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Different Methods for Enhancing Distance Relay Performance in Series Compensated Transmission Lines

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Abstract:
Abstract— The electrical power grid is undergoing a continuous revolution due to ever increasing dependence of modern society on electrical power and hence protection of such a wide, complex dynamic power system is a big challenge for protection engineers. Power transmission is highly susceptible to the various kinds of faults and their protection is very essential to increase reliability and security the of power system. Transmission lines are loaded closer to the threshold value of their thermal and stability limits. Installing fixed or controllable compensation capacitor in series with the transmission lines provides a vital solution for this. Compensation systems help to increase transient stability limits of power grid, enhance power transfer capability of transmission lines, reduce losses, optimize power-flow and improve its power-quality. With increasing popularity of power electronics, Flexible AC Transmission Systems (FACTS) are widely used as compensation systems for transmission lines. However, protection of compensated transmission lines is a crucial task as compared to uncompensated lines as inserting capacitors in series with transmission lines change magnitude and direction of fault currents and voltages. This has a large impact on the operation of protective relays and fault locators. Distance relays which are popularly used for the protection of transmission lines mal function due to wide variations in post fault voltage and current values. Several practical and theoretical schemes have been developed by the researchers to improve the performance of distance relay connected in series with the transmission lines such as Higher Order Statistics, adaptive Kalman filtering, discrete wavelet transforms, travelling wave schemes, fuzzy logic, Artificial Neural Network and many others. This paper is an attempt to throw light on these various methodologies in terms of their merits and demerits.

Keywords: *Artificial intelligence (AI), Artificial neural network (ANN), Flexible AC transmission systems (FACTS), Series compensation, Transmission lines.*

I. INTRODUCTION

Electrical transmission systems play a crucial role in power systems and its protection is very important to ensure its stability and reliability. Series compensation plays a very important role in governing power transfer capability of the transmission system by injecting a series inductance in the system which not only improves the power system stability but also reduces the losses in active power and limit the occurrences of sub-synchronousoscillations [1]. Advancements in power electronics with introduction to flexible AC transmission systems (FACTS) has significantly improved power transfer capacity and enhanced its controllability. It has also helped to improve the voltage profile at various transmission line buses to ensure stable operation [2]. Static synchronous series compensator
(SSSC) is very popular among various FACTS

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devices used for series compensation of transmission lines with improved features and replace the traditionally used thyristor-controlled reactors and other such conventional devices.

Distance relaying is a very popular and widely used method for protection of transmission system under various fault conditions like L-L, L-L-L, L-G, L-L-G and L-L-L-G and to ensure reliability and security of power system. Fast and accurate determination of various faults is its major feature. It works on the principle of impedance measurement of the transmission line by monitoring the voltages and currents flowing through the line. Impedance is calculated from these measurements and compared to threshold values set of the zonal protection of the transmission line and the relay is operated to isolate the related section of the line if any anomaly is found in the impedance values. In principle, impedance is relatively high in long transmission lines during normal operation and reduces when under short circuit fault. This condition is sensed by the distance relay scheme and appropriate action is taken to ensure protection of the power system [3-4]. However, the relaying scheme mal-operates for the series compensated transmission lines as series compensation involves change in impedance of the transmission line. Over-reaching is commonly faced by distance relays under such conditions and is a very critical problem which cannot be solved by simple calculations or adjustments. Hence, newer, improved and adaptive algorithms are necessitated to be included in the existing distance relays schemes to ensure its proper and efficient working.

This paper focusses on different methods used to enhance the performance and accuracy of the distance relay scheme for transmission line for various fault conditions in a series compensated scenario. It mainly highlights the recent increase in the use of various data science methods including Artificial Intelligence, Neural Networks, Fuzzy Logic, Genetic Algorithms among others and its importance in solving electrical power system related problems like compensation of distance relay under the influence of series compensation for various fault conditions. The paper is organized as follows: Section I Introduction is followed by Methodological Survey on various distance protection schemes for series compensated transmission lines in Section II while section III gives comparison of these methods on the basis of performance and applicability used to improve performance of distance relay. Section IV concludes the paper by providing directions of future scope.

II. Methods used for Distance Protection of Series Compensated Transmission Lines

A. Distance Protection Scheme

The traditional distance protection scheme is shown in Fig. 1. The scheme shows a transmission line connected to a generator at one end and is extended towards further zones at the other. The faults within the protected zone and out of protected zone are represented by F1 and F2 respectively. Input and output circuit breakers (CB) between section A and B are shown and an impedance relay or distance relay is connected using potential transformer (PT) and current transformer (CT) between them.

