A DISSERTATION

ON

"ENHANCEMENT OF RELIABLE OPERATION IN POWER SYSTEM OPERATION USING AN ADAPTIVE PROTECTION STRATEGY"

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

WITH SPECIALIZATION IN

POWER SYSTEM ENGINEERING

UNDER

ASSAM SCIENCE AND TECHNOLOGY UNIVERSITY

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CANDIDATE'S DECLARATION

I, hereby declare that the work presented in the dissertation **"ENHANCEMENT OF RELIABLE OPERATION IN POWER SYSTEM OPERATION USING AN ADAPTIVE PROTECTION STRATEGY"** to be accorded the degree of **"MASTER OF TECHNOLOGY"** in **Electrical Engineering,** with specialization in "**POWER SYSTEM ENGINEERING",** submitted to the Department of Electrical Engineering, Assam Engineering College, Guwahati, is an authentic record of my own work carried out under the supervision and guidance of **Dr. Purobi Patowary, Professor**, Department of Electrical Engineering, Assam Engineering College, Guwahati. The matter embodied in this project has not been submitted by me for the award of any other degree.

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CERTIFICATE FOR APPROVAL

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ABSTRACT

Due to heavy loads, modern energy transmission systems suffers from significant voltage drops. To monitor the voltage, suitable schemes should therefore be developed. Transmission lines for EHV and HV are commonly used to transfer power from the power generation regions to large load centers. Compensating systems that use new electronic control devices are now often used to increase the capacity of transmission lines for power transfer. The use of FACTS devices on transmission lines has a very significant impact on the protection system. FACTS devices such as the Static Var Compensator SVC can cause distance relay function to deteriorate at the mid-point of the transmission line, resulting in inaccurate estimation of fault locations, i.e., over-reach or under-reach for different levels of compensation. This project work presents an analysis of the performance of distance protection relays when used to secure compensated transmission lines. The purpose of this work is to assess the efficiency of distance relays with FACTS devices applied for mid-point voltage control on transmission lines. The effects of shunt FACTS devices Static Var Compensators (SVC), Static Synchronous Compensators (STATCOM) and Unified Power Flow Controller (UPFC) are studied. The evaluation is carried out in three steps. The situation is first analysed, and the errors introduced in the impedance calculation because of the existence of shunt FACTS devices in the lines are calculated. The situation is simulated in the second step using transient simulation software, PSCAD/EMTDC. This approach also models the reaction of FACTS devices to various faults and system conditions. Due to some unique features of the FACTS devices, this approach brings out some interesting issues that would be faced by the distance relays. The results of the simulation show the effect of UPFC on the efficiency of a distance protection relay under various fault conditions. The studies also provide the effect of UPFC control parameter setting and UPFC operating mode. This project work suggested a new algorithm that uses synchronized phasors measurement (SPM) to improve the activity in many aspects of the distance protection region. The proposed method is being tested with the Bergeron transmission line model for a 132 kV system simulated in EMTDC/PSCAD. In comparison with the results obtained from existing distance protection systems for transmission lines with SVC, STATCOM and UPFC, the results obtained for the new adaptive setting scheme are specific, reliable and preferable.

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LIST OF ABBREVIATIONS

Abbreviation	Description
FACTS	Flexible AC Transmission System
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
TCSC	Thyristor Controlled Switched Capacitor
EHV	Extra High Voltage
GPS	Global Positioning System
WAMs	Wide Area Measurement System
PMU	Phasor Measurement Unit
RTDS	Real Time Digital Simulator
PSCAD	Power System Computer Aided Design
EMTDC	Electromagnetic Transient including DC
FFT	Fast Fourier Transform
HVDC	High Voltage Direct Current
TSC	Thyristor Switched Capacitor
TCR	Thyristor Switched Reactor
VSC	Voltage Source Converter
DFT	Discrete Fourier Filter
GTO	Gate turn-off thyristor
SSSC	Static Synchronous Series Compensator
UPFC	Unified Power Flow Controller
SCL	Short Circuit Level

PMU	Phase Measurement Unit
FCDFT	Full Cycle Discrete Fourier Transform
SPC	System Protection Centre
PDC	Phasor Data Concentrator

Chapter 1
Introduction

1.1 Background

Transmission line operation including FACTS [4-5] devices such as SVC, STATCOM and UPFC has drawn wide scale interest as it enhances the capacity of power transfer on long transmission lines. The implementation of FACTS devices, create new complexities as the apparent impedance of the lines is dynamically changed. Depending on the operating modes of the FACTS controller, the reach setting of the relay is therefore significantly affected. Protection mechanisms have been proposed for transmission lines, including multiple FACT controllers [5-8]. The effect of SVC, STATCOM and UPFC location and fault resistance on distance relay is clearly presented in literature [30-35].

If the FACTS devices are connected at the mid-point of the line, as these devices are mostly present in the fault loop, the relay setting function will be influenced. In order to change the relay settings in the presence of FACTS devices for different operating conditions of the transmission line, the impact of the presence of earth fault resistance, control parameters and apparent impedance characteristics of the feed from both sides on the distance relay is required.

Thus, when the transmission lines bearing FACTS devices are subject to a faulty system, the distance protection problems become serious. Therefore, adaptive relay setting is proposed for transmission lines, including FACTS devices, and the effect of variations in the parameters of FACTS devices on the relay reach setting is extensively studied. It is noted that when the level of loading, source impedance, voltage level, frequency etc. varies, the trip boundaries of the relay are significantly affected.

1.2 Necessity of Distance Protection

When a fault occurs, if the protection system does not work quickly, customers will be disconnected. In power system networks, distance protection is used to protect circuits because it is reliable and fast.

Distance protection is a form of non-unit protection that can differentiate between faults occurring in various parts of the system based on the measured impedance. To calculate the impedance drawn by the line to the fault, it compares the fault current as shown by the relay to the voltage at the relay location. A relay location at A in the device in Figure 1.1 uses the line current and line voltage to measure Z = V/I. The value of the impedance Z for fault at Fa would be $ZA1Fa$, and $(ZA1B1 + ZB1Fb)$ for a fault at Fb.

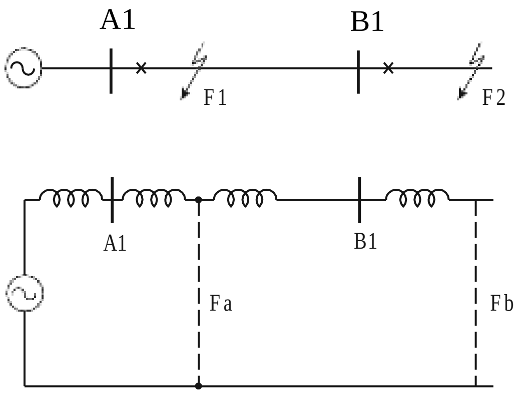

Figure 1.1: Faults occurring on different parts of a power system

1.3 Software Model in PSCAD/EMTDC

1.3.1 Protection System and Evaluation Setting Values

Transmission line protection system

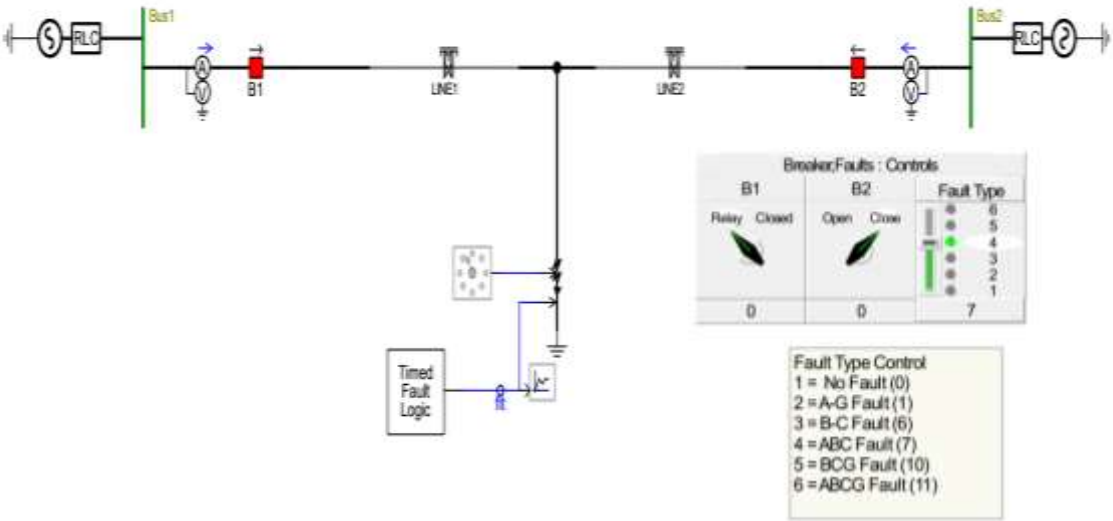

Figure 1.2: A Simple Distance Protection of two bus system with fault timer logic.

Medium and long transmission lines are protected by distance relays. The relays will respond to the fault point, which is represented by impedance, from the installed position (Z). Impedance relay, Quadrilateral relay, Offset Mho relay, and Mho relay are all examples of distance relays. Medium and long transmission lines can be protected with Mho relays. The Mho circle distance relays in the PSCAD/EMTDC in relay library are selected and modelled.

1.3.2 Setting of Zones of Protection

Distance relays normally set three zones to protect each side of transmission line. However, impedance setting may not be similar. It depends on each user scheme. In this work, the zones of protection of distance relays are illustrated in Figure 1.2 They are:

<u>Zone 1</u> normally set for 85% of transmission line length to protect the over-reach tripping effect. Over-reach in the distance relay is present when impedance is less than the apparent impedance to the fault.

<u>Zone 2</u> normally set for 100% of protected transmission line plus 20-50% to next shortest transmission line.

<u>Zone 3</u> normally set for 120% of protected transmission line plus next longest line.

Operation Mode Distance Protection Scheme

Voltage from CT

Voltage from PT

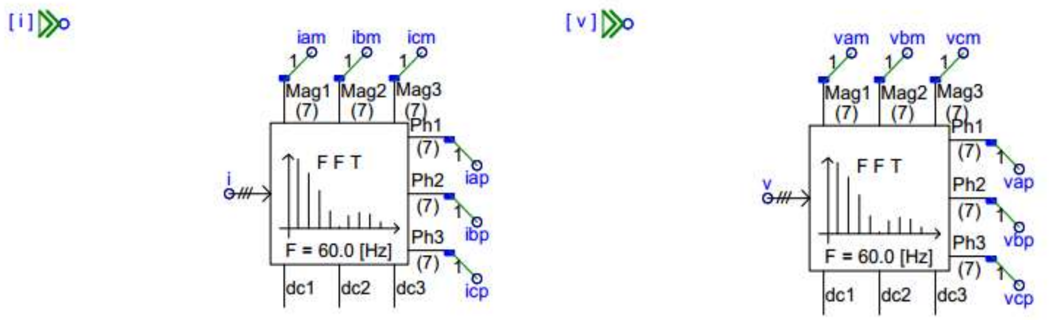

Figure 1.3: Fast Fourier transform Block

Finding Sequence component of Voltage from FFT

Finding Sequence component of Current from FFT

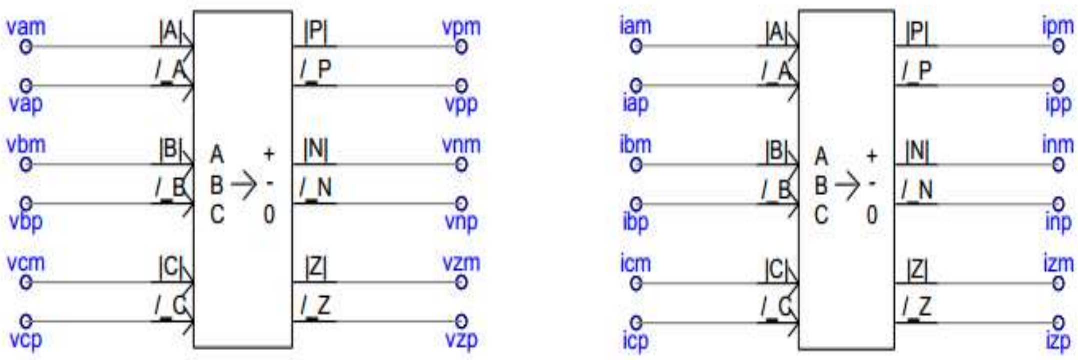

Figure 1.4: Sequence component Block

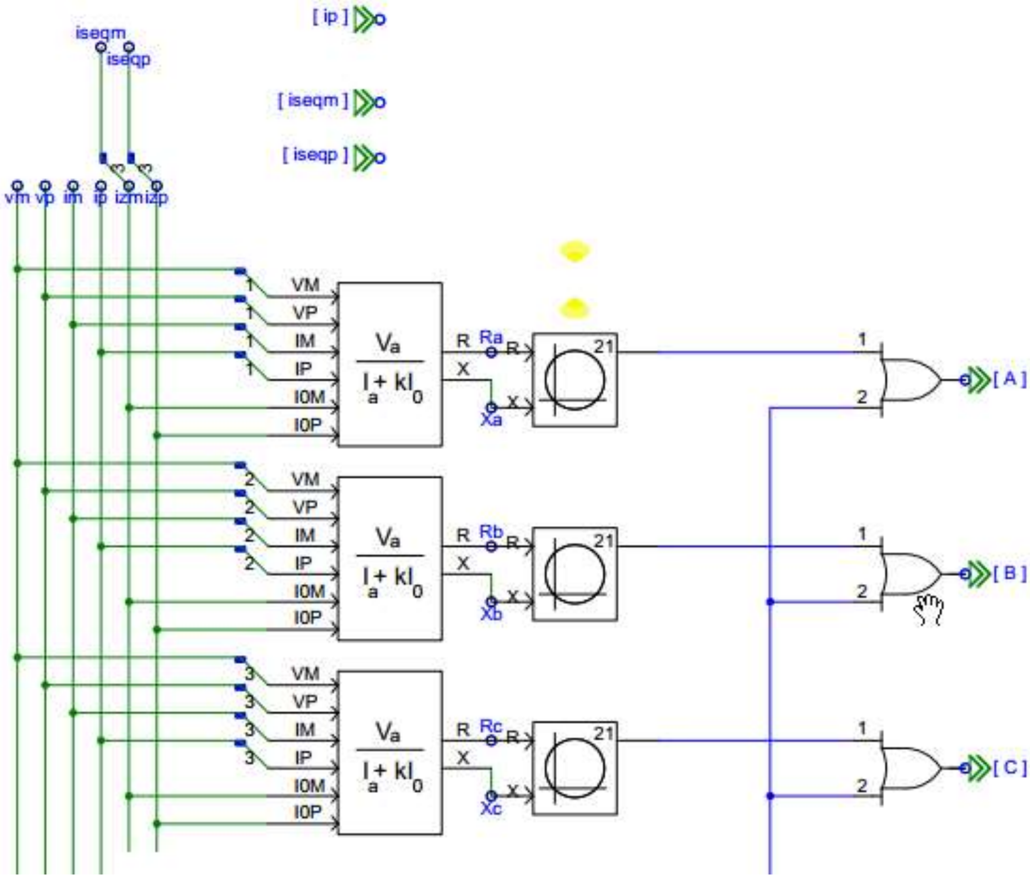

Figure 1.5: Calculation for line-to-line Impedance block

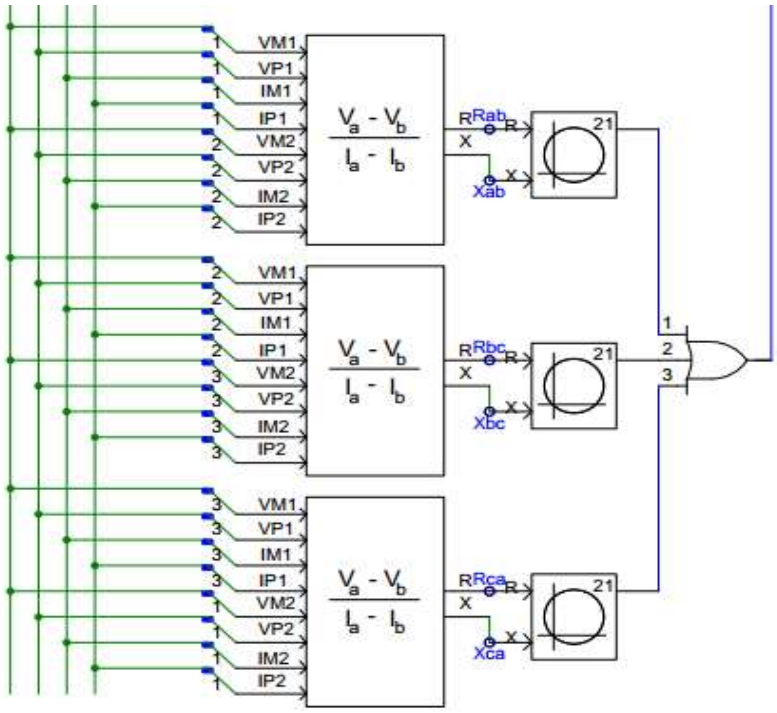

Figure 1.6: Calculation for line to ground impedance block

To detect a three-phase fault, the distance relay protection model is used. In Figure 1.3, the input signals are voltage and current, which are transformed into a Fast Fourier Transform (FFT) that can determine the harmonic magnitude and phase of the input signals as a function of time. Before being decomposed into harmonic constituents, the input signals are sampled. The output from the Fast Fourier Transform Block is used to calculate the magnitudes and phase angles of sequence components for voltage and current (Figure 1.4).

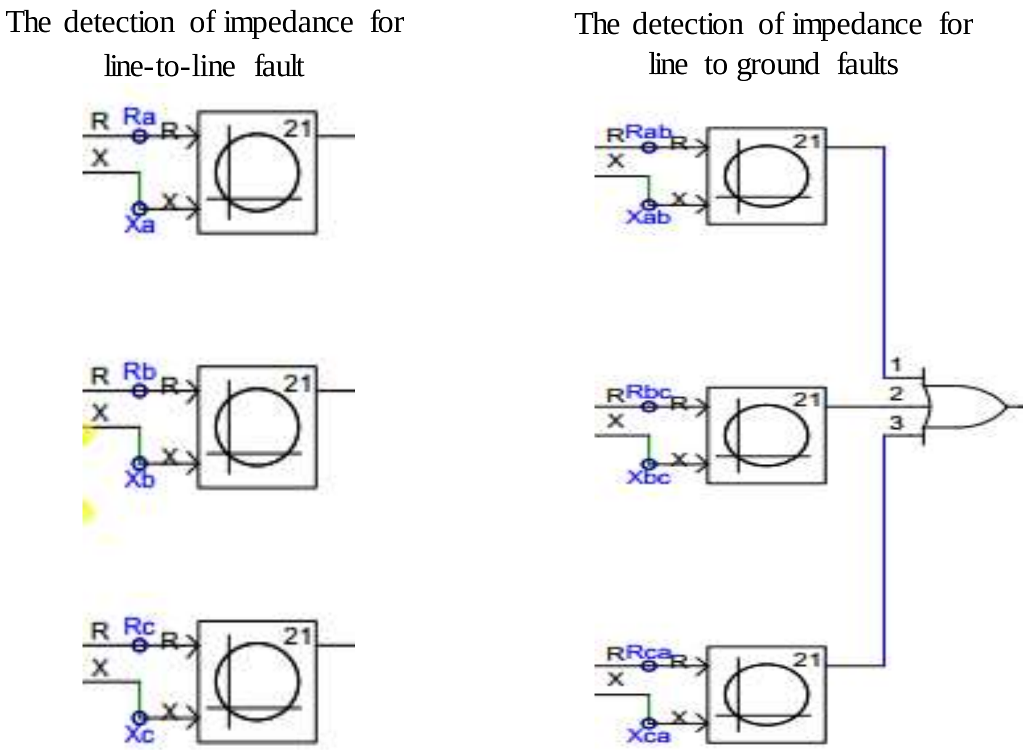

Figure 1.7: Mho characteristics of distance **relay**

The component shown in figure 1.5 is used to compute the line-to-line impedance. The output impedance is in rectangular form (R and X), and is optimized for use with the Mho circle.

Also, the component shown in figure 1.6 is used to computes the line-to-ground impedance. The output impedance is in rectangular form (R and X), and is optimized for use with the Mho circle.

Mho circle relay. It compares fault impedance from the impedance blocks and calculates the impedance value according to its setting. It determines whether a point defined by inputs R and X is located within a specified region on the impedance plane. The resistive and reactive parts of the monitored impedance are represented by R and X. When the fault impedance is within the set range, a trip signal is sent.

1.4 Literature Review

Mostly FACTS devices are installed on existing lines to enhance the transmission capability and performance of the grid [1]– [8]. The operating principle and capability to work independently under most circumstances the distance protection relays have been widely used in transmission Systems [9]. Considerable work has been carried out to study the effect of series and shunt compensation on the performance of distance protection relays [10],[13], [14], [15].

The minimize capital expenditure and the increased difficulties involved in obtaining transmission rights have made the utility community to focus on the Flexible Alternating Current Transmission (FACT) concept [1], [17]. The presence of FACTS controllers in a fault loop will affect the performance of existing protection systems [18], [19]. The paper presents analytical results of the system having STATCOM model and the authors have studied the impact of STATCOM on a distance relay at different load levels [5]. In [12], the FACTS controllers (voltage-source model) has been employed and the impact on the tripping boundaries of distance protection is studied. The thyristor-controlled series capacitor (TCSC) has certain influence on the mho characteristic which makes the protected region unstable [22], [14]. The FACTS controllers in the fault loop and voltage and current injections will both affect the steady state and transient components in voltage and current signals, and the apparent impedance seen by a conventional distance relay is different compared to system without FACTS are shown in [21] and [23].

The power system protection is expected to operate fast, reliable and accurate for better system security and stability [26]. The studies from previous large disturbances and blackouts causes mal-operation of protective relay, and the importance to study the performance of the protection systems for different system configurations are presented in the paper [27]. The FACTS controllers in power system enhanced power system controllability improved the stability and power transfer capability [28]. The presence of FACTS devices in transmission line may affect the distance relay operation and its accuracy for estimation of fault location resulting in over-reach or under-reach for different levels of compensation. The mal operation of distance relays or incorrect tripping affects system reliability and security, resulting in cascaded faults and wide area blackouts [29].

The system having SVC and STATCOM with various compensation levels and its availability at various locations, affects the distance relay operating characteristics [30]. The shunt compensation at mid-point of the system to improve the power transfer capability, the distance relay fails to trace the fault point in first zone [31,32,33]. The system having SVC installed in it causes under-reach and overreach while tracing the impedance trajectory [34]. The research work has been carried out to find the proper solution for systems having shunt compensation [35–40]. As a part of backup protection fuzzy based system is also used to reduce the problem if shunt devices are connected in the system [36–38]. Channel aided communication pilot-based protection results in delayed trip signal [39,40]. Global Positioning System (GPS) and fiber-optic data communication technology provides real time system data at high-speed communication rates of 274.1 Mbps or 155.4 Mb/s [42,43,44,45]. For high-speed data communication, Phase Measurement Unit (PMU) transfers the real time data from fault point to the relaying end of transmission system [46].

1.5 Motivation for the Present Work

Due to the tripping of one or more lines some lines get overloaded and the system voltage drops during system disruption. The encroachment of the impedance locus into the distance relay characteristics, the backup distance elements are susceptible to operation under such circumstances.

Although a distance relay's ohmic characteristic is independent of voltage, the load is not normally constant-impedance. As the load voltage varies, the apparent impedance presented to a distance relay is dependent on the voltage characteristic of the load. If a low voltage situation arises from the failure of one or more transmission lines or generating units, the real and reactive power flow through the line is significantly modified. The combination of low voltage and deteriorated phase angle makes the relay function undesirable either on a steady state basis or in response to the initiating event-related recoverable swings.

