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PROTECTION SCHEME FOR DIFFERENT FACT DEVICES IN TRANSMISSION LINE

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Abstract: In recent years, the inclusion of flexible AC transmission systems (FACTS)-based compensating devices such as a thyristor-controlled series capacitor (TCSC) and a unified power flow controller (UPFC) has been increased in high-voltage power transmission systems due to numerous technical and economical benefits. However, the operation of such FACTS devices introduces harmonics and non-linearity in power system and causes fast changes in line impedance. As a result, the most widely used fixed impedance setting based distance relaying scheme finds limitation in protecting such compensated lines. Significant research has been carried out in recent years to develop new algorithms and methods to address the problem. This paper presents a comprehensive review of recent developments in the protection of TCSC/UPFC compensated high-voltage transmission lines. The relative merits and demerits of each of the available methods are also presented for comparison. Prior to detail review, the impact of TCSC/UPFC on distance protection is evaluated by using data generated through EMTDC/ PSCAD on a 400 kV two-bus test power system. This study can be useful to both academic researchers and practicing engineers to gain insight on the protection of FACTS compensated transmission lines and for further development of newer algorithms.

1 Introduction

In the last few decades, because of the introduction of deregulated energy markets and environmental reasons, the growth in power transmission system has been restricted despite of continuous growth in the demand and generation of electricity. To fulfil the increasing electricity demand, power utilities today necessitate optimum utilisation of the existing transmission facility. However, in interconnected power systems, the various constraints such as voltage stability, transient stability and/or power stability restricts the full utilisation of the existing transmission corridors. For alleviation of these constraints and efficient utilisation and control of existing transmission networks, utility communities these days have focused on the installation of advanced power-electronic technology-based flexible AC transmission systems (FACTS) [1–3]. Amongst the various FACTS controllers, the thyristor-controlled series capacitor (TCSC) and the unified power flow controller (UPFC) are the two most important FACTS devices, which are installed widely on high-voltage transmission lines [4].

The TCSC device comprises of a thyristor-controlled variable capacitor protected by a metal-oxide varistor (MOV) and an air-gap. It offers several benefits, such as fast and continuous control of the series compensation level, dynamic control of power flow, reduction of system losses, mitigation of sub-synchronous resonance and improved transient stability [5, 6]. The UPFC consists of both the static synchronous compensator (STATCOM) and the static synchronous series compensator (SSSC). It can control the magnitude and phase angle of transmission voltage and impedance of the line simultaneously. This, in turn, helps in controlling the active and reactive power flows independently in a transmission line [7]. However, the presence of TCSC/UPFC controllers in the fault loop affects both the steady state and transient components of voltage and current signals. As a result, the widely used fixed impedance setting-based distance relaying schemes for protecting normal transmission lines find limitation in protecting such FACTS compensated lines [8, 9]. Therefore, to take full advantage of the installation of FACTS controllers on transmission lines it is crucial to study the impact of these controllers on the performance of distance protection scheme.

The various problems faced by distance relay while protecting FACTS (TCSC/UPFC) compensated high-voltage transmission lines include fault detection, fault zone identification, fault classification and fault location estimation. Significant research has been carried out in the past few decades to improve the performance of conventional distance relaying scheme protecting FACTS compensated high-voltage transmission lines. The papers published in various journals, conference proceedings and book chapters related to the protection of TCSC/UPFC compensated transmission lines from 1998 to till date is shown in Fig. 1. The chronological trend in Fig. 1 clearly shows the increasing interest of research for developing more and more improved protection schemes for FACTS compensated high-voltage transmission lines. This work presents an up-to-date review on the development of protection schemes for TCSC/UPFC compensated high-voltage transmission lines. The remaining of the paper is organised as follows. In Section 2, the impact of TCSC/UPFC controllers on distance protection is briefly demonstrated through a simulation study. In Section 3, a comprehensive review including the merits and demerits of each of the methods used for detection/zone identification, classification and location of faults in TCSC and UPFC compensated transmission lines are presented. Finally, the conclusion and future perspectives on the protection of the FACTS compensated transmission line are provided in Section 4.

2 FACTS compensated high-voltage transmission lines: protection challenges

The basic configuration and the different operating modes of TCSC and UPFC controllers and their impacts on the distance protection are well documented in [10–16], respectively. However, for the sake of completeness, in this section, the impact of TCSC/UPFC compensated transmission lines on the performance of distance relay is evaluated by using data simulated through EMTDC/ PSCAD on a 400 kV test power system.

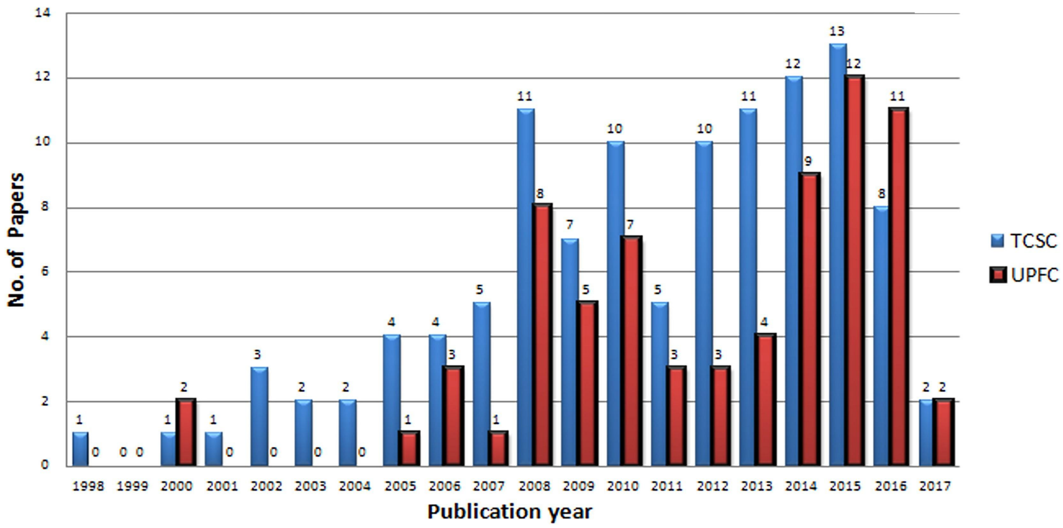

Fig. 1 *Distribution of papers on protection of TCSC/UPFC compensated transmission lines with respect to publication year*