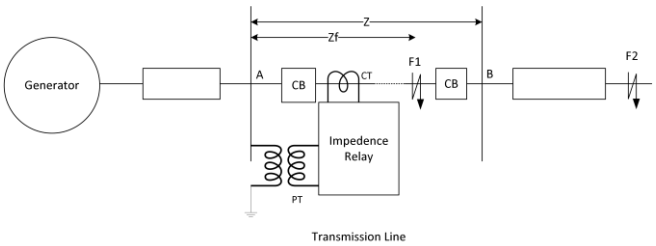

Fig. 1. Distance relay scheme

If the fault occurs at point F1, the impedance of the section Z falls to Zf which triggers the circuit breakers and the section is isolated from the network. If the fault occurs at F2, the section is not isolated and continues to operate normally.

However, series compensation disrupts this scheme as it injects more impedance at faulty conditions and impedance never falls to Zf so as to trigger the breakers. Hence, compensation algorithms are necessary to adaptively adjust the performance of the distance relay under such conditions.

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B. Categorization of various compensating algorithms

The objective of any transmission line protection scheme is provision of fast and accurate relaying along with classification of fault. Several directional relay algorithms are developed in the past which are based on Mathematical Morphology [5] and phase angle difference between sequence components of phase voltages and currents [6-7]. Several researchers have carried out research on transmission line protection using traditional methods such as least square error methods, full cycle and half cycle Fourier transform which may not be successful in providing reliable protection. Also, there is a considerable delay in phasor estimation process which requires a sliding window of a cycle [8-11]. Higher order statics [12] and S transform [13] methods are also used in classification of faults. Few researchers have analyzed series compensation circuit using wavelet transform and Kalman filtering approach [14-16]. Subsequently, some of the researchers have provided answers to the protection of series compensated power transmission lines based on travelling waves scheme [17-21]. One approach uses discrete wavelet transforms [22]. Adaptive protection technique is used by many researchers to enhance the performance of distance relay connected in series compensated transmission lines [23-29]. Another important aspect of artificial intelligent techniques known as support vector machine has been used for fault analysis, fault diagnosis and for fault classification by many researchers [30-35]. Several researchers have suggested technique using ANN and fuzzy systems for power system protection [36-45]. Extreme Learning Machine (ELM) approach is also used by many researchers in protection of series compensated transmission lines [47-47]. These schemes are graphically represented in Fig. 2.

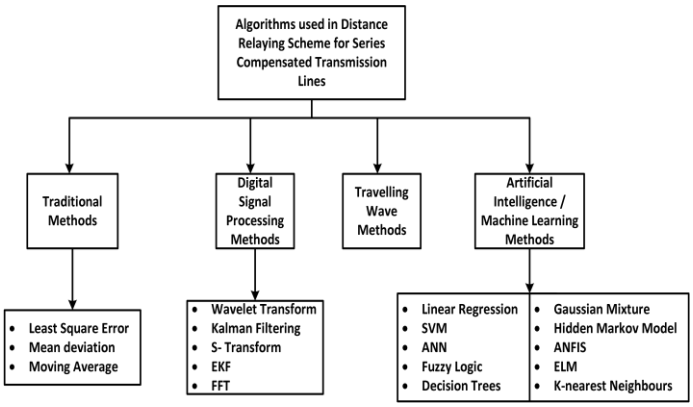

Fig. 2. Schemes for Distance Relay with Series Compensation

Many researchers have demonstrated the schemes to assist the working of distance relay in series compensated transmission lines based on adaptive logic as seen from Fig. 2. Sanaye-Pasand et al. [23] illustrated the use of trajectory of calculated apparent impedance into the relay trip decision through weighing process. Higher weights are assigned for the faults occurring in the interior protective zones of the relay and for the faults having small resistance values. Adaptive neuro-fuzzy inference system (ANFIS) is used for the implementation of the presented decision-making algorithm. The suggested method based on adaptive decision-making logic is suitable for distance protection of series compensated power transmission lines. It helps to improve the performance of distance relay and is smarter, faster and more reliable. This method improves the relay performance for close in faults with the help of fault current as one of the other inputs for ANFIS system. As the suggested logic makes use of two-stage ANFIS network in place of only one integrated network, it is necessary to train both the networks separately. Similarly, from the security point of view the proposed scheme make use of successive samples of measured impedance for the decision-making process, it requires more time for the relay operation as well as results into the complex system.

J. Upendar et al. [24] suggested a technique based on back propagation ANN for generating an exhaustive adaptive distance protection logic. The

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method is applied for a double circuit parallel transmission line. Both mutual coupling effect and shunt capacitance effect are considered while analyzing the distance relay performance in case of L-G fault. Adaptive nature of neural network for changing power flow in the lines helps to map the trip region very closely and accurately to the ideal relay reach characteristics. As ANN works on the principle of parallel data processing, the proposed method gives very fast and accurate response and is equally adaptive to the changing operating conditions of the system. But, because of the limitations of ANN in choosing training parameters as well as in obtaining the optimum network structure due to lack of definite rules result into difficulties while using the proposed logic. Similarly, the presented scheme makes use of four different neural networks in the decision-making process and in the entire training process ANN is a black box while revealing input output relationships this leads to the more training time and less trip accuracy.

