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A Comprehensive Review of Various Fault Location Methods for Transmission Lines Compensated by FACTS Devices and Series Capacitors

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Abstract- *Fault location in transmission lines compensated by flexible alternating current transmission system (FACTS) devices and series capacitor (SC) compensators is much more complicated than simple lines due to the presence of time-variant voltage and current sources in the topology of transmission lines. In recent years, due to the increasing presence of reactive power compensators in power systems and the researchers' desire to study the presence of such equipment in the network, many articles have been published in the field of fault location in transmission lines equipped with reactive power compensators. Thus, the fault location problem in electrical power transmission lines equipped with reactive power compensators, including FACTS and SC devices, is comprehensively discussed and analyzed in this paper. For the first time, all the basic indices and factors that have always been very effective in analyzing the fault location problem in transmission lines equipped with reactive power compensators in various papers are classified thoroughly. Then, based on the types of reactive power compensators, all the literature published in the field of fault location in compensated transmission lines are categorized. Finally, a comparison table is presented to examine the fundamental indices of the literature in this field.*

Keywords: Fault location, FACTS devices, Series capacitor compensator, Impedance methods, Traveling waves, Artificial neural networks.

1. INTRODUCTION

Today, the demand for electricity is so high that it is almost impossible to even imagine human life without it. This has imposed a lot of strain on governments to meet the huge demands of electricity. Therefore, the provision of quality energy has turned into one of the basic foundations of any country's macro-policies. This is especially true for transmission networks given the fact they are intermediaries between generation and consumption systems. Moreover, the expansion of transmission networks has now become very difficult due to many restrictions, including the geographical, economic, and technical ones, to name a few. Various proposals have over years been offered to solve these problems, one of the most prominent and efficient of which is the use of flexible alternating current transmission system (FACTS) devices to satisfy most of the demands of the operators with the same available network topology. On the other hand, the presence of these devices in the power system has caused many problems. One of the major challenges posed by the presence of FACTS devices and SC compensators in the power system is the issue of protection and fault location on lines equipped with these devices. Although many studies have been conducted in various fields on the presence of FACTS devices and SC compensators in the power system, there are still many challenges regarding protection and fault location in lines equipped with these compensators. Some of the challenges remain unresolved because of the high computational burden and the difficulty of analysis. In general, the literature on fault location in transmission lines equipped with reactive power compensators is divided into two main categories according to the type of compensators [1]. The first category is the traditional compensator, which includes a series capacitor with a metal oxide varistor (SC-MOV). The second category includes a new generation of compensators based on FACTS devices, which are divided into two separate sub-categories: a) FACTS compensators based on thyristor switches, which include static VAr compensators (SVCs) and thyristor-controlled capacitor series (TCSCs), and (b) FACTS compensators based on voltage source converters (VSCs), which include static synchronous compensators (STATCOMs), static synchronous series compensators (SSSCs), and unified power flow

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controllers (UPFCs). The following are the basic indices that exist in a fault location problem in transmission lines equipped with reactive power compensators:

- **First category:** Classification by the analysis domain of the fault location problem (phasor or impedance, traveling waves, time equations, artificial neural networks, and hybrid methods),
- **Second category:** Classification by the number of measurement terminals and data transmission technology (single-terminal, two-terminal (synchronous or asynchronous, multi-terminal),
- **Third category:** Classification by the multi-circuit structure of the lines (single-circuit, double-circuit, quadruple-circuit),
- **Fourth category:** Classification by the line model (short, medium, long line models or equivalent π and T circuits),
- **Fifth category:** Classification by homogeneous or heterogeneous types of transmission lines (overhead lines, cable-overhead lines, underground lines, hybrid lines),
- **Sixth category:** classification by iterative or non-iterative solvers and optimization-based solvers (simple mathematical solvers, iterative solvers, and gradient-based solvers, such as Newton-Raphson or heuristic, and optimization-based like a genetic algorithm),
- **Seventh category:** Classification by dependence on offline parameters of transmission lines (parameters such as impedance and admittance of the lines, load information, Thevenin impedance of the source, and networks connected to both sides of the transmission line),
- **Eighth category:** Classification by dependence on the nature of measurement parameters (current, voltage, combined current and voltage),
- **Ninth category:** Classification by the time of the measurement data (before the fault and during the fault), and
- **Tenth category:** Classification by the type of fault in the lines (normal shunt faults, series faults, evolutionary faults, cross-country faults, and inter-circuit faults).

The presence of FACTS devices and SCs in transmission lines causes the impedance of transmission lines to be constantly changing, so this is a very serious problem in terms of line protection and fault location. On the other hand, because these devices can control the power flow not only in a line but also in a network, the fault location problem in lines equipped with reactive power compensators is much more sensitive and important than in lines that are not equipped with a reactive power compensator [2]. When the transmission line is exposed to transient faults, the protection system operates and quickly de-energizes the fault line, and after a period of time, the breakers automatically or manually energize the line. However, when the transmission line is permanently faulty, service and maintenance personnel need to be on the site immediately to eliminate the cause of the permanent fault, which requires accurate fault location using fault location algorithms. If the fault location is not detected accurately and appropriately, it will cause confusion among the operational personnel, and depending on the length of the transmission line, it may take hours to find the exact location and the cause of the fault, clear the fault cause, and re-energize the transmission line. Therefore, designing an accurate fault location algorithm in transmission lines equipped with reactive power compensators, which can be implemented in industry locators with a very high level of reliability, is both crucial and valuable. As a large number of papers and scientific achievements in the field of fault location of electric power transmission lines equipped with reactive power compensators are annually published, including those equipped with FACTS devices and SCs, compiling a paper containing a comprehensive review of various methods, technologies, challenges, and descriptions of future complementary subjects in the field of fault location problem in electrical power transmission lines equipped with reactive power compensators is highly important and necessary. Although various review papers have been published in the field of fault location, no comprehensive review has yet been published related to fault location in electric power transmission lines equipped with reactive power compensators taking into account all aspects of the fault location problem. Hence, this paper discusses and analyzes the fault location problem in electric power transmission lines equipped with reactive power compensators in a very comprehensive manner.