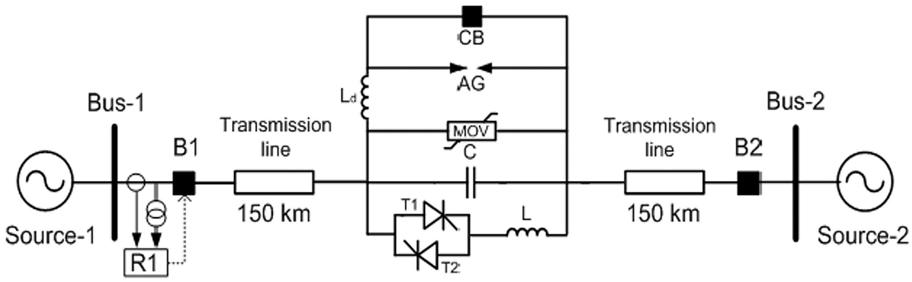

Fig. 2 *TCSC compensated transmission system*

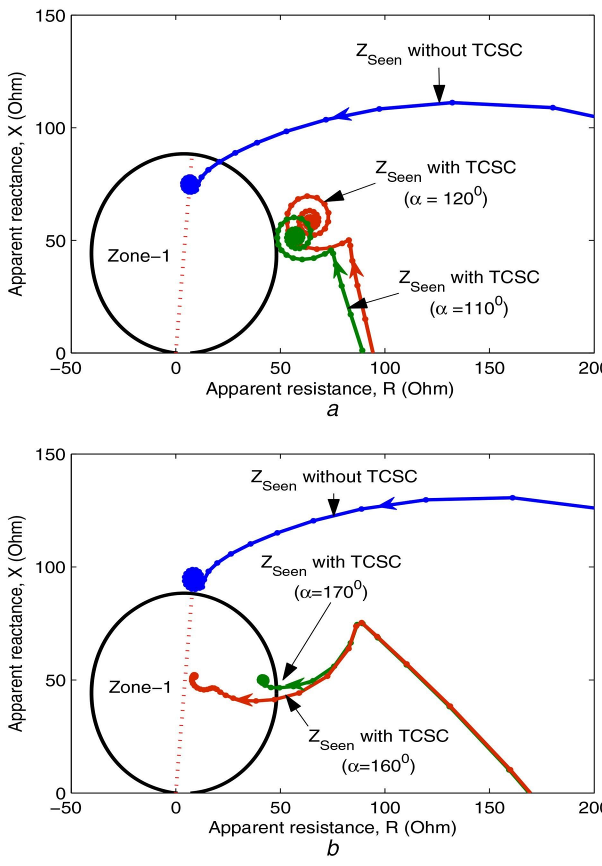

Fig. 3 *Performance of distance relay protecting a TCSC compensated transmission line*

(a) Three-phase fault at 66.67% of the line (relay underreach), ***(b)*** Three-phase fault at 83.33% of the line (relay overreach)

2.1

Performance evaluation of distance relay protectingTCSC compensated high-voltage transmission line

A 400 kV, two-source equivalent power system as shown in Fig. 2 is simulated through PSCAD/ EMTDC software where the TCSC is placed in the middle of the transmission line. The length of the line is 300 km. The zero and positive-sequence impedances of the transmission line are $Z_0 = 0.2587 + j1.174$ Ω/km and $Z_1 = 0.03293 + j0.3184$ Ω/km, respectively. The system operates at a load angle of 10°. In this study, the TCSC is designed to provide minimum and maximum compensation of 30 and 40%, respectively. Operating voltage of MOV is set at 75 kV. For performance evaluation, the distance relay *R*1, placed at bus-1 for breaker *B*1 is considered in this study. The zone-1 of the relay covers 80% of the line length.

Results of two three-phase fault cases created at two different locations of the transmission line are presented here for demonstrating the impact of TCSC on the performance of relay *R*1. The first three-phase fault is created at 66.67% of the line length (within zone-1 of relay *R*1) during the period when the TCSC operates in the inductive operating region. The second three-phase fault is created at 83.33% of the line length (outside zone-1 of relay *R*1) during the period when the TCSC operates in the capacitive operating region. The voltage and current signals are collected at relay *R*1 at a sampling frequency of 1 kHz for a 50 Hz power system. The *R*–*X* plot of the apparent impedance seen at the relay location for the above two fault cases along with the apparent impedance seen without TCSC is shown in Fig. 3. The observations in Figs. 3*a* and *b* clearly show that when the TCSC is present in the fault loop depending upon the location, fault type and operating mode of the TCSC distance relay faces either underreaching or overreaching problems.

2.2 Performance evaluation of distance relay protecting UPFC compensated high-voltage transmission line

For demonstrating the impact of UPFC on distance protection, the TCSC in Fig. 2 is replaced by UPFC and is shown in Fig. 4. The

