CHAPTER 1
PROLOGUE

1.1. Introduction

The increasing dependency on electrical energy for daily life style and transportation in the current scenario consequently leads to ever growing requisition of electrical power supply. In order to preserve the balance between generation and increasing power demand, newer generating plants along with renewable energy sources are being gradually added in the modern power network. However, the addition of newer generating units has little significance if there is no competent transmission system for transporting the energy from the generating plants to the load centers. It creates a situation where there is a surplus power generation but still not able to fulfill the energy demands due to the power transfer limiting constraints of the network. It draws the attention of power engineers towards the amelioration and up-gradation of the extant power network for enhancing the power transfer competency. For reducing the intricacy of the grid network, instead of fabricating new lines more emphasis has been given to enhance the transfer capability of extant transmission system. The power transfer competency of the transmission line shown in Figure 1.1 is given by equation (1.1)-

$$P_{transfer} = \frac{|V_S||V_R|}{|X_{line}|} sin\delta \tag{1.1}$$

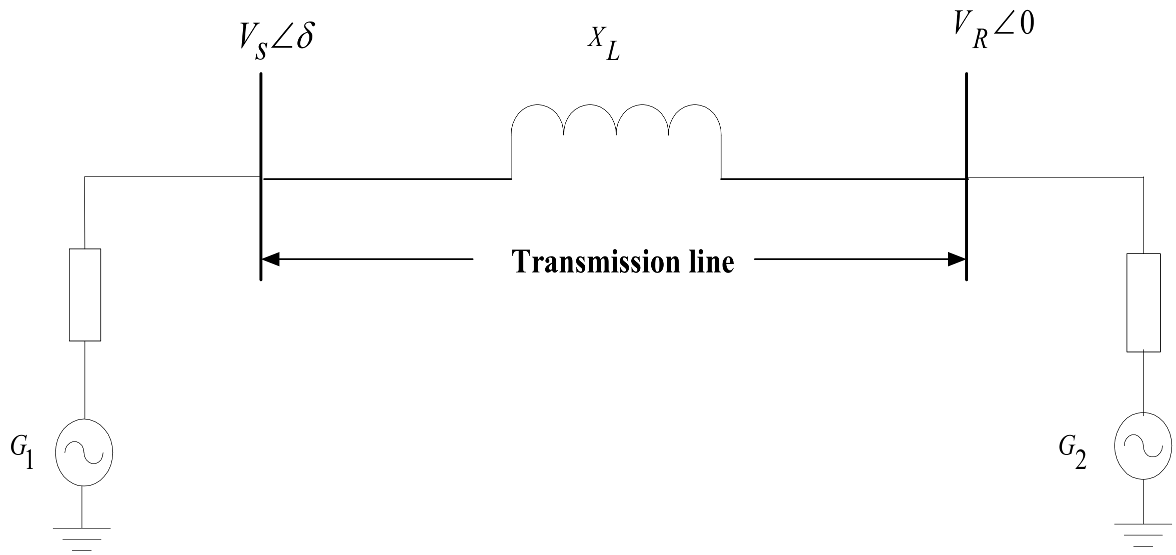


Figure 1.1 Simplified representation of power transmission network

Where, V_S represents the voltage of sending terminal; V_R is voltage at receiving terminal; X_{line} is line reactance; and δ is the respective load angle. The power carrying competency of the line can be readily improved by reducing the overall line reactance as compared to other factors like voltage level variation which needs redesigning of network insulation; similarly, excessive variation of δ directly affects stability of the system. The effective line reactance with the series compensation as shown in Figure 1.2 can be simplified as follows

$$X_{eff} = X_{line} - X_c \tag{1.2}$$

$$X_{eff} = (1-K)X_{line} \tag{1.3}$$

$$K = \left(\frac{X_c}{X_{line}}\right) \tag{1.4}$$

Where K represents the degree of series compensation; X_c is the reactance of the inserted FSC. Therefore, the expression for the power being transferred through a series compensated power transmission line is given by equation (1.5),

