main types, transient and permanent ones. Transient faults are diminished after detecting them by the protective relays and opening the breakers temporarily. For instance, collision of a bird to the phases of transmission lines is considered as a transient fault. In this case, the recloser logic will be used and the breaker will be closed again after a short delay when the fault has been cleared. In this case, the line will be returned back to the system quickly by reconnecting it [5].

Transmission line wire tearing and tower breaking are among the permanent faults. For these faults, the fault will still persist after reclosing operation and finally, after the unsuccessful operation of the recloser, the breakers will be opened permanently. Thereafter, this fault needs to be located accurately and fixed by the repair crew as soon as possible. Albeit, transient faults can also be located by appropriate algorithms to check the line condition and fix any undesirable problem.

During the past few decades, due to various factors, e.g. the ever increasing load demands in the system, power system restructuring and privatization, and the very high cost of building new transmission lines along with the limited resources, has led to operate the transmission system in the adjacency of its permissible full load operating point [6]. When a fault occurs in a transmission line and the line is separated from the rest of the network, its loading will be transferred to other lines. The remaining lines may become overloaded in turn, which can endanger system security and stability. On the other hand, increasing system security and reliability are vital in modern power systems due to presence of more important and sensitive loads. Consequently, the faulty line should be repaired and restored to the system as soon as possible to return the system to the normal operating condition.

Clearing the transmission system faults includes two main processes. In the first step, the location of the fault should be determined and in the next step, the repairing crews must fix the faulty line. During the previous decades, the fault location

process was mainly performed by the operators visual check. Whereas, the length of the transmission line can be reached to hundreds of kilometers and this fault location process will become a tough and costly task. In addition, the location of the fault cannot be determined by observing the line condition in some inaccessible cases. In such conditions, the detection time may be increased and a significant part of the system will be left de-energized.

A fault locator is an apparatus that determines the location of the fault in the transmission system by acquiring the proper measured quantities, i.e. the voltages and currents at the lines terminals. As such, the utilities can repair and fix the problem faster after determining the location of the fault using the analytical and numerical methods provided in fault locators [7]. Although the main application of the fault location methods can be considered to determine the location of the permanent short circuit faults, they can be also implemented for the transient type faults. Determining the fault location for transient faults can help utilities to fix the problem and prevent repeated occurrence of the fault in the future.

In this paper, various research works performed in the fault location area have been outlined and compared. The fault location literature has divided the fault location methods into the following categories and methods: i) distance relay algorithm, ii) traveling wave, iii) artificial intelligence, iv) wide-area, v) time reversal theory, vi) differential equations, vii) impedance calculation and viii) heuristic algorithm.

In addition, the fault location methods can also be divided into two-terminal and multi-terminal fault location with regard to the configuration of the system. Another category has been presented based on the input data of the fault location methods. In this approach, the presented methods can be classified into those that use one, two and other far terminals measured data. These methods are described in the following sections. Moreover, using the provided extensive analysis in the paper, and based on the vast experiences of the authors, some useful topics and suggestions are suggested for future works in the field of fault location.

II. DISTANCE RELAY ALGORITHM

Protecting the transmission system has been one of the most critical issues in power systems from the past decades. One of the transmission systems well-recognized protection schemes is distance protection relay, which includes three phase to phase units and three phase to ground units. Distance relays calculate the distance between the relaying point and fault point, i.e. the location of the fault, using these six units as illustrated in Fig. 1 [7], [8].

Various improved distance relays algorithms are proposed in the literature to improve its operational speed [9], [10]. In addition, more advanced approaches are suggested to upgrade distance protection performance. For example, a few advanced distance relay characteristics suitable for dynamic loading which are not affected by load impedance are proposed in [11]. Some advanced distance relay testing methods

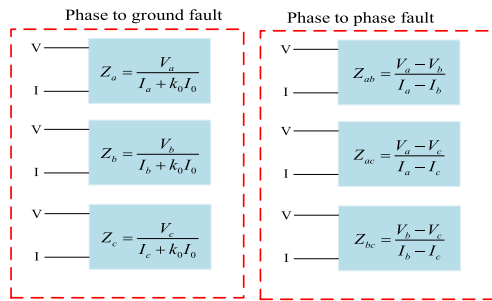


FIGURE 1. Six calculation units of distance relays.

using IEC 61850 are proposed in [12] to improve the reliability of relay operation.

Fault location using the distance relay algorithm has been broadly used in the utilities for many years, though the main function of distance relays is to protect the transmission line against short circuit faults. If the fault resistance is taken into account, the calculated line impedance (distance to the fault point) can be accompanied by a high error [13]. For the two-terminal lines fed from both sides, the effect of fault resistance is intensified and fault location error can be increased considerably. In this case, fault impedance can include inductive/capacitive elements as well. This can further complicate distance relay calculations. Also, the fault location error will be increased when dynamic motor loads are present in the grid [11].

For a practical three-terminal network, fault location error can be increased even up to the high value of 250% due to the infeed effect and fault resistance. As such, growing interests and needs to reduce the power interruptions stimulated the researchers to present more efficient fault location methods with higher accuracy to be able to repair the line faster and to return it to the service sooner.

III. TRAVELING WAVE-BASED FAULT LOCATION

One of the most common methods in calculating the location of the fault is using the concept of the traveling waves. Abrupt changes of voltage signal at the fault point results in manifestation of transient waves, which travel with the velocity of the photon in the line [14]–[16].

If the traveling waves become detected at each terminal, the fault location can be calculated considering the traveled time from the fault point to the terminal (relaying point). Traveling waves are high-frequency waves that should be distinguished from the main component 50Hz (or 60Hz) power system frequency [17]. Some of the methods that can be used to extract the high-frequency components of the signals are listed as: i) wavelet transform, ii) S-transform iii), TT-transform and iv) HS-transform [18]–[21].

The traditional traveling wave-based fault location method determines the location of the fault with an accuracy of 150-300 meters [22]. It should be noticed that some circumstances are prerequisites of the fault location using the traveling wave method to achieve high accuracy. These are described in the following.

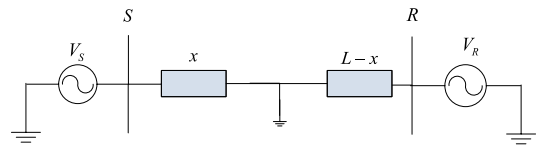


FIGURE 2. Traveling wave-based fault location using two-terminal data [19].

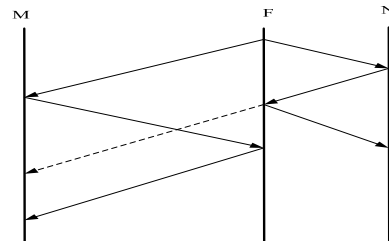


FIGURE 3. Disposition pattern of the traveling wave after occurrence of a short circuit fault [23].