The apparent impedance seen by the relay is influenced by in-feeds, the mutual coupling of the FACTS devices, and thus it is important to understand the distance relay behaviour under different system conditions whenever necessary to achieve proper synchronization of the relay. In addition, the configurations must be fine-tuned, simulating faults on a case-to-case basis, particularly for critical lines, using simulation software. These facilities available for PSCAD Simulation Software are used for studies related to system protection.

Engineers who address industry and utilities protection issues need to examine the practice that can be followed by the different utilities and develop a common philosophy such that the settings of the different relays are properly organized and that the protection system works effectively.

The adaptive relay setting methodology and the setting criteria for transmission lines of for both FACTS uncompensated and compensated line give the recommended settings that can be adopted in the Power System.

The goal is to check if reliable fault clearance is given by the system provided. The aim of the protection application and criteria used to set calculations for substations is to cover the entire fault clearance of the system used in a substation for overhead lines & cables, power transformers, shunt reactors and bus bars.

The process analysis is needed for the calculations of relay settings, both for current network conditions and for changes implemented due to the existence of FACTS devices in fault transients, as well as for changes in the network topology. Case studies can be used as a guide for different utilities to measure relay settings.

As the device configuration changes, the simulation model recommends measuring the relay settings on a regular basis. Due to operational limitations, relay setting calculations may be revisited if the system's minor setup or loading changes. Feedback on the output of the relay settings is obtained from the field/substations/PMUs, and settings are checked or corrected as required before being implemented by the device.

The protection system for critical lines, all FACTS compensated lines, and interconnected lines can be simulated for intended operation under normal and abnormal system conditions, as well as checked for the protection system's dependability and security.

1.6 Objectives of the Thesis

In the faulty transmission system, the PSCAD Software model of the SVC, STATCOM, and UPFC is implemented for performance evaluation considering various types of faults. The proposed method measures the change in impedance to the fault point in FACTS devices, taking into account a broad range of system parameters such as degree of compensation, power transfer angle, fault resistance, and fault position, as well as variations in reactive power penetration levels, source impedance, voltage amplitude, and frequency. It suggests that the transmission line's adaptive relay setting, and that the effects of FACTS devices be considered.

The main objectives of the thesis are:

1. To derive the Apparent Impedance Characteristics of Distance Relay for fault before

introducing FACTS devices in the System.

2. To derive the Apparent Impedance Characteristics of Distance Relay for fault after introducing FACTS devices in the System.

3. To generate the impedance trajectory for the system under different kinds of faults in the presence of FACTS devices and also find the under reach and over reach effect of the Mho relay using PSCAD Simulation Software.

4. To suggest an Adaptive relay setting of the System for different compensation level.

1.7 Organization of Report

The thesis is organized as follows -

Chapter-1: It gives a brief introduction of Distance Relay used in the transmission lines, Software model of protection system and evaluation setting values developed in PSCAD.

Chapter-2: It consist of the performance evaluation of the Distance Relay on Shunt – FACTS compensated Transmission Line and variation in the system impedance with change in different compensation level. The shunt devices used are SVC and STATCOM.

Chapter-3: It consists of the performance evaluation of the Distance Relay as applied to a Transmission System with UPFC. Apparent impedance analysis simply illustrates the effect of UPFC on the apparent impedance and hence on the performance of the distance relay, the simulation results, and conclusion for a system with STATCOM and SSSC of the UPFC.

Chapter-4: It explains the need for Adaptive relaying and suggests the adaptive approach for distance relay settings of the system having mid-point SVC, STATCOM and UPFC. The algorithm responsible for finding adaptive setting is given. The simulation results shows the characteristics of the adaptive relay over the conventional relay.

Chapter-5: It consist of conclusion and future scope for the present research work for a system having different FACTS devices.

Chapter 2

Performance of Distance Relays on Shunt - FACTS Compensated Transmission Lines

2.1 FACTS devices

FACTS devices have become popular over the last decade and are turning out to be a very successful solution to many problems with power system. It is possible to classify FACTS devices generally into three groups, (a) Shunt (b) Series and (c) Composite series and Shunt. For different uses, FACTS devices are currently being used as follows:

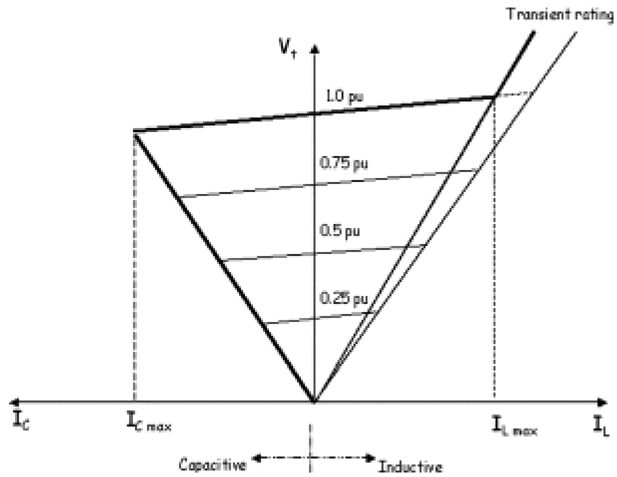

Fig. 2.1: V-I characteristics of a SVC.

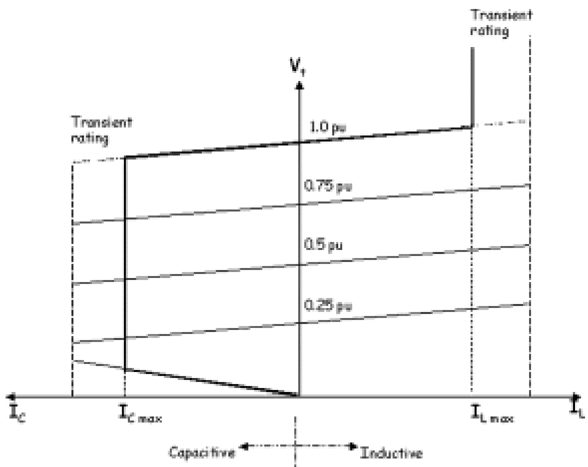

Fig. 2.2: V-I characteristics of a STATCOM.

In order to increase the power transfer capacity of a line by controlling the mid-point voltage of a transmission line around a fixed point, shunt compensating FACTS devices are used. SVC and STATCOM characteristics, which may theoretically affect the efficiency of the relay, are discussed below.

2.1.1 Static Var Compensator (SVC)

A TSC and TCR are included in the SVC, attached to the system's compensation point in parallel. The reactive output can be varied continuously between the capacitive and inductive ratings with proper coordination of the capacitor switching and reactor control.

The voltage-current V-I characteristics of an SVC are shown in Fig.2.1. Its reaction varies depending on the operating point of the SVC. The SVC acts as a fixed capacitor until the SVC's maximum capacitive output limit is reached. The maximum obtainable capacitive current decreases linearly at this point and the reactive power produced decreases as a square of the device voltage [1]-[3].

2.1.2 Static Synchronous Condenser (STATCOM)

Through electronic processing of the voltage and current waveforms in a voltage source converter, STATCOM provides the desired reactive power generation and absorption. Fig.2.2 displays the V-I characteristics of a STATCOM. Regardless of the amount of AC system voltage, the STATCOM is able to independently regulate its output current over the rated maximum capacitive or inductive range. Unlike the SVC [1]-[3], the STATCOM will provide maximum capacitive reactive current independent of the system voltage. This would mean that a STATCOM's capacitive reactance would go to a very low value.

2.2 Analytical study

It is possible to analytically compute the impedance determined by the distance relay. This will offer a clear understanding of the form of errors that can be introduced as a result of shunt FACTS compensation. Fig.2.3 indicates a simplified analogous circuit for a three phase fault of a mid-point compensated transmission line. From the equivalent circuit, the impedance measured by the relay, for a three-phase fault beyond the FACTS device location can be expressed as:

$$Zm = Zla1 + \frac{(Zla1') \times Xsc}{(Zlb1') + Xsc} \tag{1}$$

$$= Zla1\left(1 + \frac{(Zla1') \times Xsc}{(Zlb1') + Xsc}\right) \tag{2}$$

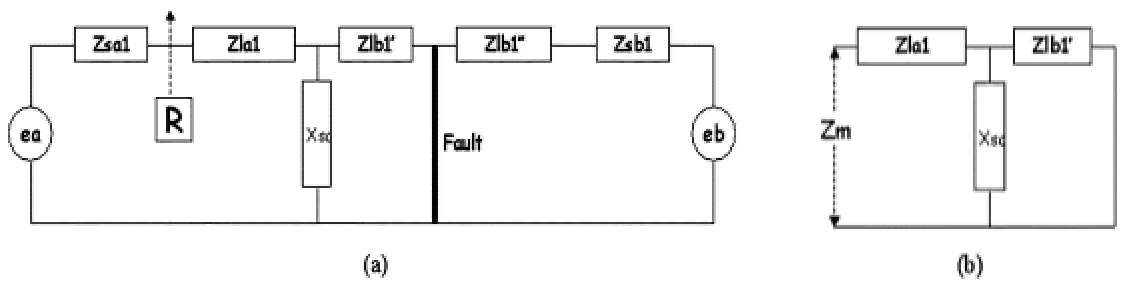

Fig.2. 3: (a) Equivalent circuit for 3 phase faults; (b) reduced equivalent circuit.

Where,

$$m = \left(\frac{Zla1 + Zlb1}{Zline}\right) = \left(\frac{Zla1 + Zlb1}{2Zla1}\right) \tag{3}$$

(Since the FACTS device is at the midpoint of the line)

Zm = Impedance measured by the relay

$Zla1$ = Positive sequence impedance of line section up to the FACTS device location

$Zlb1'$ = Positive sequence impedance of line section after the FACTS device location upto the fault point.

$Zline$ = Total line impedance

Xsc = Positive sequence reactance of the FACTS device

m = Fault location on the line in per unit of line length

When there is no shunt FACTS compensation or FACTS device is operating on the floating mode, the term Xsc in (1) tends to infinity and then (1) reduces to --

$$Zm = Zla1 + Zlb1' = m \times Zline = Z'm \quad (4)$$

However, when the line is shunt compensated with FACTS devices, the value of Xsc depends on the amount of compensation.

The system voltage decreases during faults on the line and the FACTS unit quickly attempts to provide reactive power to increase the voltage. Thus, during faults, the reaction of the shunt system is often capacitive and its value depends on the amount of reactive power that the FACTS device supplies. The higher the reactive power support, the lower the value of Xsc .

From (1), it is obvious that the value of Xsc reduces compared to $Zlb1'$, it has a greater effect on the measured impedance.

2.3 Dynamic Simulation Model

2.3.1 FACTS Device Model

A 12 pulse SVC/STATCOM is considered for the dynamic simulation study. The power rating of the FACTS equipment is chosen in such a way that all loading conditions and machine intensity can be properly accounted for.

2.3.2 Impedance Measurement

All six loop impedances (AN, BN, CN, AB, BC & CA) are calculated to estimate the impedance measured by a distance relay. Second, the information of the phasors is extracted using Discrete Fourier Filter from the three-phase voltage and current signals (DFT). Then, using these phase values, at each sampling interval, the impedances seen for the six loops are determined.

2.3.3 Study System

In order to simulate and study all possible conditions, a power system model with the facility to vary the system strength, fault location, type of fault, load flow and load direction is used. Fig. 2.4 shows the single line diagram considered for the analysis. The distance relay is located on Line I at Station A. At the midpoint of transmission line I, the FACTS device is located. In the Appendix, the system data is shown.

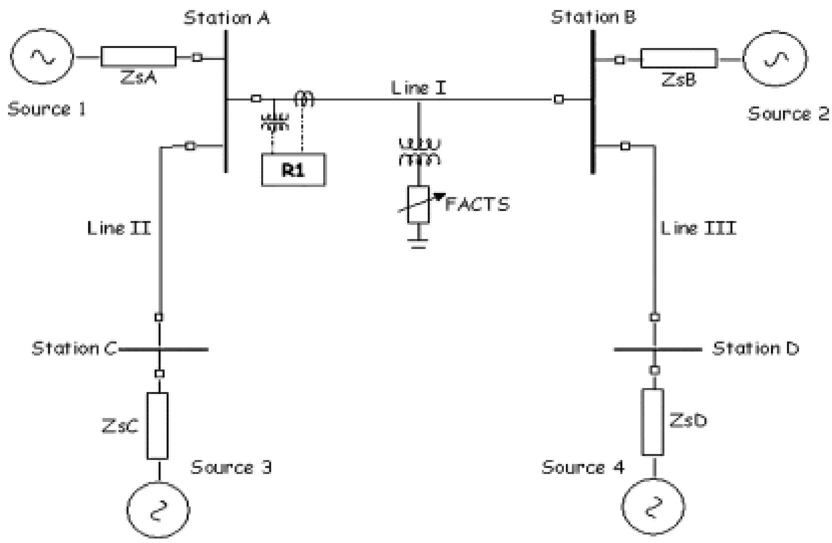

Fig. 2.4: Single line diagram of the system considered.

2.4 Dynamic Simulation Study

In the previous section, the power system and FACTS models discussed in the PSCAD/EMTDC software were developed. During the dynamic simulation analysis, there are additional insights obtained which are described in the following sections.

2.4.1 FACTS Response for Unbalanced Faults

As the FACTS devices (both SVC and STATCOM) were used for the application of voltage control, balanced three-phase firing [2] was used. A dc voltage similar to the three-phase voltage works on the FACTS computer control system. Thus, the FACTS device will have equal compensation for all three phases for unsymmetrical faults in which faulty phases experience extreme under-voltage relative to the healthy phases. In addition, this will in turn result in a reduced compensation, as the equivalent voltage will not be a true representation of the faulty phase. This effect can result in incorrect impedance measurements as will be shown in the simulation results presented in the next section.

In addition, the overcompensation of the healthy phases can result in an increased reactive current in healthy phases. This increases the possibility of incorrect phase selection.

2.4.2 Characteristics of SVC & STATCOM

In the capacitive area (Figs. 2.1 and 2.2), the difference in the V-I characteristics of SVC and STATCOM has an effect on the impedance measured during faults. In the case of an SVC, as its reactive power compensation (MVAR) increases, the shunt capacitive reactance decreases. Once the maximum of capacitive compensation is reached, the SVC functions as a constant capacitive reactance during which its shunt reactance is decreased.

2.4.3 Resonance for Three Phase Faults

As STATCOM experiences a much lower minimum capacitive reactance compared to that of an SVC, this resonance issue is more likely to occur in the case of STATCOM than SVC for faults within the protected line. This may also trigger other relays in the device to see this as a power swing. This depends on the combination of the line length, the minimum capacitance of the line reactance.

2.5 Dynamic Simulation Results

The results of the dynamic simulation, for both strong and weak systems, show the maximum under-reach and over-reach errors for each form of fault. The following conclusions and statements can be drawn based on these simulation outcomes.

2.5.1 Fault Type and Load

For three step faults, a minimal amount of error variation with respect to pre-fault loading was observed. The maximum error was observed in the case of SVC for single phase ground faults. For STATCOM, the highest error was found.

2.5.2 Fault Location

The amount of error was found to be higher at the end of the line. The analytical finding of the line, the ratio of the shunt compensating reactance to the line reactance is lower, higher errors are predicted.

For a weak system, the impact on the impedance calculation was found to be higher. Compared to a stronger one, fault voltages are lower in a weak system. The over-reach conditions in the case of STATCOM occur only when the system is weak. On the other hand, there was no case of SVC over reaching.

For a weak system with SVC under single phase to ground faults, faults are applied at 25 percent, 50 percent, 75 percent and 100 percent of the transmission line has a greater influence of the measured impedance with STATCOM for LG and LLL faults respectively. The effect for three phase faults where the relay tends to over-reach irrespective of load. For two-phase faults on similar system, the results showed both under-reaching and over-reaching cases. The mid-point shunt FACTS compensated transmission lines and distance relay performance evaluation is done using the simulation models as shown in Fig. 2.5 and 2.6. The mho relay Zone 1 = 80 percent setting. For a period of 1.5 s, all faults are applied to check the zone detection of the relay.

Fig. 2.7 to 2.11 shows the result of relay operation for system having mid-point SVC. Fig. 2.12 to 2.17 shows variation of system voltage, current and trip signal for different system faults. Also, fig. 2.19 to 2.23 shows the result of different fault conditions for the system having mid-point STATCOM. Fig. 2.23 to 2.27 shows variation of voltage, current and trip signal for different faults with the system having midpoint STATCOM.