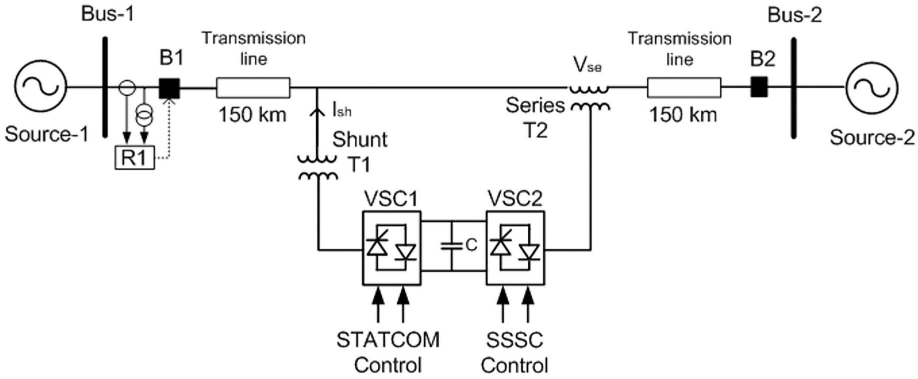

Fig. 4 *UPFC compensated transmission system*

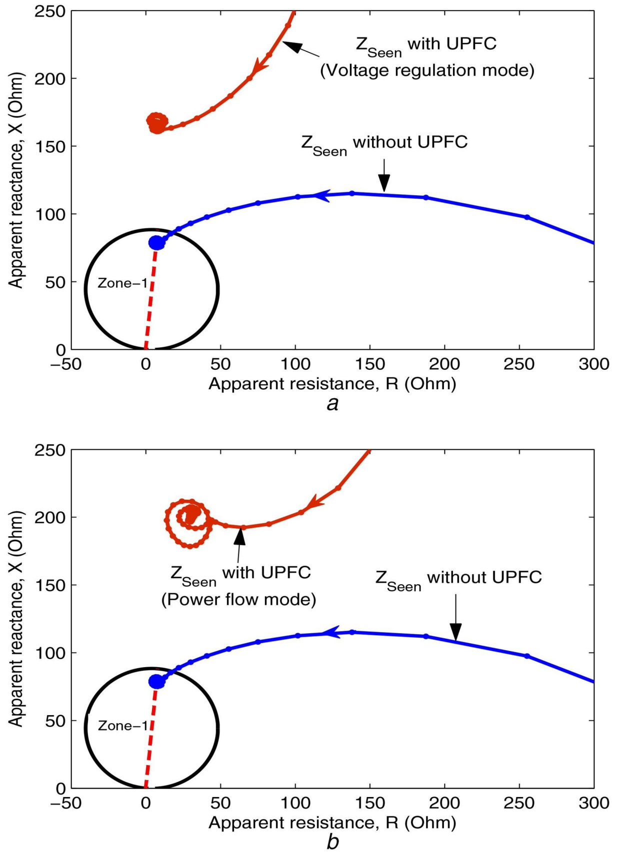

Fig. 5 *Performance of distance relay protecting a UPFC compensated transmission line*

(a) Three-phase fault at 70% of the line, ***(b)*** Single-line-to-ground fault at 70% of the line

UPFC consists of two GTO-based voltage source converters (VSCs) connected through two 2000 μF DC capacitors link. The STATCOM (VSC1) is connected to the three-phase line through a Δ/*Y* shunt transformer (400/20 kV) and the SSSC (VSC2) is connected with *Y*/*Y* series transformer (230/20 kV).

Results for two different fault cases are provided here for demonstrating the impact of UPFC on the performance of distance relay *R*1. During the voltage regulation mode of operation of the UPFC, a three-phase fault is created at a distance of 210 km (70% of the line length) from relay *R*1 keeping the voltage across the dc-link capacitor constant with $V_{\text{ref}} = 1.5$ p.u. During the power flow mode of operation of the UPFC, a line-to-ground fault of the AG-type is created at a distance of 210 km (70% of the line length) from relay *R*1. The *R*–*X* plot of the apparent impedance seen at the relay location for the above two fault cases along with the apparent impedance seen without UPFC is shown in Fig. 5. The observations in Figs. 5*a* and *b* clearly show that in both the fault cases the distance relay *R*1 faces underreaching problem [9, 17, 18]. This shows that both parts of the UPFC (SSSC and STATCOM) have an impact on the measured impedance by the distance relay.

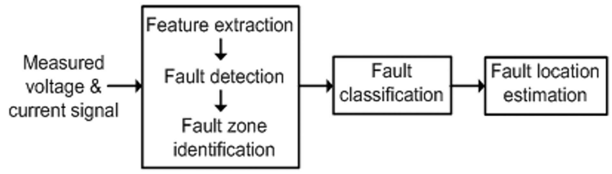

Fig. 6 *Block diagram representation of three main stages of a digital distance relaying scheme for the protection of FACTS compensated transmission lines*

3 State-of-the-art on fault detection, classification and location estimation on FACTS compensated high-voltage transmission line

Fault diagnosis in digital distance relaying-based transmission line protection scheme is performed in three stages: fault detection, fault classification and fault location estimation [19, 20]. Initiation of a fault is first identified by the fault detector unit. It basically discriminates faults from non-fault events. The fault detector unit activates the fault classifier unit to classify the fault type. Once the fault type is determined, fault locator unit computes the impedance for estimating the distance of the fault from the relay. In FACTS compensated high-voltage transmission lines the steady state and transient components of the measured voltage and current signals at relay point are affected when fault loop includes TCSC/UPFC devices. Further, in such compensated lines, the same fault or two different faults may produce the equal magnitude of the current at two different locations (before and after the TCSC/UPFC) of the line. Therefore, for protecting FACTS compensated transmission lines along with fault detection, fault zone identification is very crucial for the correct estimation of fault type and location of the fault. The links among these three units in a digital distance relaying scheme for protecting FACTS compensated transmission lines is illustrated in Fig. 6.

Significant research has been carried out especially in the last decade for fast and accurate detection/zone identification, classification and location estimation of faults occurring in FACTS compensated transmission lines. Some of the methods perform all three tasks, while some others perform one or two of the tasks. In this section, the detailed review of the available fault detection/zone identification and fault classification methods for TCSC/UPFC compensated transmission lines is carried out first. Then, the detailed review of available fault location estimation techniques is provided.

3.1 Fault detection/zone identification and classification algorithms for FACTS compensated high-voltage transmission lines

The various approaches proposed especially in the last decade for detection/zone identification and classification of faults in TCSC/UPFC compensated transmission lines are mainly based on advanced signal processing techniques and/or computational intelligence techniques. However, few fault detection and classification schemes are also proposed based on adaptive relaying [21–28] and simple circuit theory approach [29–32]. The available fault detection and classification schemes for TCSC/ UPFC compensated lines can be categorised based on successive advancement as (i) algorithms based on adaptive relaying approach, (ii) algorithms based on circuit theory approach, (iii) algorithms based on advanced signal processing approach and (iv) algorithms based on computational intelligence approach with/ without advanced signal processing tools. The detail review and comparison of available methods belong to different categories are provided below.