A. TRAVELING WAVE-BASED FAULT LOCATION FOR AC SYSTEMS

The fault location using the traveling wave concept can be performed using one- or two-terminal measured data. Fault location using two-terminal data is described in [19]. Fig. 2 shows the single line diagram of a transmission line while a short circuit fault occurs at the location of x (in p.u.) from the terminal S. It can be seen that the traveling waves begin to travel from the fault point to the both ends of the line at terminals S and R. Therefore, these signals can be detected at both terminals. It is assumed that the measured data at the two terminals are synchronized with each other. Hence, the detection times at terminals S (t_1) and R (t_2) can be calculated using (1) and (2).

$$t_1 = \frac{L - x}{v} \tag{1}$$

$$t_2 = \frac{x}{v} \tag{2}$$

where L and v are the length of the line and the velocity of the traveling wave, respectively. By subtracting (2) from (1), the location of the fault can be obtained as follows:

$$x = \frac{L - v \times (t_2 - t_1)}{2} \tag{3}$$

One of the drawbacks of the traveling wave-based methods is using both terminals synchronized data. Considering the high traveling velocity of the waves, the errors of their detection at the terminals and calculating the exact times are somehow high. Moreover, the accuracy of these methods also depends on the precision of measuring synchronized data from the terminals. If the traveling wave velocity and the error in synchronizing the data are assumed to be $3 \times 10^8 \frac{m}{s}$ and $10\mu s$, respectively, the error of this method can be calculated as follows:

$$\text{Error} = c \times \Delta t = 3 \times 10^8 \times 10 \times 10^{-6} = 3000m \tag{4}$$

The traveling fault location using only one terminal data has been presented in [23], [24]. For the presented method

in [23], if a fault occurs at the point F between the two terminals M and N, the pattern of moving these waves is depicted in Fig. 3. After the emergence of a traveling wave, it moves toward one terminal, and then it will be reflected and moves in a counter direction and returns back to the fault point. Then at the fault point, some part of the wave travels forward to reach the other terminal and the remaining part moves back to the terminal. This disposition is continued until the energy of the wave is damped in the line. By considering only one complete sweep through the line, the fault location can be calculated using (5).

$$D_{MF} = \frac{v \times (\Delta t)}{2} \quad (5)$$

where Δt and D_{MF} are the sweep time between terminals M and N and fault location, respectively. If the transmission line is splitted at a point between the terminals M and N, a third terminal will be emerged and this method will become more complex in such conditions. In addition, the distinction between the received waves from the fault point and those due to the reflection of the wave in other terminals is an arduous task. Some challenges and algorithms for fault location in compensated transmission lines are studied in [25].

B. TRAVELING WAVE-BASED FAULT LOCATION FOR DC SYSTEMS

The fault location using the traveling waves is also developed for DC transmission systems. In [26] a fault location method based on the traveling wave concept is presented for multi-terminal DC transmission systems. The high-frequency components of the signal are extracted using the sampling frequency of 10MHz. This approach consists of two off-line and on-line stages and the fault location and the faulty section (segment) are determined appropriately.

In [27], an approach to estimate the fault location in MTDC grids has been suggested which uses optically-based DC current measurement and continuous wavelet transform. To apply this method in practice, optical current transformers must be installed on all terminals of the grid as additional devices. These kinds of sensors are too expensive and limit application of this method in the real world.

The fault location based on the two-ended approach can be applied when the measured signals from both ends of the faulty segment are available. It is worth stating that the utilized optical sensor scheme can gather all sensors' data from a single acquisition point, and thus the measurements can be synchronized without the need for global positioning system (GPS) (i.e. the time intervals from all sensors are available and can be easily calculated). If the left side of the hybrid transmission media is considered as a reference, the fault location can be calculated as follows:

$$D_F = \frac{L_{seg} - \Delta t(Sup - Sdn)v_{prop}}{2} \quad (6)$$

In Fig. 4 the process of identifying two outputs Sdn and Sup which is related to the two neighbor sensors, one downstream and one upstream with respect to the fault (SB and SA) has

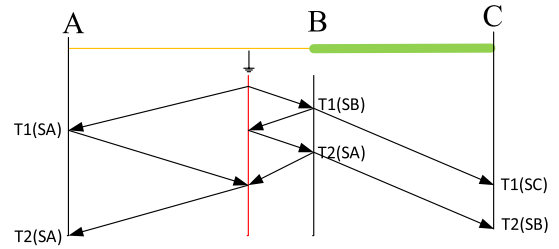


FIGURE 4. Diagram for fault location of [27].

been depicted. Here, the distance between SUP and the fault point is denoted by D_F (estimated based on the measurements of both sensors Sdn and Sup), $\Delta t(S_{UP} - S_{DN})$ is the time difference of the initial TWs at sensing locations Sup and Sdn , L_{seg} is the total length of the faulty segment, and v_{prop} is the propagation velocity in the faulty segment.

Authors in [28] present a fault location method for paralleled MTDC transmission lines based on the traveling wave theory. Using the transient characteristics of fault current and wavelet transform, a method has been suggested in [29] to locate faults for MTDC networks. High-frequency components of voltage and current generated by the traveling waves are used for fault detection and location in HVDC grids [30].

In addition, there are more performed studies for the protection and fault location of LCC-DC transmission systems using the traveling wave theory [31]–[34]. An off-line fault location technique has been presented in [35] using the time-frequency domain reflectometry method for HVDC submarine cables.

Fault location of HVDC transmission lines using the Rogowski coil-based electronic current transformer (R-ECT) has been introduced in [36]. This method investigates the high-frequency traveling wave transfer capability for fault location.

Sometimes the traveling waves are intentionally generated using appropriate equipment at the terminal to detect the fault location based on the reflection of the emitted waves. A fault location algorithm is proposed in [36] for the VSC-HVDC systems using active pulse generation and detecting the arrival time of the generated pulse.

C. TRAVELING WAVE-BASED FAULT LOCATION DISADVANTAGES

The frequency of the traveling waves is between 10 to 600 kHz and hence detection of these waveforms needs high accurate devices with high sampling rates. For instance, the sampling frequency of 1 and 7 MHz has been used in [23] and [22], respectively. In order to provide a high sampling frequency, specific apparatus should be used and implemented which increases the complexity of the detection.

As aforementioned, abrupt changes in the voltage at the fault point causes to generate traveling waves. If the fault occurs at the zero-crossing time of the voltage signal, the traveling waves cannot be emerged by the fault inception. However, if the fault occurs at the peak value of the voltage

signal, the traveling waves with high-frequency components are added to the signal after the fault occurs as shown in Fig. 5.

Fig. 6 demonstrates the measured voltage signal when a fault occurs at the zero crossings instant. It can be seen that high-frequency component signals will not appear in this situation. To sum up, the main disadvantages of the traveling wave-based fault location methods can be summarized as follows:

- The frequency response of magnetic voltage and current transformers (CTs) distort the traveling waves after passing the signals, hence their accuracy can be worsened in practice.
- For the near faults to the terminals, sweep time is too short to detect them easily.
- Complex and costly equipment and hardware are required to detect and process the very fast changing travelling waves.
- The distinction of the received wave from the fault point and the received wave reflected from other terminals is an arduous task with a high level of complexity.

IV. ARTIFICIAL INTELLIGENCE APPROACHES TO FAULT LOCATION

Due to uncertainty of the line parameters and fault resistance, impedance calculation and traveling wave-based fault location methods confront the problem of low accuracy, particularly in the case of complex network configurations. Hence, the demand of using artificial intelligence (AI) algorithms is increasing among researchers in recent years [37], [38]. In general, the AI-based fault location methods usually need to acquire and know the breakers status, electrical variables, weather information and the relay data at a different point in the system as the input. Three main AI-based algorithms have been broadly used in power system problems as listed below:

- System-specific procedures: these methods are often used in the automation and control procedures of the system and can be used for setting the protection relay.
- Artificial neural networks: these methods are used in engineering dilemmas for clustering and optimization problems. The ability of these methods in the learning of complex patterns has made these methods as appropriate tools to apply them in fault location problems. Fault location using these methods need some information of electrical variables such as measured voltage and current signals and also information about network configuration such as the status of the breakers and feeders for the learning stage.
- Fuzzy logic systems: these methods can be used when the system status and measured electrical variables information are not available accurately.