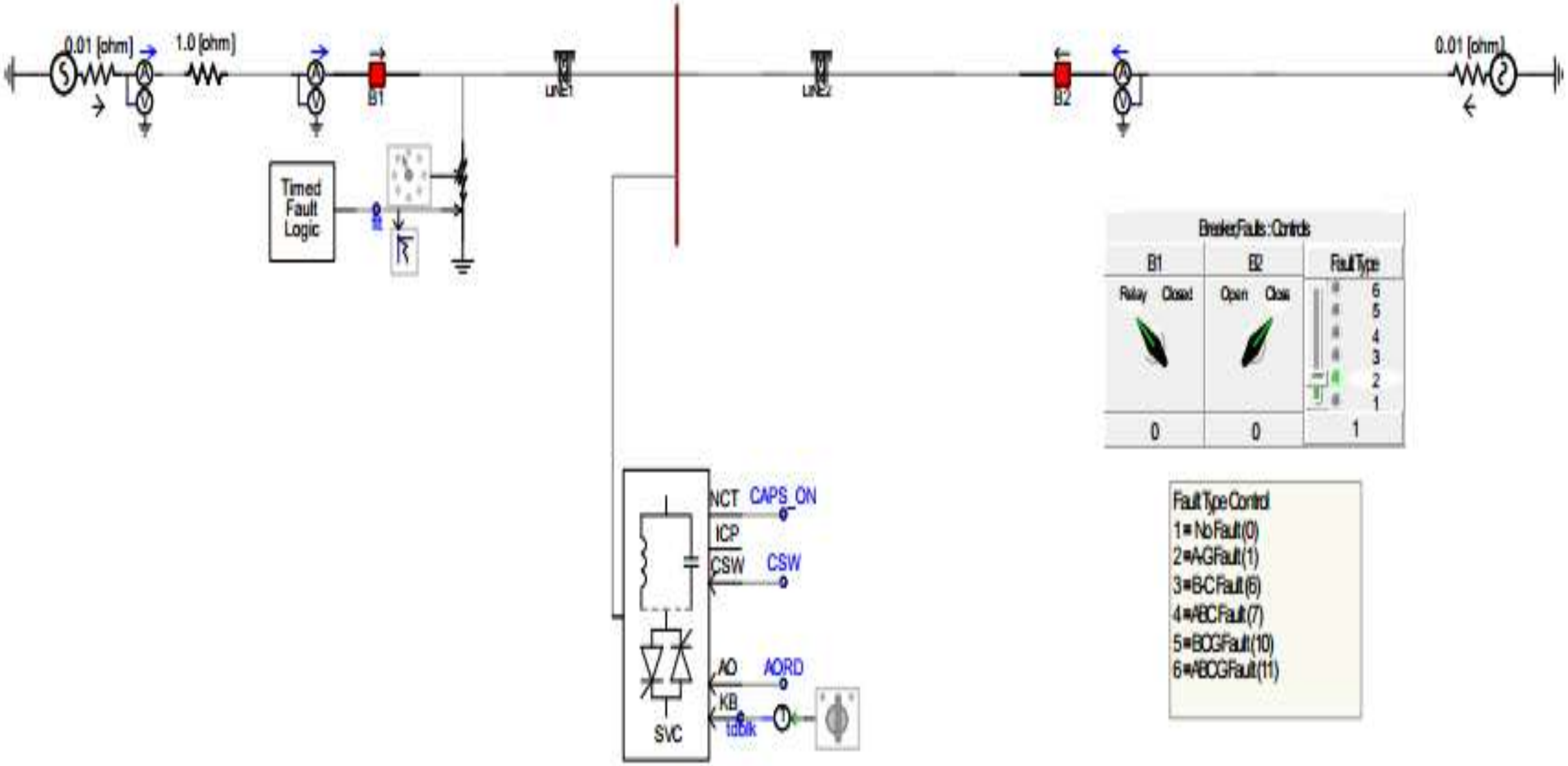

Fig. 2.5: Distance protection setting in presence of mid-point SVC

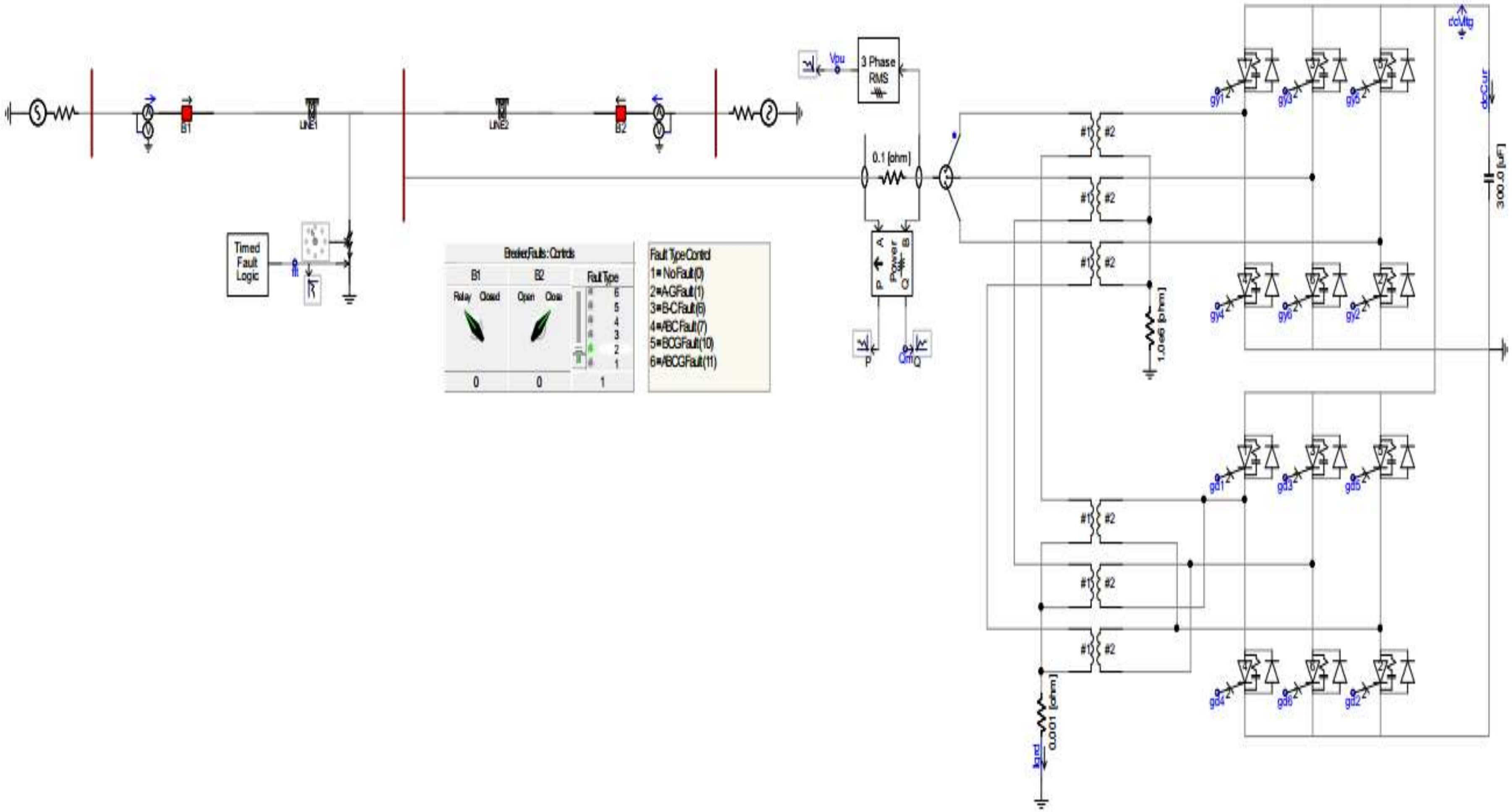

Fig. 2.6: Distance protection setting in presence of mid-point STATCOM

2.5.3 System Strength

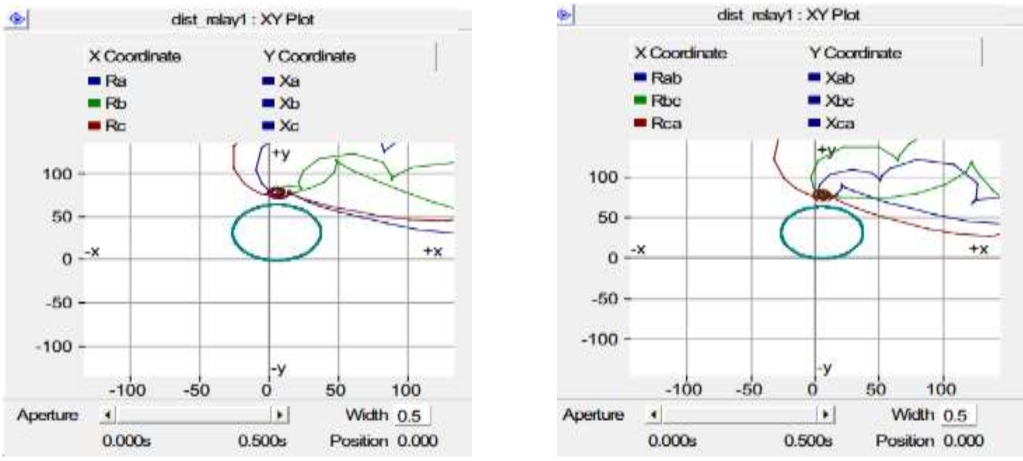

Fig 2.7: LLL-G fault for the System having mid-point SVC

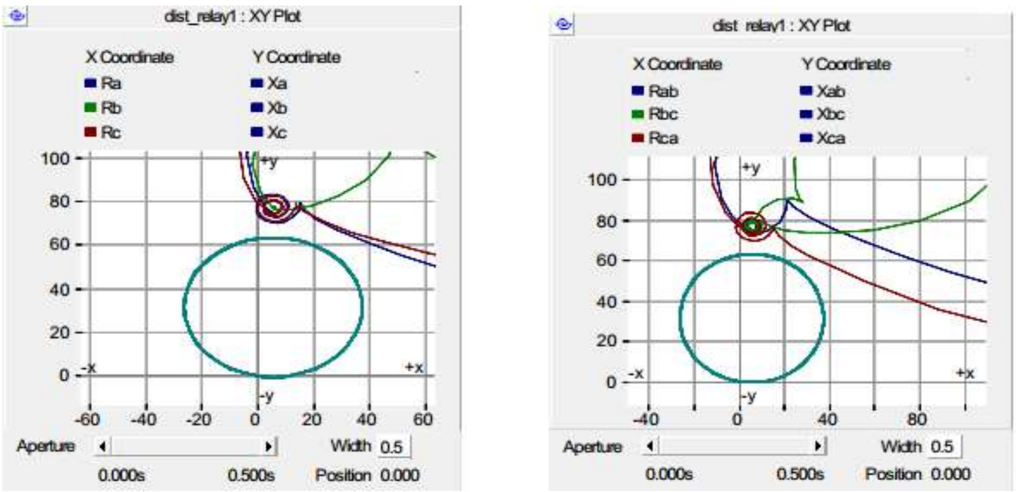

Fig 2.8: LLL fault for the System having mid-point SVC

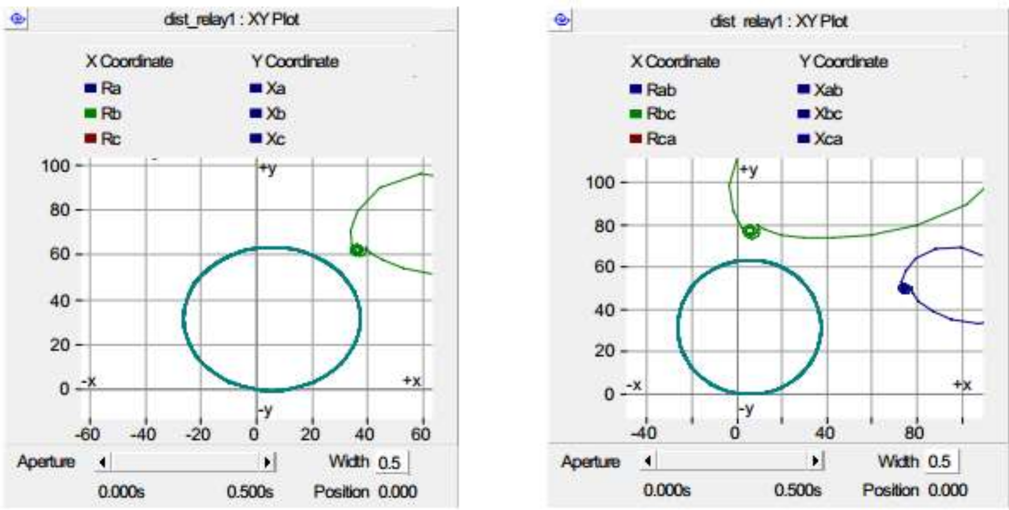

Fig 2.9: LL-G fault for the System having mid-point SVC

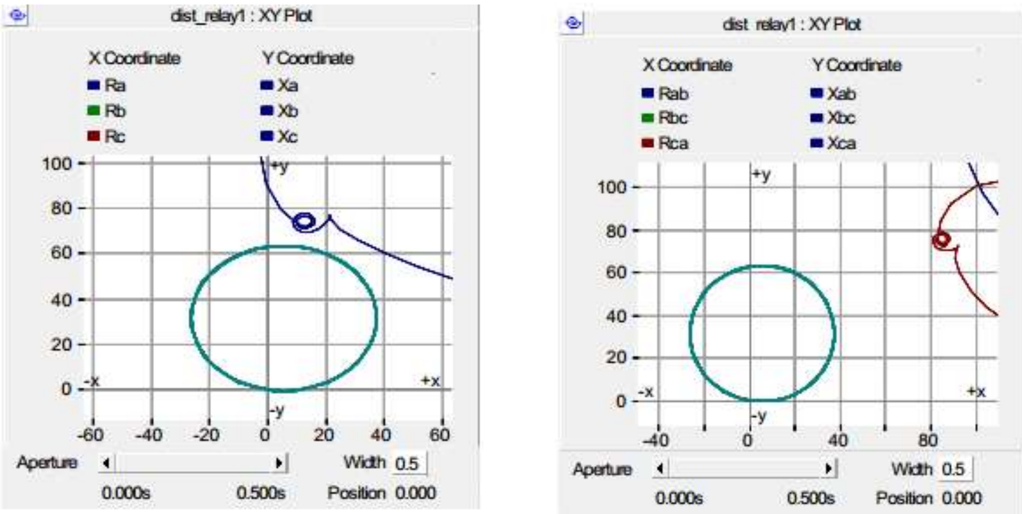

Fig 2.10: L-G fault for the System having mid-point SVC

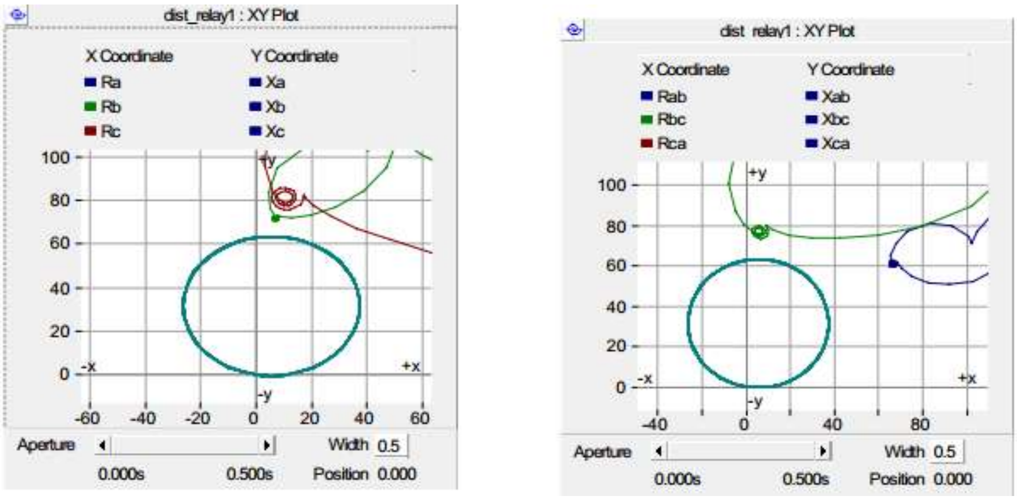

Fig 2.11: LL fault for the System having mid-point SVC

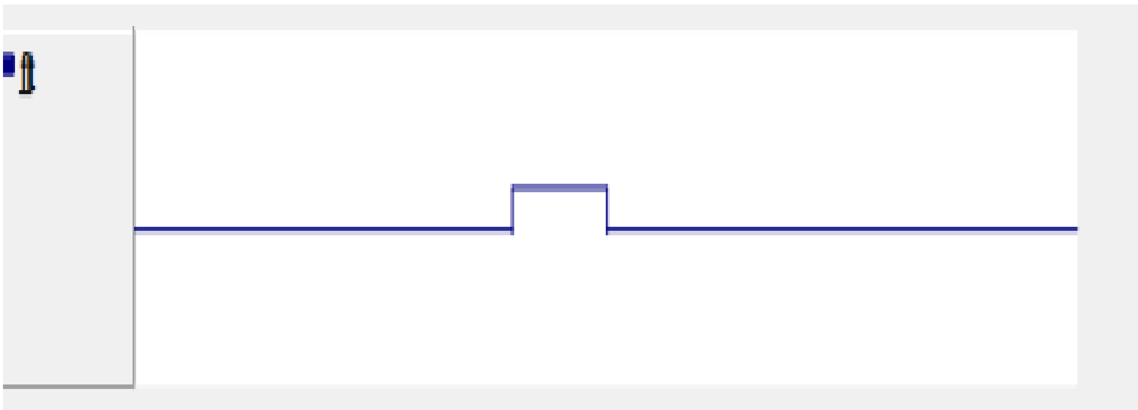

Fig. 2.12: Trip signal for SVC having L-G fault.

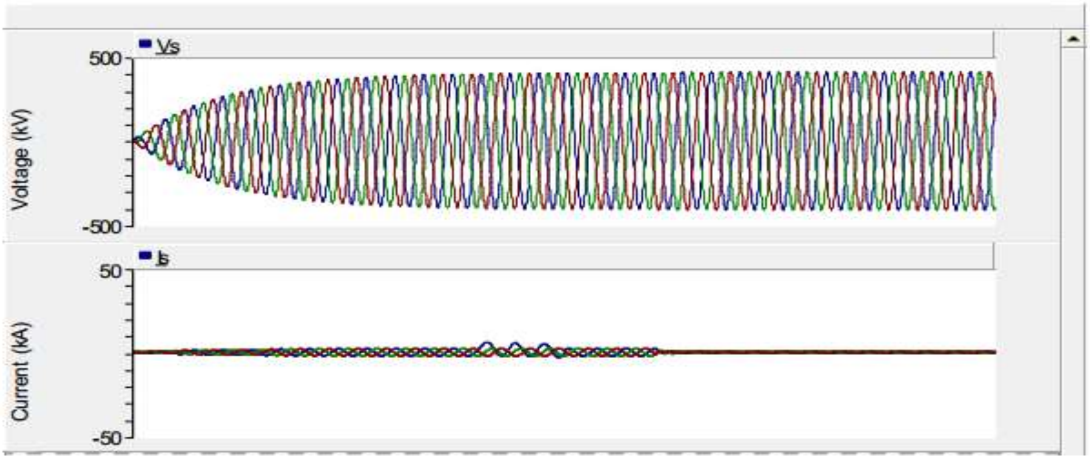

Fig 2.13: Variation of Voltage and Current signal for SVC having L-G fault.

Fig 2.14: Variation of Current for SVC having LL-G fault.

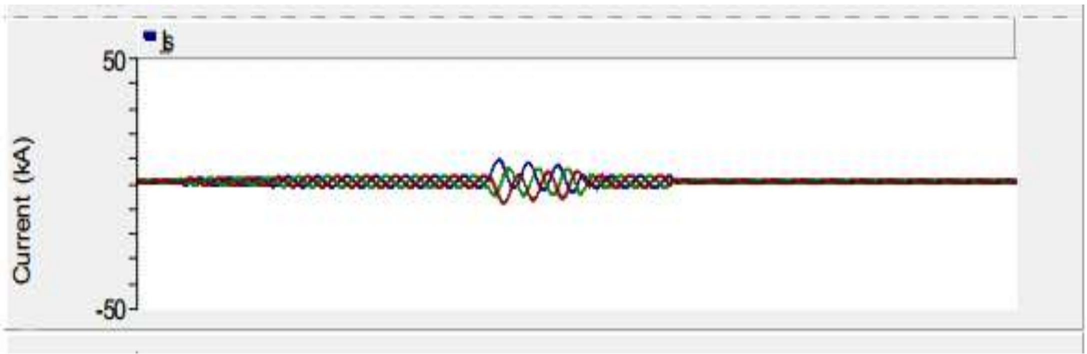

Fig 2.15: Variation of Current for SVC having LLL-G fault.

Fig 2.16: Variation of Current for SVC having L-L fault.

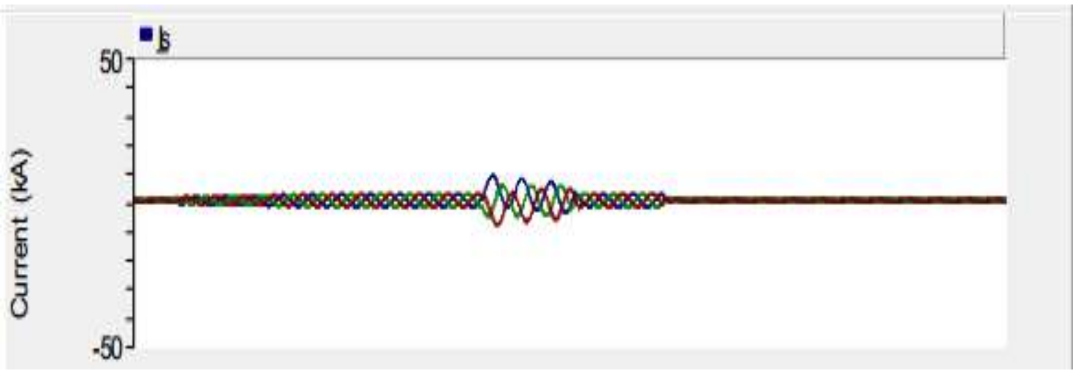

Fig. 2.17: Variation of Current for SVC having L-L-L fault.