The paper is organized as follows. Section 2 introduces various types of reactive power compensators, including those that have been addressed in various references considering fault location problem in the transmission lines equipped with them. In Section 3, the types of fault location methods in transmission lines are discussed. The methods presented in this section include five basic categories that are fully described. In Section 4, a comprehensive review and analysis of the literature on fault location in transmission lines equipped with reactive power compensators is presented. The classification considered in this section, based on the type of compensators, includes six basic categories. Finally, Section 5 presents the conclusions of the paper.

2. INTRODUCING DIFFERENT TYPES OF REACTIVE POWER COMPENSATORS

The FACTS device is a new concept and idea that encourages the utilization of power electronics devices and controllers to boost controllability and development of transmission capacity of networks, besides providing an opportunity to enhance control operations and stability in alternating current (AC) transmission networks. The exploitation of FACTS devices in power systems to improve operation indices has increasingly grown in recent years. The reason for the tendency to these devices is their salient features. FACTS systems can control parameters and characteristics of transmission lines, including impedance, admittance, and voltage (angle and phase), as the main limitations of power transmission. Although FACTS devices are the most suitable tools for these control operations and are faster and more flexible than mechanical control of transmission systems, they suffer problems in cost and reliability, which limits their applicability. Since high voltage (HV) power systems have significantly been developed in Iran in terms of both consumption and implementation and design of lines and substations during recent years, the optimal operation problem considering the available conditions and topologies has gained attention more than ever. On the other hand, the analysis of research projects in the specialized holding company of Management of Generation, Transmission, and Distribution of Electric Power in Iran (Tavanir) shows that the focus of this company has mainly been on energy policymaking concerning FACTS devices projects in the past years. In general, FACTS devices can be divided into five basic categories: shunt, series, series-series, series-shunt, and series-series-shunt FACTS devices. Table 1 briefly introduces conventional FACTS devices and their operation and structure [3-11].

3. VARIOUS TYPES OF FAULT LOCATION METHODS IN TRANSMISSION LINES BASED ON THE ANALYSIS DOMAIN

3.1. Analysis in the fundamental frequency or impedance domains

Reactive power compensators in the transmission line divide the transmission line into two parts, the left and

Table 1. Various types of reactive power compensators

FACTS compensator		Connection type	Application features
SC & MOV	Series Capacitor/ Metal Oxide Varistor	Series	Current control, line impedance compensation, dynamic and transient stability, voltage stability, increasing line capacity
TCSC	Thyristor Control Series Capacitor	Series	Current control, oscillation damping, transient and dynamic stability, line current limitation, line reactance compensation, compensation of line’s series voltage drop
PST	Phase-Shifting Transformer	Series	Continuous control of magnitude and phase angle of the line injected voltage, line voltage drop control, line reactive power control, prevention of loop rotation of power between lines, elimination of inter-area power oscillation, transient stability improvement, reducing pressures applied to the generator shaft during transient conditions
SSSC	Series Synchronous Static Compensator	Series	Current control, current limitation, oscillation damping, transient stability, dynamic stability, voltage stability, fast dynamic response to abrupt changes in the network, compensation of voltage drop along the line
IPC	Interphase Power Controller	Series	Active and reactive power control in two microgrids, fast power flow control during the first swing of the generator, addressing frequency problems, robust controller of power flow with innate angle characteristics, insensitive power to network changes
UIPC	Unified Interphase Power Controller	Series	Active and reactive power control of the line, control and conditioning of line voltage, keeping stability during short circuits
SVC	Static VARCompensator	Shunt	Voltage control, reactive power control, oscillations damping, voltage stability
STATCOM	Static Synchronous Compensator	Shunt	Voltage control reactive power compensation, oscillation damping, voltage stability, transient and dynamic stability, fast dynamic response to abrupt changes of the network
IPFC	Interline Power Flow Controller	Series-Series	Reactive power control, voltage control, oscillation damping, transient stability, dynamic stability, voltage stability, fast dynamic response to abrupt changes of the network
UPFC	Unified Power Flow Controller	Series-Shunt	Active and reactive power control, voltage control, transient stability, dynamic stability, voltage stability phase angle regulation, fast dynamic response to abrupt changes of the network
GUPFC	Generalized Unified Power Flow Controller	Series-Series-Shunt	Active and reactive power control in different lines, voltage control, fault current limiter, transient stability, dynamic stability, voltage stability phase angle regulation, fast dynamic response to abrupt changes of the network

the right sides. Fault location methods are usually performed in such basic topologies. Some algorithms, in the first stage, detect the fault area relative to the compensator, and then the fault location stage is performed. In other algorithms, in first stage, two fault locations are obtained for the left and the right sides of the device, and then the correct location is selected using the calculated distances for the fault point from the terminals and some boundary conditions for testing.