Makwana, V.H. and Bhalja [26] explored an adaptive logic based on symmetrical component theory to rectify the magnitude of measured impedance at the relay point. The scheme analyses the operation of distance relay during inter- circuit faults taking place in series compensated parallel transmission line. Value of apparent impedance at the relay location is modified in case of phase to phase and phase to ground inter circuit faults by considering the effect of both mutual coupling and high fault resistance. This proposed technique is adaptive to large changes in the system as well as fault parameters due to mitigation of high fault resistance and mutual coupling effect present in the parallel transmission lines. This system uses local end data and is immune to the loading impact of series compensated parallel transmission lines. But, in this method the effect of shunt capacitance present between transmission lines is not considered which otherwise would have improved the performance of distance relay in case of long transmission lines. Effect of noise and harmonics present also result into an added error in the performance of distance relay.

Mazniewski et al. [27], demonstrated an adaptive distance protection method using fault location logic for series compensated transmission lines. It is based on the measurement of fault loop impedance for the faults occurring before the series capacitor as well as after the series compensation capacitor bank. These procedures are applied along with the faulty line selection process. This scheme is based on collection of data obtained from ATP/ EMTP simulations. In order to calculate fault loop impedance, this algorithm requires two measurement processes, due to which efficiency of distance protection system is improved drastically. This method considers single phase to ground fault for testing the performance of proposed logic. This method is also useful in improving the relay reach accuracy as well as fault detection time. Numbers of missing operations are less in this method. Negative impact of the reactance effect on resistive faults is also nullified by this method. However, as this scheme requires determining two fault loop impedances along with the faulty line selection process, it is a lengthy process causing delay in the operation of distance relay. It is necessary to modify the algorithm for measurement of fault loop impedance depending on the fault location either in front or behind the series capacitor compensation bank.

S. Jamil [28] also has presented an adaptive scheme for distance protection of transmission line compensated by Static Synchronous Series Compensator (SSSC). In this method quadrilateral characteristic of distance relay is adaptive to changing power system conditions as well as structural and controlling parameters of SSSC and does not have impact on the first zone reach of the relay. The system requires only local end data. However, this method has not considered the variations in operating parameters of the power system and can be modified to measure the impedance with and without inclusion of SSSC in the

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fault loop.

Dash et. al. [32], have developed the method using Support Vector Machine (SVM) for fault identification and fault classification for a transmission line compensated with Thyristor Controlled Series Compensator (TCSC). This method requires half cycle current samples from the start of fault and the firing angle as input to SVM. Three distinct SVMs are used and trained for fault classification, ground detection and fault section identification. Polynomial kernel and Guassian kernel are used to train SVMs to achieve the optimized classifier. The suggested scheme requires very fewer samples for training purpose and converges faster as compared to the schemes using ANN and neuro-fuzzy systems. Thus, the proposed system provides fast and accurate response for the protection of series compensated transmission lines. However, the researchers have tested the performance of the presented approach for very few (200) cases and they have not thrown light over the issues like impact of variable source impedance and varying compensation levels. Malathi and Marimuthu [34] have demonstrated the use of SVM for faulty phase identification of transmission line. However, important issues like fault classification and fault location are not discussed in this paper. Malathi et al. [35] developed a scheme based on multiclass SVM (MCVSM) and multi class Extreme learning machines (MCELM) for fault classification for series compensated transmission line. In this method fault currents are decomposed using wavelet transform and the information extracted from this is used for fault classification. Performance of the proposed method is compared with MCSVM related to accuracy and the time required for training purpose. It is fond that MCELM method is a quite promising method and requires less training and classification accuracy is more compared to other methods for series compensated transmission lines. However, this method is used only for identifying the type of fault but the phases which are affected due to fault are not identified.

Extreme learning machines (ELM) approach is also now widely used for fault classification and regression problems taking the advantage of their universal approximation capability. Malathi et al. [46] proposed a novel method based on wavelet transform and ELM for determining fault section in front or behind the series compensation capacitor. The feasibility of the method was tested for 28,800 different fault cases. Simulation results show the robustness of the presented method against widely changing system and operating conditions by using three distinct ELM networks for fault classification, fault section detection and fault location.

