2
Review of Literature

2.1. Introduction to Transmission Line Fault Analysis

The stability of power system is largely affected by faults on the transmission line and time required to clear the faults. Thus, the power system stability and power quality are dependent on the transmission line protection schemes. Quick detection of faults helps in faster maintenance and restoration of supply, resulting in improved stability, power quality and economy of power system.

Various methodologies have been proposed in the literature for transmission lines protection. For fault analysis, a common strategy is being followed which is illustrated in Figure 2.1.

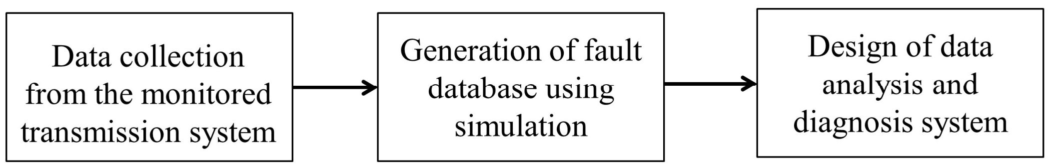

Figure 2.1: Fault Analysis Strategy

First step is collection of data from the transmission systems, has the objective of getting enough information (single-line diagrams, equipment parameters and system configuration) to model the system in simulation software. The data captured/recorded by intelligent electronic devices is used for fault detection but it has a limitation that the database provided, would not give rise to sufficient number of patterns, to be used for development and training of intelligent fault diagnosis system. Like the conditions of atmospheric discharges and high impedance faults may not be present in the real time database. Considering all the possible fault conditions, simulation software can give rise to sufficient amount of database/information to be required by fault diagnosing system for its efficient performance. Second step is to generate database for different system parameters and configurations under normal and fault conditions. This information is necessary for designing and validating diagnosis systems' models. Different computational tools are used to process the signals/information for extracting the relevant information, which is used for decision making in the third step. The last step of the module is consisting of fault diagnosis system, which has following objectives:

i. Discrimination of healthy and faulty conditions, i.e. to detect the fault.
ii. To identify the faulty phase i.e. to determine the type of fault.
iii. Estimation of fault location along the length of transmission line.

In the literature on transmission lines protection, the fault analysis task is divided into three stages: fault detection, fault classification and fault location. Figure 2.2 presents the flowchart, illustrating the links among these three modules. Fault detection is necessary to identify the instant of fault incidence. This instant or time is necessary in dividing the data into pre-fault and post-fault data, which is to be used by classification and location module, to identify the type of fault and its location.

Figure 2.2: Modules for transmission line protection

1.1.1 Fault Detection

The intelligent electronic devices are used for system monitoring to record/collect the information required for detection of fault. The fault detection information helps in maintenance and faster system restoration. The system automation is required for determining the best approach to making this data available for fault diagnosing system. For online applications, the time-lag between the sensor and detection module applications, is a limit that should be evaluated. In current scenario, the digital relays to be used in industries make use of intelligent electronic devices like Global Positioning System (GPS) for time stamping of the signals/information to be exchanged with the help of communication network. Thus, the GPS devices help in synchronization of information, which helps in determining the accurate instant of fault generation event.

2.1.2 Fault Classification

The fault classification stage aims at identifying fault type, which helps in multiple switching of conductors, i.e. only faulty phase conductor will be switched off. This pattern recognition stage generally includes the following types of fault:

- Single-line to ground faults and which phase is faulty e.g. Phase-A to ground (AG) fault, Phase-B to ground (BG) fault and Phase-C to ground fault.
- Double line fault, e.g. Phase-A to Phase-B (AB) fault, Phase-B to Phase-C (BC) fault, Phase-A to Phase-C (AC) fault.
- Double line to ground fault, e.g. Phase-A to Phase-B to ground (ABG) fault, Phase-B to Phase-C to ground (BCG) fault, Phase-A to Phase-C to ground (ACG) fault
- Three-phase fault, e.g. ABCG or ABC fault.

The fault classification may also include other types of events/ faults, such as high impedance faults (like arcing faults), atmospheric discharge, load switching (i.e. resistive, inductive or capacitive), external faults (i.e. faults occurring outside the protection zone), and others. For an intelligent classification system the types of classes are to be pre-defined before implementation of this module.