The method presented in this section is based on the analysis of the fundamental frequency components of the currents and voltages measured from the substations as well as the transmission line model in the phasor domain. In fault location algorithms based on this method, two basic methods are mainly used to calculate the fault location. The first method is based on the analysis of Kirchhoff's equations in transmission lines, and the second method employs the impedance matrix of lines to calculate the fault location. As it is known, in these methods, the fundamental frequency of voltage and current components are used, and in some cases, the calculation of the impedance of the fault location to the measuring point is used to calculate distance between the fault point and the measuring point. It ultimately leads to determining the fault location. The analysis procedure for a problem in this domain is as follows:

1. Receiving fault occurrence commands and detecting the faulty phase using fault detection and classification algorithms.
2. Receiving three-phase current and voltage phasors of the terminal(s) (depending on the number of measurement terminals used in the algorithm).
3. Calculating the zero-, positive-, and negative-sequence components of the faulty line.
4. Detecting the faulty area relative to the reactive power compensator
5. Calculating the current and voltage point of the fault point in the zero-, positive-, and negative-sequence components according to the analysis of the equations governing the line in the fault time period. At this stage, the distance between the fault location and the measured point to the point of the line or its impedance is unknown.
6. Using the current and voltage equations of the zero-, positive-, and negative-sequence components of the fault point in the boundary condition equation proportional to the faulty phase, solving the boundary condition equation, and calculating the distance of the measuring point to the fault location or its impedance.
7. Examining the test conditions of the algorithm, such as the allowable range of the fault distance.

3.2. Analysis in the traveling wave domain

According to the traveling wave theory, any abrupt disturbance or change in the power transmission lines reduces the voltage at the point of sudden disturbance or change the result of which is the production of a very high-frequency electromagnetic pulse called a traveling wave. This generates two forward and reversed traveling wave signals at that point, moving toward the buses on either side of the line. In other words, after a disturbance or sudden change such as a short circuit, the harmonics resulting from these waves are mounted on the steady-state voltage and current waveforms and propagated in the line at a speed close to the speed of light [12-13]. The inputs of traveling wave-based protection algorithms used to protect transmission lines are three-phase current and voltage signals. These signals have a very adverse effect on traveling waves due to the presence of electromagnetic induction and interdependence, so the mutual induction effect between the phases must be eliminated. To do this, phase to modal transformation techniques (which are not unique transformations) are used, among which are Clarke's transformation and Karen Bauer's transformation. After applying the mentioned transformations, the waves are generally transformed into two types of air and ground modes. To better understand these two modes, it can be said that if a phase-to-ground (LG) fault occurs, the current waves propagate in only one conductor and return from the tower wire or ground. Such waves are called ground mode waves. If a two-phase (LL) fault occurs, the resulting waves are called aerial mode waves. The methods described above are among the time domain analysis methods, which in many references are used as a preprocessor, but in some references, other transformations such as phasor transformation of the complex space have been proposed that process the signal in the phasor domain and its output components are named as one-dimensional positive and negative components. After transforming the phase to the modal or applying the initial pre-processing, it is time to extract the high-frequency components of the traveling waves caused by the fault. Once the two processing steps are applied to the signals that have reached the relay location from the short circuit point, the fault location can be calculated. This stage of the algorithm, according to the nature of each transformation, has its own philosophy. The literature addresses the use of the final results of pre-processing stages in a specialized way. For example, in the analysis of traveling waves using the wavelet transform (WT), the time of the first sharp singularity of the signal should be determined and then the fault location should be calculated using the relationships proposed in the traveling wave theory, knowing the propagation speed of the wave. The analysis procedure for a problem in this domain is as follows:

1. Receiving fault occurrence commands and detecting the faulty phase using fault detection and classification algorithms.
2. Receiving three-phase current and voltage phasors of terminal(s) (depending on the number of measurement terminals used in the algorithm) using a sampling frequency of several hundred kHz
3. Calculating the modal components using the modal transformation matrix
4. Detecting the faulty area relative to the reactive power compensator
5. Using equations $x = \frac{v\,t}{2}$ or $x = L - \frac{v\,t}{2}$ to calculate the exact location of the fault
6. Examining the test conditions of the algorithm, such as the allowable range of the fault distance

3.3. Analysis in the time domain

In this method, like the method based on the traveling wave theory, current and voltage signals in the time domain are used. Also, the method requires a high-frequency sampling technology. Because these algorithms run in the time domain, filtering of the DC component and other frequency components present in voltage and current signals is no longer required [14]. The line model considered in this technique is the distributed parameter in the time domain, so the proposed method in this domain does not require the values of line parameters to determine the fault; therefore, changing the values of the line parameters does not affect the accuracy of fault location. This method uses current and voltage equations in the time domain to calculate distance of fault point. The voltage equations written on both sides of the fault point are assumed equal and the fault point can be calculated as only unknown from the resulting equation. The analysis procedure for a problem in this domain is as follows:

1. Receiving fault occurrence commands and detecting the faulty phase using fault detection and classification algorithms.
2. Receiving three-phase currents and voltages at terminals on either side of the line in the time domain
3. Calculating the current and voltage of the fault point in terms of voltage and current of the terminals on both sides of the line and the unknown distance of the fault location from the line terminal.
4. Using the two voltage equations of the fault point calculated in the previous step and calculating the combination function of these two equations called the F function
5. Discretizing the F equation and solving its optimization to calculate the distance between the fault location and the terminal point
6. Examining the test conditions of the algorithm, such as the allowable range of the fault distance

3.4. Analysis in the artificial intelligence (AI) and artificial neural networks (ANNs) domain

All of the previously discussed fault detection methods are based on post-fault mathematical calculations. Learning or teaching-based methods such as neural networks are presented as alternatives that have fewer online computations. An artificial neural network (ANN) is an information processing system inspired by biological neural networks [15]. These networks are able to capture and display complex relationships between inputs and outputs. The ANN output is distance from the terminal to the fault point and its inputs include measured currents and voltages. ANN-based methods need an offline training phase in which they use a set of large-scale real-time scenarios or simulations as training samples. Once the training phase is complete, these networks can be used to predict the fault location based on the provided real-time data. The analysis procedure for a problem in this domain is as follows:

1. Extracting and analyzing the input and output data of the fault location problem using software simulation.
2. Assembling and preprocessing the training data to locate faults based on a single neural network.
3. Establishing a network structure and training it until the conditions of the setting parameters are obtained.
4. Testing and analyzing the performance.
5. Storing the trained network. Then, the network is ready to be tested with new inputs, which is an online process.
6. Pre-processing the new input before it is provided to the fault detector based on the single neural network.