3.1.1 Algorithms based on adaptive relaying approach: Methods based on the adaptive setting of distance relay tripping boundaries are proposed in [21–25] for protecting FACTS compensated transmission lines. The effect of variation of UPFC parameters and its location on measured impedance and the trip boundary of a distance relay is demonstrated in [24, 25]. It is demonstrated that using the artificial neural network (ANN), on-line calculations of trip boundaries of distance protection can be achieved by varying the ratio of series injected voltage to the measured voltage at relay bus and angle of the series VSC. Adaptive protection schemes based on Kalman filters are proposed in [21–23] for fast fault classification in TCSC compensated transmission lines. The differences between line current noise signals for faults before and after the TCSC are utilised for fault classification. However, protection schemes based on Kalman filtering approach have the limitation of modelling fault resistance. Also, such methods need a large number of filters for performing fault classification [26, 27].

3.1.2 Algorithms based on circuit theory approach: In this category, using the measured data, a set of equations are solved based on circuit theory approach for accomplishing fault detection and fault zone identification task in TCSC/UPFC compensated transmission lines. In [29], to avoid the impact of TCSC on distance protection, the apparent impedance seen at relay location is modified by incorporating the compensation level and location of the TCSC and instrument transformers connecting point. The study is performed by varying the compensation level from −20 to 60% at 20% step by placing the TCSC at the beginning of the line first and then at both ends of the line. To avoid nuisance tripping during a phase-to-earth fault, the apparent impedance estimated by distance relay is modified in [31] according to the variation of the parameters in TCSC compensated transmission line. Impact of compensation level of TCSC and fault resistance on measured impedance is investigated. Another method is proposed in [32] where the average values of voltage and current over a cycle is used for estimation of fault direction and faulty phase in a TCSC compensated transmission line. It is demonstrated that the performance of the method is independent of the operating modes and the location of the TCSC. The method detects the fault in less than one cycle. However, the method requires communication medium in order to confirm the fault to be internal or external.

Recently, a fault direction estimation algorithm is proposed in [28] for a TCSC compensated double-circuit line using principal component analysis (PCA)-based method. The scheme employs four features, namely angles between (i) positive-sequence fault current and voltage, (ii) positive-sequence fault and pre-fault currents, (iii) positive-sequence superimposed voltage and current and (iv) negative-sequence current and voltage as input to the PCA where an orthogonal transformation is used to convert correlated variables into linearly uncorrelated variables called principal components. The performance of the scheme is tested for faults producing voltage inversion, current inversion, far-end fault and high resistance fault situations and found to be satisfactory.

The impact of UPFC placed on the protected line or on the adjacent line of the estimated impedance is investigated in [30]. For eliminating the error in the apparent impedance such approaches require calculating the voltage drop/equivalent impedance across the compensating device using the real time measured quantities. For mid-point c require a dedicated communication channel with real-time measurements which is not cost effective. Also, some of such approaches calculate the voltage drop/equivalent impedance across the series device (TCSC) using an approximate model of the series device. The incorrect series device model or the uncertainty operation mode of the series device may introduce error in the computed impedance.

3.1.3 Algorithms based on advanced signal processing approach: Signal processing is a mathematical operation applied to extract useful information from measured raw signals for discriminating faults from non-fault events. The recently developed various advanced signal processing approaches such as wavelet transform (WT), stationary WT (SWT), S-transform (ST), fast discrete ST (FDST), fast discrete orthonormal ST (FDOST) and time-time (TT) transform are widely applied for detection/zone identification and classification of faults in TCSC/UPFC compensated transmission lines. The detail review and comparison of each of the advanced signal processing techniques applied for fault detection and classification in TCSC/UPFC lines are provided below.

WT: It is a mathematical tool used for effective time–frequency analysis of non-stationary signals. It measures the correlation of scaled and translated mother wavelet with the input signal [33]. The approach of using long windows for low frequencies and short windows for high frequencies makes WT more effective for analysis of signals having transients or distortions [34]. Using WT as a feature extraction tool, different methods are proposed for the detection and classification of faults in TCSC [35–38] and UPFC [39–41] compensated transmission lines. The relative merits and demerits of each of the reported methods are discussed below.

In [35], a fault classification and section identification scheme is proposed for a TCSC compensated transmission line using discrete WT (DWT). Here, the features for standard deviation based index are generated from one-cycle data of three-phase currents using ‘db4’ mother wavelet. The standard deviation of the eighth level decomposition coefficient is found to be maximum for fault classification. For fault section identification, the first level decomposition coefficients are used in this paper. Another method based on wavelet packet transform (WPT) is proposed in [36] for faulty phase and faulty section identification in a TCSC compensated transmission line. The signal in WPT is decomposed into both high- and low-pass components, whereas in WT, only low-pass components are decomposed further. This property of WPT provides improved frequency resolution in higher frequency ranges compared to WT. In [37], SWT is employed, which up samples the filters by zero padding at each level to avoid the translational variance problem. The method utilises three-phase currents as input to the algorithm and using ‘Haar’ mother wavelet the spectral energy is computed for detecting faults in TCSC compensated transmission line. Using one-cycle post fault currents at 30 kHz sampling frequency another hybrid DWT-extreme learning machine (DWT-ELM)-based fault classification method is proposed in [38] for TCSC compensated transmission line. In that method, features from DWT decomposition are trained by ELM without any hidden layer resulting faster fault classification. The performance of the scheme is tested by considering different mother wavelets and finally using ‘db2’ highest fault classification efficiency of 99.97% is achieved.