2.1.3 Fault Location

Subsequent to detection and classification of fault, the fault location is estimated by protection relaying system. This stage fulfills two purposes: first is to locate the fault i.e. to determine the fault's distance with respect to substation/bus. Secondly it also aims at identifying the faulty section (like in case of multi-terminal system or compensated system). Correct estimation of fault location helps in reducing time for its maintenance and continuity of supply.

2.2 Techniques used for Transmission Line Protection

The signal Processing based techniques such as Fourier Transform (FT), short time Fourier Transform (STFT), Wavelet transform (WT), Stockwell Transform (S-transform), Hilbert Huang transform (HHT), etc. have been used for the detection of faults and generation of actuating signals for relays during the events of Faulty Conditions. Wavelet Transform (WT) is an effective tool in analyzing transient current signals associated with faults both in frequency and time-domain. Wavelet transform has a key feature of analyzing transients, in both time-frequency domains. The S-transform is an invertible time-frequency spectral localization technique that combines elements of wavelet transform and short-term Fourier transform. The merits and demerits of the commonly used techniques for the analysis of faults on the transmission line are detailed in the Table 2.1.

Table 2.1: Merits and Demerits of Signal Processing Techniques

S. No.	Technique	Merits	Demerits
1.	Short Term Fourier Transform	Frequency domain analysis of stationary signals. Ease of computation.	Analysis of non-stationary signals is difficult because of fixed window size.
2.	Wavelet Transform	Analysis of signal in both time and frequency domain.	Affected by noise contamination in signals, suffering from spectral leakage and picket fence effects.
3.	Stockwell Transform	It employs a scalable and variable window length and uses the Fourier kernel to provide the phase information referenced to the time origin.	Based on block processing manner and does not satisfy real-time requirement, incorrect measurement of harmonics due to dependency of frequency window width on central frequency
4.	Hilbert Huang Transform	Significant in feature extraction of fault transients, a quadrature signal is obtained for computation of amplitude and phase.	Difficult to interpret when analyzing a wide band signal.

The machine learning based techniques such as Artificial Neural Network (ANN), Fuzzy C-means Clustering (FCM), Support Vector Machine (SVM), Decision Tree, Fuzzy Logic (FL), Genetic algorithm (GA), Expert system (ES) have been reported in the literature for the location of the transmission line faults. The merits and demerits of the machine learning techniques commonly use for the location of the power system faults have been provided in Table 2.2.

Table 2.2: Merits and Demerits of Machine Learning Techniques

S. No.	Technique	Merits	Demerits
1.	Artificial Neural Network	High accuracy for real time applications and provides mathematical flexibility	Convergence speed and accuracy depends on the network architecture as well as noise in the signal
2.	Support Vector Machine	Potential to handle large features, provide stable solution to quadratic optimization, high learning processes	Poor classification accuracy when training samples are minimum
3.	Fuzzy Logic	Accurate in modeling and analyzing complex systems	Training set for every case is fixed, hence not suitable for new disturbances
4.	Genetic Algorithm	Accurately classify PQ disturbances generated due to dynamic performance of power system and damped sub-harmonic signals	High computational time
5.	Expert System	Can be used with or without limited data	Expensive system, slow in execution, it is difficult to draw conclusion if assumptions and actual situations do not match exactly

2.3 Detailed Literature Review on Transmission Lines Protection

Detailed review of literature reported in the field of detection, classification and location of transmission line faults on two-terminal transmission line, multi-terminal transmission line and FACTS compensated transmission line have been provided in the following subsections.