3.5. Analysis in the combined domain

In some cases, when the fault detection methods provided in the previous four cases fail to find the exact location of the fault in the transmission lines, techniques that combine the previous four methods are used. In this domain, ANNs and intelligent algorithms are sometimes combined with methods such as the traveling wave or the impedance-based analysis methods to help cover their shortcomings [16]. The techniques presented in this domain lack a specific framework and are tailored according to the researchers' initiatives to solve a complicated problem. In the following, literature in this domain are comprehensively presented and reviewed.

4. LITERATURE REVIEW

4.1. Fault location in lines equipped with SC-MOV

When a fault occurs in the line, the presence of the SC-MOV device in the transmission line leads to incorrect detection of the impedance value or the distance measured from the terminal to the fault point by fault locators. When the phasor theory is used to solve the fault location problem in series capacitor compensated transmission lines, the implementation steps of the algorithm as shown in fig. 7 in the reference [23] are as follows. To solve the fault location problem in such topology, current and voltage phasor data of the two terminals at the local and remote ends of the transmission line are required. All current and voltage data of the terminals on both sides of the line are given to the fault location algorithm, either synchronously or asynchronously. To solve this problem, two basic assumptions are considered. The first assumption is that the fault has occurred on the left side of the capacitor, and the second assumption is that the fault has occurred on the right side of the capacitor. The fault location problem is solved for both assumptions and the two locations are calculated as the fault point. Then the actual fault point is determined using a test condition. For the case where the fault is assumed on the left side of the capacitor, the fault location steps are as follows.

1. First, write the fault point voltage equation for the right side of terminal L (Local). In this equation, the current and voltage of the L terminal and the hyperbolic equations of the transmission line with a length of x (the unknown distance of the fault point to terminal L) are used.
2. Then write the fault point current in terms of the current injected from the two terminals.
3. Use the boundary conditions equation in terms of the types of faults and find x (fault point distance to terminal L) as the only unknown equation.

We now assume that the fault has occurred on the right side of the capacitor.

1. First, write the fault point voltage equation for the right side of terminal R (Remote). In this equation, the current and voltage of terminal L and the hyperbolic equations of the transmission line with a length of x (unknown distance of the fault point to terminal R) are used.
2. Then write the fault point current in terms of the current injected from the two terminals.
3. Use the boundary conditions equation in terms of the types of faults and find x (fault point distance to terminal R) as the only unknown equation.

Finally, to find the correct solution, the impedance condition of the two series capacitors must be used. For the points marked on the left and right sides of the series capacitor compensator, the voltage across the capacitor and the current flowing through it can be calculated. Then the impedance of the two ends of the series capacitor can be obtained. The calculated impedance for the correct point will have a negative imaginary part. Therefore, using this test condition, the fault area and the exact location of the fault can be determined. If the information on the two terminals of the transmission line is asynchronous, then either the amount of data delay should be calculated using the pre-fault data, or the data phase delay itself or its operator should be calculated as a function of the length of the fault location and current and voltage information of terminals and use alternative function in the equations.