Generally, AI-based fault location methods are often applicable when several pieces of information are available as their inputs. In addition, the computational burdens of these methods for training and computation are somehow high and

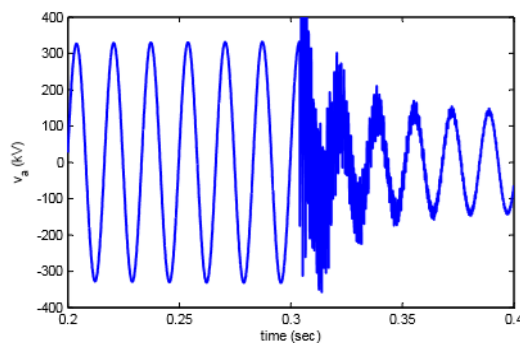


FIGURE 5. Voltage signal for a fault occurred at the peak point.

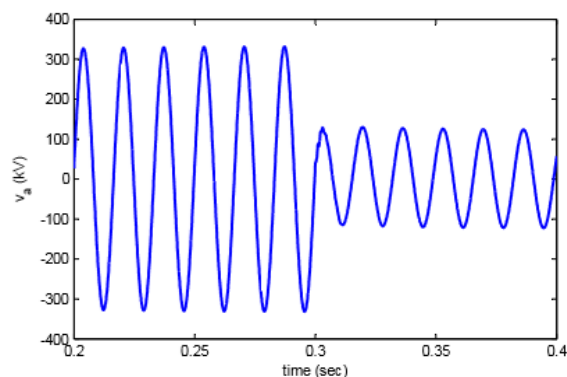


FIGURE 6. Voltage signal for a fault occurred at the zero point.

often need specific high-speed microprocessors. The data gathering process may require a wide communication system with high bandwidth to collect the synchronized information in a central server. The black-box behavior of these methods is unfavorable for most of the engineers. Hence, applying AI-based algorithms for the application of fault location becomes impractical in most cases.

Several DC systems fault location methods have been proposed recently based on signal processing and machine learning techniques. One-dimensional convolutional neural network approach and empirical decomposition have been utilized in [39] to calculate the fault location. A continuous wavelet transform (WT) is used in [27] for the current signals to improve the accuracy of the traveling-wave fault location method. In [40], the artificial neural network has been employed for finding and training a relationship between the fault location and post-fault voltage in the DC systems. Machine learning approaches and off-line continuous WT are used to calculate the fault location in [41] using the current signals in DC systems. In [42] the frequency spectrum of current signals of DC cable is obtained using the Hilbert-Huang transform, and then the fault location is determined using the captured energy in each frequency. Other methods to estimate the fault location in DC systems based on machine learning and signal processing approach are presented in [43]–[46].

An approach based on the similarity of the voltage signal is suggested to estimate the fault location in HVDC

transmission lines [46]. Pearson correlation coefficient is used to measure the similarity in this work. However, the studied system in this survey is based on the LCC-HVDC grids and does not include VSC-MTDC networks.

Fault location in AC distribution systems has been investigated in [47]. In this work, the fault location is determined using a hybrid method while a wind farm is present in the grid. Samples of one cycle of the post-fault current waveform are used at the connection point of the distributed generators. The wavelet transform was used to decompose the samples and extracting six statistical features by reconstructing the detail coefficients of the current signal.

In [48], a fault location method for two-terminal lines is presented using the artificial intelligence approach. The accuracy of this method is acceptable for high resistance faults. In [49], artificial intelligence and information theory are used for fault locating on the overhead lines.

V. WIDE-AREA FAULT LOCATION

Most of the fault location methods just use the data of the faulty line for calculating the location of the fault, while the wide-area fault location methods are based on the measured electrical variable of other lines of the system as well. The phasor measurement units (PMUs) are used to collect the measured synchronized values of the voltages and currents at other system buses. Afterward, the wide-area fault location methods use the data of the PMUs to determine the accurate location of the fault.

During the fault occurrence, the faulty line current transformer may be saturated or the voltage transformer may confront fluctuations. However, the current transformer of the terminals farther from the faulty zone usually is not saturated and the measured voltages do not fluctuate severely. Therefore, one of the important advantages of the wide-area fault location methods is using the measured voltage and current of the healthy lines, which contain less error and deterioration.

One of the wide-area fault location approaches is the simulation-based methods [50], [51]. In this approach, the power system is modeled and simulated in appropriate software with extensive case studies including different investigations of fault occurrence at several locations and with different fault resistances. As such, the location of the fault can be determined in practice when the measured signals are similar to those of the studied cases [52]. These methods should be considered in the similar operation point conditions when comparing the system outputs and the simulation results. Hence, numerous simulations should be conducted in every operational condition. This is the most important drawback of this wide-area fault location method.

In [53], [54] the traveling wave detection is used for wide-area fault location. The aforementioned obstacles and disadvantages are also present in these methods. In addition, if the farther measured data of terminals is used for fault location, the possibility of interfering with the traveling waves and their reflection is very high. Furthermore, traveling waves are attenuated by moving toward the far terminals.

A wide-area fault location method based on calculating the impedance has been used in [55], [56]. As noted before, the synchronized PMU data are used in the wide-area fault location methods, and hence these methods are inapplicable when a system is not equipped with PMUs.

Some methods for fault location of transmission lines, identification of faulted line, type of fault, and identification of faulty phase are presented in [57]. The state estimation formulation has been extended and modified in this method. Hence, this approach can be applied for both symmetrical and asymmetrical networks and all types of fault. In [58] the location of the fault is determined using the measured buses voltages and the admittance matrix of the system. In [59] fault location in MTDC network is presented using all sheath currents of the conductors. Recently, the integration of renewable resources is increasing and their high capacity forces to connect them to the transmission system. Fault location in such circumstances is discussed in [59] as an important issue in the field of research.

Also [60] uses low frequency components of voltages and currents of the terminals to calculate the fault location. As low frequency components are used, it is not required to use complex and costly instruments to catch the information of high frequency components. A current limiter has been considered in [59], [60] for fault mitigation. It was found that the fault location is estimated accurately even in presence of current limiting function.

In [61] a novel fault location method based on phasor measurement units (PMUs) for series compensated lines has been presented. Appropriate model of the series device and its operation mode are not considered in this method during the fault period. This algorithm uses a two-stage method; the first stage, and the correction stage to calculate the voltage drop and the fault location, respectively.

VI. TIME REVERSAL THEORY

Time reversal theory measures the high frequency signals and analyzes them. For the first time, this method was used in the phonemics applications, and it has been recently developed to calculate the fault location in power systems [62]. The time in the fault location equations is reversed (multiplied by -1) and new equations are achieved in this method. For instance, by throwing a stone in the water, the transient waves will be started to travel away from the dropped point. Hence, by inverting the time and pursuing the accosting waves, the thrown location of the stone is achieved.

When a fault occurs in the system, a related transient is generated. This transient moves from the fault point toward the terminals. In some of the terminals or all of them, this transient is sensed and measured. Next, the related equations for the transient are derived. Then the time in these equations will be reversed and the point that the signals are converged to it or have the highest energy is determined as the fault location point [62].