2.3.1 Protection Algorithms for Two-terminal Transmission Systems

For two-terminal systems various protection schemes have been introduced in the literature for transmission lines. Distance Relay protection scheme for long and short transmission lines was introduced by Mohammed Ismail, *et al.* [Ismail and Hassan, 2013]. F.B. Costa, *et al.* studied effects of fault inception angle in the energies of fault induced transients in [Souza, Brito, and Costa, 2012]. Kim Chul-Hwan, *et al.* used wavelet transform to detect high impedance arcing faults[Kim et al., 2002] [C. K. Jung, Kim, Lee, and Klöckl, 2007]. A protection scheme using Haar wavelet was introduced in [Jiang et al., 2003][Joe-Air Jiang, Ping-Lin Fan, Ching-Shan Chen, Chi-Shan Yu, and Jin-Yi Sheu, n.d.], which detects dc component for identifying the faulty phases. Distance protection schemes using wavelet based phasor estimation were reported in [Liang and Jeyasurya, 2004] & [Osman and Malik, 2004]. Wavelet based protection scheme for fault detection, classification and location was proposed by Gafoor, et al. [Shaik Abdul Gafoor and Rao, 2006]& [Bhaskar, Gafoor, and Amarnath, 2015]. In [S. R. Samantaray, Tripathy, and Dash, 2012a] [Dash, et al., 2007], protection scheme, based on wavelet transform, had been proposed for parallel transmission systems. A wavelet based transient analysis utilized to detect transmission line faults, was proposed by Rao, *et al.* in [Rao, Gafoor, and Venkatesh, 2011a]. Chanda, *et al* introduced a scheme for fault location on transmission lines, using wavelet multi-resolution analysis, for transmission line [T47]. A transmission line protection scheme using maximum wavelet singular value and Euclidean norm was proposed in [Idarraga, Guillen, Ramirez, Zamora, and Paternina, 2015]. A wavelet-based relaying scheme for directional protection, fault classification and fault location has been proposed by Valsan and Swarup [Valsan and Swarup, 2009]. The application of wavelet entropy principle for transmission line protection has been illustrated in [El Safty and El-Zonkoly, 2009] & [Fan, Li, Chan, and Yu, 2006]. For parallel transmission lines fault location estimation technique, based on wavelet transform, has been proposed by Jung, et al., [H. Jung et al., 2007]. The protection scheme with improved performance and accuracy had been reported in [Bo et al., 2008] which make use of GPS clock for synchronized sampling of signals. Artificial Neural Networks with their excellent capabilities of pattern recognition and non-linear mapping were used to estimate the fault location [Tawfik and Morcos, 2001], [Martín and Aguado, 2003], [Mazon et al., 2000] [Zahra, Jeyasurya, and Quaicoe, 2000] [He, Lin, Deng, Li, and Qian, 2014] [Sanaye-Pasand and Khorashadi-Zadeh, 2006] [Alves Da Silva, Lima, and Souza, 2012] [Santos and Senger, 2011]. Purushothama G.K. *et al* have discussed applicability of ANN techniques for determination of fault location [Purushothama, Narendranath, Thukaram, and Parthasarathy, 2001]. For the location of cross-country faults and evolving faults, an algorithm making use of ANN, with input as standard deviation values of approximate DWT coefficients of three-phase current and voltage signals, has been proposed [Aleena Swetapadma and Yadav, 2015a]. Protection schemes, making use of wavelet transform and neural network have been proposed for two-terminal transmission systems. Discrete Wavelet Transform is used to extract features from the signals, which are then fed to neural network for fault detection, classification and location of fault [Bhowmik, Purkait, and Bhattacharya, 2009], [C. K. Jung et al., 2007] [Koley, Kumar, and Ghosh, 2016]. A DWT-DTR based fault distance estimation scheme has been proposed for transmission lines [Aleena Swetapadma and Yadav, 2016a]. And also comparison of the same has been done with DTR-DFT fault location scheme. For this, the current and voltage signals have been pre-processed with DWT and DFT, which are used as input to Decision tree. A fault identification method, making use of decision tree with input as fundamental components of voltage and current signals, was proposed [Aleena Swetapadma and Yadav, 2016b].