In References [17-24], a variety of impedance theory-based fault location algorithms is presented in transmission lines compensated by a series capacitor. In Ref. [17], the data of one terminal and the SC-MOV model are used to calculate the fault location. In this reference, the fault location problem is solved for both sides of the compensator, and then the exact location of the fault is selected using the test condition. In Ref. [18], a fault location algorithm is presented in the single-circuit transmission lines compensated by the series capacitor. The proposed method uses the series capacitor impedance as a key point to determine the exact location of the fault. In References [19-20], a fault location problem in parallel transmission lines using asynchronous data of two terminals is raised. In these references, due to the mutual coupling between the two circuits, the zero-sequence component circuit has been used to calculate the zero-sequence voltage of the fault point. In Ref. [21], a fault location algorithm is presented in the transmission lines compensated by the series capacitor and the recorded information from the PMUs on both sides of the line is used. In addition to voltage and current measurements, the active and active powers of the terminals have been used in this algorithm. The proposed algorithm in Ref. [22] uses asynchronous measurements of the two ends of a transmission line and a system monitoring device if a fixed series compensator (FSC) device is installed. Data synchronization is performed using post-fault data samples to increase accuracy. In Ref. [23], using a combination of mathematical computational methods based on impedance analysis and pattern search optimization algorithm, an algorithm is proposed to solve the fault location problem in single-circuit and double-circuit transmission lines compensated by series capacitors. The reference also provides a mathematical model of SC-MOV to increase the accuracy of the fault location algorithm. The authors in Ref. [24] present a fault location algorithm based on the analysis of current and voltage phasors in SC-MOV compensated transmission lines. Due to the fact that the MOV impedance is a nonlinear quantity, the accurate estimation of the voltage drop across the compensator cannot be obtained in the faulty phase. As a result, the positive-sequence component voltage obtained for a fault on the two ends of the compensator is inaccurate, which prevents the use of conventional fault location algorithms for lines compensated by a set of series capacitor compensators. However, bypassing the MOV in the faulty phase either due to excessive energy accumulation or a relatively large fault current makes the system linear. The proposed algorithm is based on fact that the MOV may be bypassed in some fault scenarios, in the faulty phase, or in all phases before the fault is cleared. Removing the MOV from the fault loop will provide the presented algorithm with accurate results. In analyzing the fault location problem in lines equipped with series capacitor compensators using the traveling wave theory, the series capacitor is short-circuited and has no role in problem analysis because high-frequency signals are used to analyze the problem and the capacitor impedance has a reverse ratio with the frequency during the fault. In Ref. [25], the fault location algorithm is presented in three-terminal transmission lines compensated by a series capacitor based on the traveling wave theory and the discrete wavelet transform. In this reference, the information of one terminal is used for fault location. In the case of fault location problems in lines compensated by a series capacitor using the equations analysis techniques in the time domain, as in the impedance method, one step is to detect the fault area and the other is to solve the fault location problem and find the exact distance of the fault to the terminal. In references [26-27], a fault location algorithm is presented in series capacitor compensated transmission lines based on synchronous measurements of two terminals of the transmission line. In these references, the distributed time-domain model of the transmission line is utilized to analyze fault location equations. In the analysis, first the fault location on both sides of the compensator is hypothetically calculated and then the correct point is selected using the test conditions. In references [28-29], an intelligent fault algorithm in double-circuit transmission lines compensated by series capacitors is used based on a combined method comprising experimental wavelet transform (EWT), Hilbert transform (HT), and weighted randomized vector functional line network (WRVFLN). In these references, an effective feature is used for support vector structure. The selected feature can be the standard deviation of the amplitude, energy, Rényi entropy, and crest factor of Hilbert's transform array. The algorithm provided in this reference can be trained online, but in terms of teaching and learning, it requires complex hardware for planning. In Ref. [30], a novel distance protection scheme is proposed for series capacitor compensated transmission lines. In a new combination, the hyperbolic S transform (HST) and support vector machines (SVM) are used to detect, classify, and locate faults, which are the three main aspects of distance relays. The HST is employed to extract the useful features of current and voltage signal samples of a terminal in the system. The extracted features are used for distance protection, and support vector classification and regression methods are used. In Ref. [31], by combining the WT and support vector regression, a new fault location scheme is presented in a transmission line compensated by a series capacitor. The WT is used to extract the distinctive features of the fault in half of the cycle and post-fault signals are used after noise elimination by the low-pass filter. Also, the support vector regression is trained with the features obtained from the WT. Once trained, the support vector regression is used to accurately locate the fault in the transmission line.

The authors in Ref. [32] present the fault location algorithm for three-terminal transmission lines compensated by series capacitor. The proposed scheme employs zero-, negative, and positive-sequence circuits and the analysis of boundary condition equation for various types of normal shunt faults and the synchronous information of the terminal; thus, it is independent of the information of the fault classification phase for performing fault location. In Ref. [33], a fault location algorithm is introduced for double-circuit transmission lines (DCTLs) compensated by series capacitor. The design utilizes the phasor theory and asynchronous data of the terminals. Also, the study exploits the SC model for determining the fault location.

4.2. Fault location in lines equipped with TCSC

Since the TCSC device has different operation modes, its impedance value cannot be used as a test condition to detect the fault area relative to the TCSC. In [34], a fault area detection algorithm in TCSC-compensated transmission lines is presented in two stages based on impedance theory and synchronous measurements of the two terminals of the line using phasor measurement units (PMUs). In Refs. [35-37], current and voltage equations and distributed parameter model of the transmission line in the time domain are utilized for fault location in TCSC-equipped lines. In Ref. [35], using the partial differential equations (PDEs) of the long transmission line and a recursive algorithm, a fault location scheme in TCSC-compensated transmission lines is presented. The scheme ignores the voltage difference across the TCSC in the first step so that it can estimate the initial location. In this reference, the modal transform is used to analyze asymmetric faults. In Ref. [36], simultaneous samples of voltage and current from the two ends of the transmission line and the distributed parameters model of the line in the time domain are used to locate the fault in the transmission lines compensated by TCSC. This method consists of three steps. In the first and second steps, it is assumed that the fault is located on the right and left side of the series compensator, respectively. Two fault locations are calculated corresponding to each step. In the third step, the results obtained from the first and second steps are compared and the correct location of the fault is selected. The introduced fault location algorithm does not require calculating and using the voltage drop across the TCSC, and the algorithm avoids iterative calculations. In Refs. [37-38], a fault location algorithm is presented in TCSC-compensated transmission lines based on the analysis theory in the time domain. These algorithms use a time-domain model for TCSC and a distributed parameter model of the transmission line. The proposed algorithm requires synchronized information on both sides of the line. A fault section identifier (FSI) has also been introduced that calculates the voltage and current of the TCSC over a short period of time (less than one cycle) after the fault occurs at the TCSC location. The FSI signal determines the faulty section and sends the result to both sides of the line. In Refs. [39-41], fault location algorithms are presented in TCSC-equipped lines using AI and ANNs. In Ref. [39], a combination of radial neural networks and fuzzy neural networks has been used to locate faults in TCSC-compensated transmission lines. This combination provides the minimum number of neurons using continuous learning and pruning strategy. In other words, fuzzy neural networks, using pruning strategies, lead to fewer fuzzy rules. In Ref. [40], an approach based on the fast machine learning method with nonlinear kernel has been proposed to locate faults in lines compensated by TCSC. The given method provides higher accuracy with less training time and parameter setting. In Ref. [41], a fault location method based on ANN and WT is presented for the transmission lines with three terminals compensated by TCSC. The sampling rate is 40 kHz and there are a large number (about 54,000) of data sets for neural network training. Based on the gained results, its accuracy in estimating the fault location is very high (average error of 0.05% to 0.2% for different types of faults), but the model can only be used for the given structure and test system and cannot be implemented for other structures.