$$P_{transfer} = \frac{|V_S||V_R|}{|X_{line} - X_c|} sin\delta \tag{1.5}$$

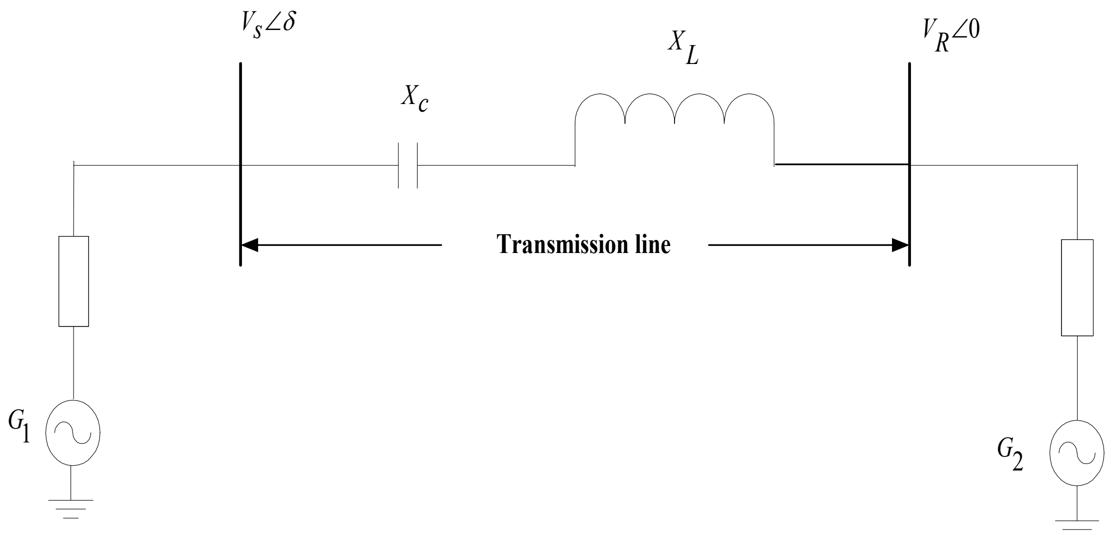


Figure 1.2 Simplified representation of series-compensated power network

The line compensation technique has considerably changed the scenario; as it directly helps the Transco's utility for improving the line flow limits along with better voltage control of the system. It is an excellent alternative over other reinforcement ways (like diffuseness of transmission network) for fulfilling the continuous growing requisition of power in the current scenario. Fixed series capacitor (FSC) or FACTS (flexible AC transmission systems) controller installation in the network offers an effectual way for adjusting the line flow limit along with preferable network stability control. FACTS controller like TCSC

(Thyristor controlled series capacitor) endowing variable level of line compensation and helps in slacking the inter-area oscillations with dynamic power flow control. Although of many benefits of line compensation, on account of distance relaying the incorporation of series capacitor/FACTS device creates additional protection challenges.

1.2. Impact of Series Compensation on Distance Relaying

Albeit of significant benefits of compensating device (CD), its presence in the faulted network and the nonlinear behavior of associated safety circuit adversely influence the functioning of lineal distance relaying [1]. The erratic operating modes of line compensating units during abnormalities in the power network perverted the current and voltage signals. It creates additional critical challenges for the relaying system. Authors in [2-4] have discussed that the line compensation causes erratic tripping of the switchgear system. It has been suggested that the protection zone boundaries must be adopted according to the modified impedance due to the involvement of the compensating device in the faulted network. Authors in [5] have explained the variation of modified impedance with the connected compensated series reactance in the transmission network. Similarly, in [6] it has been reported that the relay zone settings are directly incumbent on the reactance and extinction angle of the compensating devices. Current inversion (CI), voltage inversion (VI), under reach, over reach and additional transient harmonics are the prime unsuited phenomena that arise due to line compensation.

1.2.1 Under and Over Reaching of Relays:

In case of compensated power network shown in Figure 1.2, the incorporation of the compensating unit comprehensively transformed the impedance observed by the relaying system [7]. Figure 1.3 clearly shows that due to the incorporation of compensating unit, the observed impedance got modified as represented by solid lines. It usually causes mal-functioning of the relaying system and hence creates undesirable tripping of the breakers.

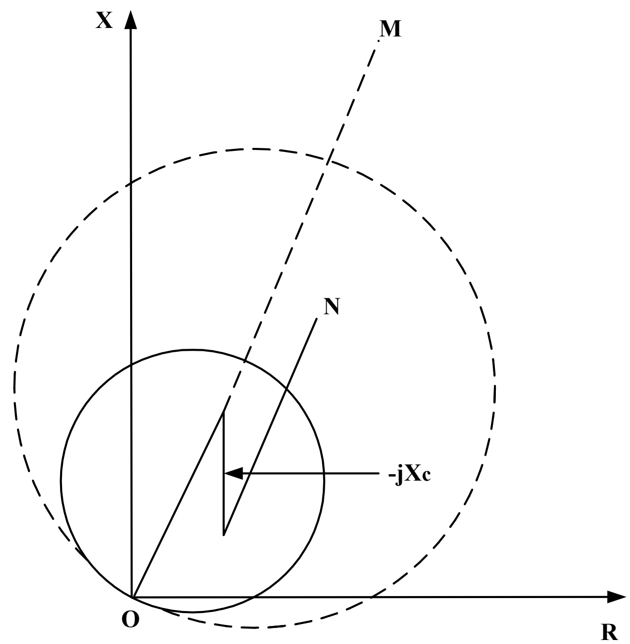
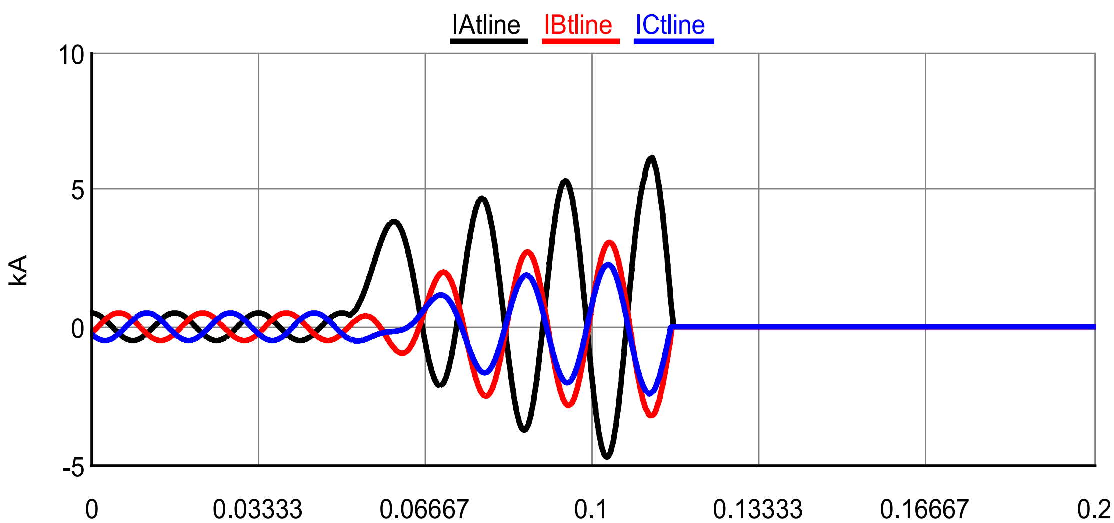