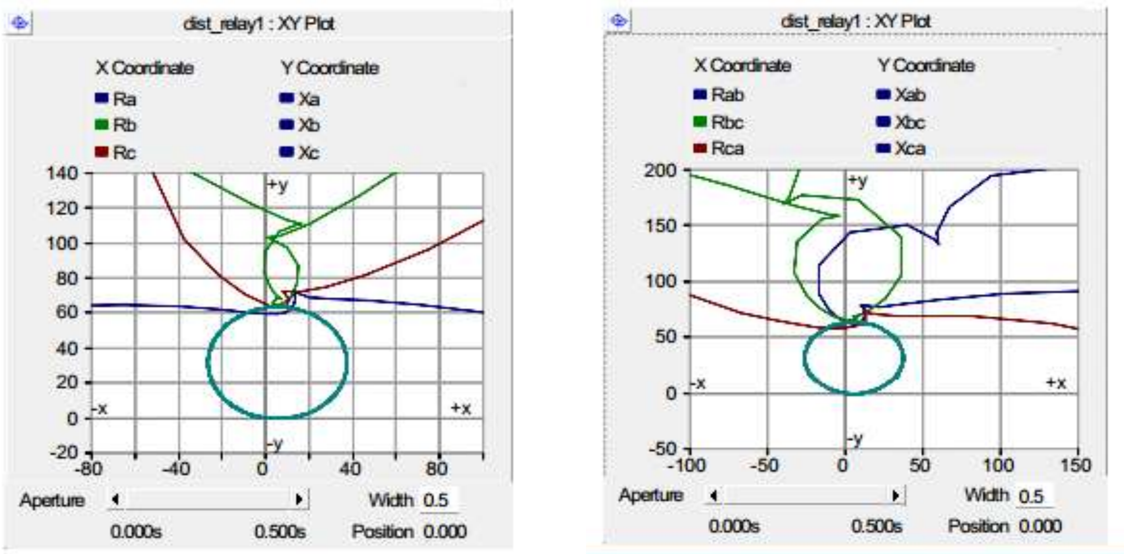

Fig. 2.18: LLL fault for the System having mid-point STATCOM

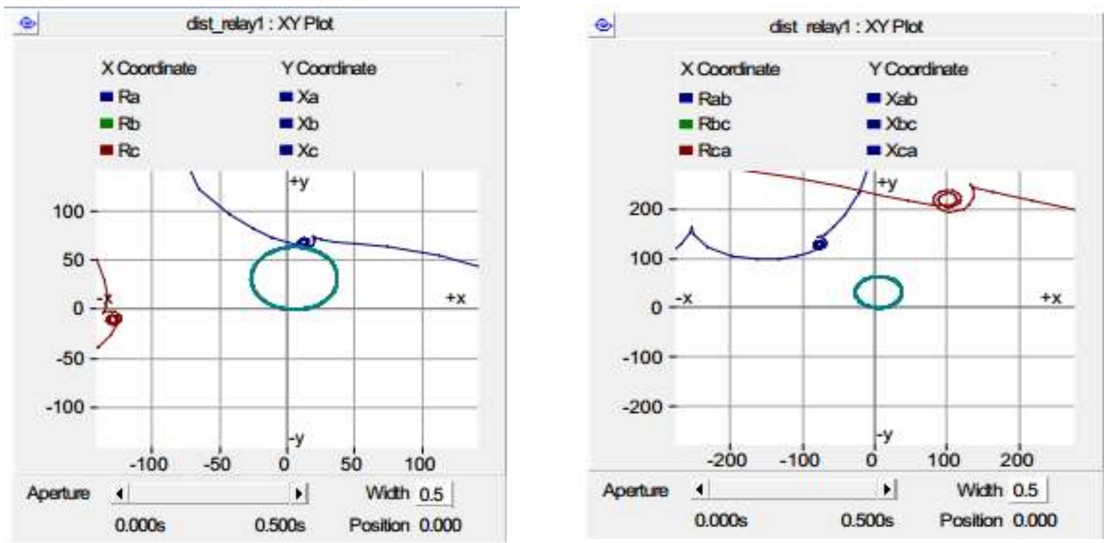

Fig. 2.19: L-G fault for the System having mid-point STATCOM

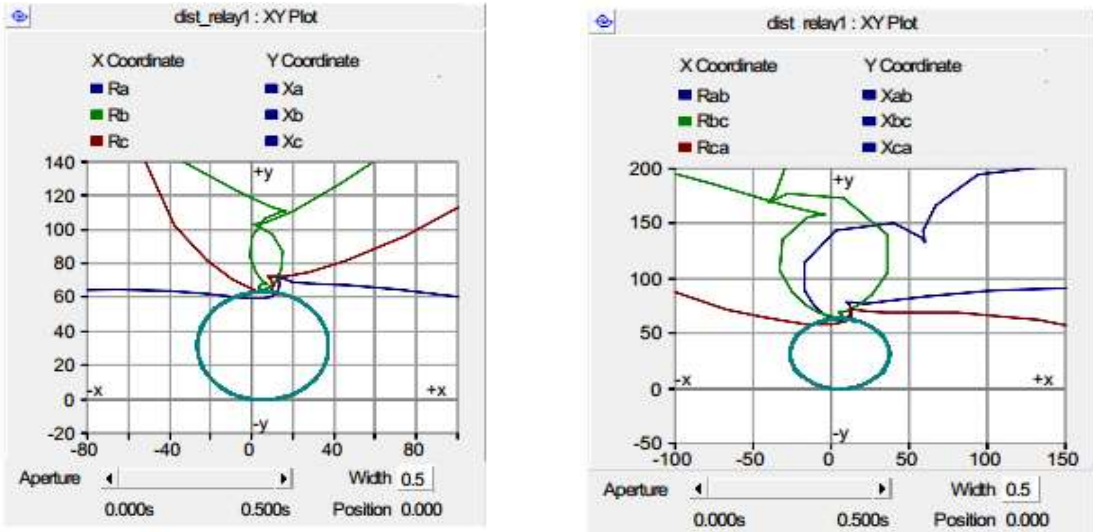

Fig. 2.20: L-L fault for the System having mid-point STATCOM

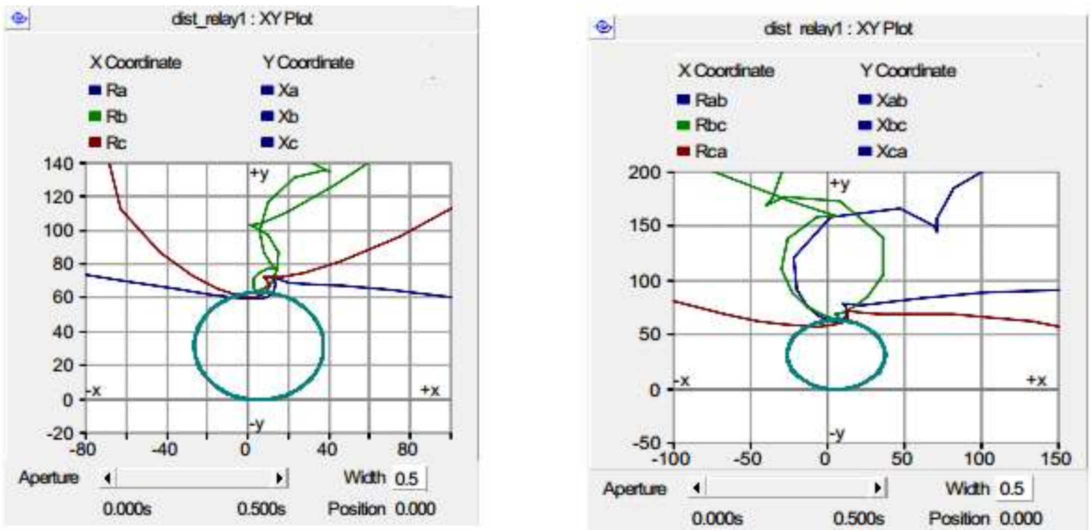

Fig. 2.21: LLL-G fault for the System having mid-point STATCOM

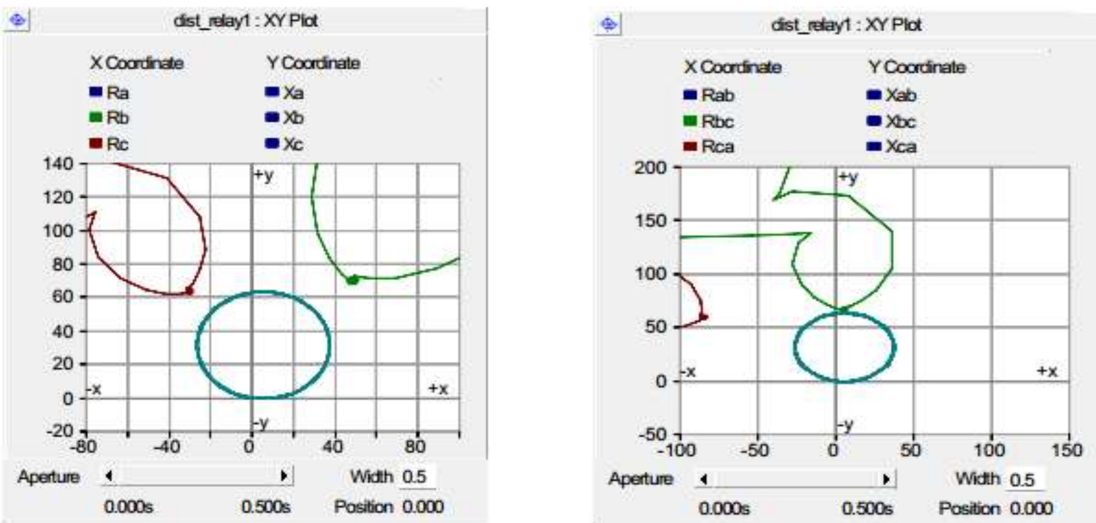

Fig. 2.22: LL-G fault for the System having mid-point STATCOM

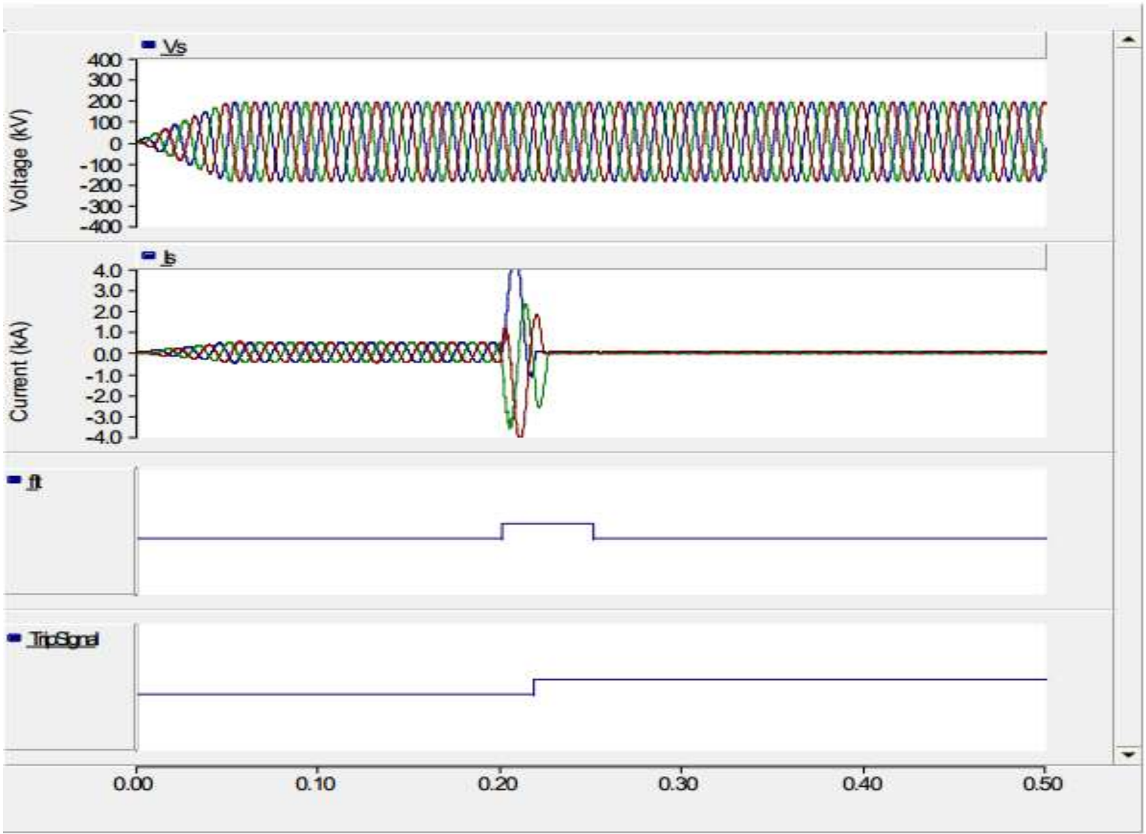

Fig. 2.23: Variation of Voltage, Current and Trip signal result for STATCOM having LLL fault.

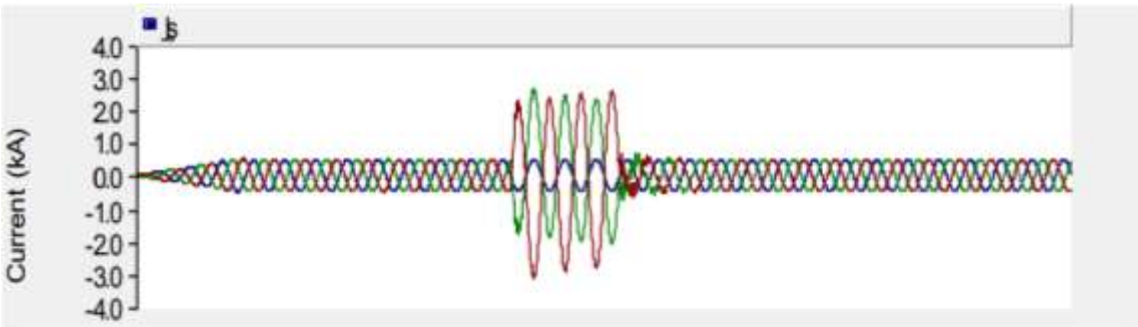

Fig. 2.24: Variation of current for STATCOM having L-L-G fault.

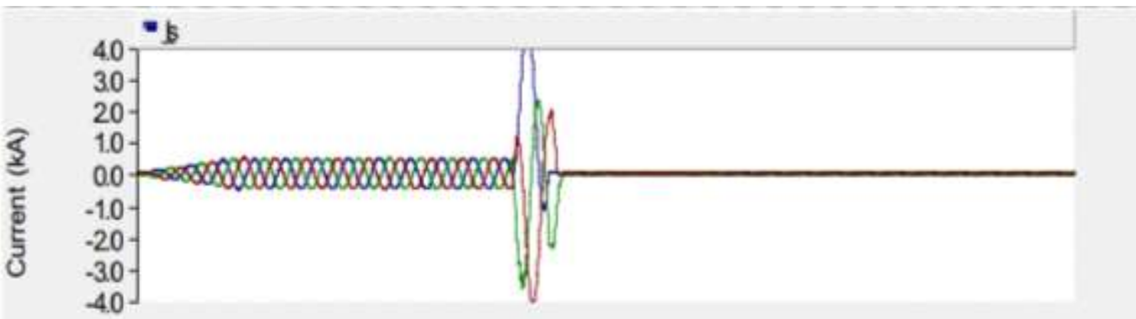

Fig. 2.25: Variation of current for STATCOM having LLL-G fault.

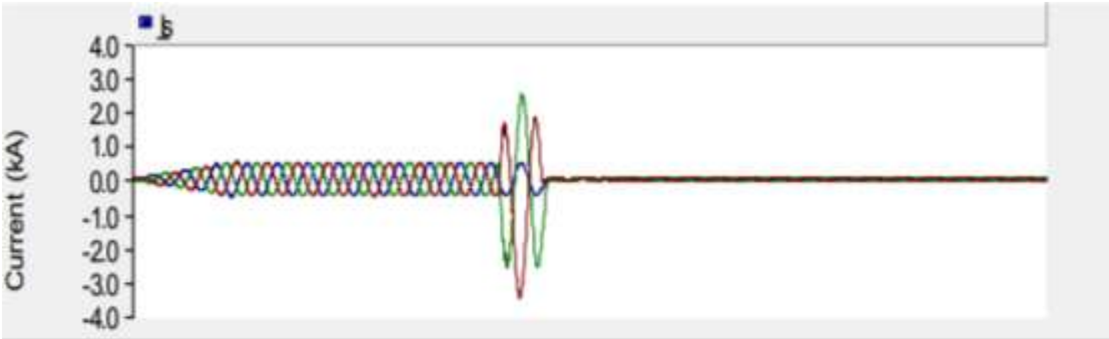

Fig. 2.26: Variation of current for STATCOM having L-L fault.

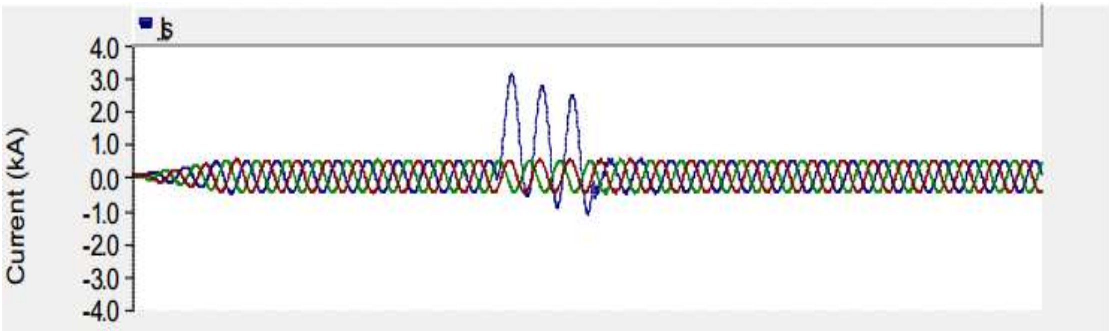

Fig. 2.27: Variation of current for STATCOM having L-G fault.

2.6 Inference

The effect of mid-point shunt FACTS compensation on distance relays can be inferred from the above studies, as follows:

An SVC may cause the under-reach of a standalone distance relay. However, this issue can be solved by channel aided distance schemes that use either permissive or blocking schemes. Nevertheless, the under-reaching impact caused by SVC when setting the distance relay should be given serious consideration.

The other effect of an SVC is to cause incorrect phase selection. If allowed, this may lead to a failure of the single pole tripping system, regardless of the distance relay operation in the standalone or communication-aided system.

In the event of a STATCOM, a stand-alone distance relay will trigger both under-reaching and over-reaching. Under-reaching phenomena can lead to the non-operation of a distance relay for covered line faults, which can be solved by properly setting communication-aided distance schemes. When distance relays over-reach, however, as can occur in the presence of STATCOM, for faults beyond the protected line, the distance relay will malfunction.

Chapter 3

Performance Evaluation of Distance Relays as Applied to a Transmission System with UPFC

3.1 UPFC and Transmission System Model

3.1.1 Transmission System Employing a UPFC Model

In this analysis, PSCAD EMTDC simulation software is used to model the 132-kV parallel transmission system with UPFC (Fig. 3.4) mounted in the center of one transmission line. In the center of the transmission line, the 100 MVA UPFC is connected.

The UPFC consists of two 48-pulse voltage source inverters connected by two common dc capacitors of 2000 μf. By means of an 11 kV/132 kV Δ/Y shunt transformer, the first inverter known as STATCOM connects to the transmission system and injects or consumes reactive power to the transmission system to control the voltage at the link point; another inverter known as Static Synchronous Series Compensator (SSSC) connects into the system through a 11 kV/33 kV

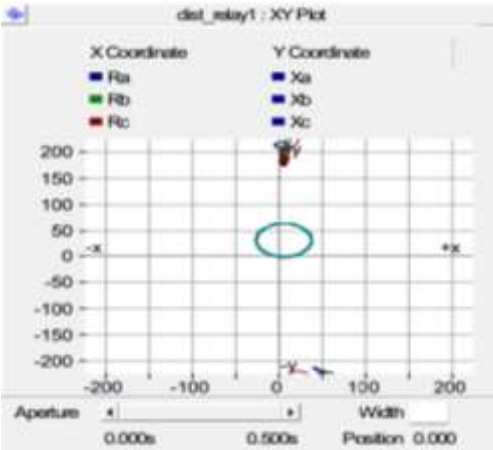

Fig. 3.1: Result of Distance Relay Operating with mid-point UPFC

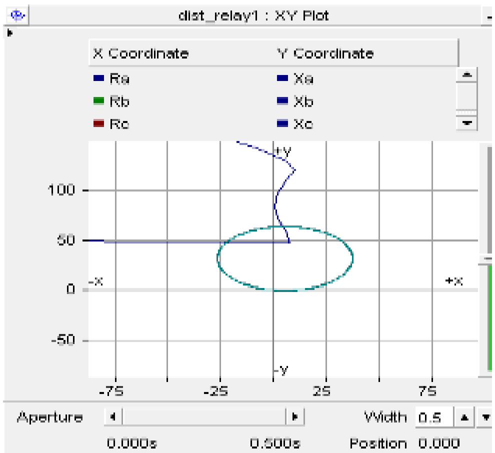

Fig. 3.2: Result of Distance Relay Operating without mid-point UPFC

Y/Y series transformer to inject an almost sinusoidal voltage of variable magnitude and angle, in series with the transmission line to regulate the power flow through the transmission line, the positive sequence, negative sequence and the zero-sequence transmission line impedance can be calculated.

3.1.2 Voltage Source Inverter Model

The voltage source inverter employed herein is based on the 48-pulse thyristor-based inverter. It consists of four 3-phase, 3-level thyristor-based inverters and phase shifting transformers. These voltages are fed to the secondary windings of phase-shifting transformers whose primary windings are connected in series to produce an almost sinusoidal voltage output. A dc capacitor is connected to the four 3-level inverters, the magnitude of square-wave voltage can be $+Vdc$, 0, $-Vdc$. The fundamental component of voltage source inverter has the amplitude of

$$VX,n = \frac{2}{\pi} Vdc\, cos\left(\frac{\pi}{24}\right) cos\, \gamma \tag{1}$$

As seen from above, the magnitude of the injection can be adjusted through changing the value of angle and/or the dc voltage of the capacitor. The phase angle of the output voltage can be adjusted by using the input signal from the pulse generator. In this study, the STATCOM inverter is operated as 48-pulse inverter, and the SSSC inverter is operated with a variable phase angle to control the amplitude of the injection voltage.

3.1.3 UPFC Control Model

The UPFC's control system can be split into two parts: STATCOM control and SSSC control. The STATCOM control is used to operate the inverter voltage source to inject or absorb reactive power to regulate the voltage of the connecting point to the V_{ref} setting value. Using the phase-lock-loop angle as a reference, the three phase currents of STATCOM are decomposed into their real part I_d and reactive part Iq through the abc-dq transform. The magnitude of the connecting point positive sequence component of the voltage is compared with the desired reference voltage V_{ref} and the error is passed through a PI controller to generate the desired $I_{q\,ref}$ reactive current; compared with the reactive part of the shunt current, this current relation generates an error that will be passed into another PI controller to obtain the relative phase angle of the inverter voltage relative to the phase voltage. The phase angle reference is fed to the STATCOM firing pulse generator along with the phase-lock-loop signal to generate the desired pulse for the voltage source inverter. The SSSC control strategy is based on automatic power flow control. A closed loop control system determines the injected voltage sequence to ensure that the desired active and reactive powers flowing through the transmission line are maintained despite changes in the power system. The required P_{ref} and Q_{ref} are compared in the transmission line with the measured positive active and reactive power flows, the errors are used as a reference to the PI controllers, to get the desired direct and quadrature components of the series inverter voltage, V_{dref} and V_{qref}, respectively. A rectangular to polar transformation of V_{dref} and V_{qref} components will obtain the magnitude V_{pq} and phase angle of the series converter voltage. The phase angle alpha, dead angle gamma along with the phase-lock-loop signal are used by the SSSC firing pulse generator to produce the desired pulse for the SSSC voltage source inverter.

3.2 Apparent Impedance Analysis

3.2.1 Apparent Impedance Calculation

On the right side of the UPFC, when a single phase-to-ground fault occurs and the distance n x L is from the relay point, the system's positive, negative and zero sequence networks during the fault are as shown in Fig. 3.3

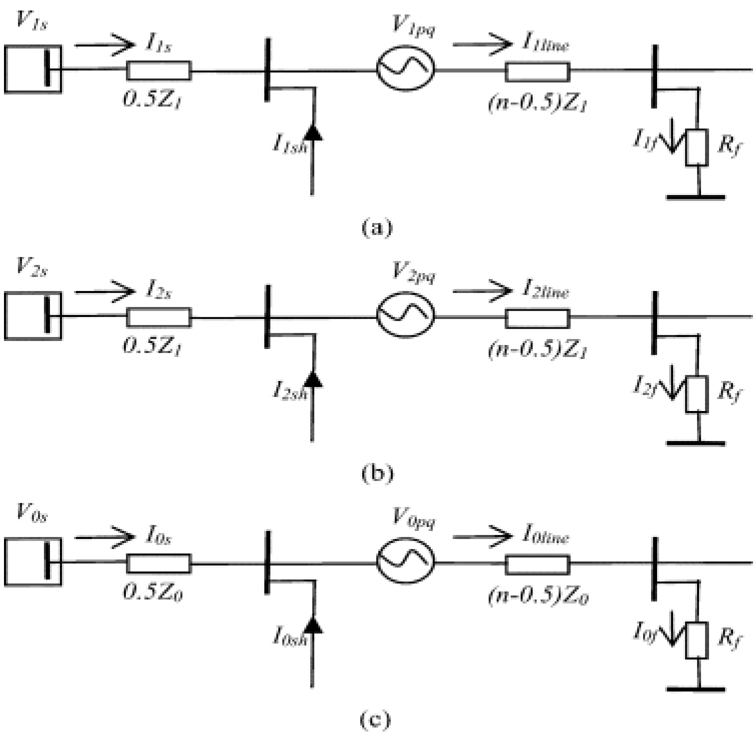

Fig.3.3: Sequence networks of the system from the relay location to fault. (a) Positive sequence network. (b) Negative sequence network. (c) Zero sequence network.

$$V_{1s} = I_{1s}0.5Z_1 + V_{1pq} + I_{1line}(n-0.5)Z1 + RfI1f \quad (1)$$

$$V_{2s} = I_{2s}0.5Z_1 + V_{2pq} + I_{2line}(n-0.5)Z1 + RfI2f \quad (2)$$

$$V_{0s} = I_{0s}0.5Z_0 + V_{0pq} + I_{0line}(n-0.5)Z0 + RfI0f \quad (3)$$

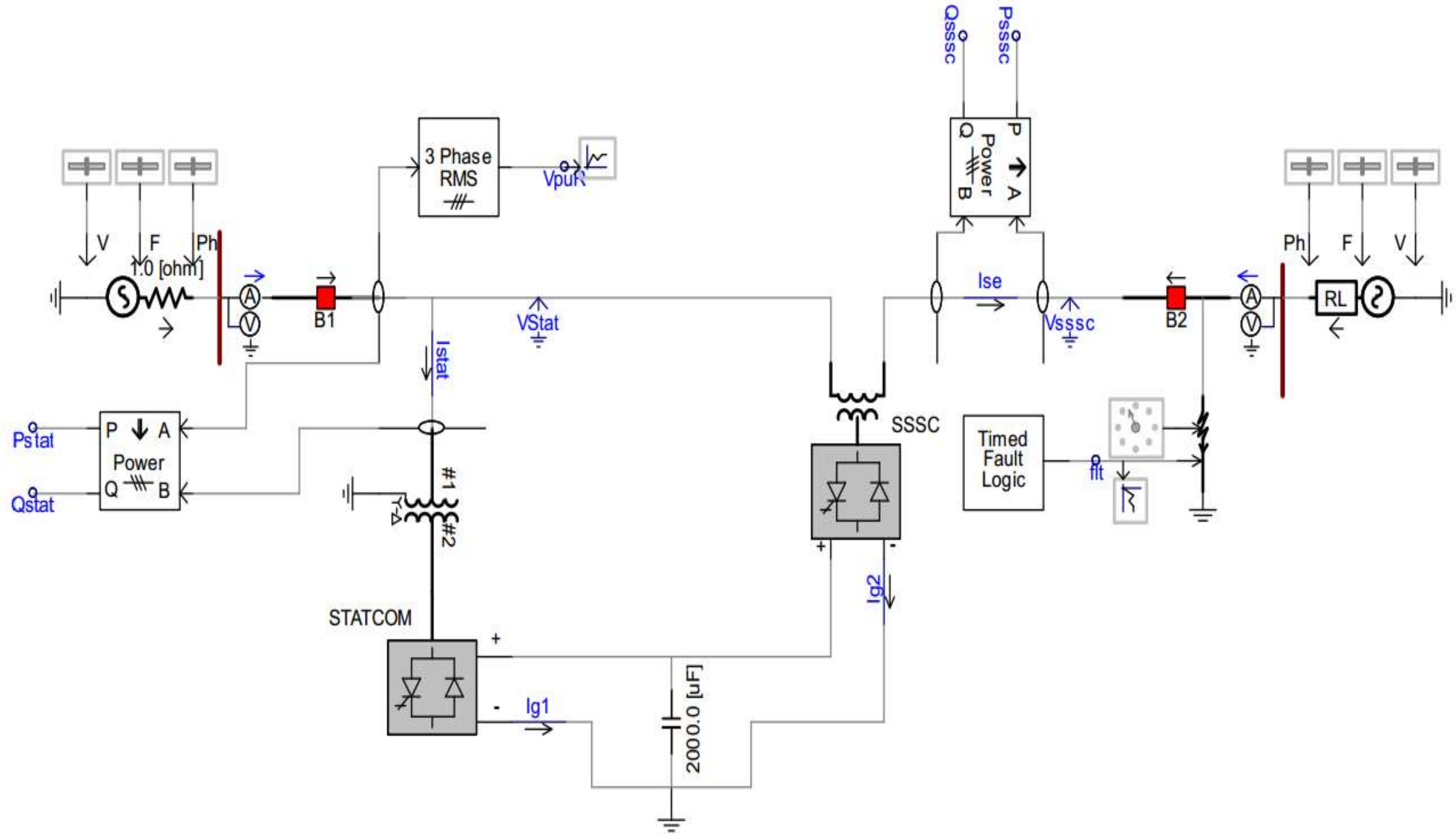

Fig. 3.4: Distance protection setting in presence of mid-point UPFC

$$I_{1line} = I_{1s} + I1sh \quad (4)$$
$$I_{2line} = I_{2s} + I2sh \quad (5)$$
$$I_{0line} = I_{0s} + I0sh \quad (6)$$

Where,

V_{1s}, V_{2s}, V_{os} sequence phase voltages at the relay location;

$V_{1pq}, V_{2pq}, V_{opq}$ series sequence phase voltages injected by UPFC;

I_{1s}, I_{2s}, I_{os} sequence phase currents at the relay location;

$I_{1line}, I_{2line}, I_{oline}$ sequence phase currents in transmission line;

I_{1f}, I_{2f}, I_{of} sequence phase currents in the fault;

$I_{1sh}, I_{2sh}, I_{osh}$ shunt sequence phase currents injected by UPFC;

$Z1, Z0$ sequence impedance of the transmission line;

n per − unit distance of a fault from the relay location.

From above, the voltage at the relay point can be derived as where

$$Vs = nIsZ1 + nI0s(Z0 - Z1) + Ish(n - 0.5)Z1 + (n - 0.5)I0sh(Z0 - Z1) + Vpq + RfIf \quad (7)$$

Where,

$$V_{1s} = V_{1s}, V_{2s}, V_{os} \quad (8)$$
$$I_s = I_{1s}, I_{2s}, I_{os} \quad (9)$$
$$I_{sh} = I_{1sh}, I_{2sh}, I_{osh} \quad (10)$$
$$V_{pq} = V_{1pq}, V_{2pq}, V_{opq} \quad (11)$$

In the transmission system without UPFC, for a single phase-to-ground fault, the apparent impedance of distance relay can be calculated using the equation

$$Z = \frac{VR}{IR + \frac{Z_0 - Z_1}{Z_1}} = \frac{VR}{Irelay} \quad (12)$$

Where,

V_R, I_R phase voltage and current a relay point,

I_{R0} zero sequence phase current,

I_{relay} relaying current.