Table 2.3: Protection techniques reported for Two-terminal System

S. No.	Technique Used	Reference	Task performed
1	Wavelet Transform	[Bhowmik et al., 2009] [Aleena Swetapadma and Yadav, 2016c] [Koley et al., 2016] [Valsan and Swarup, 2009] [Joe-Air Jiang et al., n.d.] Jiang et al., 2003 [El Safty and El-Zonkoly, 2009] [Fan et al., 2006] [H. Jung et al., 2007] [Seyedi and AsghariGovar, 2016] [Aleena Swetapadma and Yadav, 2015a] [Kim et al., 2002] [Usama, Lu, Imam, Sen, and Kar, 2014]	FD,FC,FL FC,FDR FD,FC,FL FD,FC,FL FD,FC FC FL FL FD FC,FL FD FD,FC
2	Artificial Neural Network	[Mazon et al., 2000] [Zahra et al., 2000] [He et al., 2014] [Bhowmik et al., 2009] [C. K. Jung et al., 2007] [Sanaye-Pasand and Khorashadi-Zadeh, 2006] [Alves Da Silva et al., 2012] [Purushothama et al., 2001] [Koley et al., 2016] [Santos and Senger, 2011] [Koley, Shukla, Ghosh, and Mohanta, 2017] [Aleena Swetapadma and Yadav, 2015a]	FL FD,FL FC FD,FC,FL FL FL FL FL FD,FC,FL FL FL FL
3	Support Vector Machine	[Aleena Swetapadma and Yadav, 2016c] [Koley et al., 2017]	FC,FDR FD,FC
4	Fuzzy Inference System	[Yadav and Swetapadma, 2015]	FDR,FC,FL
5	Decision Tree	[Aleena Swetapadma and Yadav, 2016b] [Aleena Swetapadma and Yadav, 2016a]	FD,FC FL
6	Travelling Wave	[Hasheminejad, Seifossadat, Razaz, and Joorabian, 2016] [Pathirana and McLaren, 2006]	FD,FC FD,FL
7	Circuit Theory	[Hinge and Dambhare, 2015] [Bolandi, Seyedi, Hashemi, and Nezhad, 2015] [Hashemi, Seyedi, and Ghanizadeh Bolandi, 2014] [Yusuff, Jimoh, and Munda, 2011] [Noori and Shahrtash, 2013]	FD FD,FC FD,FC FD,FC FD,FC
8	Phase-Measurement Unit	[Z. Jiang et al., 2012] [J.-A. Jiang, Ching-Shan Chen, and Chih-Wen Liu, 2003]	FL FD,FDR,FC,FL
9	K-NEAREST NEIGHBOUR	[A. Swetapadma and Yadav, 2018]	FL
10	Alienation Coefficients	[Masoud and Mahfouz, 2010]	FD,FC

* FD=Fault Detection, FC=Fault Classification, FL=Fault Location, WT=Wavelet Transform, ST=S-Transform, DTR=Decision Tree, FIS=Fuzzy Inference System, ANN=Artificial Neural Network, FSI=Fault Section Identification, FDR=Fault Direction.

M. E. Masoud and M.M.A. Mahfouz presented a protection scheme for transmission lines based on alienation coefficients of current signals [Masoud and Mahfouz, 2010]. Gafoor, *et* *al.* developed a transmission line protection scheme using detail coefficients based alienation technique using current signals of local buses [S.A. Gafoor, Yadav, Prashanth, and Krishna, 2014]. A fault analysis algorithm, combining features of Discrete Wavelet Transform and Support Vector Machine is reported by Swetapadma and Yadav [Aleena Swetapadma and Yadav, 2016c]. This protection scheme provides protection against cross-country and inter-circuit faults also. Andre De Souza Gomes, *et al.* developed a fault detection and classification algorithm based on model parameter analysis [Gomes, Costa, Giovani, Faria, and Caminhas, 2013]. Jiang et al proposed the use of phase measurement units (PMU) for transmission line protection [Z. Jiang, Miao, Xu, Liu, and Zhang, 2012]. A fault location method, for parallel transmission system, has been proposed, based on KNN algorithm, with input as standard deviation values of three-phase voltage and current signals [A. Swetapadma and Yadav, 2018]. A FIS based protection scheme has been proposed for transmission line faults, which aims at detecting the fault, its direction, faulty phase and its location [Yadav and Swetapadma, 2015]. The signal processing techniques reported in the field of protection of two terminal transmission lines have been provided in Table 2.3.