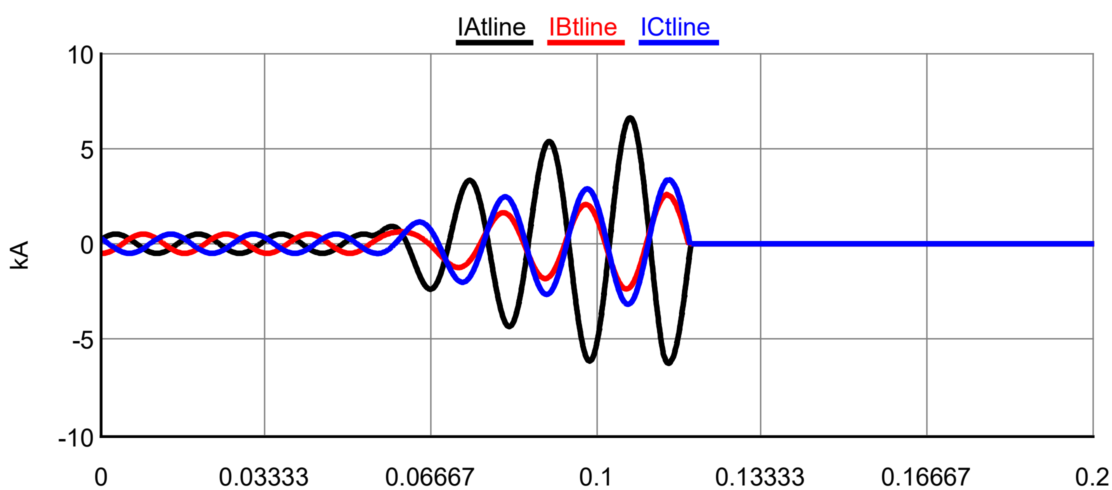
Figure 1.3 Modification in seen impedance due to CD in the transmission network

1.2.2 Current and Voltage Inversion

Current inversion usually causes a significant variation in the current phase angle (90° or more). It has been observed in a SCPN if a shunt fault is actuated just after the CD. The equivalent circuit along one side of the fault is capacitive and at the other side of the fault circuit is inductive. However, it is uncommon in case of high-current faults, as during these events the spark gap or MOV will bypass the CD. It commonly observed in case of high-resistance fault events. The CI case is shown in Figure 1.4 observed during line to ground fault event close to compensating unit. Similarly, voltage inversion transformed the voltage phase angle by 90° or more. It has been observed if the total impedance from the voltage source to the fault point is inductive and the impedance from the relay to the fault point is capacitive. CI and VI significantly enhance the complexity in directionality discrimination of the fault events [8-10].



(a)



(b)

Figure 1.4 A case of current inversion due to CD in the transmission network; (a) A-G fault ahead of CD; (b) A-G fault immediately upon CD

1.2.3 Precarious Operation of MOV

The functioning of MOV unit during the fault occurrence in the network is erratic in nature which directly affects the distance relaying mechanism. In case of high instantaneous voltage along the capacitor, the MOV starts conducting and bypass the capacitor and hence the net impedance will be only impedance of MOV. However, in case of low current fault condition, the MOV remained in its high impedance state and offers impedance equal to parallel combination of series capacitor and MOV. A relay setting without considering the MOV conduction causes over reaching of distance relay where as if relay setting are made with sustained consideration of MOV, may cause under reaching of relay during low fault condition. Authors in [11-15] have described the effects of modified impedance seen to the relaying circuit due to compensating devices in the faulted network.

1.2.4 Addition of Transients and Harmonics

Installation of series CD in the network adds up different transients and sub harmonic frequency oscillations in the system. It comprehensively affects the assessment of voltage and current at the relaying point. The presence of non-fundamental decaying frequency components, odd harmonics, and the fundamental frequency components, causes the current seen by the relay more than the actual, which may leads to overreaching of relaying system. In [16] the authors have explained the impact of harmonic frequencies arises in TCSC compensated power network on distance protection.