III. Performance Analysis of Various Algorithms Under Study

Traditional methods such as least square error, full cycle DFT and half cycle DFT work on the basis of digital signal processing. Techniques using Fourier transform are unsuccessful in processing nonstationary and non-periodic accurately. These methods consume minimum a cycle of sliding window for estimation of phasors. Hence, they cause considerable delay in the process. Protection schemes working on DSP methods for deriving the useful frequency components from the signal are primarily based on processing fundamental and other harmonic components of the current signal. These schemes show disparity in the performance due to noise present in measurement and processing system.

Wavelet transform (WT) act as a powerful tool in transient signal analysis due to its capacity to derive time and frequency information both from the transient signal very effectively in comparison with Fourier transform. However, methods based on WT have shortcomings in terms of selection of mother wavelet, highly sensitive to noise, missing absolute reference phase information, development of undesired time-scale plots in case of intuitive visual analysis and delayed performance because of batch processing. The S-transform, a hybrid signal processing method is found to perform better in time domain analysis and has advantages of both the

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methods, short time Fourier transform and wavelet transform. The S-Transform works on the basic principle of obtaining time frequency energy distribution of the signal for isolating and processing independently the components of the signal in time frequency plane. It uses a varying and a scalable window length along with Fourier kernel for obtaining phase information with reference to the time origin. Thus, it is capable of providing allied information about the spectra which not possible to obtain in case of locally referenced phase of the continuous WT. Hence, protection system based on S-Transform is found to be reliable for protection of series compensated transmission lines. Techniques using Kalman filtering approach have limitations as modelling of fault resistance is not possible in this method and also for implementation of this technique it needs large number of variety of filters.

Travelling wave approach uses single ended protective scheme based on the timings of generated transient signals during faulty conditions travelling between the relay location and the fault point. This method provides extra discriminating features depending on the pre-fault conditions at the relay location compared to other schemes. In this method exact location of the fault is based on outgoing and incoming travelling waves at the relay point. This method is advantageous in protection of transmission lines equipped with the series capacitor as the impedance of capacitor is negligibly small due to the incremental components required by this method. However, these methods have shortcomings such as they are not able to detect faults closer to zero voltage condition and are highly sensitive to noise.

With the advent in digital processing techniques and artificial intelligence techniques facilitated the development and applications of novel approaches in solving complex problems of series compensated transmission line protection. These techniques allowed researchers to classify patterns based on faulty and non-faulty conditions of the power system. Back propagation neural network (BPNN), radial basis function neural network (RBFNN), ANN and ANIFIS are based on adaptive approach for the protection of series compensated transmission lines where the primary principle of protection philosophy is pattern classification. Voltages and current measured at the relaying location are used for generating necessary trip or block signals. The above techniques are highly sensitive to variations in the system frequency. These approaches require large data sets for training and testing purpose, large training period and large number of neurons. The pros and cons of various algorithms are highlighted in Table I.

Table I. Performance analysis of various algorithms for improving performance of distance relay under study for series compensation

Method	Pros	Cons
Pilot Scheme	Very high reach and accuracy	Expenses incurred in sending and syncing data from both the ends of power transmission line
Non-Pilot Scheme	Based on local end data and hence does not require dedicated communication channel or synchronization of data	Decisions are based on measurement of data from one end only
Power Frequency Based Methods	High sampling rates of data acquisition are not necessary	Design is based on lumped parameter model, resulting in less accuracy
Travelling Wave Methods	Accuracy of location is high and is isolated from the impacts of	Requires very high sampling rate and thus an expensive setup.

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	resistance change due to transition.	
Fuzzy Logic Methods	Provides natural frame work for combining numerical information and linguistic information in a uniform fashion.	There is no procedure for systematically learn rules, tune, determine and take decisions.
SVM Methods	Requires less training time and classify linear data very precisely	Accuracy is less for multi-dimensiona l data
ANN Based Methods	Excellent generalization capability, noise immunity, robust.	Requires rigorous training to work properly.

It can be said from the exhaustive survey that ANN is widely used to tackle the problem of fault identification and classification in a series compensated power transmission networks, yet the amount of training effort these algorithms require is quite considerable for obtaining optimal performance from the system as there are various changes in system parameters during fault conditions.

IV. Conclusion

An exhaustive review of advanced methods for improvement of distance protection scheme for series compensated transmission lines was presented in this paper. It was observed that technological advancements in the field of data science is now being increasingly applied for protection of power systems. These newer methods are exploited due to their speed and accuracy and they possess complex decision-making capabilities. AI techniques like fuzzy logic, neural networks, genetic algorithms and more can provide optimum and efficient performance of relays for handling relaying operation under abnormal conditions by learning from previous data. Many more such algorithms can be explored for improvement of distance protection scheme and enhance performance of relay for all types of faults for series compensated transmission line and more such complex networks.

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