2.3.2 Protection Algorithms for Multi-terminal Transmission Systems

Multi-terminal lines allow higher power supply capability and more flexibility in dispatching power during peak times and could be an economical solution because it reduces the necessity of new stations. However, this configuration also causes a lot of issues in ensuring the power system operation security. Increasing the number of terminals in transmission lines means that a longer time is needed to collaborate all signals for all terminals to make a final decision, hence operating times for relays clearing faults will increase. The normal protection schemes applied to two-terminal lines cannot be implemented to multi-terminal lines without some limitations due to their special topology and in some cases may cause insecurity and in-selectivity issues. Some of the issues are Impact of infeed and out-feed currents, impact of Current Transformer (CT) saturation and Impact of high resistance. Various protection schemes have been proposed for the A protection scheme for multi-terminal transmission lines using distance relay was proposed by A.Y. Abdelaziz in [Abdelaziz, Rahman, and Moussa, 2011]. A universal fault-location method was proposed in [Chih-Wen Liu, Kai-Ping Lien, Ching-Shan Chen, and Joe-Air Jiang, 2008] for N-terminal ($N \geq 3$) transmission lines by calculating ($N-1$) indices. In [A. Ahmadimanesh and Shahrtash, 2012] a novel wavelet transform-based fault location algorithm was introduced. Fault location schemes for multi-terminal transmission lines using synchronized voltage and current measurement were proposed in [Brahma, 2005] & [Azizi, Afsharnia, and Sanaye-Pasand, 2014]. Another fault location schemes for multi-terminal transmission lines using transient current measurement and unsynchronized measurements had been proposed in [Cheng, Guan, Tang, and Huang, 2014] & [Hussain and Osman, 2016]. Ahmadimanesh and Shahrtash proposed a transient based fault location method for multi terminal transmission lines based on S-transform [Alireza Ahmadimanesh and Shahrtash, 2013]. An advanced fault location technique, making use of Phase-Measurement Unit was introduced by Jiang Quanyuan, *et al* [Q. Jiang, Wang, and Li, 2014]. A fault location scheme for three-terminal and multi-terminal transmission lines, making use of synchro phasor measurement, had been proposed in [Lin, Lin, and Liu, 2014] & [Wu, Li, Kamwa, Chung, and Qin, 2016]. J. Uday Bhaskar, *et al.* proposed a wavelet-fuzzy based fault location technique for three-terminal transmission system [Bhaskar et al., 2015]. Funabashi Toshihisa, *et al.* proposed a digital fault location scheme for double circuit multi-terminal transmission lines, which make use of phase voltage and current information [Funabashi, Otoguro, Mizuma, Dube, and Ametani, 2000]. The signal processing techniques reported in the field of protection of multi-terminal transmission lines have been provided in Table 2.4.

Table 2.4: Protection techniques reported for Multi-terminal System

S.No.	Technique Used	Reference	Task performed
1	Wavelet Transform	[A. Ahmadimanesh and Shahrtash, 2012] [Bhaskar et al., 2015] [Cheng et al., 2014] [Bhalja and Maheshwari, 2006]	FL FL FL FD
2	S-Transform	[Alireza Ahmadimanesh and Shahrtash, 2013] [Tripathy, Jena, and Samantaray, 2014]	FD,FL FD,FL
3	Artificial Neural Network	[Yadav, Walayani, and S. Thoke, 2012]	FSI,FC,FL
4	Support Vector Machine	[Mohanta, Gopakumar, and Reddy, 2015]	FC,FSI
5	Travelling Wave	[Azizi et al., 2014]	FL
6	Circuit Theory	[Funabashi et al., 2000] [Brahma, 2005] [Abdelaziz et al., 2011] [Manassero, Senger, Nakagomi, Pellini, and Rodrigues, 2010]	FL FD,FL FSI,FL FL FL
7	Phase-Measurement Unit	[Chih-Wen Liu et al., 2008] [Q. Jiang et al., 2014] [Wu et al., 2016] [Jafarian and Sanaye-Pasand, 2013]	FL FL FL FD,FL

2.3.3 Protection Algorithms for FACTS-Compensated Transmission Systems

In modern power system, the power transfer capability and the power quality are enhanced by using FACTS devices. These devices are used for reactive power management in transmission system. FACTS devices can have adverse effects on distance protection both in steady state and transient periods. Current injection and absorption by these compensators can lead to under-reach and over-reach of traditional distance relays. Thus, it is a challenge to access correct fault location on the compensated transmission line.