An efficient time–frequency analysis based on wavelet combined entropy is proposed in [39] for detection and classification of faults and fault section in UPFC compensated transmission line by utilising post-fault voltage and current signals. Detection and classification of faults in a double-circuit UPFC compensated transmission line is proposed in [40] by using a combined wavelet and fuzzy logic approach. However, the method requires global position system (GPS) time stamped synchronised current signals at both ends of the line for accomplishing the fault detection and classification tasks. In [41], a fault detection and classification method is proposed for UPFC compensated transmission line using wavelet singular entropy (WSE). The method employs the summation of the fourth level detail

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Table 1 Comparison of WT and ST based techniques employed for detection/zone identification and/or classification of faults in TCSC/UPFC compensated high voltage transmission lines

Reference	Purpose/task	Compensated device	Signal processing technique	Input quantities	Key indicator	Data requirement	Response time
[35]	FSI, FC	TCSC	WT	three-phase currents			

db4 wavelet and d1,d8 coefficient					1 cycle at 10 kHz —		
[36]	FSI, FC	TCSC	WPT	”	db1 wavelet and d1–d15 coefficient	1 cycle at 1.6 kHz	fault classification time <20 ms
[37]	FD	TCSC	SWT	”	Haar wavelet and d1 coefficient	1 cycle at10 kHz	—
[38]	FD, FC	TCSC	WT	”	db2 wavelet and d1–d8 coefficient	1 cycle at 30 kHz	—
[41]	FD, FC	UPFC	WSE	three-phase currents and ground current	db4 wavelet and d4 coefficient	3 cycles at 1.2 kHz	—
[42]	FSI, FC	TCSC	ST	three-phase currents	standard deviation and energy	1 cycle at 1 kHz	—
[44]	FD, FC	UPFC	FDST	three-phase currents from both ends	spectral energy	1 cycles at 3.8 kHz	fault classification time <20 ms
[45]	FD, FSI	UPFC	FDOST	three-phase currents	FDOST coefficient	1 cycle at 3 kHz	—
[49]	FD, FC	TCSC	TT-transform	three-phase currents from both ends	TT-matrix	1 cycle at 1 kHz	fault detection classification time <60 ms

FD: fault detection, FC: fault classification, FSI: fault section identification.

coefficients for fault detection and the WSE of three-phase currents for fault classification.

The above study clearly shows that in recent developments the protection schemes using WT-based feature extraction techniques have the potential for detection and classification of faults in TCSC/UPFC compensated transmission lines. However, most of the wavelet-based methods need multi-level filtering which makes them computationally inefficient. The other challenges such as noise sensitivity, proper mother wavelet selection, sampling frequency and narrow high frequency support impose difficulty in designing a systematic fault detection and classification technique using WT [42–45].

ST: To overcome the limitations of WT, a modified WT known as S-transform is introduced in [46] for analysis of transient signals. ST introduces variable window to short-time Fourier transform by using a moving and scalable Gaussian window function. The time–frequency representation of a transient signal using ST is more effective than WT. As compared to WT, it is less sensitive to noise and able to analyse the features of a particular harmonic precisely [47, 48]. Different methods using ST and improved version of ST are proposed for the detection and classification of faults in TCSC [42, 43, 49] and UPFC [44, 45, 50] compensated transmission lines. The relative merits and demerits of each of the reported methods are discussed below.

In [42], the fault detection and classification task is performed for a TCSC compensated transmission line by using probabilistic neural network (PNN)-based pattern recognition technique. The method extracts the features using one-cycle of current signals sampled at 1 kHz through ST. Using the ST-coefficients the features such as standard deviation and energy are extracted and a PNN is trained and tested for automatic fault classification and section identification. The method achieves an accuracy of 98.62 and 99.86% for fault classification and section identification, respectively. In that paper, the advantage of the Bayesian classifier-based probabilistic model is explored. A hybrid method based on the ST-logistic model tree is proposed in [43] for fault classification and section identification in a TCSC compensated line. In that paper, using one-cycle post fault currents six features (per phase) are extracted from the time–frequency contours of the ST. Finally, the square height value of level 1 obtained from frequency contour and the sum of square values of levels 1–9 obtained from frequency contour are used for fault classification and section identification, respectively. The advantage of the method is that the features trained by LMT need only one single model classifier for both fault classification and section identification.

Recently, a protection scheme has been proposed for TCSC compensated transmission line in [49] by employing time–time transform (TT-transform) on current signals retrieved at both ends of the line. TT-transform is derived from ST and it decomposes one-dimensional (1D) time series to 2D TT series. The method utilises the *z*-score of the TT-matrix calculated for each phase of the sending and receiving end currents for fault detection and faulted phase selection. The difference between the absolute sum of the TT-matrix between sending and receiving end are used for fault section identification. The maximum delay time in fault detection, classification and section identification using TT-transform is less than three cycles at a base frequency of 50 Hz. The authors have demonstrated through result that the fault detection and classification method using TT-transform has better performance compared to WT-based methods, especially in noisy environment.

A cross-differential protection scheme is proposed in [44] for a parallel transmission line installed with UPFC. The scheme employs a cumulative sum-based method for fault detection. The spectral energy calculated from normalised frequency contour extracted from three-phase currents through FDST is used for fault classification. The reduced computational complexities of FDST over conventional discrete ST are demonstrated in that paper. A pattern recognition technique based on FDOST and support vector machines (SVMs) is proposed in [45] for fault zone and fault type identification in a transmission line installed with UPFC. The advantage of FDOST over ST for fault analysis is explored in that paper.

For easy reference and better understanding, comparative assessment of WT and ST-based feature extraction techniques employed for detection/zone identification and classification of faults in TCSC/UPFC compensated transmission lines is provided in Table 1. The comparison is made considering the implementation complexity, computational burden and response time.

3.1.4 Algorithms based on computational intelligence techniques with/without advanced signal processing tools: The various intelligence learning-based techniques such as

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ANN, SVM, fuzzy inference system (FIS), decision tree (DT) and so on, with/without advanced signal processing tools are proposed for fast and accurate detection/zone identification and classification of faults in TCSC/UPFC compensated transmission lines. The detailed review and comparative assessment of available intelligence techniques are provided below.

ANN: It is a computational training based non-linear statistical model which consists of simple processing units that imitate behaviours of connected neurons within the biological neural system [51]. ANN is a simple, efficient and robust classification tool that can deal with non-linear inputs and can also be implemented in digital systems [52]. Using ANN, different methods are proposed for detection/zone identification and classification of faults in TCSC/UPFC compensated transmission lines [21, 24, 53–59]. The relative merits and demerits of each of the reported methods are discussed below.