The fault location for AC/DC networks using time reversal method has been introduced in [63]. The line losses are

neglected in most of the fault location algorithms based on the time reversal theory, while a new algorithm has been presented in [64] to model the line losses in the fault location. In [65] fault location is calculated using only one terminal measurement. High sampling devices are required in this method, which restricts its application in practice due to the high cost. In addition, transient signals might be distorted due to the low accuracy of capacitive voltage transformers (CVTs) for measuring this high frequency transient component. Consequently, the calculated fault location method contains some error restricting application of the time reversal-based fault location algorithms.

VII. FAULT LOCATION USING DIFFERENTIAL EQUATIONS

One other fault location methods uses transient state equations of transmission lines. In this method, time-domain signals are used directly, without the need for any special signal processing to remove or extract some of the signal components [66], [67].

In [68]–[70] the differential equations are used to calculate the location of the fault. Based on the presented method in [68], the relation between voltage and current can be written as follows:

$$v(t) = R \times i(t) + L \times \frac{di(t)}{dt} \quad (7)$$

where $v(t)$ and $i(t)$ are the measured voltage and current of the line at the sending end, respectively. R and L are resistance and inductance of the portion of the faulty line between the sending end and the fault point, respectively. The fault resistance is assumed to be zero in (7).

By writing equation (7) for two different snapshots, the following relations can be obtained:

$$\int_{t_0}^{t_1} v(t)dt = R \times \int_{t_0}^{t_1} i(t) + L \times [i(t_1) - i(t_0)] \quad (8)$$

$$\int_{t_1}^{t_2} v(t)dt = R \times \int_{t_1}^{t_2} i(t) + L \times [i(t_2) - i(t_1)] \quad (9)$$

The integral form of the voltage can be represented as follows:

$$\int_{t_0}^{t_1} v(t)dt = \frac{\Delta t}{2} \times [v(t_1) + v(t_0)] = \frac{\Delta t}{2} \times (v_1 + v_0) \quad (10)$$

Similarly, all of the integral forms in (8) and (9) can be rewritten and the obtained equations can be presented in the matrix form as follows:

$$\begin{bmatrix} \frac{\Delta t}{2} \times (i_{k+1} + i_k) & i_{k+1} - i_k \\ \frac{\Delta t}{2} \times (i_{k+2} + i_{k+1}) & i_{k+2} - i_{k+1} \end{bmatrix} \begin{bmatrix} R \\ L \end{bmatrix} = \begin{bmatrix} \frac{\Delta t}{2} \times (V_{k+1} + V_k) \\ \frac{\Delta t}{2} \times (V_{k+2} + V_{k+1}) \end{bmatrix} \quad (11)$$

By solving equation (11) the impedance between the sending terminal and the fault point can be calculated using

three sampling points. The accuracy of the algorithm can be enhanced by increasing the number of samples say to six samples. The calculation time will be increased slightly and the location of the fault can be determined as follows:

$$\begin{bmatrix} \frac{\Delta t}{2} \times (i_{k+1} + i_k) & i_{k+1} - i_k \\ \frac{\Delta t}{2} \times (i_{k+2} + i_{k+1}) & i_{k+2} - i_{k+1} \\ \frac{\Delta t}{2} \times (i_{k+3} + i_{k+2}) & i_{k+3} - i_{k+2} \\ \frac{\Delta t}{2} \times (i_{k+4} + i_{k+3}) & i_{k+4} - i_{k+3} \\ \frac{\Delta t}{2} \times (i_{k+5} + i_{k+4}) & i_{k+5} - i_{k+4} \end{bmatrix} \begin{bmatrix} R \\ L \end{bmatrix} = \begin{bmatrix} \frac{\Delta t}{2} \times (V_{k+1} + V_k) \\ \frac{\Delta t}{2} \times (V_{k+2} + V_{k+1}) \\ \frac{\Delta t}{2} \times (V_{k+3} + V_{k+2}) \\ \frac{\Delta t}{2} \times (V_{k+4} + V_{k+3}) \\ \frac{\Delta t}{2} \times (V_{k+5} + V_{k+4}) \end{bmatrix} \quad (12)$$

One of the drawbacks of this approach is that the fault resistance is ignored. In addition, this method is somehow sensitive to the noise and its accuracy can be diminished due to the derivative form of the applied equations. Also, harmonics can affect the algorithm and increase the error of the obtained fault location.

In [71], differential equations are used to estimate the fault location in series compensated transmission lines. In this method transmission lines are modeled using distributed time-domain model. The suggested algorithm consists of two steps, one for the case that the fault is located behind the series compensator and another for the fault in front of it. The current and voltage samples at both ends of the line are assumed to be synchronized in this method. It is worth stating that the method is independent of fault resistance value and does not require to have the amount of source impedance.

VIII. FAULT LOCATION BASED ON IMPEDANCE CALCULATION

In this method, the phasors of current and voltage signals are calculated and the equations are expressed in the frequency domain. There are various long-window and short-window algorithms to estimate the current and voltage phasors, such as least-squares error (LSE), Fourier, Man-Morrison, and so on. The most famous one is the Fourier algorithm which is used due to its superior performance in eliminating annoying harmonics [72]–[76]. In the Fourier method, the measured samples are multiplied by two orthogonal sine and cosine filters and then the amplitude and phase of the signal are obtained. In most applications, the full-cycle Fourier method is applied in which the time to calculate the phasor is one cycle and it provides very good accuracy. On the other hand,

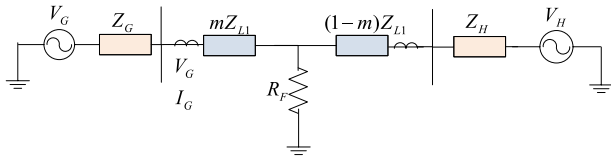


FIGURE 7. Two-terminal fault location using one terminal data [78].

the half-cycle Fourier method is used when the time is limited, and it provides a higher speed but with less accuracy.

By having the impedance of the line and calculating the impedance between the relay and fault points, the fault location can be determined. The advantage of this method over the fault location methods using the differential equation is that the current and voltage signals are studied in the frequency domain and their harmonics can be eliminated.

The fault location process can be classified into three main groups as follows:

- Fault location of a two-terminal transmission system using data of just one terminal,
- Fault location of a two-terminal transmission system using data of both terminals,
- Fault location of the multi-terminal transmission system.

Algorithms that use the information of both terminals for finding the fault location in the two-terminal system are more accurate than those that use the information of only one terminal [77]. Sometimes, however, the fault location accuracy may be compromised due to the inaccessibility of some terminals' data or the lack of synchronized data.

A. FAULT LOCATION OF A TWO-TERMINAL TRANSMISSION SYSTEM USING ONE TERMINAL DATA

A two-terminal fault location method using only one terminal data has been proposed in [78]–[81]. The studied system can be seen in Fig. 7, in which the fault location is calculated using the measured data of terminal G [78]. The KVL equation can be written from the terminal G to the ground through the fault resistance R_F as follows:

$$V_G = m \times Z_{L1} \times I_G + R_F \times I_F \quad (13)$$

where I_F, m, Z_{L1} are fault current, fault location and impedance of the faulty line, respectively. (13) can be also rewritten as follows:

$$\frac{V_G}{I_G} = m \times Z_{L1} + R_F \times \frac{I_F}{I_G} \quad (14)$$

By considering the imaginary part of equation (14) and assuming that the angles of the I_F and I_G are equal, the fault location m can be calculated as follows:

$$m = \frac{\text{imag}(\frac{V_G}{I_G})}{\text{imag}(Z_{L1})} \quad (15)$$

The main disadvantage of this method is the assumption on the angles of I_F and I_G . In many cases, these angles are not equal which leads to some errors.