If this traditional distance relay is applied to the transmission system with UPFC, the apparent impedance seen by this relay can be expressed as

$$Z = \frac{Vs}{Is + \frac{Z0 + Z1}{Z1} IS0} = \frac{Vs}{Irelay} \tag{13}$$

$$= nZ_1 + \frac{I_{sh}}{I_{relay}}(n-0.5)Z_1 + \frac{I_{0sh}}{I_{relay}}(n-0.5)(Z_0 - Z_1) + \frac{V_{pq}}{I_{relay}} + \frac{I_f}{I_{relay}} R_f. \tag{14}$$

In practice, one side of the shunt transformer is often based on a delta connection, and thus there is No zero-sequence current injected by UPFC, that is to say $I0sh = 0$, then the equation can be rewritten as

$$Z = nZ_1 + \frac{I_{sh}}{I_{relay}}(n - 0.5)Z_1 + \frac{V_{pq}}{I_{relay}} + \frac{I_f}{I_{relay}} R_f. \tag{15}$$

When a conventional distance relay is used on a transmission line with UPFC during a phase-to-ground fault, the apparent impedance seen by this relay has three parts: positive sequence impedance from the relay point to the fault point, and negative sequence impedance from the relay point to the fault point, which is what the distance relay is set to measure, the second is due to the influence of UPFC on the apparent impedance, which is further divided into two parts: one is due to the shunt current I_{sh} injected by the STATCOM, and the other is due to the impact of the series voltage I_{pq} injected by the SSSC; the fault resistance of the apparent impedance.

The study described is merely a theoretical illustration of the effect of the UPFC on apparent impedance and thus on distance relay efficiency.

3.2.2 Practical Consideration and Relay Modelling

The primary device fault information is obtained using the PSCAD EMTDC Simulation Software, as previously stated. The digital simulation works at a frequency of 50 kHz. The output of the distance relay is achieved using an impedance chart (R/X diagram), as shown in Figure 3.1. This graph plots the characteristic curves of the relay operating limit and system impedance shown by the relay under defined operating conditions.

3.2.3 The Impact of STATCOM (shunt part of UPFC) on Distance Relay

When only the shunt voltage source inverter is connected to the UPFC system, it operates as STATCOM alone; when only the series component is connected to the system, it operates as SSSC; and when both components work together, it operates as the full UPFC system. When in STATCOM mode, the main objective is to regulate the connecting point voltage by injecting or absorbing reactive power into or out of the power system. If the UPFC is run as STATCOM and only a solid single phase-to-ground fault is considered, the equation becomes (16).

$$Z = nZ1 + (n-0.5)Z1\frac{If}{Irelay} \qquad (16)$$

It is possible to express the effect of STATCOM on the apparent impedance using the ratio: I_{sh}/I_{relay}. The location of the fault, system source capability and STATCOM settings will be taken into account in the following sections. As a zone one distance relay, a Mho characteristic with positive sequence voltage polarization is used to cover 80 percent of the transmission line.

3.2.4 The Effect of Fault Location

When an phase to ground fault is on the right side of STATCOM, i.e., at a fault distance of 120 km from the relay point, and the desired voltage $Vref$, the apparent impedance trajectory seen by the phase to ground element of the system with and without STATCOM together with the distance relay mho characteristic; the corresponding apparent resistance and reactance with and without STATCOM as a function of time are as shown in Fig. 3.1 and 3.2. Therefore, the apparent impedance of both the resistance and the reactance components of the transmission system with STATCOM is higher than for the system without STATCOM. A direct effect of these variations is that the distance relay would under-reach. Faults at different locations have been tested to study the coverage of the mho element, and the apparent resistance and reactance are seen respectively as a function of the fault location. The voltage at the STATCOM connecting point is higher compared to the device without STATCOM because of the reactive power injection by STATCOM, i.e., the distance relay would perceive that the fault is further away than the actual distance; so an improvement in the apparent impedance would result in the distance relay under reaching. For an increase in fault distance, the impact ratio increases. This is due to the fact that the relay current and STATCOM injecting current can decrease for a remote fault, but the difference in relay current is greater than in the injecting current.

If the STATCOM is located in the center of the transmission line (as is the case for the results shown in Figs. 3.1 and 3.2), and the coverage range of the original distance relay is 80 percent, the current relay coverage for the STATCOM system can be extracted from the following:

$$50\%.Z1 + (Nnew - 50\%)\left(1 + \frac{Ish}{Irelay}\right)Z1 = Z1.80\% \quad (17)$$

$$Nnew = 50\% + \frac{30\%}{1+\frac{Ish}{Irelay}} \quad (18)$$

It clearly indicates that the real coverage of the relay is always less than the 80 per cent required.

3.2.5 The Effect of System Source Capacity

It is evident that the STATCOM would inject less reactive power to maintain the connecting point voltage at the appropriate level when a fault occurs on a relatively strong transmission system and the apparent impedance shown by the distance relay being smaller in the stronger system compared to the system terminated with smaller SCLs.

3.2.6 The Effect of STATCOM Setting

The STATCOM can have different setting values for the target voltage, depending on the different device conditions, and this setting may also have an effect on distance relay performance. Figs. 3.1 indicates the apparent impedance and reactive power injected by STATCOM during a single phase-to-ground fault. The STATCOM can inject more reactive power when the setting voltage is high during a fault to sustain the voltage at the desired amount, i.e., I_{sh} is high; this eventually increases the impact ratio, resulting in an increase in the apparent impedance shown by the distance relay.

The STATCOM connecting point voltage may exceed the original setting value under certain circumstances, such as when the SCL is high, the voltage setting value is low, and the fault is outside the zone 1 setting. In this situation, the STATCOM absorbs reactive power from the device, resulting in a decrease in the apparent impedance as shown by the distance relay and thus an apparently undesirable probability of overreaching the relay. Fig. 3.1 and 3.2 displays the apparent impedance trajectory when the fault is at the same spot, with and without STATCOM. For a single-phase earth fault at 165 km from the relay site, as I_{sh} can be seen (i.e., outside the 80 percent setting).

3.2.7 Simulation Results and Conclusions for a System with STATCOM

The apparent impedance will increase during a fault if the STATCOM supplies the system with reactive power, which will also result in the under-reach of the distance relay; if the STATCOM absorbs the reactive power from the system, the apparent impedance will decrease, causing the over-reach of the distance relay. Thus, the STATCOM's setting has a major influence on the apparent impedance. As compared to a lower voltage setting, a higher voltage setting often results in a greater apparent impedance. With an increase in fault distance, the impact ratio would increase.

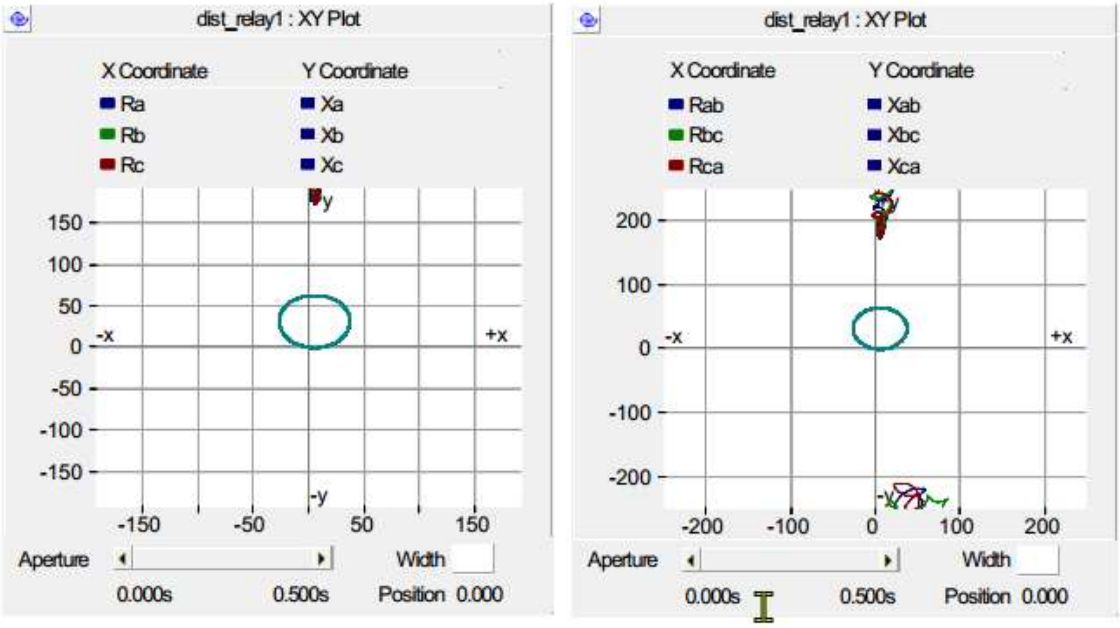

Fig. 3.5: The apparent impedance seen by the distance relay during a L-G phase fault

3.3 UPFC and its Influence on Distance Relay

The UPFC functions as a complete system when both the shunt and series parts operate together, and its function is to both control the power flow in the transmission line and maintain the voltage at the connecting point of STATCOM. The active and reactive reference powers V_{ref} are set the same as without UPFC for the device.

3.3.1 Single Phase-to-Ground Fault

When comparing the apparent impedance seen by the distance relay for a phase-earth fault 130 km from the relay point, the impedance trajectory for a STATCOM and UPFC device at a fault distance, it is clear that the deterioration in relay efficiency is much worse in the case of a device using the maximum UPFC. As previously said, this may be directly due to the generation of a large zero-sequence voltage.

3.3.2 Phase-to-Phase Fault

As in the case of a STATCOM device, there is again a tendency for the relay to under-reach and this is as a direct consequence of the apparent impedance being substantially higher than when there is no UPFC. Importantly, with the full operation of the UPFC, the impact on the apparent impedance is greater than when only the STATCOM is in use.

3.3.3 Simulation Results and Conclusions for a System with UPFC

The apparent resistance increases when the SSSC section of the UPFC consumes active power, and the apparent reactance increases when the SSSC consumes reactive power. UPFC has a greater effect on the apparent resistance compared to STATCOM, due to both SSSC and STATCOM's successful power injection and absorption. The effect of UPFC on the apparent impedance, compared to STATCOM, is much more complex and complicated.

3.3.4 SSSC and its Influence on Distance Relay

The impact on the apparent impedance as seen by the distance relay is very similar between having the full UPFC (comprising both the STATCOM and SSSC) and the SSSC on its own, particular for single phase-to-ground faults. This is because the magnetizing branch of the SSSC series transformer is included in the fault circuit in both cases, which in turn gives rise to a large zero sequence voltage element in the voltage of the relay point that has a significant impact on the apparent impedance. For a phase-to-phase fault, the SSSC's effect on distance relay is relatively simple: when the SSSC injects reactive power into the device, it operates like a series capacitor and decreases the apparent impedance, while when it absorbs reactive power from the system, it operates like a series inductance and increases the apparent impedance.

Chapter 4

Enhancement of Power System Reliable Operation Using an Adaptive Protection Strategy

4.1 Introduction

Adaptive relaying recognizes that the characteristics of relays that protect a power network adjust to fit the current power system conditions. In most situations, a protective mechanism reacts to faults or irregular events in a predetermined and predictable manner. This predetermined behavior, which is expressed in the relays' characteristics, is based on certain assumptions about the power system. However, if the actual load reaches this load current level over time, the pickup setting of the relay becomes inadequate, and the relay can malfunction during heavy loading conditions. It is often important to establish a framework that covers a wide range of conditions, and it is desirable to make relays adapt to changing conditions and with adequate safeguards.

To fully explain the current adaptive relaying model, it involves the possibility that protection systems will allow for automatic adjustments within the protection system as the power system undergoes normal and abnormal changes during operation. As a consequence, adaptive protection is a protection concept that requires and aims to automatically change different protection functions to make them more attuned to current power system conditions.

4.1.1 Computer Relaying and Adaptive Relaying

Only digital computer-based relays will completely adopt the adaptive relaying philosophy. These relays, which are becoming more prevalent on many power systems, have two main features: their roles are determined by software, and they have a communication capability that can be used to modify the software in response to higher-level supervisory software or instructions from a remote-control center. Any relay or communication system must be conscious that it may malfunction at some point, and sufficient fallback positions and safety checks should be installed into the relays.

4.2 SVC and Power System Model

4.2.1 Study System Modelling

To simulate all possible flow conditions, a power system model with the facility to vary the system strength, types of fault and their position, load flow and load direction is used. On distance protection, the incorrect estimate of fault positions due to SVC is studied. Fig. 4.1 shows the SVC single line diagram with power system model. At station A, on line 1, the distance relay is located. The SVC is installed at the mid-point of transmission line 1. On the SVC bus and relay bus, a PMU is presumed to be available. For data transmission, high-speed optical fiber data communication is also available.

4.2.2 Adaptive Protection for Distance Relay with mid-point SVC

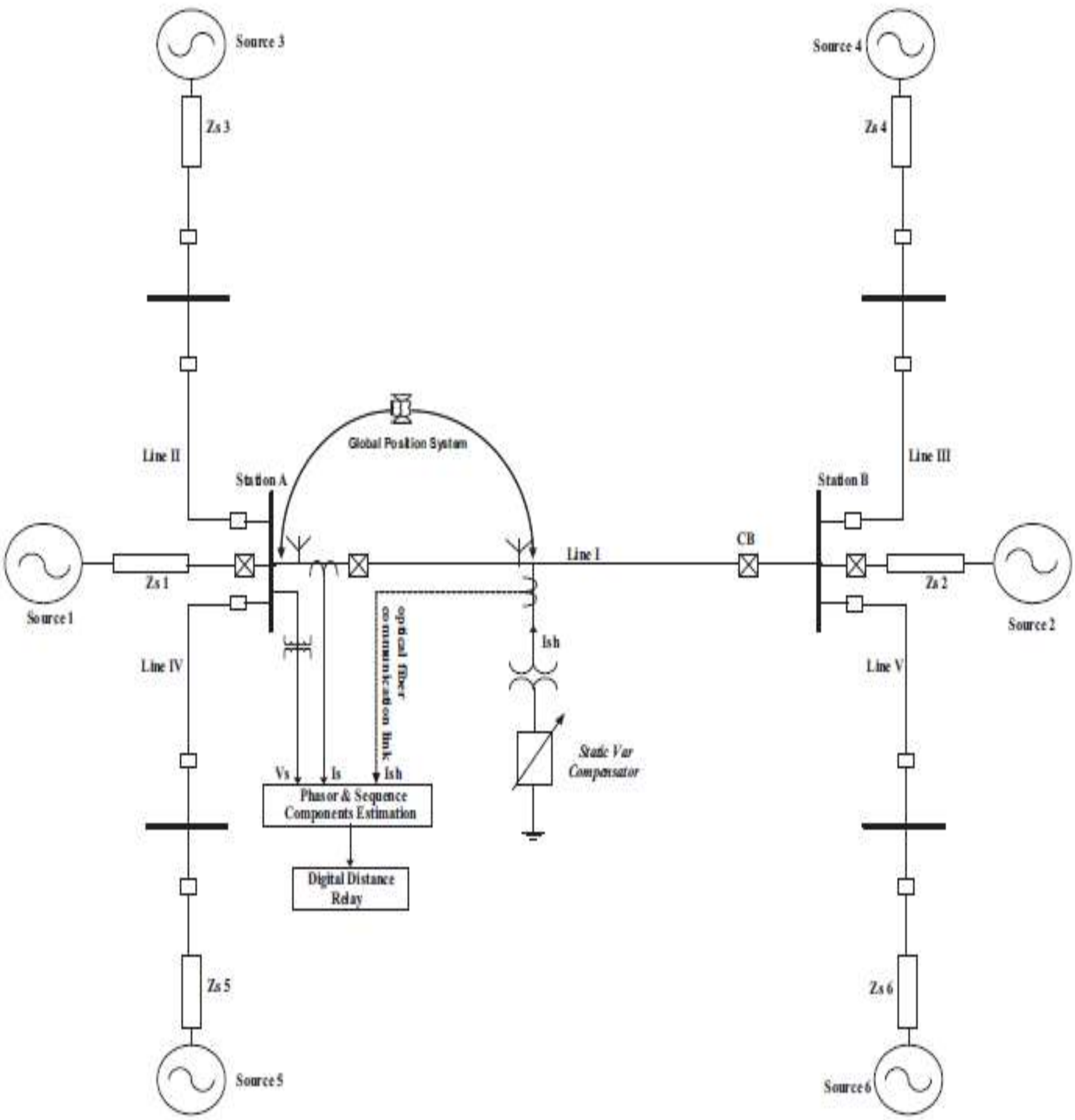

Fig. 4.1. Single line diagram of study system model with mid-point SVC

The main objective of this analysis is to adjust the algorithm for distance protection when SVC is present at the mid-point of the transmission line. Taking input from SVC in the distance protection algorithm on shunt injected current ($\mathbf{I}_{sh}$) to make it adaptive, synchronized calculation at the connecting point of the relaying bus and SVC is used. Time-stamped synchronized GPS measurement at both terminals is assumed with a high-speed optical fiber data transmission device that transmits ($\mathbf{I}_{sh}$) information without any communication delay to the relay bus (Fig. 4.1). Then the measured apparent impedance is compared with the distance relay zone setting (Z_{set}) to make the trip or no trip decision in the protection zone for fault. Since the shunt injected current (I_{sh}) information is available on the relaying bus, the expression of the new distance relay setting that defines the setting adaptively is required.

The line to be protected from station A to station B, the relay setting with three zones setting parameters, which is for 80 percent, 120 percent and 150 percent of the line to be protected, is expressed in equation (1), (2) & (3) considering the apparent impedance measured to be equal to the setting of first zone, second zone and third zone of distance relay.

$$Z1 = Zset = 0.8\ Zline1 \tag{1}$$

$$Z2 = Zset = 1.2\ Zline1 \tag{2}$$

$$Z3 = Zset = 1.5\ Zline1 \tag{3}$$

$$\rho = 0.5 + \frac{0.3}{\left(1+\frac{Ish}{Is+mIso}\right)} \tag{4}$$

$$\rho = 0.5 + \frac{1}{\left(1+\frac{Ish}{Is+mIso}\right)} \tag{5}$$

$$\rho = 0.5 + \frac{1.75}{\left(1+\frac{Ish}{Is+mIso}\right)} \tag{6}$$

$$Z1new = \left(0.5 + \frac{0.3}{\left(1+\frac{Ish}{Is+mIso}\right)}\right) Zline1 \tag{7}$$

With this new setting, the adaptive distance protection will check the measured apparent impedance ($\mathbf{Z}_{app}$) and take the decision when the SVC is present at the center of the transmission line. multiply Eq. (4) with Zline1 to get the new setting,

$$Znew = \rho Zline1 \tag{8}$$

Multiplying Eq. (4) with (Zline1) and substituting in (7), we get first zone setting

$$Z1new = \left(0.5 + \frac{0.3}{\left(1+\frac{Ish}{Is+mIso}\right)}\right) Zline1 \tag{9}$$

Multiplying Eq. (5) with (Zline1) and substituting in (7), we get second zone setting

$$Z2new = 0.5 + \frac{1}{1+\frac{Ish}{Is+mIso}} \tag{10}$$

Multiplying Eq. (6) with (Zline1) and substituting in (7), we get third zone setting

$$Z3new = \left(0.5 + \frac{1.75}{\left(1+\frac{Ish}{Is+mIso}\right)}\right) Zline1 \tag{11}$$

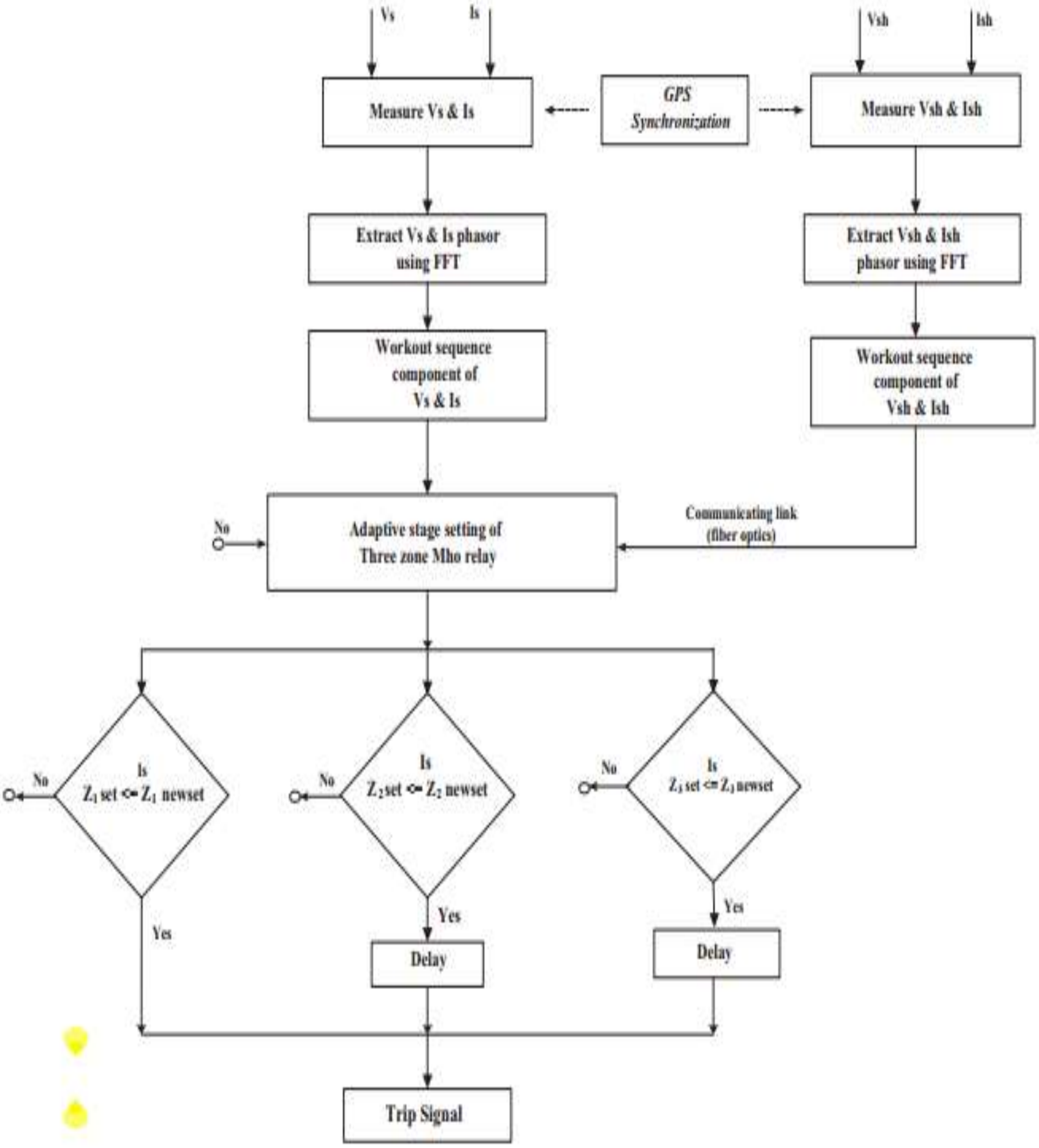

Fig. 4.2. Flow Chart of three zones adaptive distance with mid-point SVC

From Eqs. (8)– (11), important conclusions can be made:

The mid connected SVC affects the apparent impedance calculation. The SVC injected current has dominant effect on apparent impedance calculation for fault. The adaptive distance protection zone setting formula adaptively adjusted with the different levels of SVC injected current. Depending on the amount of compensation, the adaptive distance protection setting will change the zone reach automatically. If SVC injects capacitive current ($\mathbf{I}_{sh}$), the adaptive zone is positive and increased, while the inductive current ($\mathbf{I}_{sh}$) is negative and the adaptive zone is reduced.

Fig. 4.2 shows the flowchart for adaptive distance protection settings as derived from Eqn. (8) to (11) in the PSCAD Simulation Software. From Eqs, (8)-(11) the adaptive distance relay adaptively sets the zone setting using shunt injected current data. Comparing the apparent impedance, it modifies the setting parameter to adapt to the new level of compensation as soon as there is some adjustment in the SVC compensation level and when fault is on the line, the relay compares the calculated apparent impedance with this setting to provide signal to the circuit breaker to clear faults.