Various protection schemes have been proposed in the literature for compensated transmission lines. A comprehensive analysis of TCSC effects on distance protection of transmission lines, was illustrated in [Sidhu and Khederzadeh, 2005] and [Khederzadeh and Sidhu, 2006] by Khederzadeh and Sidhu. Jena, *et al.* illustrated the possible mal-operations of zone-2 and zone-3 operations of distance relays, caused by impedance offered by TCSC during fault transients in [Manas Kumar Jena, Panigrahi, Das, and Samantaray, 2017]. An adaptive distance relaying scheme has been proposed for series compensated transmission line, considering the effects of high resistance faults [Biswal, Pati, and Pradhan, 2013]. A time-domain model based algorithm has been proposed for series compensated transmission line for computing fault location and fault resistance [Sadeh and Adinehzadeh, 2010]. A fault location algorithm based on two-end synchronized measurements of current phasors, is reported by Apostolopoulos and Korres [Apostolopoulos and Korres, 2012]. For compensated transmission lines fault detection and classification algorithm, based on wavelet entropy, was introduced by Zonkoly and Desouki [El-Zonkoly and Desouki, 2011]. An algorithm for faulty phase selection and fault section identification, based on discrete wavelet transform, was introduced by Dash and Samantaray [P. K. Dash and Samantray, 2004]. Wavelet based digital relying was proposed by Samantaray and Dash for series compensated lines [Samantaray and Dash, 2007]. The combined approach of wavelet transform and travelling waves has been used for fault analysis on TCSC-compensated transmission system by Zadeh et al., [Karbalaye-Zadeh, Sharafi, and Lesani, 2010]. Similarly the wavelet transform and extreme learning machine based fault classification scheme has been proposed. The features obtained from wavelet transform are used by intelligent computational tool for fault analysis. A new fault section identification technique, based on DC measurement, has been introduced [Mazniewski and Izykowski, 2009]. A combined DWT and ANN based scheme has been proposed for fault location on TCSC compensated transmission line [Aleena Swetapadma and Yadav, 2015b]. Input to ANN was standard deviation data computed by approximate DWT coefficients. Samantaray, *et al,* introduced a S-transform based protection algorithm for TCSC-compensated line, making use of differential energy, obtained by subtracting spectral energy content of receiving end and sending end current signals[S. R. Samantaray et al., 2012a]. A new approach for fault zone identification and fault classification in FACTS based transmission lines using decision tree was introduced by Samantaray [S.R. Samantaray, 2009]. For fault location estimation a hybrid method has been introduced for series compensated transmission line. The algorithm makes use of DWT and decision tree for estimation of fault location [Aleena Swetapadma and Yadav, 2018]. Jovcic, *et al.* proposed different models of TCSC based on fundamental frequency and non-linear state-space dynamics and their verification results [Jovcic and Pillai, 2005]. A Differential equation based distance relay scheme was introduced for series compensated transmission lines [Qi et al., 2015]. The fault classification and section identification techniques, based on support vector machines, were illustrated by in [P K Dash, Samantaray, and Panda, 2007] and [Parikh, Das, and Maheshwari, 2010]. Giovanni, *et al.* introduced a fault location algorithm based on voltage and current signals of both the sides and on an heuristic method [Manassero Junior, Di Santo, and Rojas, 2016]. A combined approach of Genetic Algorithm and Support Vector Machine has been proposed for fault classification on TCSC-compensated transmission system [Tripathi, Pillai, and Gupta, 2012]. A non-unit protection scheme based on DWT and k-nearest neighbor (k-NN) algorithm has been proposed for series capacitor compensated transmission line. For detection and classification of faults standard deviation, of approximate coefficients of current signals, is used and for fault location determination the approximate coefficients of three-phase voltage and current signals are used, to be given input to KNN module [Aleena Swetapadma, Mishra, Yadav, and Abdelaziz, 2017]. A digital relaying scheme, based on pattern recognition approach, for protection of series compensated transmission system has been proposed by Samantaray and Dash [S. R. Samantaray and Dash, 2008]. A performance study of distance relay application on UPFC-compensated transmission system, including modeling of UPFC, its control strategy and its integration into system, was done by Zhou, *et al* [Zhou, Wang, Aggarwal, and Beaumont, 2006]. Ghazizadeh and Sadeh proposed a fault location algorithm for transmission line with UPFC controller based on synchronized data of both the ends [Ahsaee and Sadeh, 2012]. An adaptive and modified distance protection schemes, considering influence of UPFC, were proposed in [F59]. The distance protection application on UPFC- compensated transmission lines was illustrated by Dash, *et al* [P. K. Dash, Pradhan, and Panda, 2000]. In this presented apparent impedance calculations for fault analysis on a double circuit system with varying UPFC parameters and location. An adaptive distance relay settings for parallel transmission lines connecting wind farms and UPFC were given by Dubey, *et al* [Dubey, Samantaray, Panigrahi, and Venkoparao, 2015]. A back-up protection scheme for UPFC-compensated transmission line, during high impedance faults and power swing, has been proposed making use of power differential feature obtained from apparent power flow in each phase [Kumar and Yadav, 2017]. A fault detection and classification algorithm has been proposed for shunt-compensated transmission line based on integrated impedance of the system. For this, synchronized three-phase voltage and current signals are pre-processed and phasors are evaluated using DFT for computation of integrated impedance [Kumar, Yadav, and Abdelaziz, 2017]. Kumar and Yadav proposed a wavelet entropy approach for fault detection and classification of UPFC-compensated transmission lines [Kumar and Yadav, 2016]. Wavelet based protection scheme for transmission line with UPFC was given by Goli et al., in [Goli, Gafoor Shaik, and Tulasi Ram, 2015]. A wavelet based differential protection scheme was introduced for tapped transmission lines connecting UPFC and wind farm [Tripathy, Jena, et al., 2014]. A fault locator for compensated transmission line with UPFC was proposed by Moravej *et al.*, using S-transform and SVM, based on features extraction of current signals [Moravej, Pazoki, and Khederzadeh, 2017a].