The fault system can be considered as a superposition of the pure-fault and pre-fault systems as shown in Fig. 8 [78].

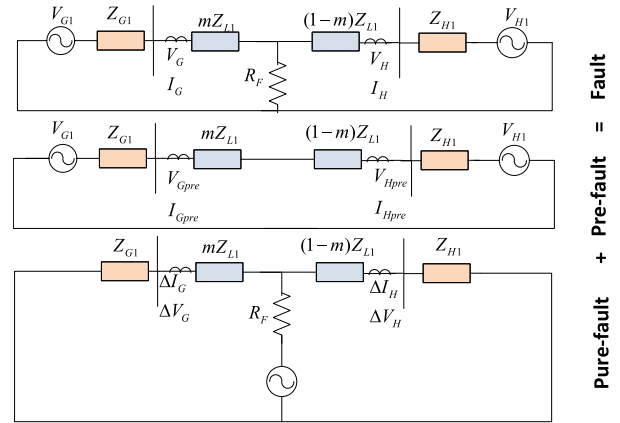


FIGURE 8. The pure-fault and pre-fault systems [78].

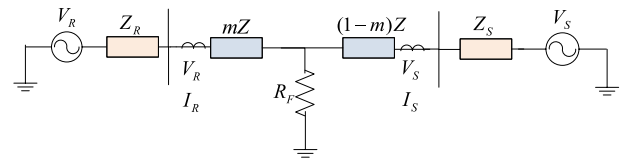


FIGURE 9. Studied system in [84].

Therefore, the KVL equation can be applied to the pure-fault network, which is the subtraction of fault and pre-fault networks. Therefore, the fault current can be calculated as follows:

$$I_F = \left(\frac{Z_{G1} + Z_{L1} + Z_{H1}}{(1-m) \times Z_{L1} + Z_{H1}} \right) \Delta I_G = \frac{1}{d_s} \times \Delta I_G \quad (16)$$

where Z_{G1}, Z_{L1}, m and I_F are Thevenin and line impedances, fault location and fault current, respectively. Using the KVL in pure-fault network and using (16) we have

$$V_G \times \Delta I_G^* = m \times Z_{L1} \times I_G \times \Delta I_G^* + R_F \times \left(\frac{1}{d_s} \right) \quad (17)$$

where ΔI_G^* is the conjugate of ΔI_G . By assuming that the angles of Z_G and Z_H are equal to the line impedance angle, d_s has only a real part and the fault location can be obtained by using the imaginary part of (17) as follows:

$$m = \frac{\text{imag}(V_G \times \Delta I_G^*)}{\text{imag}(Z_{L1} \times I_G \times \Delta I_G^*)} \quad (18)$$

The aforementioned assumption on the angles of Z_G and Z_H is the main flaw of this method. In addition, it is assumed in this method that the voltage resources values are constant during the fault and pre-fault conditions, whereas the generators oscillate during the fault and their voltages magnitudes are not constant [82].

B. FAULT LOCATION OF A TWO-TERMINAL TRANSMISSION SYSTEM USING BOTH TERMINALS DATA

The accuracy of fault location can be increased by using the measurements from both sides of the transmission line. The proposed methods in [77], [83], [84] are based on the data of two terminals for fault location. In [84] the fault location

has been calculated by the assumption that the measured data at the terminals are not synchronized. The studied system is demonstrated in Fig. 9 and the fault point voltage can be obtained as follows:

$$V_F = V_S - m \times Z \times I_S \quad (19)$$

$$V_F = V_R - (1 - m) \times Z \times I_R \quad (20)$$

where V_F , V_S , V_R , m and Z are the voltages of fault point, sending and receiving end points, fault location and impedance of the line, respectively. If the difference between measured data from both ends of the line is equal to δ , the following equation can be derived

$$V_S \times e^{j\delta} - V_R + Z \times I_R = m \times Z \times (I_S \times e^{j\delta} + I_R) \quad (21)$$

where δ and m are the unknown parameters that can be obtained by separating the real and imaginary parts in (21).

The distributed model of the transmission line has been used in [77] for fault location by calculating the fault point voltage using both terminals data (terminals R and S) as follows:

$$V_F = \cosh(\gamma x) \times V_S - Z_0 \sinh(\gamma x) \times I_{FS} \quad (22)$$

$$V_F = \cosh(\gamma(1-x)) \times V_R - Z_0 \sinh(\gamma(1-x)) \times I_{FR} \quad (23)$$

where Z_0 and γ are the surge impedance and propagation constant, respectively. By solving equations (22) and (23) simultaneously, the fault location x can be acquired as follows:

$$x = \frac{\tanh^{-1}\left(\frac{B}{A}\right)}{\gamma} \quad (24)$$

The variables A and B are defined as:

$$A = Z_0 \times \cosh(\gamma L) \times I_{FR} - \sinh(\gamma L) \times V_R + Z_0 \times I_{FS} \quad (25)$$

$$B = \cosh(\gamma L) \times V_R - Z_0 \times \sinh(\gamma L) \times I_{FR} - V_S \quad (26)$$

where L is the line length. In [85] the measured voltage data of two terminals and the measured value of current at one terminal have been used to calculate the location of the fault. In the case of current transformer saturation due to the close faults to the terminal, the current of another terminal can be used to increase the fault location accuracy. In [86], a method for fault location in series compensated transmission lines has been presented. Also, the possibility of bypassing the surge arresters in finding the location of fault in the compensated lines is considered in this method.

C. FAULT LOCATION OF THE MULTI-TERMINAL TRANSMISSION NETWORKS

The fault location of the multi-terminal transmission system are investigated using

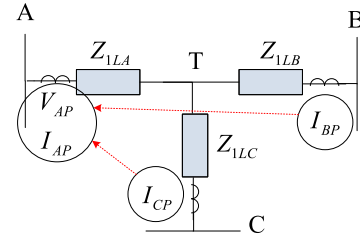


FIGURE 10. Measurement data transfer of the proposed method in [89].

- The data of all terminals,
- The data of some terminals,

which are described in the following sections.

1) MULTI-TERMINAL FAULT LOCATION USING THE DATA OF ALL TERMINALS

Sometimes, the data from all terminals are available using the wide communication systems, relays, and PMUs. In such cases, using the data of all terminals for fault location provides more accurate results. In [87]–[90] the fault location has been investigated for a three-terminal configuration using the information of all three terminals.

In [89] the voltage signal at the terminal of the faulty segment and the current signals of all three terminals have been used to calculate the fault location in the three-terminal transmission systems. The synchronized measurements of voltage and currents are used in this method. The measured data transfer scheme of this method has been depicted Fig. 10.