4.2.3 Simulation Results

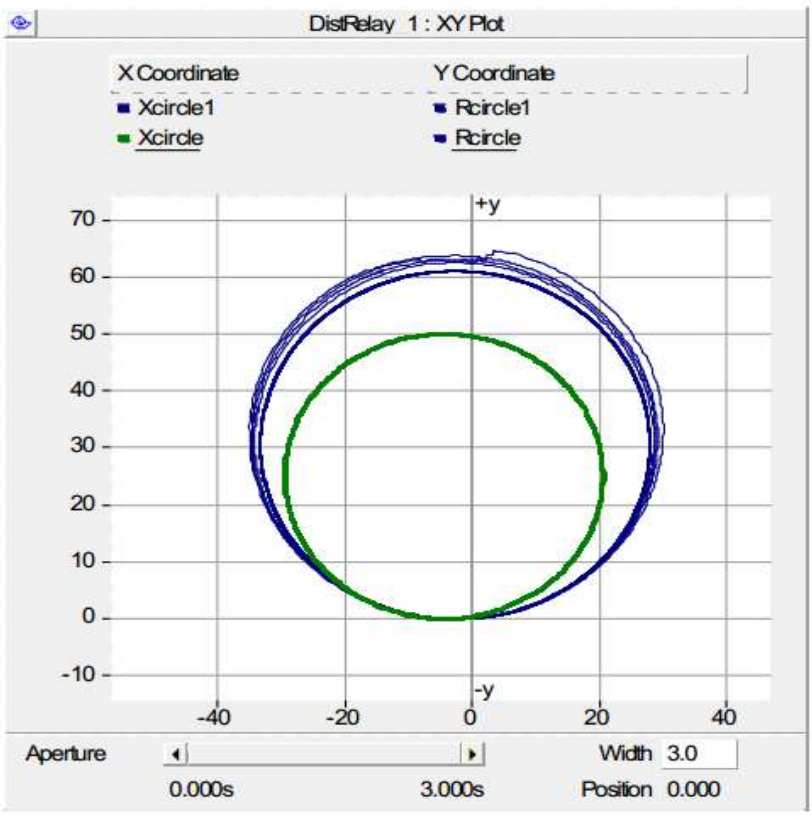

Fig. 4.3 Adaptive mho relay second zone characteristics with SVC supplying inductive reactive power of 100 MVAR into the system with forward power flow.

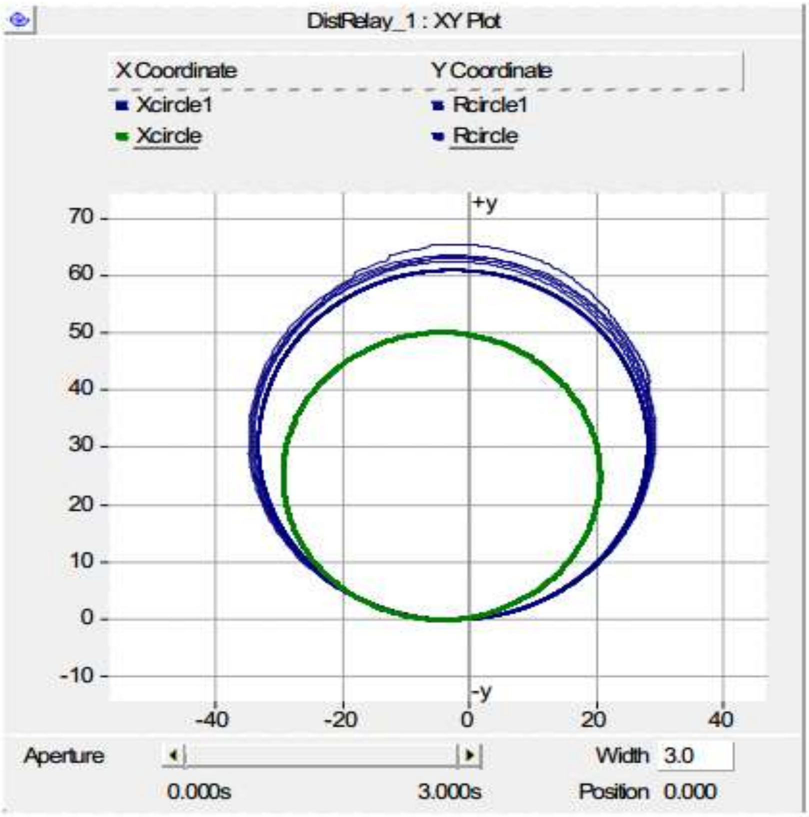

Fig. 4.4 Adaptive mho relay second zone characteristics with SVC supplying capacitive reactive power of 100 MVAR into the system with forward power flow.

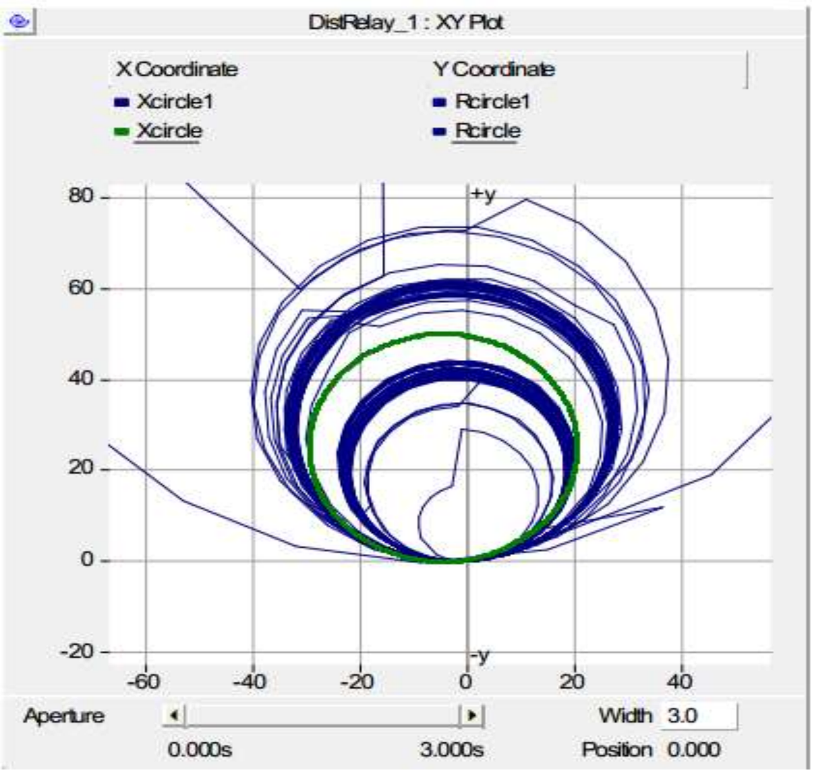

Fig. 4.5 Adaptive mho relay second zone characteristics with SVC supplying capacitive reactive power of 100 MVAR into the system with reverse power flow.

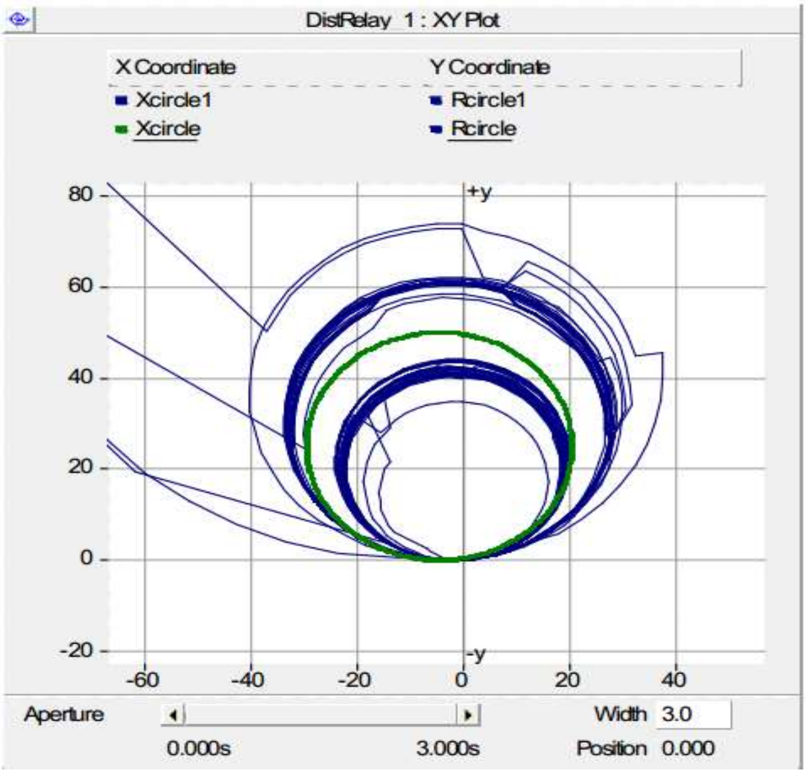

Fig. 4.6 Adaptive mho relay second zone characteristics with SVC supplying inductive reactive power of 100 MVAR into the system with reverse power flow.

Adaptive distance protection is modeled in PSCAD software to measure different distance relay adaptive zone settings and control over the injection of reactive power (±100 MVAR). When, SVC absorbs inductive reactive power, the mid-point voltage decreases, from normal operating voltage. This results in decrease in relaying bus voltage due to the apparent impedance seen by distance relay decreases causing over-reach. It is observed that the shunt current (I_{sha}) is zero prior to the SVC implementation. When the SVC is connected at 0.1 s and the inductive reactive power of 100 MVAR is absorbed, the setting factor ∂ is adaptively reduced and set to a new adaptive zone setting per unit distance value. This adaptive setting factor is used to dynamically define the mho distance relay reach, as shown in Fig.4.3. It is observed that the adaptive mho distance relay reach shown in blue color has set to new value in comparison to the conventional setting shown in red color for inductive reactive power injection. When SVC is injecting capacitive reactive power into the system, the mid-point voltage increased as compared to normal operating voltage without SVC. Consequently, there is increase in relaying bus voltage and the apparent impedance seen by distance relay increases causing under-reach. The mid-point voltage increases compared to normal operating voltage without SVC as SVC injects capacitive reactive power into the system. Consequently, the relaying bus voltage is increased and the apparent impedance increases causes under-reach of the distance relay. The new adaptive relay characteristics for capacitive reactive power into the system is shown in Fig. 4.4, the setting factor ∂ is adaptively increased and set to a new adaptive zone setting per unit distance value.

4.3 Adaptive Distance Protection with mid-point STATCOM

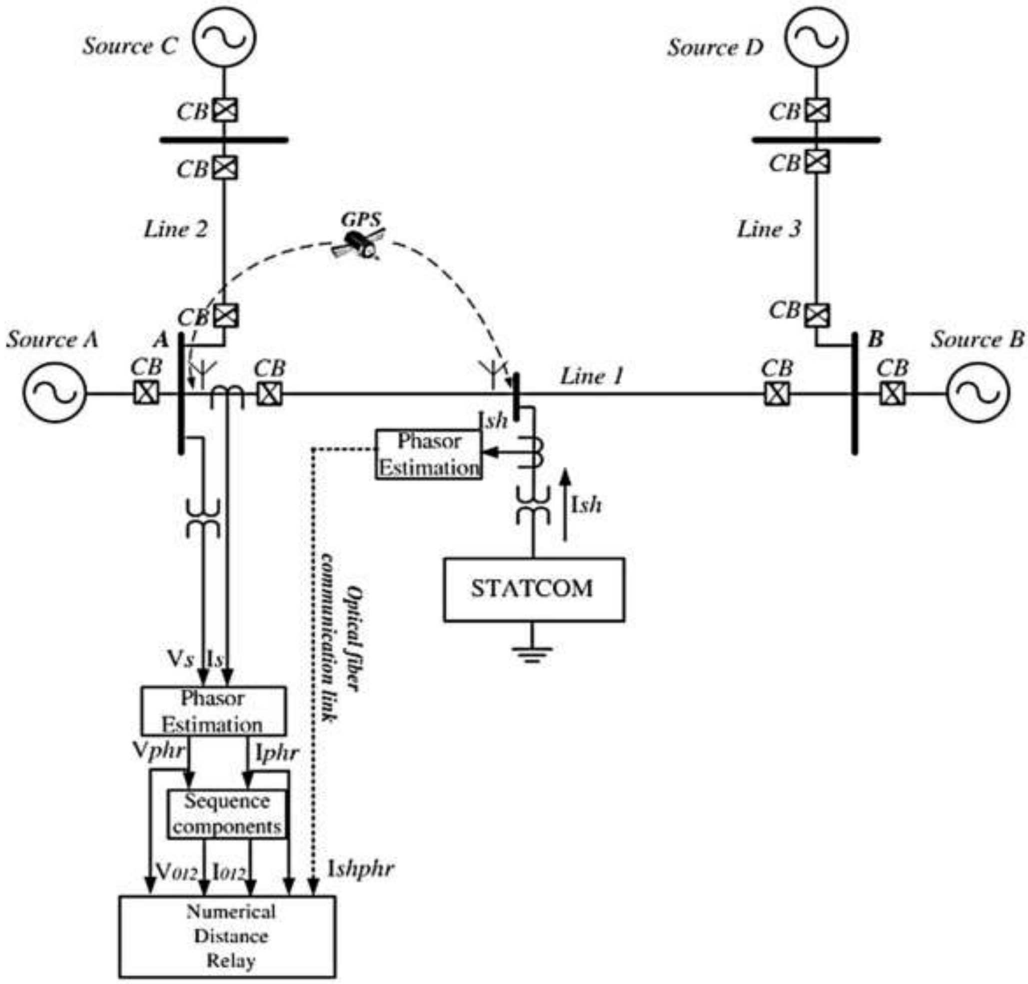

Fig. 4.7: Single line diagram of study system model

The main objective of this work is to adjust the algorithm for distance protection when STATCOM is present at the mid-point of the transmission line and take STATCOM's feedback on synchronized relay bus and STATCOM link point measurement. Synchronized GPS time-stamped measurement at both terminals is assumed with a high-speed optical fiber data transmission device that transmits (I_{sh}) information to the relaying bus without any communication delay, as shown in Fig. 4.7. Calculated apparent impedance is compared with distance relay first zone setting (Z_{set}) of relay to make the decision of trip or no trip for fault in the zone of protection. As, the information of shunt injected current (I_{sh}) is available at relaying bus, the new distance relay setting expression is required which adaptively defines the setting. The measured apparent impedance is compared with the distance relay first zone setting (Z_{set}) of the relay to determine whether to trip or not to trip for protection zone faults. Since the shunt injected current (I_{sh}) information is available on the relaying bus, the expression of the new distance relay setting that defines the setting adaptively is required.

Therefore, the apparent impedance calculated is equal to the distance relay setting, which is 80% of the line. With this new setting, the adaptive distance protection will check the calculated apparent impedance (Z_{app}) and take the trip decision when STATCOM is present at the mid-point transmission line.

Therefore, we can conclude that the primary zone setting formula of adaptive distance protection is adaptively adjusted to the existence of the shunt injected current, depending on the amount of compensation. The adaptive distance protection setting will change the first zone reach automatically, if STATCOM injects capacitive current (I_{sh}), which is positive and the adaptive zone is increased, while the inductive current (I_{sh}) will be negative and the adaptive zone is reduced.

4.3.1 Adaptive Distance Protection Modelling in PSCAD

Based on system parameters the new adaptive setting is obtained. The GPS synchronization is associated to the same time frame provided at two separate locations. Assuming a fiber-optic communication link and the measured shunt injected current (I_{sh}) information transferred at the relaying point. The adaptive setting function is used to dynamically obtained First Zone settings. The adaptive distance relay adaptively sets the first zone setting using the injected current shunt information and after comparing the apparent impedance estimated, it adjusts the setting parameter to adjust to the new compensation level as soon as there is some change in the STATCOM compensation level. When fault is on the line, the relay compares the measured apparent impedance with this setting to issues trip or no trip signal to circuit breaker.

4.3.2 Simulation Results

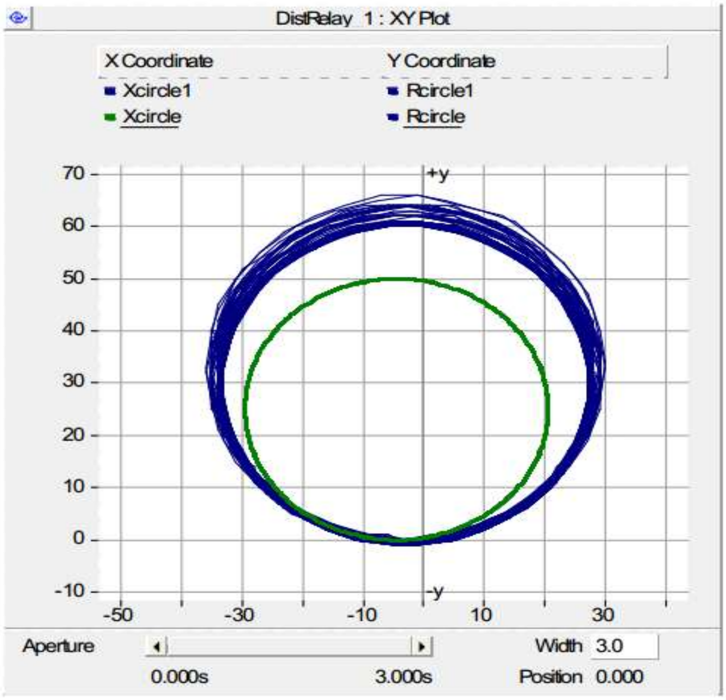

Fig.4.8: Adaptive distance protection mho relay characteristics with STATCOM supplying inductive reactive power of 100 MVAR into the system with forward power flow from A to B.

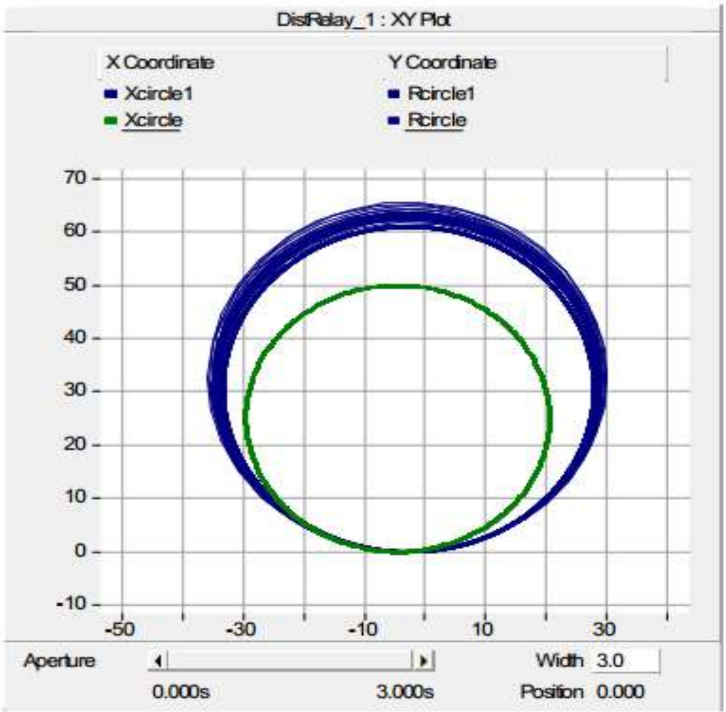

Fig.4.9: Adaptive distance protection mho relay characteristics with STATCOM supplying capacitive reactive power of 100 MVAR into the system with forward power flow from A to B.

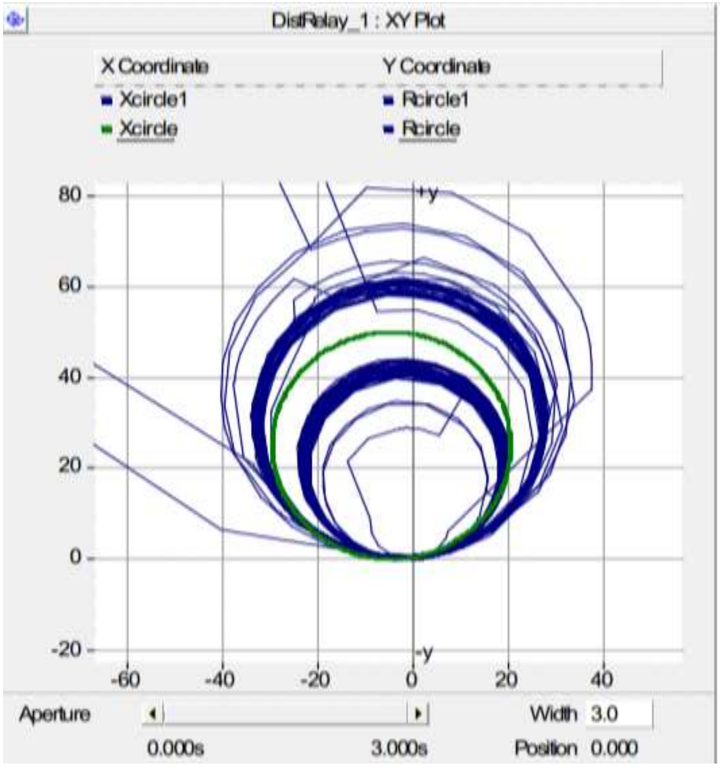

Fig.4.10: Adaptive distance protection mho relay characteristics with STATCOM supplying capacitive reactive power of 100 MVAR into the system with reverse power flow from B to A.

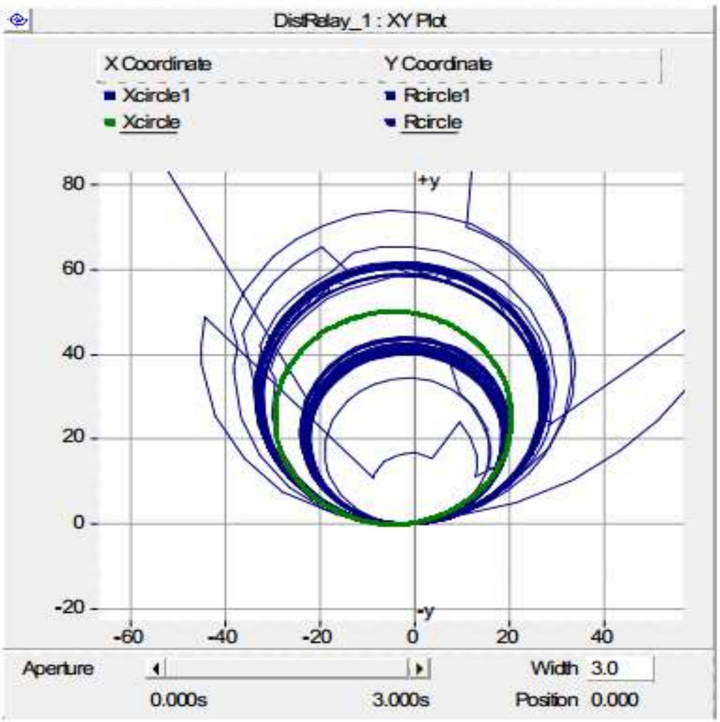

Fig.4.11: Adaptive distance protection mho relay characteristics with STATCOM supplying inductive reactive power of 100 MVAR into the system with reverse power flow from B to A.

The study method shown is modelled on PSCAD software to test the efficiency of the suggested adaptive distance protection. The mid-point STATCOM absorbs inductive reactive power, the relay bus voltage reduces. Therefore, apparent impedance seen by distance relay decreases, resulting in over-reach. The adaptive distance relay simulation with STATCOM absorbing inductive reactive power of 100 MVAR for forward power flow from A to B, the shunt current (I_{sha}) is noted to be zero prior to the implementation of STATCOM. As STATCOM is connected to the device at 0.1s and the inductive reactive power of 100 MVAR is absorbed, the setting factor x is adaptively reduced and set to the unit distance value taken to obtain the first zone's new adaptive setting. It is observed that the adaptive mho distance relay reach shown in blue color is reduced in comparison to the traditional setting shown in red color for inductive reactive power injection.