Table 2.5: Protection techniques reported for FACTS-compensated transmission system

S. No.	Technique Used	Reference	Task performed
1	Wavelet Transform	[P. K. Dash and Samantray, 2004]	FSI,FC
		[Karbalaye-Zadeh et al., 2010]	FD
		[Ray, Panigrahi, and Senroy, 2012]	FD,FC
		[Kumar and Yadav, 2016]	FD,FC
		[Rao et al., 2011b]	FD
		[El-Zonkoly and Desouki, 2011]	FD,FC
		[Goli et al., 2015]	FD,FC
		[Aleena Swetapadma and Yadav, 2015b]	FC,FL
		[Aleena Swetapadma and Yadav, 2018]	FL
		[Aleena Swetapadma et al., 2017]	FD,FC,FL
		[Tripathy, Jena, et al., 2014]	FD,FC
2	S-Transform	[S. R. Samantaray and Dash, 2008]	FSI,FC
		[Tripathy, Dash, et al., 2014]	FD,FC
		[Moravej et al., 2014]	FD,FSI
		[S. R. Samantaray, Tripathy, and Dash, 2012b]	FD
		[Tripathy, Dash, et al., 2014]	FD
		[Krishnanand and Dash, 2013]	FD
		[P K Dash, Moirangthem, and Das, 2014]	FD,FL
		[Pradipta Kishore Dash, Das, and Moirangthem, 2015]	FD,FC,FL
		[Subhransu Ranjan Samantaray et al., 2015]	FL
		[Moravej, Pazoki, and Khederzadeh, 2017b]	FL
3	Artificial Neural Network	[Aleena Swetapadma and Yadav, 2015b]	FL
		[Aleena Swetapadma and Yadav, 2016a]	FL
4	Support Vector Machine	[Moravej et al., 2014]	FC,FSI
		[Tripathi et al., 2012]	FC
		[Parikh et al., 2010]	FC
		[P K Dash et al., 2007]	FC,FSI
		[Moravej et al., 2017b]	FL
		[Parikh, Das, and Maheshwari, 2008]	FSI
5	Fuzzy Logic/FIS	[Mazniewski and Izykowski, 2009]	FC,FSI
		[Raman et al., 2013]	FD,FL
		[Goli et al., 2015]	FL
6	Decision Tree	[S.R. Samantaray, 2009]	FC,FSI
		[M K Jena, Tripathy, and Samantray, 2013]	FC
		[Aleena Swetapadma and Yadav, 2018]	FL
7	Circuit Theory	[Karbalaye Zadeh et al., 2009]	FD,FL
		[Biswal et al., 2013]	FD,FL
		[Qi et al., 2015]	FD,FL
		[Sadeh and Adinehzadeh, 2010]	FL
		[Ghazizadeh-Ahsaee and Sadeh, 2012]	FD,FC,FL
		[Kumar and Yadav, 2017]	FD
		[Kumar et al., 2017]	FD
		[Ahsaee and Sadeh, 2012]	FL
		[Samet and Razavi, 2015]	FSI