If the segment AT is assumed as the faulty segment, the KVL equation can be applied from terminal A to the fault point as follows:

$$V_{AP} - d_A \times Z_{1LA} \times I_{AP} - R_{FA} \times I_F = 0 \quad (27)$$

where d_A is the fault location, R_{FA} is the fault resistance and I_F is the fault current, which is the summation of the currents initiating from all of the terminals as presented in (28).

$$I_F = I_{AP} + I_{BP} + I_{CP} \quad (28)$$

d_A and R_{FA} are the unknown parameters in (27), which can be obtained by separating the real and imaginary parts of the equation. Consequently, the fault location d_A can be determined using (27) and (28) as (29), shown at the bottom of the page.

The zero-sequence network has been used in [90] for fault location calculation as depicted in Fig. 11. As shown, it is assumed that the fault has occurred on segment 1, between bus 1 and T point.

In this method, the fault location can be calculated using only the voltages of all three terminals and without using any

$$d_A = \frac{\text{real}(V_{AP}) \times \text{imag}(I_F) - \text{imag}(V_{AP}) \times \text{real}(I_F)}{\text{real}(Z_{1LA} \times I_{AP}) \times \text{imag}(I_F) - \text{imag}(Z_{1LA} \times I_{AP}) \times \text{real}(I_F)} \quad (29)$$

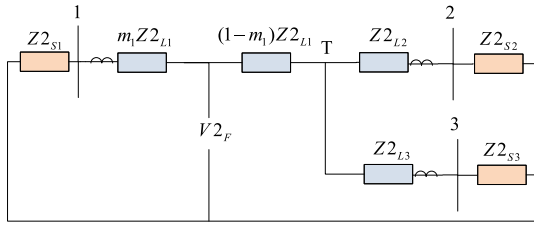


FIGURE 11. Zero sequence network used in [90] for fault location.

current signal. The following relations can be written for the zero sequence network of Fig. 11.

$$V2_{R1} = V2_F \times \frac{Z2_{S1}}{Z2_{S1} + m_1 \times Z2_{L1}} \quad (30)$$

$$V2_{R2} = V2_F \times \frac{Z2_2 || Z2_3}{Z2_2 || Z2_3 + (1 - m_1) \times Z2_{L1}} \times \frac{Z2_{S2}}{Z2_{S2} + Z2_{L2}} \quad (31)$$

$$V2_{R3} = V2_F \times \frac{Z2_2 || Z2_3}{Z2_2 || Z2_3 + (1 - m_1) \times Z2_{L1}} \times \frac{Z2_{S3}}{Z2_{S3} + Z2_{L3}} \quad (32)$$

$$Z2_3 = Z2_{S3} + Z2_{L3} \quad (33)$$

$$Z2_3 = Z2_{S3} + Z2_{L3} \quad (34)$$

where $V2_{Ri}$ and $V2_F$ are the measured zero sequence voltage of terminal i and zero sequence voltage of fault point, respectively. The fault location can be calculated straightforwardly using the division of (30) to (31) and the division of (30) to (32). The main flaw of this method is the assumption that the third terminal is a load bus without any generation. In addition, the seen impedances behind the terminals (Thevenin impedances of the system) are required in this method.

In [91] the resistance R and inductance L between the terminal and the fault point are calculated using the voltage and current of a multi-terminal DC transmission system.

This fault location scheme reduces the computational burden for accurate determination of the location and type of fault in DC networks. In addition, a simplified R - L representation of the line has been used to consider the dependency of the transmission line to frequency by estimating the parameters R and L .

2) MULTI-TERMINAL FAULT LOCATION USING SOME TERMINALS DATA

In [92], [93] the fault location of the three-terminal system using two terminal information is investigated. In [92] the faulty segment is detected and then the location of the fault is determined. The studied system in this method is illustrated in Fig. 12. In this system, just the data of two terminals S and R are available and the fault location is obtained using the data of these two terminals.

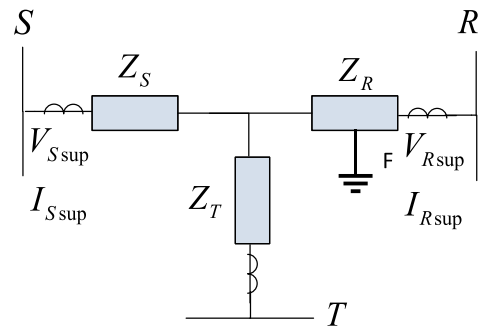


FIGURE 12. Three-terminal system studied in [92].

If the fault occurs on the segment R , the fault location can be obtained using the superposition method as follows:

$$D = \frac{\ln(\frac{N_t}{M_t})}{2\gamma} \quad (35)$$

where an extended representation of N_t and M_t have been derived in (36) and (37).

$$N_t = \frac{1}{2} \times (V_{Rsup} - Z_C \times I_{Rsup}) - \frac{1}{2} e^{\gamma(l_R+l_S)} \times (V_{Ssup} - Z_C \times I_{Ssup}) + \frac{1}{2} e^{\gamma l_R} \times Z_C \times I_{TJsup} \quad (36)$$

$$M_t = -\frac{1}{2} \times (V_{Rsup} + Z_C \times I_{Rsup}) + \frac{1}{2} e^{-\gamma(l_R+l_S)} \times (V_{Ssup} + Z_C \times I_{Ssup}) + \frac{1}{2} e^{-\gamma l_R} \times Z_C \times I_{TJsup} \quad (37)$$

where γ , Z_C and l_i are propagation constant, characteristic impedance and length of the line i , respectively and I_{TJsup} can be obtained using the Thevenin impedance behind the terminal. One of the deficiencies of this method is that the impedance behind the terminals is assumed to be constant.

If the fault occurs on the S segment, the fault location can be calculated similarly. Now if the fault occurs on the third segment T , the following two assumptions are taken into account to find the location of the fault:

- Fault type is known,
- Pre-fault and fault Thevenin voltage of the terminal T are equal.

Practically, the length of this segment is usually short and if a fault occurs on this segment, large fluctuations in the power and voltage would occur. Hence, it cannot be assumed that the Thevenin voltage is constant.

Using a different algorithm, the fault type is assumed to be predetermined and the fault resistance is pure resistive type (with no imaginary part) for the proposed fault location in [93]. The investigated system in this method is illustrated in Fig. 13.

This method first assumes that the fault occurs on the RT section. Then, the voltage of the T point is obtained using the S terminal data. Then two sets of equations are written for which the unknown parameters are the fault location D and the injected current from the T terminal. Finally, the

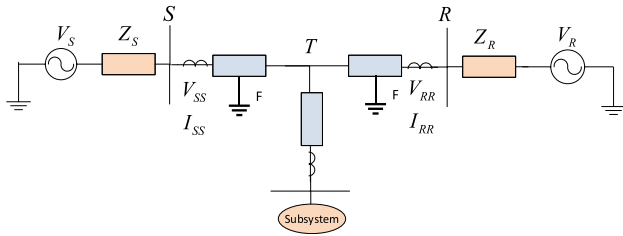


FIGURE 13. Three-terminal system studied in [93].

Gauss-Seidel method is used to find the fault location as follows:

- Assuming a location for the fault,
- Considering the assumed fault location and calculating the injected current from terminal T toward the fault point,
- Replacing the calculated injected current and re-calculating the location of the fault,
- Re-executing the last two steps until finding the exact location of the fault.

Similarly, the fault location is determined for the faults on the ST section. In this method, the possibility of the fault occurrence on the third segment (the line between the subsystem and the T point) has been ignored due to its short length.