An adaptive protection scheme based on ANN is proposed in [21] for the protection of TCSC compensated transmission line. The main emphasis is given for performance evaluation of zone-1 protection of distance relay. The extracted features from bus side voltages, line currents and firing angles of thyristors at the inception of a fault are used for training and testing the ANN. The method has a limitation when TCSC is installed in the middle of the line. A fault classification algorithm based on ANN is proposed for a TCSC compensated transmission line in [53]. The method employs DWT in combination with self-organising map (SOM) methodology for feature extraction and training the ANNs. This method reduces the amount of training data. Thus, achieves faster learning process and fault classification. An algorithm using radial basis neural network (RBNN) is proposed in [55] for the protection of the TCSC compensated transmission line. To avoid the influence of TCSC on distance relay performance the voltage across the TCSC is calculated first and then it is subtracted from the voltage measured at relay point. A fault classification and location estimation algorithm is proposed in [56] using multi-layer perceptron neural networks (MLPNNs). For fasted training, the Levenberg–Marquardt (LM) algorithm is employed. An ANN-based adaptive trip boundary setting for distance relay is proposed in [24] for protecting a UPFC compensated transmission line.

The above study clearly shows that using ANN efficient and robust fault classification in TCSC/UPFC compensated transmission lines can be accomplished. The other advantage of ANN is that it can be easily incorporated into the existing digital distance relaying scheme. However, for proper implementation of ANN training of large data set and time is required. Also, ANN based protection schemes require retraining in case of a significant change in the system configuration [27, 38, 58].

SVM: It is a statistical learning method invented by Cortes and Vapnik in 1995 [60, 61]. In SVM, input features are mapped into an optimal hyperplane that maximises the margin between two different data groups for better classification. The different data groups are mapped into higher dimensional spaces by using non-linear kernel functions. SVM-based fault classifier has better generalisation ability in case of maximisation of decision boundary margin and it does not need much expert knowledge for classification purpose [45, 62]. Using SVM, different techniques are proposed for classification of faults in TCSC/UPFC compensated transmission lines [27, 45, 62–65]. The relative merits and demerits of each of the reported methods are discussed below.

In [27], fault classification and section identification task is performed for TCSC compensated transmission line using SVM, where half-cycle post fault current signals and firing angle of the thyristor are used as inputs to the SVM. The method employs polynomial kernel and Gaussian kernel for training the SVMs. The classification accuracy is above 95%. In [63], another SVM-based fault classification scheme is proposed for TCSC compensated transmission line by using one-cycle post fault currents. The method employs the genetic algorithm technique for setting optimum values of SVM parameters. The impact of sampling frequency on the performance of the method is demonstrated. The overall classification accuracy of the method is above 99%. In [45], three separate SVM operations are proposed for fault classification,

fault loop status and zone identificat

compensated with a 48-pulse converter-based UPFC. In that method, features are extracted through FDOST by using one-cycle post fault voltages and currents sampled at 3 kHz. The extracted features are then used as inputs to the DT and SVM-based fault classifier. It is demonstrated that the fault classification accuracy of SVM is superior over DT. In [64], a comparative analysis of SVM and random forest (RF) based fault classifier is used for TCSC and UPFC compensated transmission line. The method utilises half-cycle post fault voltage and current samples at 1 kHz sampling frequency as input to both the classifiers. It is demonstrated that the overall fault classification accuracy, as well as processing time of RF classifier, is superior compare to SVM classifier.

However, selecting a suitable kernel function and the values of margin parameters make SVM-based classifier computationally inefficient [38, 45]. Moreover, SVM requires a new set of classification parameters in case significant changes in the system configuration.

FIS: It represents fuzzy logic based on if–then rules. The FIS has three operational stages, i.e. fuzzification stage, inference stage and defuzzification stage. The degrees of linguistic inputs for different membership functions are computed first and then fed to the inference stage where the if–then operations are performed and after defuzzification, the final decision is provided for the inputs [66].

A fuzzy logic-based algorithm is proposed in [67] for fault detection and fault zone identification in a TCSC compensated transmission line using the dc components of the current signal. In that paper, the difference of the digitally integrated three-phase current signal and DC rejected current signal is fuzzyfied by certain criterion. The value obtained from the fuzzifier of the triangular membership function is compared with a threshold for fault zone identification. However, the method has a poor fault detection accuracy (around 85%) when TCSC is present in the fault loop. The application of fuzzy logic for FACTS compensated line protection is very limited due to the large variation of system parameters in such lines.

DT: It is a successful data mining tool recently used in power system applications such as power quality classification, islanding detection, fault classification and so on [68]. Compare to ANN and SVM, DT provides transparent solutions for high dimension pattern classification problems [69]. Using DT, few algorithms are reported for fault zone identification and fault classification in TCSC/UPFC compensated transmission lines [67, 69–72]. The relative merits and demerits of each of the reported methods proposed are discussed below.

Using one-cycle post fault voltage and current signals and zero-sequence currents a DT-based fault classification and fault zone identification technique is proposed in [69] for the TCSC compensated transmission line. In that paper, the performance of the DT classifier is compared with SVM classifier. It is demonstrated that the DT-based scheme is superior over SVM-based technique with respect to classification accuracy, computational burden, response time and during noisy operating condition. In [71], another DT-based intelligent differential relaying scheme is proposed for fault classification in a UPFC compensated transmission. In that paper, the differential features are extracted using the voltage and current signals from both ends of the transmission line. The classification accuracy of the method is shown to be 100% with a maximum delay in the response time is 30 ms. However, the setting of proper thresholds at different nodes of the classification tree of DT is a very difficult task and may result in misclassification in certain circumstances. To avoid such drawbacks of DT an improved fault classification scheme is proposed in [72] for a UPFC compensated transmission using DT-induced fuzzy rule-based intelligent differential relaying scheme. In that scheme, the fuzzy membership function is set by using the DT thresholds and the corresponding fuzzy rule-base is developed for final relaying decision.