1.3. Literature Survey

Power transmission line is an integral part of the power system, as it plays as a vital clinch between the power producer and its consumer. Though the fault occurrence in the power system is rare event, but it is almost indispensable. As the power transmission network is widely spread in the open environment conditions, it has the highest fault incidence rate. Fault events in transmission network are mainly classified as symmetrical and unsymmetrical faults. In practice, about 50 % faults in power system occurs on overhead lines and out of which, 85% of faults on transmission lines are single-line-to-earth faults, followed by phase-phase, double-phase-earth, and three phase faults, in that order [17]. Apart from the aforementioned events, there are few more types of fault events that have been also seen like cross-country and evolving fault events. Cross-country faults (CCF) are the additional kinds of faults which are usually observed in double circuit lines. The CCF events are generally actuated at the same time but on different locations in the transmission circuit and can involve same or different phases. Similarly, evolving fault events in the transmission network are also much more complicated than the commonly occurring shunt events mainly due to the transition of phases are involved in the evolving abnormality. A fault event usually actuated with one phase and then spread to the others phases within a few cycles are termed as evolving fault events. It may cause delays in tripping and reclosing problems. Power outages caused due to abnormality events in the transmission network have a profound impact on the economy and productivity of any nation. In view of it, the modern regulatory policies have the provision of inflicting monetary penalties for poor power quality and long power outages. It propels the power utilities for focusing on issues like sustaining the better quality of electric supply with least abnormality interruption. Fault incidences in transmission system not only lead to the outage of that specific line but also create an extra burden on adjacent lines. The absence of rapid and pertinent protection methodology may actuate wide spreading of outages and leading to collapsing of the whole system. Distance relaying mechanism is widely used as main and backup protection for power transmission lines. However, the conventional relaying mechanism is significantly affected by the changing network conditions due to installation of compensating devices in the transmission system. Hence, amelioration and up gradation of protective mechanism is also very imperious for safe operation of current power network. These challenging conditions of series compensated network have driven the researchers for designing adaptive and competent protection mechanism based on intelligent computing techniques for modern grid network. In last few decades, a plethora of protection schemes focuses on classifying and locating the fault events in series compensated power transmission network have been reported in literature. The available protection schemes can be broadly categorized in tow section i.e. methodologies for FSC compensated power network and methodologies for FACTS compensated power network.

1.3.1 Protection Methodologies for Fixed Series Capacitor Compensated Power Network

This section mainly focuses on the algorithms reported for the protection of fixed series capacitor compensated (FSCC) power network. Multiple network modelling and soft computing based strategies have been effectually developed and presented for protection of capacitor compensated transmission network. Majority of the reported approaches focuses on detection, classification, and location of fault events in the network. A detailed review in terms of best-acquired accuracy, measurement needed, applied mechanism, utilized simulation tool and limitations of various reported protection strategies for a FSCC power network have been provided in this section.

1.3.1.1 Mathematical Network Modelling based Protection Methodologies

The network modelling based protection methodologies are principally inspired by estimating the voltage drop across the CD and the modified impedance of the network due to the installation of CD in the network. Some of the reported protection methodologies also adopt the concept of bypassing the non-linear elements for accurate location of faults in the compensated transmission system. This section specifically discusses and presented a review of different mathematical modelling based protection methodologies reported for capacitor compensated transmission network. The mathematical network modelling protection approaches can further be classified into based on synchronized or un-synchronized measurement.

Synchronized Measurement based Methodologies:

In [18] a PMUs measurement based fault location methodology has been presented for a FSCC power network, wherein 3 distinct sets of current and voltage samples measured at both ends of the network have been utilized for the analysis. A non-iterative loop algorithm has been applied on the Thevenin's equivalent of the system for determining the location of fault events in the network. However, the impact of delay in synchronized measurement has not been addressed. In [19] an iterative network modelling and pattern search algorithm based approach has been reported for localizing the fault events in a FSCC power network.

The fault distance has been determined by estimating the post-fault voltage at the actuating point. However, the reliability of the scheme is totally dependent on the efficacy of the additional electronic devices considered for acquiring the voltage and current data at both terminals. In [20] a lumped network modelling based protection mechanism has been explained for a FSCC power network wherein the measured data at both the terminals, network parameters and zero sequence current have been utilized for predicting the location of fault events in the transmission system. In [21] a faulted phase detection and back-up protection scheme for a series-compensated power transmission network have been reported. Faulted phase detection has been performed by comparing the norm of Koopman eigenvectors to the fixed threshold value. In [22] an iterative (Newton-Raphson) method has been presented for predicting the location of shunt fault events in the FSCC transmission lines wherein the modal transformation based estimated equivalent sequence impedance has been utilized. However, the performance of the reported mechanism is mainly dependent on the precise selection of the subroutine, and the error percentages get significantly increased during incorporation of network measurement flaws. In [23] a synchronized measurement based fault location scheme for multi-circuit FSCC power network has been presented. The phenomenon that is the identical current in an unaffected phase on both sides of the shunt fault has been utilized as the fault locator index. However, very few test cases and only variations of fault resistance have been considered during efficacy assessment of the reported protection scheme. Authors in [24] have presented a lumped network modelling based protection strategy for a CC transmission network wherein the estimated Thevenin equivalent model (using synchronized PMUs data) of the circuit has been utilized for identifying whether the fault is on the right or left side of the

CD. However, the condition of mismatch or delay in synchronized measurement has not been evaluated.