In [94] a fault location algorithm for a parallel three-terminal transmission system has been presented using only one terminal data. It was assumed in this method that all of the terminals are connected to the load except for the terminal which its voltage and current are measured. This paper uses KVL equations from the terminal to the fault point, and with solving this equation the fault location is obtained. Fault location in three-terminal networks with the integration of renewable resources to the transmission network has been studied in [95].

IX. HEURISTIC ALGORITHM

Some methods use optimization algorithms to find the location of the fault [96]–[99]. The important point about these algorithms is that due to application of optimization methods, some of the currents which are measured with lower accuracy can be dismissed. For example, currents with a high level of error due to saturation of current transformers can be ignored to locate the fault accurately.

The whale optimization algorithm (WOA) has been used in [100] to find the fault location in two-terminal transmission lines. The accuracy of this method has been compared with that of the genetic algorithm. The WOA is applied in [101] with discussing the grey wolf optimization (GWO) method in fault location. Current and voltage of both ends of the line are used in this method. In this paper, several types of faults are simulated and considered. The objective function in this method identifies the location of the fault with high accuracy in a short duration. Also, using the distributed model of the line, the location of the fault is determined accurately.

Based on the provided results, the WOA-based optimization method leads to significant reduction in computational time. Accuracy and quickness of fault location greatly facilitates the operation of the repair team.

X. COMPARISON, CHALLENGES, NEW IDEAS AND FUTURE WORKS

In this section, different methods proposed for fault locating are compared with each other and their abilities and shortcomings are stated. Then, new tips and recommendations are suggested to obtain better results for the fault location in power system transmission networks. Finally, new ideas and research topics are presented for future research works.

A. COMPARISON OF FAULT LOCATION METHODS

Several aspects are introduced in this section for comparing the fault location techniques performance in electric transmission networks. Table 1 shows the comparison results of different methods in the same benchmark. Also, different fault location methods are compared and their features are investigated in Table 2. These tables provide a general and simple comparison between different proposed methods.

In these tables, very fast time means from 0.1-1 ms. Fast time refers to 1-10 ms. Also, methods with the calculation time of more than 10 ms are classified as medium. High-cost means those items requiring high sampling frequencies, special sensors and new equipment. Medium-cost items do not require installation of new expensive equipment while they need minor changes in the measuring system. Those which are referred as low-cost can be applied in practice using the available equipment in the system.

As can be seen in this table, traveling wave-based methods have high speeds in estimating the fault location while requiring very high frequency sampling rates, which necessitates very expensive equipment and hardware.

Wide-area fault location methods require measurements from different terminals, consequently reliable communication systems are required to run these methods. While large amount of data might be required in these methods, they provide high accuracy and their cost of implementation is medium. Methods based on the differential equation and impedance calculation do not rely on particular equipment and their implementation cost is low. Also, their speed in obtaining the fault location is medium comparing that of the others. The main disadvantage of differential equation-based methods is that their estimation error will be increased by the presence of noise and harmonics.

After conducting extensive review of the DC system fault location algorithms, it can be deduced that the traveling wave and impedance-based methods are the most popular approaches for DC network fault location and they have good potential for expanding and implementing them in practice.

B. NEW IDEAS TO OBTAIN BETTER RESULTS

Based on the extensive analysis and scrutiny in this paper, and different research works and experiences of the authors in this

area, the following tips, recommendations and suggestions are proposed for further works and obtaining better results in the field of fault location in power system transmission networks:

1) USING THE HEALTHY PHASES DATA TO REDUCE THE EFFECTS OF INSTRUMENT TRANSFORMERS TRANSIENTS

In most of the existing methods in the literature, the faulty phases data have been used to determine the fault location. Whereas, the current and voltage of the faulty phase are associated with some errors due to CT saturation and CVT transient behavior. However, healthy phases data are not subject to CT saturation due to their lower current amplitude and do not experience undesired CVT transients. Consequently, using these data results in higher accuracy.

Hence, healthy phases information can also be effectively used to increase the accuracy of fault location estimation.

2) UTILIZING THE CABLE'S SHEATH CURRENT TO INCREASE THE ACCURACY

For fault location on cables, most of the fault location methods usually use the measured current of the cable's conductor. While the cable's sheath current is also available and can be measured and used. This provides some beneficial data which can be exploited in the fault location algorithm to obtain more truthful results. Hence, it is necessary to pay more attention to the sheath current for improving the accuracy of fault location [59].

3) USING THE INITIAL DATA WINDOW FOR REDUCING THE CT SATURATION EFFECTS

The installed CT for measuring the fault current mostly does not get saturated at the initial cycle of the fault occurrence. Consequently, these measured signals contain less error compared to the error of the subsequent samples. Therefore, considering the CT initial data window can be suggested as one of the effective methods for improving the fault location performance and accuracy.

4) EXPLOITING FARTHER TERMINALS' DATA FOR DIMINISHING THE IMPACT OF THE CT AND CVT ERRORS

As aforementioned, some transients may be added to the measured current and voltage signals of faulty line terminals due to the CT saturation and CVT transient response. An appropriate approach for decreasing the raised error in this situation is suggested to use the measured data from the remote terminals [53], [54]. By using the remote terminals current and voltage data, higher accuracies can be obtained as those data are less affected by the instrument transformers fluctuations and transients.

5) CONSIDERING THE LAST SAMPLING DATA IN CALCULATING THE FAULT LOCATION TO REDUCE CVT TRANSIENT EFFECT

At the beginning of the fault inception, the measured samples of CVT usually contain some error due to its transient

behavior. However, this error will be attenuated and significantly decreased after few cycles. Therefore, the last samples can be used for the fault location process to increase the accuracy of estimation.

6) ANALYZING OTHER HARMONICS OF THE STUDIED SIGNALS

Usually, the existing fault location methods use only the main 50 Hz component of the voltage and current signals. However, other harmonics can also be evaluated and applied to obtain more data from the fault signal, as their amplitude and phase contain useful information. It should be noted that the magnitudes of other harmonics of the fault signal are usually significant and they can be measured to be considered in fault location process. Hence, new fault location methods can be proposed considering this suggestion and based on the harmonic analysis of the fault signal [60].

7) RECONSTRUCTING THE CURRENT AND VOLTAGE SIGNALS

Some of the methods reported in the literature assume that the measured current and voltage signals are error-free. In other words, the undesirable effects of CT and CVT transients have not been considered in their studies. To increase the accuracy of fault location, the input signals of the algorithm can be reconstructed first and then the correct modified signals be fed to the fault locating process. Different signal reconstruction methods are proposed in the literature. Some of the suggested algorithms are based on application of ANNs. The other methods calculate the transfer function of instrument transformers and multiply the faulty signal into the inverse of this function to obtain the actual values of the measured samples [102], [103].

8) CALCULATING THE PARAMETERS OF THE LINE

In some conditions, the correct transmission line parameters are not available. By using the pre-fault data and before occurrence of the fault, the parameters of the line can be estimated. After calculating those parameters, fault location method can be done with higher accuracy.

C. NEW TOPICS FOR FUTURE WORK

In this subsection some novel topics for future works in this area are suggested.

1) CALCULATING THE FAULT LOCATION FOR INCIPIENT FAULTS

It would be desirable to present a sensitive fault location algorithm for cables. The conductor to shield fault is the most studied case for the DC network fault location in the existing methods. Meanwhile, incipient faults can occur due to the aging of the cable where a small leakage current flows from the conductor into the shield. Therefore, it is necessary to propose a thoughtful method for obtaining the location of a fault in such circumstances in the initial stages to prevent expanded damage to the cable.

