

# **CHAPTER ONE**

## **INTRODUCTION**

### **1.1 General Concepts**

Now days the demand for power has increased gradually but due to limitations in resources the generation and transmission has some restrictions. Due to these shortcomings in generation and transmission, some grid networks are heavily loaded and some minimally loaded which results in limitations for the power transfer capacity and ultimately the system stability. In order to overcome these shortcomings FACTS (Flexible AC Transmission Systems) controllers are deployed. These FACTS controllers contribute and improve the transmitting capacity of the long transmission line and provide maximum power at relatively higher efficiency.

STATCOM (Static Synchronous Compensator) is one of the key FACTS Controllers. It can be based on a voltage sourced converter (VSC) or current-sourced converter (CSC). STATCOM is capable of generating and /or absorbing reactive power whose output can be varied so as to maintain control of specific parameters of electrical power system. On transmission level, Systems are normally balanced, but during fault condition system get disturbed. Because of the presence of STATCOM devices in a fault loop, the voltage and current signals at relay point will be affected in both steady and transient state. This impact will affect the performance of existing protection methods, such as distance relay. Apart from power system components and their controlling

parameters as well as their installations points on transmission line affect the measured impedance.

Distance protection is based on the measurement of the impedance of lines. Distance relays are used as protection device for transmission line.

## **1.2 Problem Statement**

The added complexity due to the interaction of FACTS devices with the transmission system, the transients superimposed on the power frequency voltage and current waveforms particularly at the occurrence of fault can be significantly different from those systems not connected FACTS devices and it will result in rapid changes in system parameters like line impedance.

## **1.3 Objectives**

The main objective is to study and explore the impact of STATCOM employed in a transmission system on the Performance of distance relay at both normal operation and fault conditions.

## **1.4 Methodology**

The operation principles of distance relay and STATCOM is studied and a simulation with MATLAB/SIMULINK model is analyzed in order to achieve these objectives.

## **1.5 Project Layout**

This project contains of five chapters. The first chapter is general introduction, problem statement, objectives, methodology and the layout of the project. The second chapter is a review of the protection method and the VAR compensator. The third chapter is the mathematical model of the STATCOM and the distance relay. The fourth chapter is the simulation model and the discussions of the results. The last chapter is the conclusion and recommendations.

# CHAPTER TWO

## DISTANCE RELAY AND VAR COMPENSATION

### 2.1 Introduction

The measured impedance at the point that relay is connected is the basis in distance protection. There are some parameters influencing the measured impedance at the relaying point. Some of these parameters are related to power system parameters before fault instance and some of them are related to the kind of fault and the fault impedance. The first parameters (system parameters) can be divided into two groups; first is called structural conditions (such as short circuit level) and second is called operational condition (load angle and voltage magnitude ratio at the line ends). As mentioned above, fault resistance can greatly affect the measured impedance by distance relay. When fault impedance is zero, the effect of power system parameters is negligible and when the fault impedance increases, the effect of power system parameters becomes more and more. In some cases the application of FACTS devices has been increased. For instance, increase in transmission capacity and optimal operation of power systems capability. But it is known that the effect of FACTS devices on power system dynamics is really high. Because of these changes in power system dynamics, many sub-systems like protective system's dynamics will change. Therefore it is important to study the effect of FACTS devices on protective devices; in this project we have studied the effect of STATCOM on distance relay as an example. [1]

## **2.2 Distance Relay**

Distance relays are primarily used to protect power system transmission lines. One of their functions is to discriminate between faults that are within the protected line and those that are not. Hence a distance protection relay must be able to determine if the fault location is in the forward direction looking into the protected line or in the reverse direction. Once it has determined the fault is in the forward direction it then has to decide if the fault lies within the line it is protecting. [2]

### **2.2.1 Zones of Protection**

Distance relays are normally set for protection in terms of the zones of protection. Distance relays have Zone 1, Zone 2, Zone 3, and Zone 4. Each zone has settable timers. Zone 1 is normally set to protect 80% of the protected line in the forward direction, while the remaining 20% is to account for the accuracies of the current and voltage transformers feeding the distance relay. This 20% is covered under the distance schemes which will aid the tripping faster in zone 1 time. Normally zone1 is set to provide the output trip command to the breaker instantaneous. Zone 2 is set to cover for 100% of the protected section in the forward direction plus 50% of the adjacent forward section. Zone 2 tripping time is co-ordinate with the circuit breaker failure protection. Zone 3 is set to cover 200% of the protected line length in the forward direction. Zone-3 can also be set to provide an output tripping after a time delay which is larger than the tripping times of Zone2 and Zone1. Zone 3 can also be set to cover for close up 3 phase faults during closure of breaker. This is termed as Zone3 Offset Mho characteristics Zone4 is the reverse looking zone that is set in the distance relay which is normally set to trip for faults behind the protected line section. This zone is typically set for 25% of Zone1 in the reverse direction. Zone4 also is set

to issue a trip output command after a set time delay. Normally a distance relay will issue a trip command if the particular zone element has operated and also when the respective phase is selected.