Un-Synchronized Measurement based Methodologies:

In [25] a non-iterative protection scheme has been presented for a FSCC power transmission network. It is based on the measurement of both terminals line data along with the estimation of parameters of the compensating unit with the help of additionally applied monitoring system. The positive, negative loop impedances (for unsymmetrical events) and positive, superimposed positive impedances (symmetrical events) have been mathematically calculated for identifying the fault position in the transmission circuit. In [26] improved impedance assessment based mechanism has been presented for locating the fault points in a FSCC power network wherein, the concept of bypassing the erratic and non-linear functioning element (MOV) from the fault loop has been utilized. However, the estimation of the voltage drop across the CD involves pervasive mathematical calculations. In [27] a single end fundamental frequency assessment based mechanism has been presented for ascertaining the zone of the fault events (i.e., in front or after the CD) in a FSCC transmission system. The equivalent frequency model of the network and the corresponding coordinates of each phase have been utilized for identifying the location of faults in the network. However, it involves presumptions like static fault resistance; shunt capacitance is neglected. In [28] a protection strategy has been reported for a FSCC transmission circuit wherein the estimated instantaneous reactive and active power trajectories have been utilized for ascertaining the fault events in the network. The variation of the polarity of the computed power quantities has been applied for fault detection, whereas yes/no consequences classification tree mechanism is employed for events categorization. It has been seen that various mathematical network modelling based (both synchronized and un-synchronized) methodologies have been effectually applied for localizing the fault events in SCC power network. However, the reliability of such schemes gets easily affected by induced error due to improper modelling of the CD or unsteady operating modes of the non-linear elements during faults in the network.

1.3.1.2 Signal Processing and Intelligent Computing based Protection Methodologies

A detailed review of different signal decomposition and soft computing based protection strategies for a FSCC transmission network in terms of reported accuracy, measurement needed; utilized simulation tool and limitations have been provided in this section.

Signal Processing based Protection Methodologies:

The inherent disadvantage, i.e., the resolution and localization limitation of FFT restricts its application in transient analysis. Similarly, the complexity regarding the constant sliding window length throughout the entire plane or trade-off situation between the time and frequency representation during STFT also create problems in proper analysis. Wavelet decomposition based mechanism has been effectively applied for identifying and locating different fault events in the FSCC power network. In [29] a protection scheme has been presented for a FSCC power network wherein the estimated average value of the D6 coefficients of phase and ground current have been utilized for ascertaining the affected phase and involvement of grounding. Two distinct mother wavelets, i.e., db4 and Harr have been applied during pre-processing mechanism. But, the obtained accuracy of events categorization is not reported, and different critical issues like change in fault resistance, inception angle and current transformer (CTs) saturation situation have not been taken into consideration. Authors in [30] have presented a fault event identification mechanism for a parallel FSCC power network by ascertaining the polarities of the DWT coefficients of the corresponding modal phase current in the network during a fault. For internal fault cases, the coefficients have adverse polarities. Authors in [31] have presented a protection algorithm based on monitoring of the high spectral energy content of travelling voltage waves originated after fault actuation in the compensated network using WT. The fault events have been categorized by estimating the level of spectral energy in a particular phase. But the reported scheme fails in identifying LLG and 3-phase events occurred at zero crossing. The above analysis indicated that the WT based protection mechanisms are very effectual in ascertaining the fault events and location in a FSCC power network. However, WT mechanism significantly involves its own limitations such as selection of pertinent mother wavelet and finding the exact level of decomposition which imposes additional challenges in designing protection mechanism using WT mechanism.

Fuzzy and ANN based Protection Methodologies with/without Signal Processing:

The combination of signal processing mechanism with intelligent computing techniques has also been significantly applied by various authors in developing protection strategies for a FSCC transmission system. In [32] a DWT and adaptive neuro-fuzzy inference system (ANFIS) logic based protection mechanism has been discussed for a FSCC power network. The entropy of the main frequency harmonic and transient coefficient of the fault signal has been utilized for recognizing the faults in the network. In [33] a fault events classification scheme has been reported for compensated power network based on the application of WT and Fuzzy mechanism. The fuzzy logic classifier has been applied for discriminating the kinds of fault events in the network using the computed normalized max value of detail and approximation coefficients. However, many critical issues such as variation of line compensation level, fault resistance, inception angle have not been addressed. In [34] a TW and ANN technique based protection scheme has been reported for a FSCC transmission system. The modal transformation mechanism is applied for avoiding the mutual coupling effect on travelling waveforms. The discriminated components of the signals have been estimated by applying karrenbauer and wedepohl transformation for identifying the phase and kinds of events in the network using four distinct ANN models. In [35] a two-stage fault section identification scheme has been discussed for a FSCC power network using un-decimated DWT and ChNN algorithm. The extracted features from the detail coefficients have been fed to the ChNN model for identifying the position of events in the network, i.e. in front or after the CD. In [36] an ANN-based protection strategy has been discussed for a FSCC power network wherein the MOV energy level of each phase has been utilized as the feature set for ascertaining the fault events in the network. The particular fault category has been identified by comparing the MOV energy of each phase with prefixed threshold value respectively and for localization of events position in the network, four different ANN models have been applied. However, the effect of variation of a fault resistance and change in load angle has not been estimated. The Application of fuzzy based protection mechanism is very limited because the fabrication of fuzzy rule-base becomes very complicated due to network parameters variations in a compensated power network.