4.3. Fault location in lines equipped with SVC

When the SVC device is placed on the transmission line, it disrupts the performance of the fault location algorithms due to the injection of current into the transmission line. Because the operation of the SVC during the fault depends on the faulty phase, its distance from the fault location, and the fault resistance, it is very difficult to estimate the injection of current by the SVC from the terminal point of view where the fault locator is located.

Based on the phasor theory and the use of the negative-sequence component circuit, ref. [42] presents a fault location algorithm in SVC-compensated double-circuit transmission lines. In this work, the current and voltage of one terminal are used and the mutual coupling between the two conductors is fully considered. The proposed scheme does not require information on the fault classification stage and calculates the exact location of the fault using only one formula. One of the disadvantages of this analysis is that it avoids fault resistance when intra-phase faults occur.

4.4. Fault location in lines equipped with STATCOM

The STATCOM device, like the SVC, is a time-variant current source placed in the transmission line, which disrupts the operation of conventional fault location schemes. In references [43-45], fault location methods are provided in series capacitor-compensated transmission lines. Ref. [43] presents a fault location algorithm in STATCOM-compensated transmission lines. In this method, synchronous data are used on both sides of the transmission line and the distributed parameter model of the line is used in the time domain. This algorithm consists of three steps. In the first and second steps, it is assumed that the fault is located on the left and right sides of the compensator, respectively. Then two discrete equivalents are obtained, which are used to extract an optimization problem in the third step. Based on neural networks and using the Levenberg-Marquardt training, authors in Ref. [44] provide a fault location algorithm in the double-circuit transmission lines compensated by STATCOM. In this design, current and voltage phasors of one side of the line have been used to estimate the fault location. In Ref. [45], a fault location algorithm is presented in three-terminal transmission lines compensated by STATCOM based on the combination of deep neural networks and the WT without the need for offline information of the lines. The sampling frequency of current and voltage signals in this scheme is 40 kHz and requires more than 50,000 pieces of training to train the neural network.

4.5. Fault location in lines equipped with SSSC

The SSSC device, when placed in the transmission line as a time-variant voltage source in the transmission line, disrupts the fault location scheme and line protection. In Ref. [46], a fault location algorithm is presented in SSSC-compensated transmission lines based on the traveling wave theory and the WT. This algorithm is based on the use of a modal transform for current and voltage signals sampled at high frequencies. Then, the WT is employed to calculate the current and voltage traveling waves, and the low-frequency interference generated by the system and the SSSC is avoided. Using the fuzzy neural networks, ref. [47] presents a fault location scheme in the lines compensated by the SSSC. In this design, first, the SSSC is modeled and then its impedance is used in the proposed scheme to locate the fault.

4.6. Fault location in lines equipped with UPFC

As the UPFC device has both serial and shunt converters, its impact on fault location algorithms is much greater due to simultaneous current injection and the establishment of a variable series voltage source in the transmission line. In Ref. [48], a fault location algorithm based on the differential equation analysis method is presented for a UPFC-equipped transmission line using phasors synchronous measurements. The proposed method involves identifying the faulty section in a transmission line equipped with UPFC using a wavelet-fuzzy identifier. Once the faulty section has been detected, it is transferred to the fault location section based on the differential equation, which estimates the faulty section in terms of line inductance from the relay point to the fault point. The proposed method in this reference uses the current injection model to determine the fault location in terms of line inductance and the main model is reduced to the current injection model. One of the disadvantages of this method is that the equivalent admittances of the series and shunt sections of the UPFC are known parameters and are part of the data of the fault location problem. In Ref. [49], a fault location algorithm is presented based on the theoretical analysis of voltage and current equations in the time domain for the UPFC-compensated lines. The proposed method consists of three steps. In the first two steps, assuming that the fault is on the left and right sides of the UPFC, two quadratic equations are obtained in terms of fault resistance, which are used to extract the optimization problem in the third step. The direction and location of the fault and its resistance are determined simultaneously by solving this optimization problem, so this algorithm does not need to provide a selector. In brief, it can be said that the method presented in this reference uses the average power flow in the UPFC to determine the fault location, which depends on three factors: 1) ohmic losses of serial and shunt transformers and ohmic losses of power electronic switches of series and shunt converters of the compensation device, 2) the average power absorbed by/injected to the series and shunt transformers, and 3) the average power absorbed by/injected to or loss in the DC-link capacitor. In Ref. [50], a fault location algorithm based on sparse S-transform is provided for a UPFC-equipped transmission line. The proposed algorithm is based on a new version of the conventional S-transform matrix called sparse S-transform, so that this transformation can be considered very efficient by using the selected frequency components to increase the computational speed. The new transformation uses the formulated transformation of matrix S by an intelligent frequency scaling method. This method significantly reduces the computational burden. In addition, to obtain the exact phase of the fundamental frequency voltage component using a phase correction method, the sparse S-transform calculates the phase value of the fundamental frequency voltage components, which has a huge impact on the accuracy of the fault location. In Ref. [51], a fault location algorithm based on time-frequency signal processing analysis called hyperbolic S-transform is presented in transmission lines equipped with the UPFC. Three types of features are extracted from fault signals at one end of the compensated line. The first, second, and third categories of features (i.e., Type 1, 2, and 3) are based on the fundamental frequency components of the signals, the time-frequency information, and the hidden statistical features, respectively. The intelligent fault detector provided in this reference provides an accurate estimate by improving the hidden statistical features, which includes a new type of time-frequency characteristics. In

Ref. [52], a fault location algorithm used in UPFC-compensated transmission lines is based on the phasor theory for detecting external and internal faults as well as locating the fault. The proposed scheme uses synchronous local and remote terminal measurements as the inputs to the algorithm. Ref. [53] discusses a phasor there-based fault location scheme for GUPFC-compensated DCTLs, in which the synchronous data of terminals and the boundary condition equation is used for various types of single-circuit faults. The fault location scheme for UPFC-compensated transmission lines has also been described [54]. In this scheme, the UPFC is placed on one side of the line and negative-sequence current phasors are used for determining the faulty area.