For easy reference and understanding of the topic, comparative assessment of the important methods proposed for detection and classification of faults in TCSC/UPFC compensated transmission lines using ANN, SVM, FIS and DT-based computational intelligence techniques are provided in Table 2.

3.2 Fault location algorithms for FACTS compensated high-voltage transmission lines

Accurate fault location estimation is the third most important requirement of a digital distance protection scheme for the fast restoration of transmission lines [73, 74]. The presence of FACTS devices in the fault loop introduces an error in the estimation of fault location due to the non-linear variation of impedance across the compensating device. Traditionally, the voltage drop across the series device is computed by using the simplified model of the MOV and series capacitor combination and operating modes of the compensating device [75]. However, the approximation model of the series capacitor and MOV introduces an error in the computation of equivalent impedance and compensation voltage during the transient period due to the non-linear operation of the MOV. Again the non-linear operation of TCR of TCSC and STATCOM and SSSC of UPFC also introduces new difficulties in computing the compensation voltage [76]. To overcome the limitation of traditional fault location schemes, recently more advanced algorithms are proposed by using measurements from one end or both ends of the transmission line. Based on the operating principles, the available fault location estimation methods can be categorised as (i) algorithms based on travelling waves (TWs) approach, (ii) algorithms based on computational intelligence techniques based on signal processing approach and (iii) algorithms based on two-end synchronised measurements. The detail review and comparison of available fault location estimation techniques for TCSC/UPFC compensated high-voltage transmission lines is provided below.

3.2.1 Algorithms based on TWs approach: Fault location estimation using TWs concept has been used for a long time in high-voltage transmission lines [77]. However, a very few methods are reported for fault location estimation using TWs concepts in TCSC/UPFC compensated. The merits and demerits of each of the reported methods are discussed below.

The interaction between TWs generated by faults and the harmonic frequencies produced by TCSC are analysed in [78] for fault location estimation in TCSC compensated transmission line. The method employs DWT- and PNN-based pattern recognition techniques for analysis of high frequency components of three-phase voltages that are generated during a fault. However, the accuracy of the fault location estimation algorithm depends on the sampling rate of the signal. Another TWs-based fault location method for TCSC compensated transmission line is proposed in [79]. By using DWT, features are extracted from one-cycle post fault voltage signals sampled at 20 kHz. The second wave front of the first level decomposition is used to locate the fault. The result shows the signals with the high sampling frequency the fault location distance error is less compared to signals with the low sampling frequency.

The main advantage of fault location schemes based on TWs is that such techniques are independent of network configurations and installations. Thus, can be applied to FACTS compensated transmission lines. However, the harmonic frequencies generated by FACTS controllers can distort the high frequency pattern of the TWs during a fault. This imposes difficulty for detecting the desired high frequency components for accurate fault location in FACTS compensated transmission lines. Moreover, the requirement of the high sampling rate for identifying the signal is another limitation for practical implementation.

3.2.2 Algorithms based on computational intelligence techniques with advanced signal processing approach: To overcome the limitations of TWs-based fault location algorithms recently some advanced fault location algorithms are proposed for TCSC/UPFC compensated transmission lines by using computational intelligence schemes. For accomplishing the fault location estimation task mainly the computational intelligence schemes such as ANN and SVM are used along with DWT, sparse ST (SST) and hyperbolic ST-based [illegible] [56, 80–84]. The detail review and comparison of each of the reported methods are provided below.

In [80], the DWT-ANN-based fault location estimation algorithm is proposed for the TCSC compensated transmission line by utilising the three-phase voltage and current signals. Here, SOM is employed for thorough visualisation and analysis of input features. The number of training data is reduced by SOM resulting faster learning process. The fault location estimation accuracy of the method obtained is above 99%. Another DWT-ANN-based fault location estimation technique is proposed in [82] for a TCSC compensated transmission line by using one-cycle pre-fault and two-cycle post-fault three-phase current and voltage signals. The method utilises the LM algorithm for training the ANN for faster convergence. Apart from the normal shunt faults, the performance of the method is also tested for multi-location faults. For all fault cases, it is demonstrated that the percentage error in estimation of fault location lies below 1%.

In [83], a fault location algorithm is proposed for a UPFC compensated transmission line by using a new matrix version of the conventional ST called SST. In that paper, impedance trajectory and hence the location of the fault is estimated by using the features extracted from SST matrix. The method employs an intelligent frequency scaling technique by which the computational speed of the SST is achieved 30 times faster than the conventional DST. Recently, an improved fault location estimation algorithm is proposed in [84] for UPFC compensated transmission lines by using the measured three-phase voltage and current signals. Using hyperbolic ST which is an improved version of the ST the method extracts three features namely impedance, time–frequency and hidden statistical features from the measured voltage and current signals. Then the features extracted for different fault cases are fed as input to the SVM with a non-linear kernel function for fault location estimation. However, the method needs information about fault type and fault section for fault location estimation by SVMs.

3.2.3 Algorithms based on two-end synchronised measurements: To overcome the limitations of one-end fault location schemes, two-end fault location schemes are proposed for TCSC/UPFC compensated high-voltage transmission lines by using synchronised voltage and current phasors at both ends of the line [85–90]. In such schemes, GPS time stamped phasor measurement units (PMUs) placed at both ends of the transmission line provide synchronised voltage and current phasors [91, 92].

A fault location algorithm is proposed in [85] by utilising the synchronised voltage and current samples at both ends of a transmission line compensated with TCSC. Considering distributed line model the scheme estimates the voltage and current phasors at the fault location by using the synchronised voltage and current of sending end and receiving the end of the line. The voltage and currents are sampled at 40 kHz. Then by applying an optimisation technique to the estimated voltage and current, the location of the fault is estimated. The advantages of the method are that it does not need the series device model and operating modes of compensating device for estimating the voltage drop across the series device as done in the traditional method. Also, the fault location error lies below 0.5% for a wide variety of fault cases.