Support vector machine based Protection Methodologies with/without Signal Processing:

SVM has been comprehensively applied by various researchers for mainly categorizing the fault events in the transmission network. In [37] a TW and SVM technique based approach has been presented for discriminating the actual fault events and switching transients in a FSCC power network. Clarke decomposition and multi-resolution morphogical gradient technique have been utilized for estimating the decision components. Ultimately the discrimination task has been performed by designed SVM models. In [38] the authors have presented a fault section identification mechanism in a FSCC power network using DWT and SVM mechanism. The high-frequency DWT coefficients (41 per phase) have been utilized as the input features to the SVM classifier models for predicting the section of fault events in the network. But the overall accuracy of the scheme is quite low. In [39] a multi-SVM model's based fault classification approach has been presented for a FSCC transmission system, wherein the zero sequence and phase current signals are directly utilized as the input feature samples. Four distinct SVM models have been applied for ascertaining the associated fault event in the transmission circuit. It reported 98.7% accuracy for events classification. In [40] the authors have presented a fault section and events categorization methodology by using ST and SVM mechanism. Eight distinct feature vectors like standard deviation (SD), max and minima amplitude, THD, the energy of the voltage, zero sequence and phase current samples are acquired using ST analysis. The events classification accuracy obtained by applying proposed approach is 98.75 %. In [41] the authors have reported two separate events classification mechanism based on SVM and extreme learning machine (ELM) for a FSCC transmission circuit. Events classification accuracy is 98.4% with SVM & 97% with ELM respectively. In [42] a protective mechanism has been discussed for a SCC power network based on current signal decomposition and ELM technique. The first level DWT coefficients are utilized as the input samples to the ELM models for ascertaining the fault events in the network. The fault events classification accuracy reported is 99.11 %.

1.3.2 Protection Methodologies for FACTS Compensated Power Network

This section mainly focused on the protection strategies that have been reported for the FCATS compensated power network. On the basis of the applied mechanism, different available protection methodologies can be classified as mathematical circuit modelling or intelligent computing based. A detailed review in terms of best-acquired accuracy, measurement required, applied mechanism, utilized simulation tool and limitations of various reported protection strategies for FACTS compensated power network have been provided in this section.

1.3.2.1 Mathematical Network Modelling based Protection Methodologies

These protection methodologies are conceptually based on estimating the voltage drop across the compensating FACTS device and the modified impedance of the network due to the incorporation of the compensating element in the network. On the basis of the required measurement information of the network, these can be categorized as synchronized and un-synchronized protection methodologies.

Synchronized Measurement based Methodologies:

In [43] a recursive fault location algorithm has been reported for series FACTS compensated transmission network using distributed network modelling. A discrete optimization function based on the estimation of current and voltage at fault point in terms of sending and receiving ends parameters has been utilized for locating the faults point in the network. For symmetrical events the network is divided into three sections of the distributed model, i.e. model from sending terminal to CD; form CD to fault point and from fault point to receiving terminal, whereas during unsymmetrical events modal transformation mechanism has been utilized. However, during testing fault cases only in the first section, i.e. ahead of CD have been considered. Authors in [44] have reported a distributed time domain modelling based fault location approach for a TCSC compensated transmission system. For locating the fault events in the network, an objective function consists of estimated voltage and current at sending/receiving, and front/behind of the TCSC has been minimized. However, it essentially needs reliable synchronized channel between both ends of the network. Authors in [45] have reported a fault location scheme for a TCSC compensated power network based on synchronized information acquired by PMUs in the network. The impedance of the compensating device has been estimated using PMUs measurement for predicting the location of events in the network. However, it essentially needs a proper communication link, and the condition of delay in synchronized measurement has not been addressed.

Un-Synchronized Measurement based Methodologies:

In [46] a pilot protection scheme has been presented for TCSC compensated power network, wherein the integrated impedance along the line terminals has been utilized for ascertaining the internal and external fault events. The integrated impedance (ratio of the summation of voltage and current phasor at both ends) has been mathematically estimated for various fault events with changing the position of TCSC in the network. The particular fault is within the protected section or not has been identified based on magnitude and sign of the imaginary part of the integrated impedance. In [47] an adaptive mathematical scheme has been reported for UPFC compensated transmission circuit wherein, fault events are classified as within the relaying zone or an external event based on monitoring the measure impedance trajectory. Both ends current and voltage along with offset voltage and current inserted by UPFC controller have been utilized for estimating the impedance trajectory. However, the categorization and localization of fault events in the network have not been addressed.

1.3.2.2 Signal Processing and Intelligent Computing based Protection Methodologies

This section presents a review of various protection methodologies for FACTS compensated power network based on signal decomposition and intelligent computing mechanism in terms of reported accuracy, measurement needed; utilized simulation tool and limitations.