4.7. Discussion and comparison

FACTS devices are a flexible solution to overcome the problems occurring in the field of power management and control in today's power systems and are expanding constantly [55]. On the other hand, despite their numerous advantages, the FACTS devices may introduce many challenges to the system. One of these challenges concerns the protection of lines equipped with a FACTS device [56-57]. As FACTS devices operate in different modes and control conditions, they can inject a series variable voltage or a shunt variable current along the line depending on the type and model of the device. FACTS devices, and power compensators in general, have different operating modes in transmission networks and lead to changes in the power flow direction, four-quadrature power control, very fast dynamic response, and abrupt operating mode changes under various conditions and events of the network, and they can easily affect the apparent impedance of the line. This change the impedance seen from the fault point to the near end of the line depending on the

Table 2. Results obtained from the comparison of the literature in the field of fault location in lines equipped with FACTS devices and series capacitor compensators. (NA: Not Available, C: Circuit, T: Terminal, Im: Impedance, Hy: Hybrid, Tds: time-domain signals Ann: artificial neural networks, Tw: traveling waves, Sy: synchronous, US: un-synchronous)

Author's name	references	Compensator type	Method	Line structure	Number of measurement terminals (synchronous and asynchronous)	Has the compensator model been used in the algorithm?	Sampling frequency (k Hz)	Average of error (%)	Publication year
M. Saha,	[17]	SC-MOV	Im	1-C, 2-T	1	Yes	1	0.3	1999
A. Capar,	[18]	SC	Im	1-C, 2-T	1	No	10	1	2015
J. Izykowski,	[19]	SC-MOV	Im	2-C, 2-T	2-US	No	1	0.5	2011
N. Kang,	[20]	SC-MOV	Im	2-C, 2-T	2-US	No	NA	0.02	2014
A. mohammed,	[21]	SC-MOV	Im	1-C, 2-T	2-SY	No	0.24	0.7	2014
S. Hussain,	[22]	SC-MOV	Im	1-C, 2-T	2-US	No	NA	0.01	2014
G. Junior,	[23]	SC-MOV	Im	2-C, 2-T	2-SY	No	1.92	0.5	2016
T. Bains,	[24]	SC-MOV	Im	1-C, 2-T	2-SY	No	20	0.1	2016
C. Evrenosogh,	[25]	SC-MOV	Tw	1-C, 3-T	1	No	333.3	0.16	2005
J. Sadeh,	[26]	SC-MOV	Tds	1-C, 2-T	2-SY	No	NA	0.5	2000
M. Dabbagh,	[27]	SC-MOV	Tds	1-C, 2-T	2-SY	Yes	100	0.1	2005
M. Sahani,	[28]	SC-MOV	Hy	2-C, 2-T	1	No	1.6	0.16	2019
M. Sahani,	[29]	SC-MOV	Hy	2-C, 2-T	1	No	1.6	0.16	2020
Z. Moravej,	[30]	SC-MOV	Hy	1-C, 2-T	1	No	2.5	0.1	2012
A. Yusuff,	[31]	SC-MOV	Hy	1-C, 2-T	1	No	12.8	0.02	2011
A. Saffarian	[32]	SC-MOV	Im	1-C, 3-T	3-US	No	2.4	0.1	2020
Cai. Daiying	[33]	SC-MOV	Im	2-C, 2-T	2-US	Yes	NA	0.15	2020
C. Shan,	[34]	TCSC	Im	1-C, 2-T	2-SY	No	1.92	0.03	2002
J. Sadeh,	[35]	TCSC	Tds	1-C, 2-T	2-SY	No	NA	0.07	2010
M. Ghazizadeh,	[36]	TCSC	Tds	1-C, 2-T	2-SY	No	NA	0.06	2011
S. Nobakhti,	[37]	TCSC	Tds	1-C, 2-T	2-SY	No	100	0.4	2014
M. Ghazizadeh,	[38]	TCSC	Tds	1-C, 2-T	2-SY	No	100	0.5	2020
P. Dash,	[39]	TCSC	Hy	1-C, 2-T	1	No	NA	0.5	2003
P. Tripathi,	[40]	TCSC	Ann	1-C, 2-T	1	No	4.8	0.3	2016
M. Mirzaei,	[41]	TCSC	Hy	1-C, 3-T	3-SY	No	40	0.04	2018
A. Ghorbani,	[42]	SVC	Im	2-C, 2-T	1	No	NA	0.14	2020
M. Ghazizadeh,	[43]	STATCOM	Tds	1-C, 2-T	2-SY	No	NA	0.03	2011
S. Sawmya,	[44]	STATCOM	Ann	2-C, 2-T	1	No	NA	0.9	2017
M. Mirzaei,	[45]	STATCOM	Hy	1-C, 3-T	3-SY	No	40	0.09	2019
R. Archundia,	[46]	SSSC	Tw	1-C, 2-T	2-SY	Yes	100	0.6	2015
E. Mohagheghi,	[47]	SSSC	Ann	1-C, 2-T	1	Yes	NA	0.3	2012
S. Samantarag,	[48]	UPFC	Hy	1-C, 2-T	2-SY	Yes	1	2.9	2008
M. Ahsaee,	[49]	UPFC	Tds	1-C, 2-T	2-SY	No	NA	0.43	2012
L. Tripathy,	[50]	UPFC	Im	1-C, 2-T	1	No	3.84	2	2015
Z. Moravej,	[51]	UPFC	Hy	1-C, 2-T	1	No	6	0.15	2017
B. Chattrejee,	[52]	UPFC	Im	1-C, 2-T	2-SY	No	4	0.03	2020
M. Abasi,	[53]	GUPFC	Im	2-C, 2-T	2-SY	No	2.4	0.1	2020
M. Kundu,	[54]	UPFC	Im	2-C, 2-T	2-SY	Yes	NA	0.5	2020