Compared to the standard operating voltage without STATCOM, the mid-point voltage rises when STATCOM injects capacitive reactive power into the network. As a consequence, relaying bus voltage is increased and the apparent impedance seen by distance relay increases, causing under-reach. The adaptive relay setting factor x obtained for the transmission of 100 MVAR capacitive reactive power into the system by STATCOM is shown in Fig. 4.9 for forward power flow. It is found that there is increase in setting factor with the implementation of STATCOM, it increases and settles adaptively. It is observed that adaptive mho relay reach is increased in comparison with traditional mho relay reach for capacitive reactive power injection. Similarly, as STATCOM injects inductive and capacitive reactive power into the system for reverse power flow from B to A, results obtained are shown in Fig. 4.10 and 4.11.

4.4 Adaptive Protection for Transmission Line in the Presence of UPFC

The voltage and current signals are transmitted to the SPC from buses and the active power is measured at both ends of the transmission line. Firstly, from measured active powers, fault resistance is obtained. UPFC parameters will then be estimated from the active and reactive powers in the compensated transmission line, and UPFC effects to fault estimation will be removed simultaneously. The goal of the proposed method is to remove the influence of UPFC on all types of faults.

4.4.1 Modelling of Power System with Relays or PMUs

In order to obtain the protection of transmission, bus data (voltage and current signals) will be sent to the SPC. In the SPC, the fault location will be identified and appropriate commands will be sent to the circuit breakers.

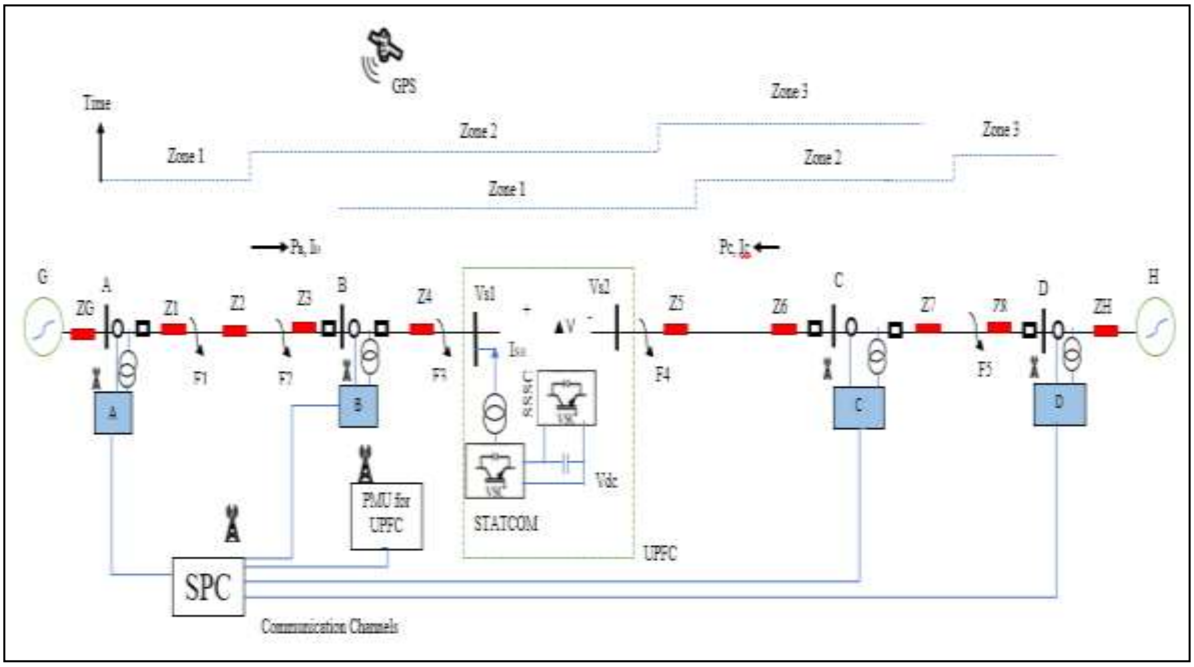

Fig.4.12: Single-line diagram of multi-line system with UPFC

The configuration is as follows: in buses A, B, C and D, PMUs are placed. For more information about how to calculate signals, see Fig. 4.12. When CT and VT calculated signals are filtered and then converted to phasor using the Full Cycle Discrete Fourier Transform (FCDFT) method and eventually using the Global Positioning System (GPS), they will be applied with time information. This data will be transmitted by optical fiber to SPC and synchronized by a phasor data concentrator (PDC). None of the relays recognize the faults due to the influence of UPFC. Relays have properly identified the faults in their respective positions in previous cases (without UPFC). The successful approach is to remove the effect of the UPFC on the performance of the relay. In the calculated impedance of relay, the maximum variations can be seen when the UPFC operates in full mode. In other words, UPFC has the most effect on apparent impedance when both the UPFC series and shunt converters are in the circuit.

4.4.2 Modified Distance Protection Scheme

In this paragraph, the assumption is that there is a PMU at the UPFC location and its data is sent to the SPC. For better monitoring of FACTS controllers, PMUs are used. In this application, data is normally sent to the communication channel control center. In this case, the UPFC injection voltage (ΔV) and current (I_{Sh}) are sent to the SPC. It should be noted that for its control, the two listed signals at the UPFC location will be used and no additional measurement is needed. In other words, these two signals of the UPFC controller are evaluated. From the received signals in the SPC, ΔZ_{Sh} and ΔZ_{Se} will be calculated (Fig. 4.13).

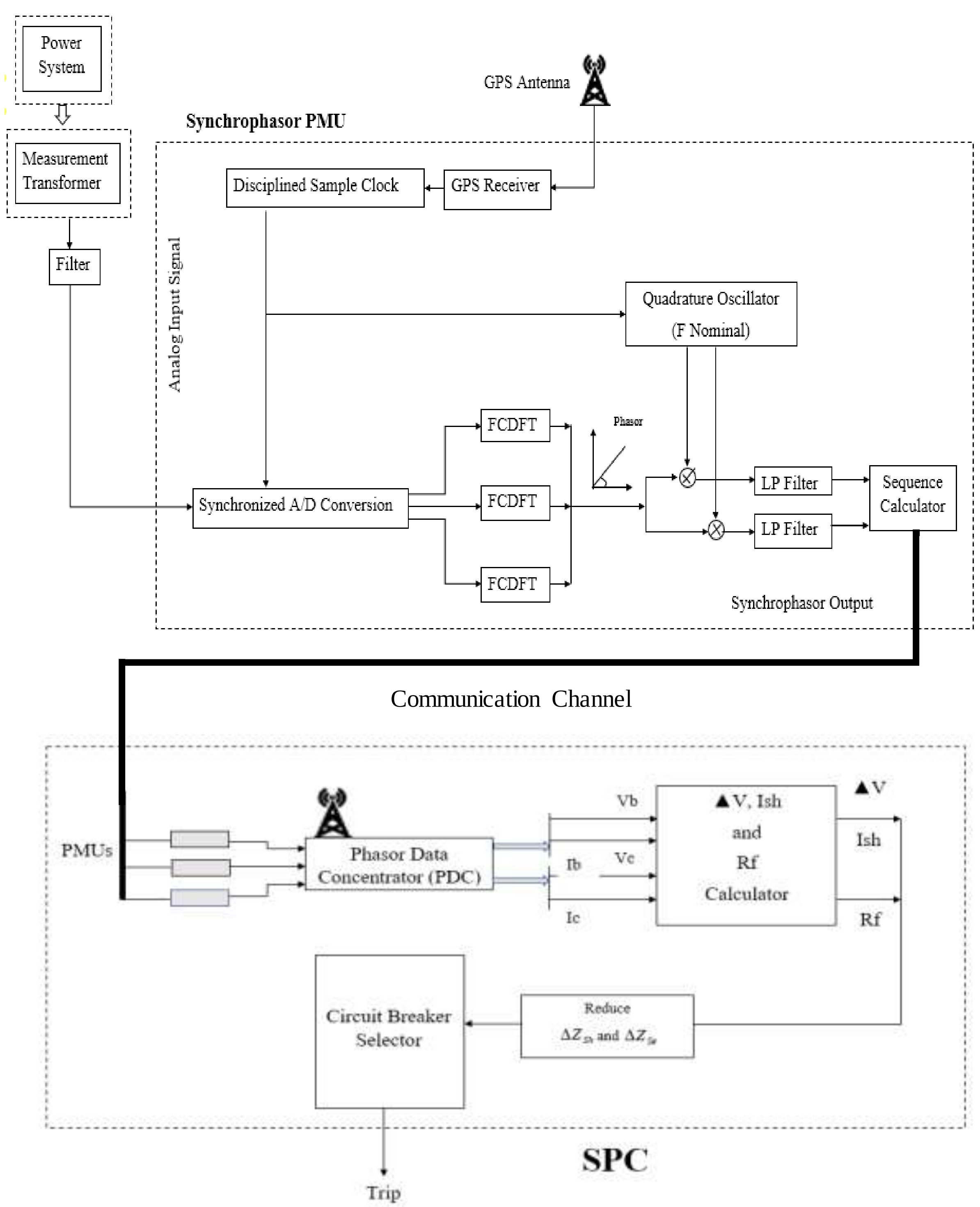

Fig.4.13: The main parts of the new modified method for distance relay

If a fault occurs in F1 and Zone-1 of the RA(relay near the A bus) or in F2 and Zone-2 of the RA, the fault resistance could be calculated as UPFC is not located in the fault loop in this situation and RA is working correctly. Suppose the fault occurred in F4 and UPFC is also located in both RA and RB relays in the fault loop. The presence of UPFC causes relays to under-reach and the F4 fault cannot be identified. ΔZ_{Sh} and ΔZ_{Se} are determined and reduced by the relays from the measured impedance in this condition. Then, appropriate command will be sent to circuit breakers regarding which zone the fault is located.

The main component of the signal is computed using FCDFT and other harmonics are removed by the DC filter circuit.

4.4.3 Response Time of Modified Distance Relay

The delay can be divided into two parts: the first part is directly linked to the estimation of the PMU and the fiber optic data transmission. This period is referred to as the delay caused by PMU, including the time for sampling and computation of the synchrophasor, the delay in transmitting data from PMU to PDC through communication channels and the amount of delay needed for PDC to synchronize PMU data. The second part of the delay is about the distance relay protection zones. Suppose, the distance relay has three zones of operation: Zone-1 without delay, Zone-2 with a delay of 0.5 s and Zone-3 with a delay of 1.0 s. In other words, the trip signal will be sent after the associated delay if the measured impedance is concentrated in each of the zones. In other words, the latest techniques suppress the mal-operation of the relay and the fault is correctly defined. As fibreoptic is used, the contrast with the traditional method and the adapted method would reduce the delay.

Chapter 5

Conclusion and Future Scope

5.1 Conclusion

A comprehensive analysis should be carried out if a new FACTS system is mounted. This will include details on the suitability of distance relaying and, if applicable, the type of scheme to be used and several necessary modifications. The simulation results illustrate the effect of UPFC on the distance relay when it is run as STATCOM and UPFC, respectively. The apparent impedance is affected by the reactive power injected/absorbed by the STATCOM when the UPFC is run as STATCOM, which results in the under-reach or over-reach of the distance relay. Importantly, when the full UPFC is in service, the influence on the efficiency of a distance relay is significantly higher compared to a device which only uses the STATCOM portion of the UPFC. The findings presented clearly demonstrate the fundamental challenges of securing a UPFC transmission device using distance protection.

Using shunt injected current data by SVC and STATCOM at the mid-point of the line, an adaptive distance protection setting scheme is presented in this work. The setting procedure of the adaptive distance protection zone 1 provides absolutely required data to adjust the zone range of the mho distance relay for various compensation levels. The adaptive distance protection setting factor is found to be lower for inductive reactive power compensation. Adaptive distance protection setting at capacitive reactive power compensation is increased. Comparing the adaptive scheme with the traditional technique, it is found that there is a substantial improvement in distance relay coverage area, and prevents malfunctioning of the distance relay with midpoint SVC and STATCOM. The results shows the suggested setting of the distance relay zones is adaptively improved and provides a very reliable decision on the relay trip. With knowledge of the transmission system and the operating modes of SVC and STATCOM, the proposed scheme is new and simple to configure. The first zone setting technique for adaptive distance protection offers crucial information to increase or decrease the zone reach of the mho distance relay for different levels of compensation.

In the presence of mid-point connected shunt FACTS device (SVC and STATCOM), the proposed adaptive distance protection setting algorithm using synchronized measurement on the relay bus provides a better solution for distance protection of the transmission line. Depending on the level and mode of compensation, this increases the distance relay performance and can be used to detect faults very effectively in the presence of STATCOM and SVC. The results of the simulation indicate the efficiency, reliability and robustness of the proposed algorithm for adaptive distance protection.

First, the fault resistance of UPFC site is obtained by measuring the active power at both ends of the transmission line in the presence of the PMU. Secondly, the injected voltage and current of the UPFC are determined using transmitted data and their effects are minimized by the calculated measured impedance of the relay. Since the proposed approach measures both the series and the shunt converter in the presence of the UPFC, the delay in transmitted signals can be compensated by reducing the delay in the protection zones. This compensates for the affect of the delay on the transmitted signals and increases the efficiency of the relay.

5.2 Future Scope

5.2.1 Performance Evaluation and Developing Adaptive Protection for the System having Interline Power Flow Controller (IPFC).

It acts like a capacitor when an IPFC injects reactive power into the transmission line and decreases the apparent impedance shown by the distance relay and may cause the distance relay to over-reach. It behaves like a series inductance if it absorbs reactive power, which in turn gives rise to the apparent impedance shown by the distance relay and thus a probability of under-reaching the relay. Presenting a new relay system to solve the phenomena of under-reaching is part of on-going work. For the mho distance relay for different levels of compensation, the adaptive distance protection first zone setting procedure can be created.

5.2.2 Performance Evaluation and Developing Adaptive Protection for the System having Interconnected VSC-HVDC System.

The affect of the presence in the AC grid of a multi-terminal VSC-HVDC system leading to lack of coordination in the distance relay protection zones. The analysis implies that under fault conditions, the impedance perceived by the distance relay is influenced by a change in either the reference AC voltage of the VSC or the change in the active power reference. Hence, designing an adaptive protection device which will operate on various Vacref and thus, the reactive power supply or monitoring the P_{ref} of the VSC may be one of the options to correct the mal-operation of distance relays.

5.2.3 Performance Evaluation and Developing Adaptive Protection for the System having Power Injection from the Multiple Renewable Energy Sources.

Via high-voltage outgoing transmission lines, large-scale renewable energy sources are normally linked to the AC grid so that massive power capacity can be transported from the windy or light-rich regions to the load centers. The operating state of the power system has no effect on the sensitivity of the distance protection for the traditional ac grid; hence, distance protection is commonly used in complex high-voltage power grids. Renewable energy sources, however, are typically linked to the AC grid through converters whose fault characteristics are affected by control strategies. Due to the different characteristics between renewable energy generators and synchronous generators, the requirement for renewable energy systems cannot be satisfied by traditional protection based on the fault characteristics of synchronous generators. Therefore, with renewable energy generators, the adaptability of distance protection needs to be increased.

5.2.4 Performance Evaluation and Developing Adaptive Protection for the System having Distributed Generation

The addition of DG can result in a loss of protection sensitivity and coordination with out-of-zone fault tripping. In overcoming these problems, distance relays should have operating features that can be reshaped and should respond to the changing conditions of the system.

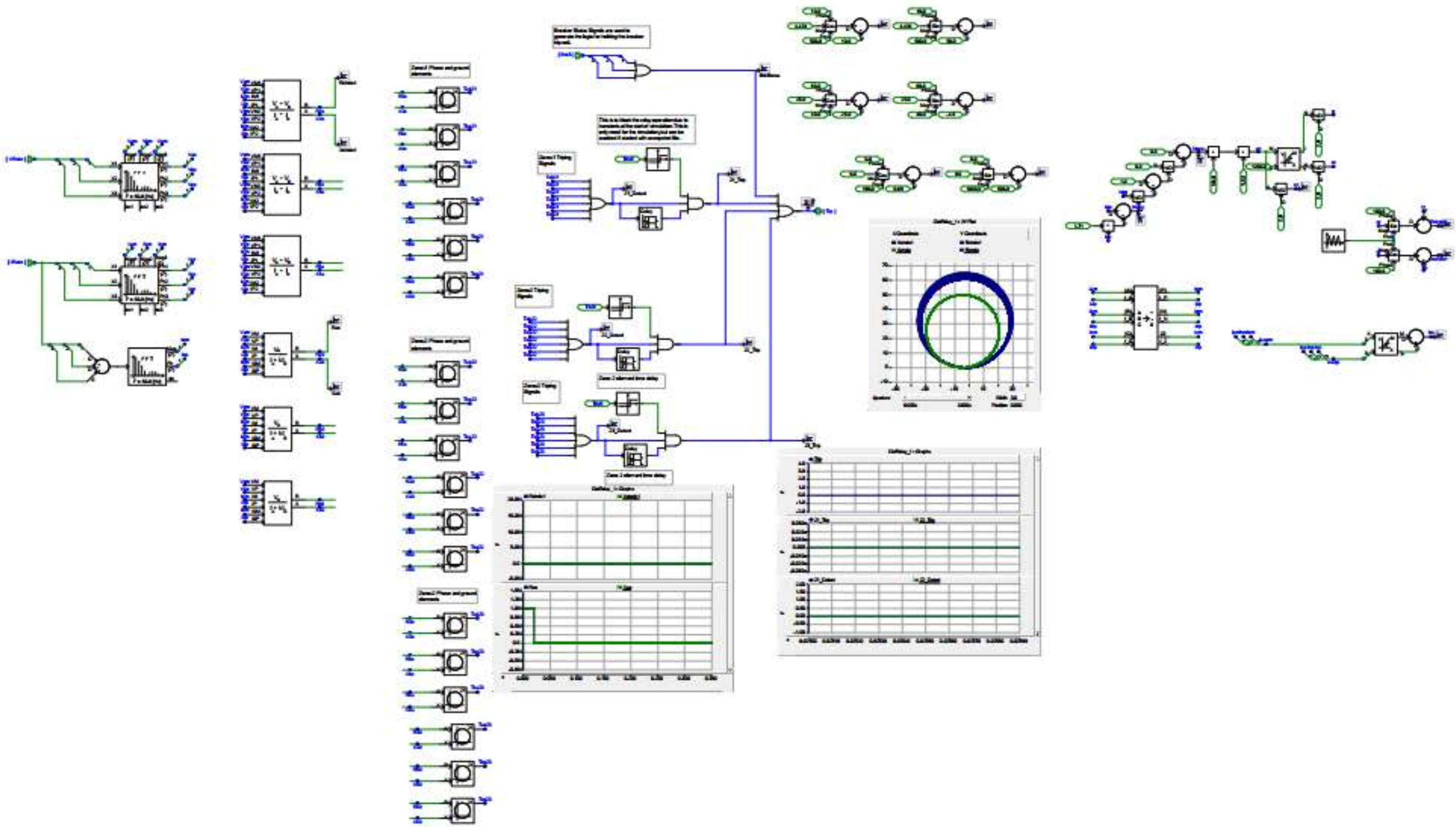

Figure: Workspace for Adaptive mho relay second zone characteristics with STATCOM supplying inductive reactive power of 100 MVAR into the system with forward power flow.

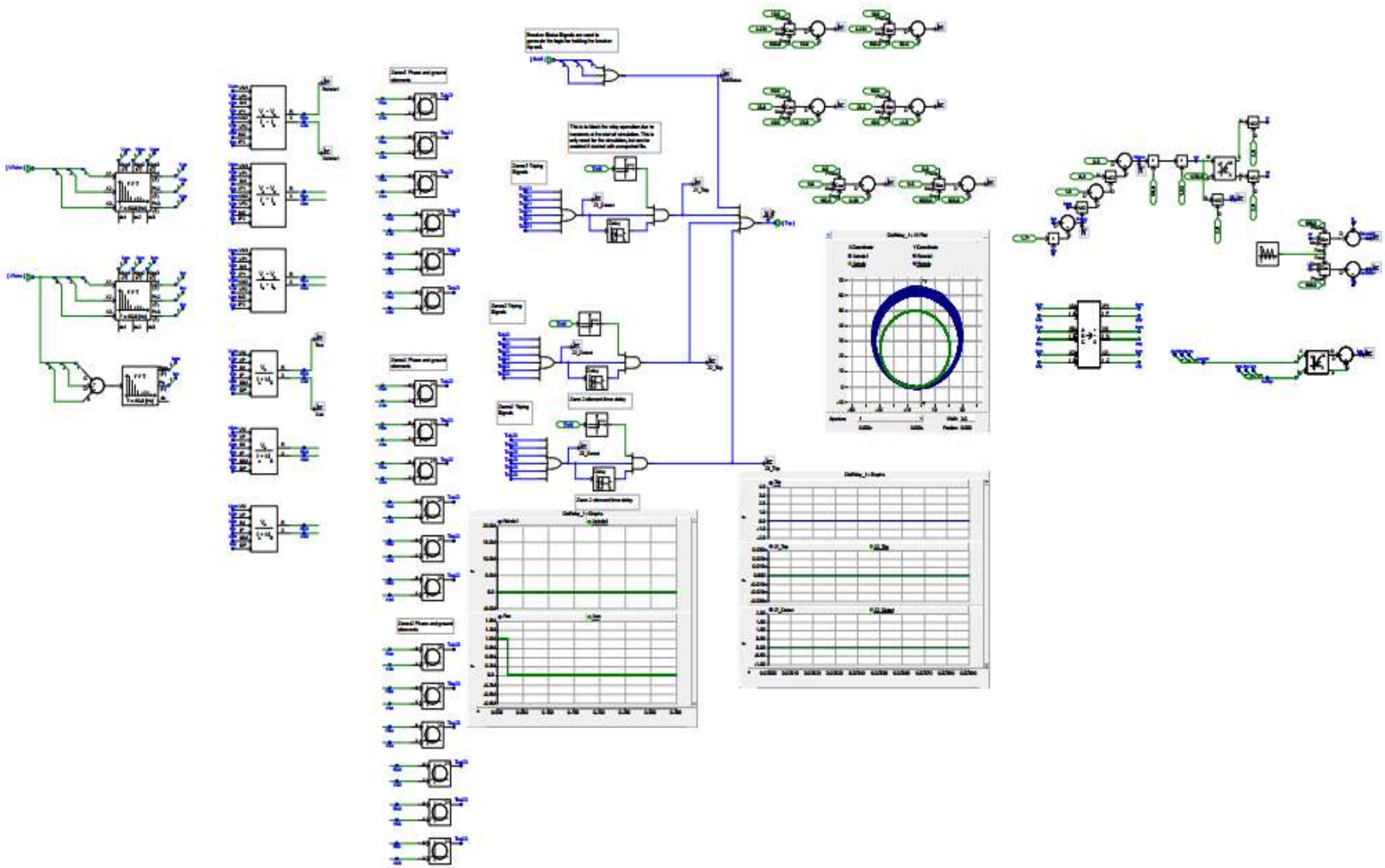

Figure: Workspace for Adaptive mho relay second zone characteristics with STATCOM supplying capacitive reactive power of 100 MVAR into the system with forward power flow.