Signal Processing based Protection Methodologies:

The authors in [48] have presented a protection scheme for a FACTS compensated power network, wherein the estimated summation of absolute entropy of the wavelet coefficients have been utilized for identifying the fault events in the network. DWT mechanism has been applied for decomposing the phase, ground current, and voltage signals. In [49] a digital protection methodology has been reported for a TCSC compensated power network by using wavelet packet decomposition mechanism. The estimated features from the decomposed components of the post-fault current signals have been utilized for ascertaining the fault events by comparing it with the threshold THD value. However, the percentage of fault detection or events classification accuracy has not been reported. In [50] a protection scheme has been reported for TCSC compensated power network by using time-time (TT) transform mechanism. The fault identification index (Z score of TT matrix) has been computed by transforming the acquired current samples of both ends. The fault detection in the network and phase identification has been performed by comparing the computed index with prefixed threshold THD. Authors in [51] have presented a protection scheme for TCSC compensated hybrid power network using TW and fast discrete S-transform (FDST) mechanism. The modal components of the acquired current samples at both terminals have been processed with the FDST technique for weighing the arrival time of the waves at the terminals. The estimated time has been utilized for ascertaining the section of the fault, whereas for localizing the events in the network a distance index has been used. However, the performance of the approach is totally dependent on functioning of GPS system and the condition concerning with delay or error in synchronized measurement have been not evaluated. In [52] a protection strategy has been reported for a SSSC / UPFC compensated power network wherein the estimated summation of the entropy of DWT coefficients have been utilized for ascertaining and classifying the fault events in the network. However, the influences of critical conditions such as variations of fault resistance, inception angle, CTs saturation have not been addressed.

ANN and Fuzzy based Protection Methodologies with/without Signal Processing:

In [53-54] ANN based protection mechanism has been discussed for the compensated power network. Two distinct ANN models (one for events classification and other for locating fault position) have been utilized for ascertaining the location and types of fault events in the network. Phase voltage and current samples along with firing angles are utilized as the input vectors to the ANN models. However, the average error percentage of the presented scheme is quite large, i.e. 3.63 % classification error and 5.01 % distance estimation error. In [55] a TW mechanism based protection scheme has been reported for TCSC compensated transmission network using modal transformation, DWT and PNN techniques. The fault in the network has been ascertained by comparing the DWT coefficients of modal voltages with the threshold setting. The position of the fault in the network has been identified by monitoring the time delay between two consecutive waves at the relaying terminal. The energy spectrum of the phase and modal domain coefficients have been applied to the PNN model for categorizing the fault events. However, the impact of some critical issues such as variation of inception angle and line compensation level has not been evaluated. In [56] an intelligent protection mechanism has been reported for UPFC compensated power network wherein, the summation of detail coefficients of phase currents have been utilized for ascertaining the fault events in the network. A fuzzy logic mechanism is used for predicting the distance of faults in the network. However, the maximum distance estimation error is 3%. In [57] also discussed an intelligent relaying mechanism for TCSC compensated power network wherein the computed SD of the wavelet coefficients of pre and post-fault current samples have been utilized in ANN model for fault localization in the transmission lines. However, the concern related to the impact of the change in inception angle and CT saturation has not been addressed.

SVM and Recent computing techniques based Protection Methodologies:

In [58] a SVM technique based protection algorithm has been presented for TCSC compensated power network wherein the normalized post fault current samples and firing angle have been utilized for identifying the zone and types of fault events in the network. However, very limited cases have been taken into consideration during the efficacy assessment of the scheme and events classification reported is 97.84%. In [59] a data-mining technique based protection scheme has been reported for TCSC/UPFC compensated transmission circuit. The half cycle current and voltage transient samples have been utilized for finding whether the faulty section encompasses the TCSC/UPFC or not. A random forest and SVM based algorithm has been utilized. However, the actual position of the fault events in the network has not been ascertained. In [60] a relaying scheme has been presented for TCSC/UPFC compensated transmission circuit wherein two distinct decision tree based models have been utilized for ascertaining the section and types of fault events in the network. However, as no signal processing mechanism has been applied, the dimensionality of the training vectors is very large. The maximum fault events classification accuracy acquired is 98.17%. In [61] a protection strategy based on ST and Logistic Model Tree (LMT) learning mechanism has been presented for a TCSC compensated power network. The critical information (S-matrix) of the post fault current samples have been acquired by applying ST decomposition. A single LMT model has been utilized for ascertaining the types of fault events and respective zone in the network. However, the impact of CT saturation has not been addressed and only 97.47 % accuracy has been reported for fault events classification.

1.3.3 Summary of Literature Survey

In the last two decades, multifarious methodologies based on both mathematical and intelligent techniques have been reported for the protection of series compensated power transmission network. The observations of the aforementioned articles can be summarized as follows-

- Most of the approaches reported in the literature have only considered the shunt fault events for the analysis. The issue of detection and localization of transforming fault events and cross-country fault events is still almost untouched.
- Majority of the articles have not discussed the impact of CTs saturation on the reported protection methodologies. Several are restricted to ascertaining fault section i.e. prior or after the SC point and have not reported the percentage accuracy of fault classification or location of the fault events.
- The communication channel based protection approaches require both terminals measurement of current and voltage are more likely to be affected by noise and essentially depends on the performance of communication link.
- A majority of approaches have directly utilized the 3-phase current for analysis without any processing which leads to larger dimension of training and testing data set and hence has slower time response.