TABLE 1. Comparison of several fault location algorithms.

Ref. no.	Method	Sampling frequency	Accuracy	Network	System	Data	Speed	Cost of equipment
[19]	Traveling wave	200 kHz	0.5 %	2-terminal	AC	2-terminal	Very fast	high
[23]	Traveling wave	1 MHz	0.7%	2-terminal	AC	1-terminal	Very fast	high
[26]	Traveling wave	1 MHz	0.1%	Multi-terminal	DC	Multi-terminal	Very fast	high
[41]	Neural network	5 kHz	0.1%	Multi-terminal	DC	Multi-terminal	Fast	low
[50]	Wide area	1 MHz	0.2%	2-terminal	AC	Multi-terminal	medium	medium
[64]	Time reversal	1 MHz	0.6 %	Multi-terminal	AC	Multi-terminal	Very fast	high
[66]	Differential equation	2 kHz	0.5%	2-terminal	AC	2-terminal	medium	low
[70]	Impedance	2 kHz	0.3%	2-terminal	AC	1-terminal	medium	low
[82]	Impedance	2 kHz	0.3%	2-terminal	AC	2-terminal	medium	low
[87]	Impedance	1 kHz	0.3%	3-terminal	AC	3-terminal	medium	low
[90]	Impedance	4 kHz	0.4%	3-terminal	AC	2-terminal	medium	low

TABLE 2. Comparing different features of fault location methods.

Method	Speed	Cost	Sampling frequency	Practically implementable	Noise robustness
Traveling wave	Very fast	high	high	low	medium
Artificial intelligence	fast	low	low	medium	medium
Time reversal	Very fast	high	high	low	medium
Differential equation	medium	low	low	medium	low
Impedance calculation	medium	low	low	high	high

2) FAULT LOCATION FOR TRANSIENT FAULTS

Most of the performed researches in the literature focus on determining the fault location for permanent faults. Proposing a method to find the fault location in transient faults is very useful. By determining the location of these kinds of faults, the vulnerable fault points for a transmission line/cable can be identified. Hence, the operators can maintain and repair those sensitive fault points to avoid future incidences.

3) FAULT LOCATION IN PARALLEL TRANSMISSION LINES

In many transmission lines configurations, there are two transmission lines installed on the same tower, which induce on each other. In specific, zero-sequence coupling is considerable which results in high error for fault location. Finding the location of the fault in these lines is still challenging.

4) FAULT LOCATION IN COMPACT TOWERS

In compact towers, mutual effects are considerably high due to the short distance between different circuits installed on the two sides of the tower. Accordingly, proposing a method for fault location in these towers is indeed required to raise the accuracy of fault location. In such conditions, not only zero-sequence mutual effects should be considered, but also positive- and negative-sequences play a major role due to the closeness of parallel circuits.

5) FAULT LOCATION IN UN-TRANPOSED LINES

The existing works are mostly suitable to find the fault location in transposed lines while exploiting them for the un-transposed line will lead to some error. Since most of the lines are not fully transposed in the real world, providing a solution to accurately find the location of fault in these

circumstances is a significant challenge and guides to considerable improvement.

6) FAULT LOCATION IN LINES INCLUDING SERIES CAPACITORS AND FACTS DEVICES

When a line is compensated with a series capacitor, the impedance of the line depends on the fault location and the capacitor installation location; hence this situation is quite challenging to locate the fault and deserves more research studies to identify the faulty section and locate the fault accurately. Series compensation results in various problems including voltage inversion, current inversion and low frequency oscillations imposed on the main frequency component which should be studied carefully.

7) FAULT LOCATION IN OFFSHORE CABLES

In offshore transmission cables, most of the faults are due to the failure of insulation between the conductor and shield, while for a small group of faults, cable’s conductor is directly short-circuited to the ground. The shield wire may be grounded at different points in the seabed or at the cable ends inside the substations; hence the fault current will be fed into the ground through different points. Consequently, this is the reason behind the fact that why locating faults on these lines is so difficult and challenging.

8) FAULT LOCATION OF JOINT TRANSMISSION LINE AND CABLE

In some cases, a cable is linked to an overhead line to construct a composite transmission line including two different types of lines. For instance, a cable is connected to an overhead line to continue the transmission line in the seabed at shores. Hence, the overall line consists of different

specifications, i.e. different impedances and characteristics. Consequently, fault location in such condition is challenging and appealing for future researches.

9) FAULT LOCATION IN MULTI-TERMINAL NETWORKS WITHOUT HAVING ACCESS TO ALL DATA

In multi-terminal lines, the data of one terminal may not be available and it is necessary to find the fault location without using the data of all terminals. The lack of data could be due to different reasons. Sometimes multi-terminal lines are built for temporary loading of a remote or low-load area, and therefore substations including complete equipment are not installed in those remote terminals to save the costs. Hence, measurements are not available in such terminals. Another reason is that a reliable communication system may not be easily available in the remote area and then the measured data is not accessible in this situation. Also, the data may consist some errors due to communication channel noise. Considering these facts, fault location in multi-terminal lines without having access to all data is an important problem that requires more research studies.

10) FAULT LOCATION IN OFFSHORE MULTI-TERMINAL DC NETWORKS (MTDC)

Offshore energy harvesting using MTDC networks has become a hot topic in the recent years. Consequently, reliable and fast protection and fault location schemes for the voltage source converter-based multi-terminal DC (VSC-MTDC) power grids has become quite important and challenging. However, various problems such as high resistance faults, noise interference and distributed capacitance can reduce the performance of existing schemes. Accurate fault location and faulty section identification algorithms should be proposed for the new VSC-MTDC networks.

11) FAULT LOCATION USING ASYNCHRONOUS DATA

The presented methods in most of the literature assume that the data from different terminals are gathered synchronously, while in most cases the data is not synchronized and it is necessary to propose an accurate algorithm to find the location of the fault with asynchronous data or propose appropriate methods to synchronize the received remote data with the local data. Even 1 ms time difference between the remote and local data due to the communication system delay, inaccuracy in data alignment, and lack of synchronization algorithms will cause 18 degrees angle deviation for the measured signals in the 50 Hz network. This can greatly increase the error of fault location procedure. Hence, proposing a method to precisely synchronize the data is of vital importance.

XI. CONCLUSION

In the new power systems, with the proliferation of overloading in electricity networks on of hand and increasing the importance of the electricity for well-being of modern societies on another hand, it is of vital importance to quickly eliminate any fault on the network and fix the faulty line

for its fast restoration. One of the time-consuming issues in diagnosing the fault in the network is identifying the location of the fault. In general, fault location algorithms can be classified into different methods, e.g. traveling wave, differential equations, and impedance calculation-based methods. In this paper, different fault location methods have been reviewed and their pros and cons were explored. Another approach for classifying the fault location techniques is their capability to be used for two-terminal and multi-terminal networks. This category has been also investigated in the paper for illustrating their effectiveness. The main purpose of this work is to get acquainted with different methods of fault location in transmission systems and comprehensively reveal their applications and challenges for modern power systems. Some of the fault location methods have been compared from different facets and it was shown that each of them is suitable for specific conditions and networks. Hence, an appropriate and applicable method for fault location for a specific network and condition can be effectively selected using the performed studies in this work. For further studies and paving the way for researchers in tracing the gaps in this field, several useful and viable suggestions and recommendations have been provided in this paper.

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