A S-transform based protection schemes were given for transmission lines operating with UPFC, by Tripathy *et al* [Tripathy, Dash, and Samantaray, 2014] & [Subhransu Ranjan Samantaray, Tripathy, and Dash, 2015]. For UPFC based double-circuit transmission lines, a differential relaying scheme had been proposed, making use of fast-discrete S-transform

[Tripathy, Samantaray, and Dash, 2016]. For UPFC-compensated transmission lines, a pattern recognition method has been introduced for fault analysis, which made use of s-transform and support vector machine [Moravej, Pazoki, and Khederzadeh, 2014]. Zhang, *et al.* suggested various modifications to distance relaying for STATCOM compensated transmission lines [Dash, Samantaray and Panda, 2007]. In [Karbalaye Zadeh, Shayegani Akmal, and Ravaghi, 2009] presented the analytical study indicating the effects of STATCOM operation on distance relaying. Sidhu, *et al.* had presented performance of distance protection relays with shunt compensated transmission lines [Sidhu, Varma, Gangadharan, Albasri, and Ortiz, 2005]. The performance comparison of various distance protection schemes, was reported in [Albasri, Sidhu, and Varma, 2007] by Albasri, *et al*. A fuzzy logic based distance protection algorithm for transmission line, with STATCOM installed at generator bus, was reported by Raman, *et al.* [Raman, Gokaraju, and Jain, 2013]. Wavelet based protection schemes for transmission line equipped with STATCOM had been reported in [Rao, Gafoor, and Venkatesh, 2011b] respectively. S-transform based distance protection schemes for transmission system, operating with STATCOM, were reported in [Krishnanand and Dash, 2013], [Dash, et al., 2014] . The signal processing techniques reported in the field of protection of FACTS compensated transmission lines have been provided in Table 2.5.

2.4 IDENTIFIED RESEARCH GAPS

From the critical review of the literature, related to transmission line protection, following research gaps have been identified, which are to be explored. These research gaps have been considered for the research work presented in the thesis.

- The quick detection of fault is important for the stability and reliability of the system. Therefore efforts have been done for reducing the detection time of fault, which is 8-10ms stated so far in the in the articles. Hence there is a need for reduction of fault detection time, which is to be investigated.
- The proposed algorithms in the literature made use of separate techniques for detection and classification of faults. Hence it is required to develop an algorithm which can both detect and classify the faults.
- Based on the configuration and complexity of the transmission systems, the protection scheme has to be adaptive in nature in nature for different types of transmission systems. Design of such relaying scheme is needed which could be used for various types of transmission systems.
- It is required to develop a fault location scheme which makes use of minimum information that can be available after the fault incidence and before the tripping of circuit breaker.
- The computational tool/technique to be used for the implementation of the relaying scheme has to be of less computational burden and to be reliable with the dedicated communicated system.