1.4. Objective of the Research work

After reviewing different reported approaches of fault diagnosis in series compensated power transmission network, it has been felt that the issues of transforming faults and cross-country fault events should also be thoroughly addressed. In the area of fault events ascertaining mechanism in the transmission network, there is still a chance of amelioration by applying of advanced intelligent techniques which gives faster time response and better accuracy. The data mining mechanism simply helps in identifying the patterns and relationship among the large data set. The acquired information or pattern from data mining mechanism can be efficiently used for making the decision regarding the type of particular fault events or its position in the transmission network.

- The prime objective of the present research work is to develop a protective scheme for a series compensated power transmission network through Machine learning using data mining.
- It has been intended to provide a contribution to the abnormality identification in series compensated power transmission network and further to enhance the events ascertaining performance by applying emerging signal processing techniques and ML mechanism.
- The aim is to design a fault ascertaining mechanism which is well competent of dealing all kinds of shunt fault events, transforming fault events, and cross-country fault events in the transmission system. It must be capable providing accurate output despite of changes in fault conditions such as varying fault inception angles, fault locations in the network, fault resistances, percentage of line compensation and

different topologies of transmission system. It should also well effectual in handling large amount of data pattern.

1.5. Thesis Outline

The work embodied in the present thesis is organized into seven chapters. The first chapter of the thesis briefly describes the challenges in relaying due to series compensation of transmission lines and respective literature review. The second chapter gives an overview of theory behind signal pre-processing techniques that has been utilized in the present work for acquiring fault feature vectors. The Third, Fourth, Fifth, and Sixth chapter of the thesis comprehensively describes the application of signal processing and intelligent computing techniques for ascertaining the types and location of fault events in the transmission network. Finally, seventh chapter presents the conclusion and future work. The organization of the same is as follows:

Chapter 1: Prologue

This chapter briefly introduces the merits of line compensation technique and its undesirable impact on the relaying unit of the transmission network. Further, it also presents a comprehensive review of different fault events ascertaining schemes reported for series compensated power network. Finally, the chapter concludes with the research objective and detailed outline of the thesis.

Chapter 2: Concepts of Signal Processing & Feature Vector Extraction

This chapter thoroughly describes the theory of signal processing techniques applied in present work for decomposing the 3-phase post fault current samples. The mathematical expressions of wavelet transform and its significant attributes over other commonly utilized signal processing techniques such as FT, FFT and STFT are also discussed. Then the critical concern associated with DWT mechanism and an adaptive signal decomposing technique (EMD) is explained. Further, the chapter also explains the mechanism of critical feature extraction from the decomposed wavelet and IMFs coefficients in terms of defined indexes.

Chapter 3: Fault Events Classification using DWT & Machine learning Techniques

The chapter 3 introduces the structure of the proposed integrated DWT and machine learning based methodology for ascertaining the fault events in the power transmission network. The fundamentals of machine learning algorithm are briefly described in this chapter. Then the basic concepts of parametric, non-parametric machine learning algorithms and their application for fault events identification in the compensated transmission network are comprehensively addressed. Further, the competency of the proposed integrated fault events ascertaining methodology is analyzed for various fault scenarios in two distinct simulated transmission networks. A comparative analysis of the acquired accuracy by proposed methodology for various fault conditions is also reported in the third chapter.

Chapter 4: Fault Events Classification using EMD & Machine learning Techniques

This chapter discusses the application of EMD and machine learning algorithms for fault events classification in the simulated test network. The feature vectors have been extracted by EMD based signal decomposition. The proposed EMD based methodology; its training and testing mechanism are explained in detail. Further, the robustness of the EMD and ML based scheme is assessed for various fault scenarios in two simulated test networks. Finally, the observed events classification accuracy for different considered test cases by the non-parametric ML classifier models is summarized in the chapter.

Chapter 5: Fault Events Classification using Ensemble & Deep learning Techniques

This chapter describes the application of ensemble and deep learning algorithms for fault events identification. The fundamentals of ensemble and deep learning mechanism are thoroughly described in this chapter. In addition, this section presents the advantages of ensemble and deep learning techniques over other machine learning algorithms. Then the ensemble and deep learning techniques based fault events identification methodology is explained for a compensated transmission circuit. Further, the viability and the robustness of the proposed ensemble and deep learning based fault ascertaining scheme is analyzed for all considered fault scenarios in different simulated test networks. Eventually, the comparative analysis of the procured events categorization accuracy for different test cases by the ensemble and DNN classifier models is summarized in the chapter.

Chapter 6: Fault Events Distance Estimation using Intelligent Computing

This chapter details the structure of the proposed integrated intelligent computing based methodology for locating the fault events in the compensated power transmission network. The fundamentals of different utilized distance estimator models are briefly explained in this chapter. Further, the ability of the proposed fault distance estimating methodology in the compensated transmission circuit is analyzed for different fault scenarios. Finally, the fault location results and distance estimation error acquired by the proposed integrated scheme is summarized.

Chapter 7: Conclusion & Future Scope

Finally, this chapter summarizes the research work. The significant contributions and conclusion of the present work are drawn in this chapter. In addition, this chapter also gives the future prospective of the present work.

1.6. Conclusion

This chapter briefly describes the principle of line compensation, its merits and undesirable impacts on conventional relaying system of the power transmission networks. In addition, this section also gives the overview and summary of multifarious protection schemes reported for series compensated power transmission networks. Finally, the chapter one concludes with research objectives and outline of the present thesis.