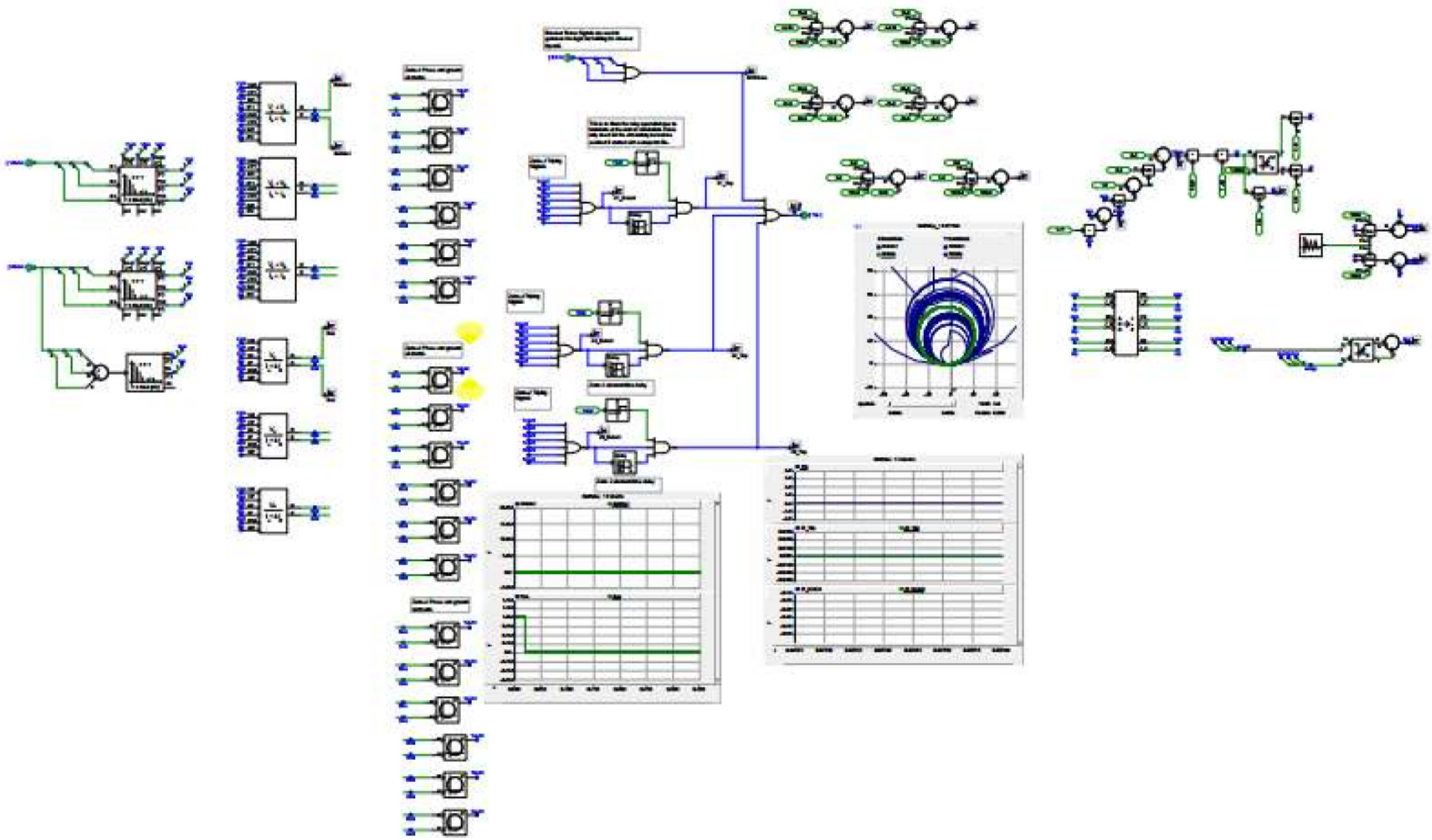

Figure: Workspace for Adaptive mho relay second zone characteristics with STATCOM supplying capacitive reactive power of 100 MVAR into the system with reverse power flow.

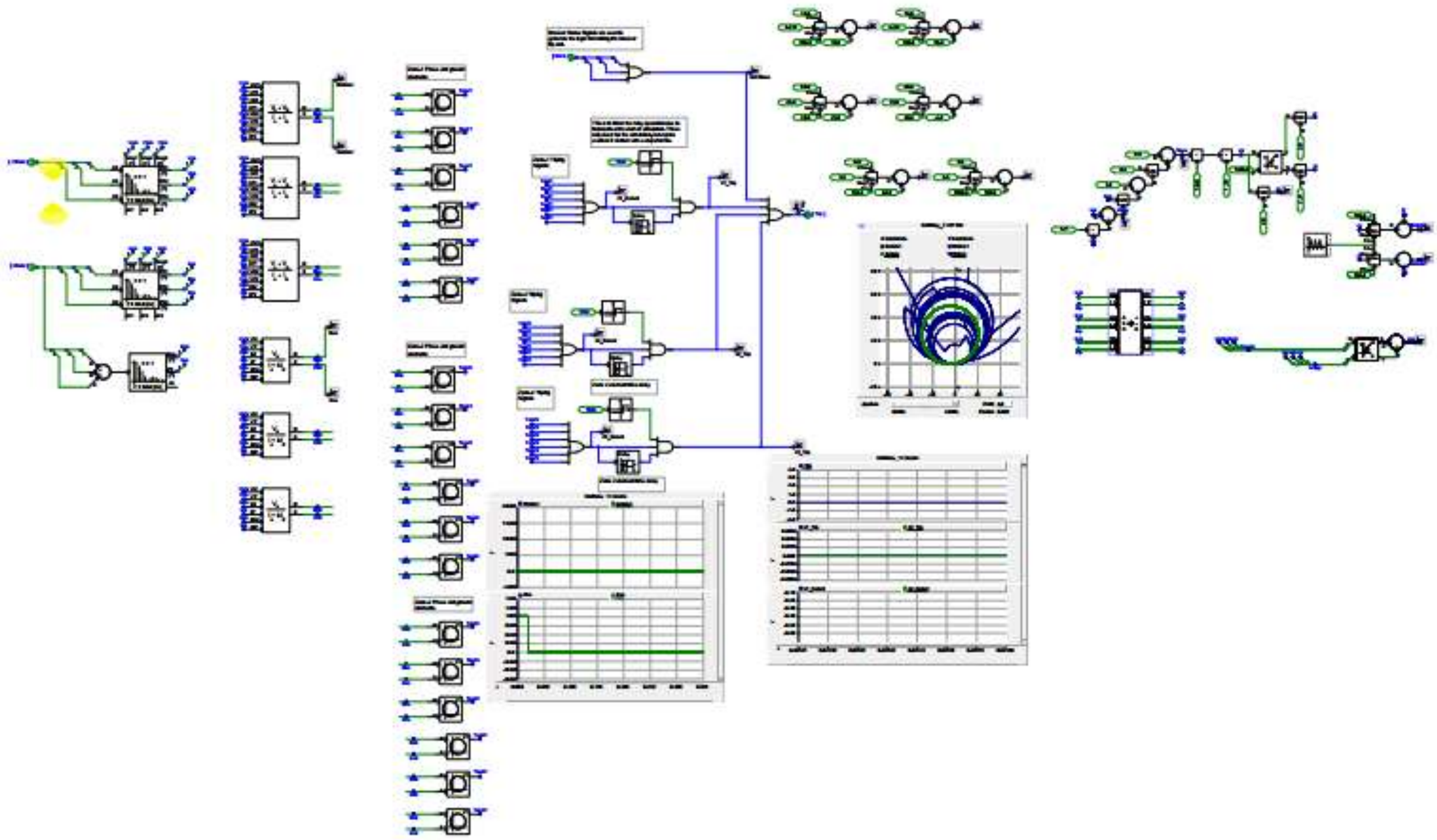

Figure: Workspace for Adaptive mho relay second zone characteristics with STATCOM supplying inductive reactive power of 100 MVAR into the system with reverse power flow.

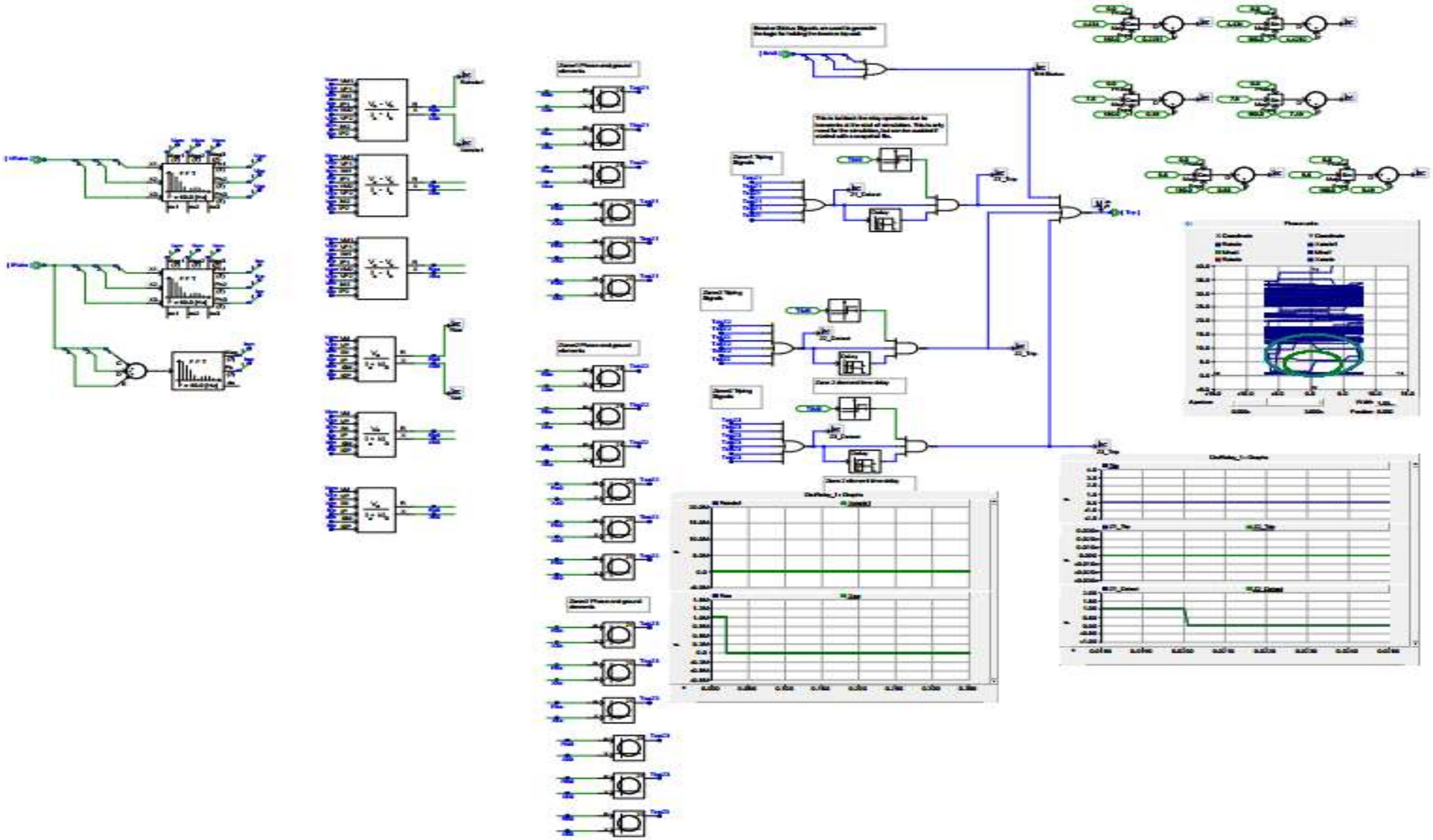

Figure: Workspace for Adaptive mho relay third zone characteristics with SVC supplying capacitive reactive power of 100 MVAR into the system with forward power flow.

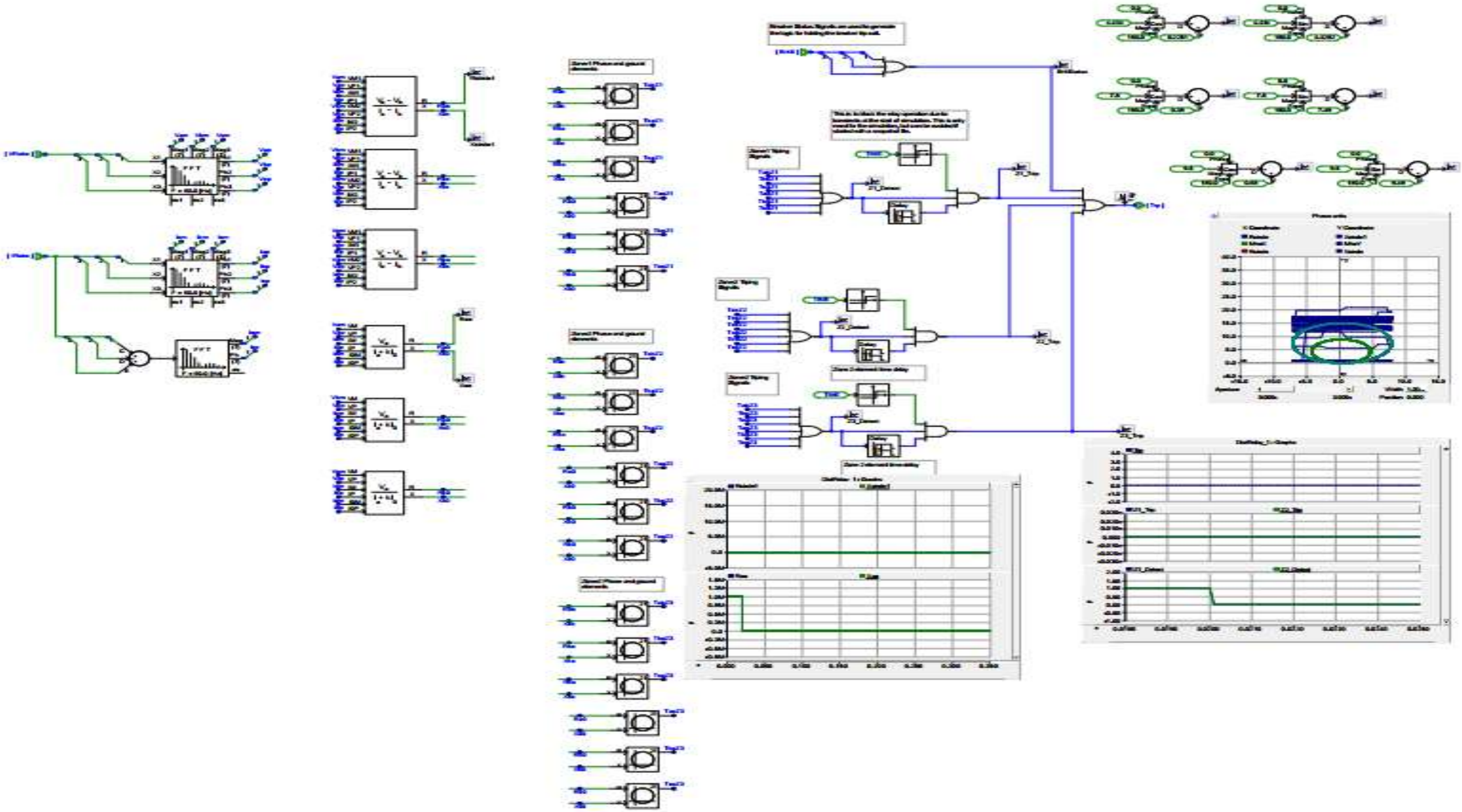

Figure: Workspace for Adaptive mho relay third zone characteristics with SVC supplying inductive reactive power of 100 MVAR into the system with forward power flow.

APPENDIX I

System Data

Transmission lines (I, II & III). Line lengths = 300 km.

Positive seq. impedance = $0.51/85.92°\Omega$ km.

Zero seq. impedance = $1.385/74.68°\Omega$ km.

Equivalent sources (1,2,3 & 4):

Power rating = 100 MVA.

System voltage = 230 kV.

System frequency = 60 Hz.

Positive seq. impedance = $25.9/80.0°$

Zero seq. impedance = $25.9/80.0°$

FACTS Device:

a) SVC:

Interfacing transformer = 3 winding (Y/y/d).

Transformer ratio = 230/11/11 kV.

Transformer rating = 200 MVA.

Transformer impedance = 0.1 pu.

SVC capacitive rating = 167 MVA.

SVC inductive rating = 100 MVA.

b) STATCOM:

Interfacing transformer =3 winding (Y/y/d).

Transformer ratio = 230/11/11 kV.

Transformer rating = 100 MVA.

Transformer impedance = 0.1 pu.

STATCOM rating 100 MVA.

(inductive & capacitive).

APPENDIX II

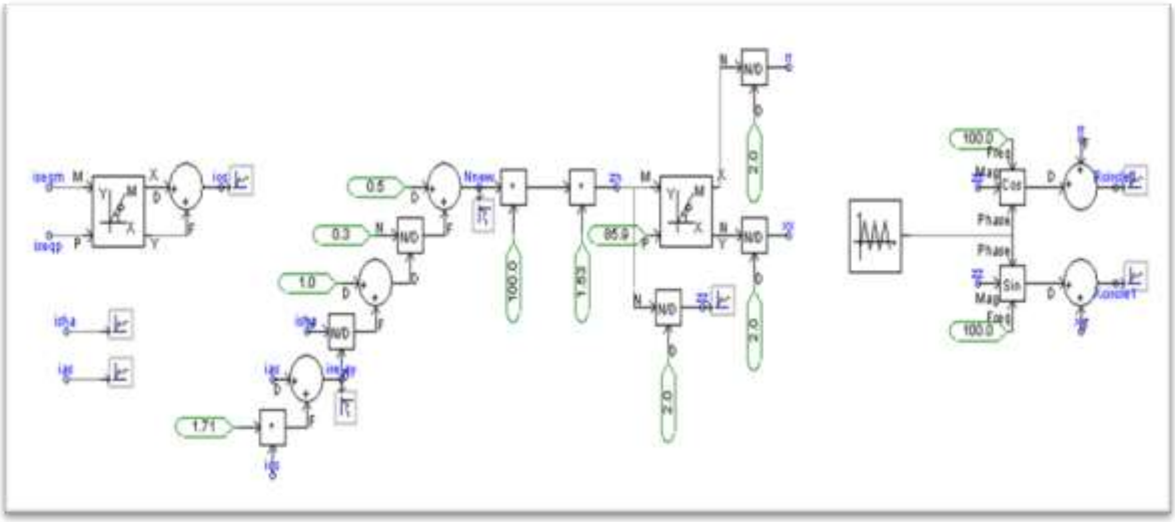

Figure: Modelling of Adaptive Distance Protection in PSCAD

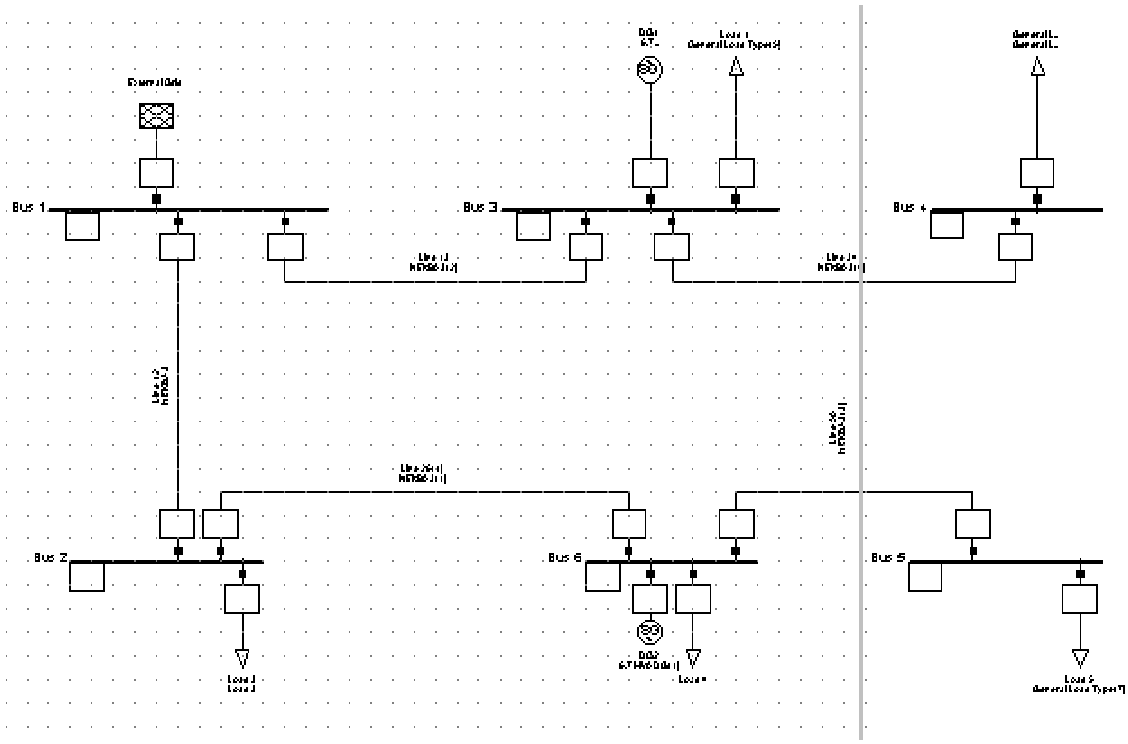

Figure: 6 Bus System Designed in DlgSILENT Power Factory Software 15.1

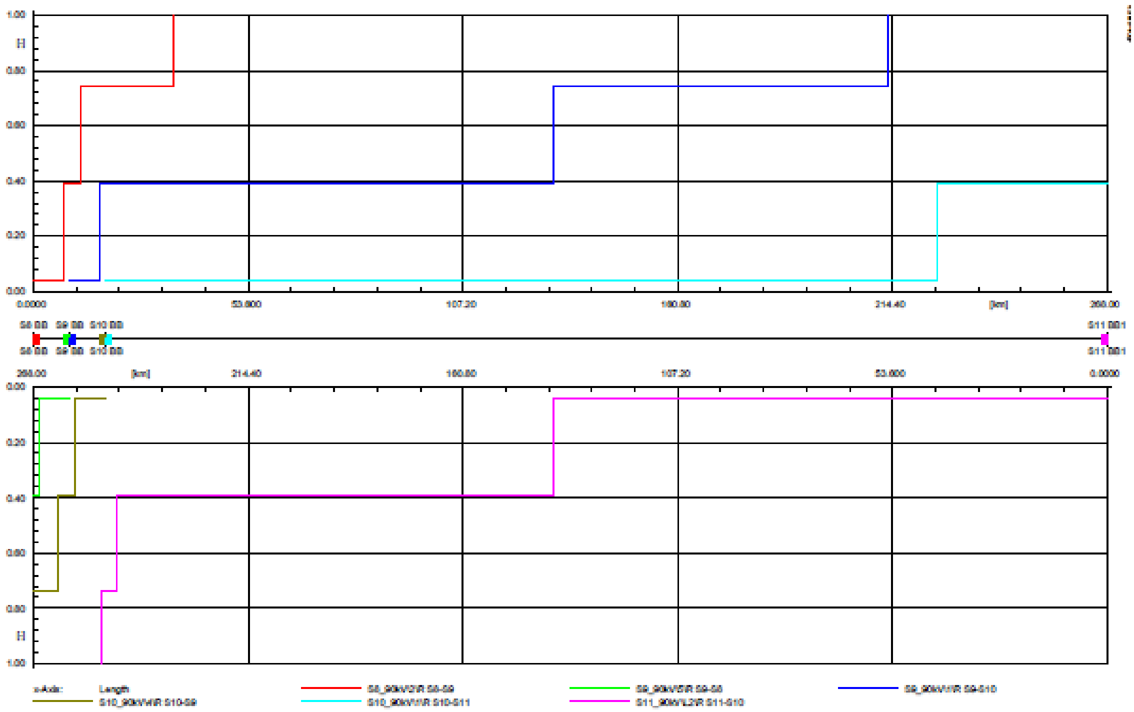

Figure: Result of Distance Relay Operation for Three Zone Protection, Zone 1 = 80km (red), Zone 2 =120km (blue), Zone 3= 180km(violet) in DIgSILENT PowerFactory Software.

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PUBLICATIONS

International Conference:

[1] **Pawan Kumar Saha**, Dr. Purobi Patowary, Enhancement of Power System Reliable Operation Using an Adaptive Protection Strategy", *Online International Conference on "Smart Modernistic in Electronics and Communication"-2022, PAPER ID: ICSMEC22-0099, ISBN: 978-81- 953918-6-8.*

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