The method proposed in [85] requires iterative calculations to accomplish the fault location estimation task. To carry out calculations, the initial guess of unknown values plays an important role for convergence of these algorithms. To overcome such limitations a non-iterative fault location algorithm is proposed in [86] by utilising the synchronised voltage and current samples at both ends of a TCSC compensated transmission line. The method operates in three stages. The first and second stages assume that the fault is located on the right-hand and left-hand sides of the series compensator, respectively. For each stage, two locations of faults are calculated. However, only one of them is correct. In the third stage, the results obtained for the first and second stages are compared and the correct location of the fault is determined. The average fault location error of the method is about 0.0625%.

In [87], a fault location algorithm is proposed for a UPFC compensated transmission line by using synchronised voltage and

Table 2 Comparison of some important computational intelligence techniques employed for detection and/or classification of fault in TCSC/UPFC compensated high-voltage transmission lines

Reference	Purpose/ task	Compensated device	Computational intelligence technique	Input quantities	Data requirement	Remarks
[56]	FC	TCSC	MLPNN	three-phase voltages and currents	1/4 cycle at 0.96 kHz	mean square fault classification error =0.01% and the longest delay time for fault classification =12 ms
[57]	IM	TCSC	TDNN	three-phase currents	11 cycles at 0.96 kHz	mean square impedance error =1.28 × 10^{-3}%
[59]	IM	TCSC	RBNN	”	1 cycle at 0.96 kHz	mean square impedance error =3.65 × 10^{-3}%
[38]	FC	TCSC	ELM	”	1 cycle at 0.96 kHz	average fault classification efficiency =99.97%
[45]	FC, FSI	UPFC	SVM	”	1 cycle at 3 kHz	fault classification efficiency =97.6% and fault section identification efficiency =100%
[63]	FC	TCSC	SVM	”	1 cycle at 1 and 4 kHz	fault classification efficiency ≥ 97.401%
[67]	FC, FSI	TCSC	FIS	”	1/2 cycle at 1 kHz	fault classification efficiency ≥ 95% and the longest delay time for fault classification =27 ms
[69]	FC, FSI	TCSC, UPFC	DT	three-phase voltages and currents	1 cycle at 1 kHz	the computational burden and fault classification accuracy of DT is superior over SVM and the longest delay time for fault classification =25 ms
[71]	FC	UPFC	DT	three-phase voltages and currents from both ends	1 cycle at 400 samples/ cycle	fault classification efficiency =100% and the longest delay time for fault classification =30 ms

FD: fault detection, FC: fault classification, FSI: fault section identification, IM: impedance measurement.

Table 3 Comparison of some important fault location techniques employed for TCSC/UPFC compensated high-voltage transmission lines

Reference	Compensated device	Fault location technique	Input quantities	Data requirement	Remarks
[21]	TCSC	ANN	three-phase voltages, currents and firing angle	2 cycle at 0.96 kHz	average fault location error =5.01%
[56]	TCSC	MLPNN	three-phase voltages and currents	1/4 cycle at 0.96 kHz	mean square fault location error =0.04%
[78]	TCSC	TW	—	1 cycle at 100 kHz	average fault location error <0.1%
[83]	UPFC	SST	—	1 cycle at 3.84 kHz	fault location error ≤5.78%
[84]	UPFC	SVM	—	1 cycle at 6 kHz	fault location error <0.95%
[85]	TCSC	distributed parameter modelling	three-phase voltages and currents from both ends	2 cycle at 40 kHz	fault location error <0.5%
[87]	UPFC	PMU	—	1 cycle at 1 kHz	fault location error ≤5.75%

current measurements at both ends of the line. The algorithm operates in two steps. In the first step, a combined wavelet-fuzzy logic approach is employed for fault section identification and in the subsequent step using a differential equation-based approach location of the fault is estimated in terms of the line inductance. Another fault location algorithm using synchronised voltage and current samples from both ends of UPFC compensated transmission lines is also proposed in [89]. The algorithm solves two quadratic equations assuming that the fault is once located on the left-hand side and once on the right-hand side of the UPFC using a distributed parameter line model in the time domain. The fault location error of the method lies below 1.2229%. In that method, UPFC modelling is not required. In addition, the method does not need to identify the fault section unlike [87].

Recently, a synchrophasor measurement based protection scheme is proposed in [90] for accurate fault location estimation in UPFC compensated transmission lines. To eliminate the impact of UPFC and the fault resistance on the performance of distance protection, the scheme calculates the active powers at both ends of the line by using synchronised voltage and current signals which are later used for fault resistance calculation. Then, using the relationship between active and reactive powers in the compensated transmission line, UPFC parameters (change in shunt and series impedances) are calculated and finally, the impact of UPFC and the fault resistance on distance protection is eliminated. In that scheme, the authors assume that PMUs are part of a smart grid, usually, data is sent to the control centre through communication channels. So no additional cost will be required for implementing the scheme. Though, the additional cost is not required to implement the method reliability of the method may not be guaranteed in case of communication failure.

For easy reference and understanding, comparative assessment of important fault location estimation methods proposed for TCSC/ UPFC compensated transmission lines is provided in Table 3.

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4 Conclusions

This paper presents a comprehensive review of the available methods in the technical literature for the protection of FACTS (TCSC/UPFC) compensated high-voltage transmission lines. Prior to detail review of the available protection strategies, the impact of TCSC/UPFC on distance protection is investigated using data simulated through EMTDC/PSCAD on a two-bus power system. To reduce complexity, methods available for fault detection/fault zone identification and fault classification are discussed together and fault location estimation algorithms are discussed separately. Protection schemes based on modern signal processing and computational intelligence techniques are given more attention. The relative merits and demerits of each of the available methods are compared and evaluated to lead the best technique to address the issue. Though the available artificial intelligence classifiers (e.g. ANN, FIS, SVMs, DT etc.) based on advanced signal processing techniques are fast in response, have their own merits and demerits. This indicates a requirement to explore more advanced signal processing tools and intelligence classifiers that can provide a very fast and reliable protection to FACTS compensated high-voltage transmission lines. The recent advancements in computation and communication facility will also increase the possibility of developments of more and more precise fault location algorithms in future for such FACTS compensated high-voltage transmission lines by using two-end synchronised measurements.

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