control behavior of the device and may lead to the misoperation of relays and fault locators. In other words, the presence of FACTS devices in the line poses a new problem to the fault location algorithms. Since control systems of these devices react to the fault, the voltage and currents used by the fault locators in the transient mode are affected. As is shown in the literature review of subsections 4.1 and 4.6, fault location problems in transmission lines compensated by FACTS devices or series capacitor can be categorized in terms of the type of FACTS compensator, dependence or independence of the FACTS device model, and solution steps of the fault location problem. The following provides the effects of series and shunt FACTS devices on the performance of fault locators and distance relays.

4.7.1. The effect of series FACTS devices on fault locators and relay distances in transmission line

A. The change in the impedance seen by the relay or fault locators

Regarding that distance relays or fault locators available in the industry are based on the amplitude of the measured impedance, the presence of FACTS devices directly impacts their operations during fault incidence. This type of device changes the apparent impedance seen by the relay or fault locators from fault point to the near end of the line, which results in misoperation of the relay or fault locator; thus unexpected trip of breakers.

B. Current inversion

Current inversion is a phenomenon that shifts the current phase angle degrees or more. This event occurs in series compensated transmission lines when an internal fault appears in a distance exactly after the compensator. The equivalent system on one side of the fault is capacitive, while it is inductive on the other side. This phenomenon is rare during solid faults or faults with a high current because, during such faults, the arcing distance of the MOV bypasses the series capacitor. Nonetheless, this often occurs for high-impedance faults (HIFs), when the low fault current prevents the capacitor bypass. Current inversion affects conventional directional relay algorithms negatively because a conventional relay cannot discriminate frond and back faults.

C. Addition of transients and harmonics

The placement of series FACTS devices in the transmission network leads to the appearance of various transients and subharmonic frequency oscillations in the power system while affecting the voltage and current signal estimation of the relay and fault locator distance. Due to the presence of non-fundamental damping frequency components, odd-order harmonics, high-frequency components, and fundamental frequency, the current seen by the relay or fault locator is greater than the real case, which leads to the relay overreach and incorrect estimation of the fault point.

D. Effects of MOV

The MOV and a spark gap with a bypass breaker are used for the protection of series capacitors against additional transient voltage. When the instantaneous voltage across the capacitor significantly soars, the MOV starts to conduct so that the capacitor is bypassed and the impedance seen is merely the impedance of the MOV. During low current fault locations, the MOV is in its high impedance mode and presents an impedance value equal to the impedance of the shunt combination of a series capacitor and an MOV. Distance relay or fault locator settings in the case of neglecting the conductance of the MOV leads to the relay overreach. However, if the settings are realized by constantly observing the MOV, it results in relay underreach under low current fault conditions.

E. The effect on transient components

The presence of series compensators, especially series capacitors, increases sub-synchronous frequencies, which is inversely proportional to the impedance of the equivalent source and fault location and is directly proportional to the compensation level. Issues and problems of protection systems occur when the faults appear on the end of the transmission line where low-frequency components cause oscillations in the impedance seen by the relay.

4.7.2. The effect of shunt FACTS devices on distance relays or fault locators of the transmission line

The effect of shunt FACTS devices on the algorithms employed in the available fault locators is described below.

A. When a shunt FACTS device is in the fault loop, e.g., when it is placed in the middle of the line and the fault occurs on the second half of the line, the fault impedance seen by the relay distance or fault locator will deviate from its real value, thus leading to misoperation of relay or fault locator (overreach or underreach).
B. Misoperation of distance relay or fault locators if the fault resistance is non-zero, whether a FACTS device in the fault loop or not.
C. When the shunt FACTS device is out of the fault line and the fault resistance is zero, it does not affect the measuring impedance.

D. Concerning the changes in the value of the fault resistance, the resistive part of the measuring impedance is more affected in the case the fault occurs at the far end of the line, not at the near end.
E. The deviation of the measuring impedance from its real value depends on the placement point of the shunt FACTS device and its operating mode.

Table 2 tabulates the results of analysis and comparison of the literature presented in the Literature review section of the paper.

5. CONCLUSION

This paper provides a comprehensive review of the types of fault location methods in transmission lines compensated by FACTS devices and the SCs. This study, for the first time, discusses in detail the fault location problem in transmission lines equipped with reactive power compensators. First, the structure and function of various FACTS devices and the SCs in transmission lines are introduced. Then, five basic domains are introduced to categorize the analysis domains of fault location problems and their basic principles are presented separately. Then, all the literature published in the prestigious journals in this field are critically and thoroughly reviewed and, in the end, all the advantages and disadvantages of the methods are presented. These compensators in transmission lines act as time-variant current and voltage sources, which inject an unknown current and voltage from the point of view of the fault locator or relay in the transmission line, which is thought to disrupt the operation of fault locators and distance relays. Therefore, transmission lines equipped with these compensators require a special protection scheme, specifically designed for that line, which can correctly detect the fault location in different conditions. Due to advances in the power electronics industry and control systems, the utilization of this device to compensate for reactive power, to improve network operation conditions, to release line capacity, and so on has encouraged the researchers to use this device instead of designing new lines. Thus, this paper presents a very comprehensive review of published research on fault location in transmission lines equipped with reactive power compensators, to be presented to researchers as a complete summary.

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