A distance protection relay is designed to operate only for fault incidents between the relay location and selected reach capability (balance point or tripping threshold) and remains stable for faults outside its operating region or zone. Besides that, it contains phase-to-phase and phase-to earth elements that will respond to phase-to-phase or phase-to-ground faults in its operating area. A distance relay is normally employed in a transmission system to detect different types of faults on the transmission line. One of the techniques used in distance relaying is based on calculated impedance seen by the relay using the measured voltage and measured current. In simplistic terms, the distance relay calculates an apparent impedance using:

$$Z_{calc} = \frac{V_{meas}}{I_{meas}} \quad (2.1)$$

Where  $V_{meas}$  is the measured voltage at the relaying point and  $I_{meas}$  is the measured current at the relaying point. The calculated impedance  $Z_{calc}$  is then compared against a set value  $Z_{set}$ . The relay will trip if:  $Z_{calc} < Z_{set}$ . [2]

### **2.2.2 Impedance Diagram**

An impedance diagram is an important tool for evaluation of the behavior of distance protection. In this diagram, impedances are represented as points in a two-dimensional x-y plane where x is the resistive part of the impedance (R) and y is the reactive part of the impedance (Y). For this reason it is commonly referred to as the R-X plane. Within this R-X plane the protected line, the relay characteristic and the load characteristic can be plotted.

By using a complex R-X plane, it is easy to understand how the relay operates and the operation of the relay with the presence of system faults can be analyzed.

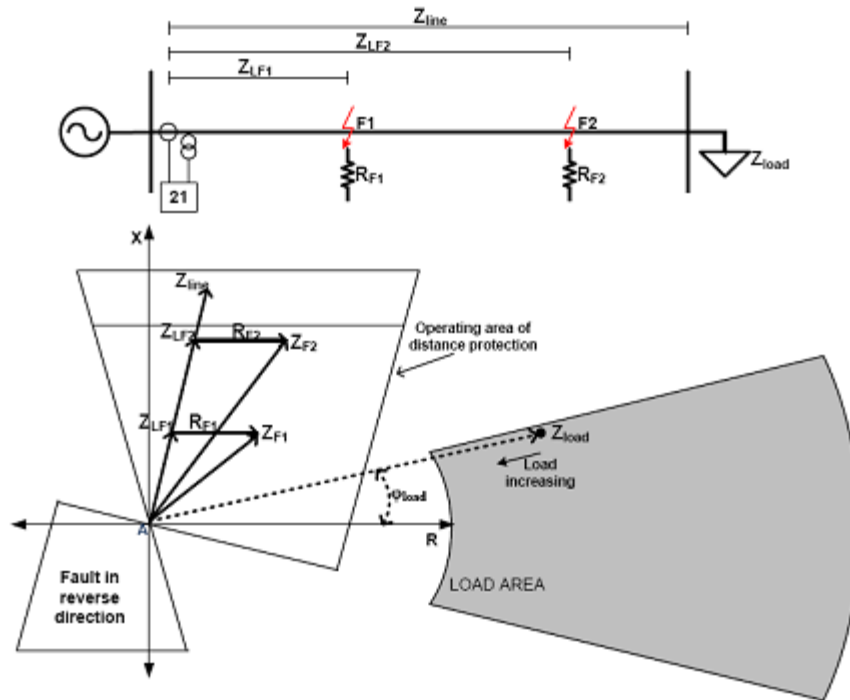


Figure 2.1: Impedance measurements drawn on R-X Plane

The power system one-line diagram shows: The distance relay location, the impedance of the protected line ( $Z$  line), two possible fault locations at F1 and F2.

$Z_{LF1}$ - Impedance of the line from the relaying point to the fault point F1

$Z_{LF2}$ - Impedance of the line from the relaying point to the fault point F2

$R_{F1}$  – Resistance of the fault at fault point F1

$R_{F2}$  – Resistance of the fault at fault point F2

$Z_{F1} = Z_{LF1} + R_{F1}$  – Impedance of the fault at Fault point F1

$Z_{F2} = Z_{LF2} + R_{F2}$  – Impedance of the fault at Fault point F2. [2]

## **2.3 VAR Compensation**

VAR compensation is defined as the management of reactive power to improve the performance of ac power systems. The concept of VAR compensation embraces a wide and diverse field of both system and customer problems, especially related with power quality issues, since most of power quality problems can be attenuated or solved with an adequate control of reactive power. [3]

### **2.3.1 Reactive Power Compensation Principles**

In a linear circuit, the reactive power is defined as the ac component of the instantaneous power, with a frequency equal to 100 / 120 Hz in a 50 or 60 Hz system. The reactive power generated by the ac power source is stored in a capacitor or a reactor during a quarter of a cycle, and in the next quarter cycle is sent back to the power source. In other words, the reactive power oscillates between the ac source and the capacitor or reactor, and also between them, at a frequency equals to two times the rated value (50 or 60 Hz). For this reason it can be compensated using VAR generators, avoiding its circulation between the load (inductive or capacitive) and the source, and therefore improving voltage stability of the power system. Reactive power compensation can be implemented with VAR generators connected in parallel or in series. [3]

### **2.3.2 Shunt Compensation**

Figure 2.2 shows the principles and theoretical effects of shunt reactive power compensation in a basic ac system, which comprises a source  $V_1$ , a power line and a typical inductive load. Figure 2.2(a) shows the system without compensation, and its associated phasor diagram. In the phasor diagram, the phase angle of the current has been related to the load side, which means that the

active current  $I_p$  is in phase with the load voltage  $V_2$ . Since the load is assumed inductive, it requires reactive power for proper operation and hence, the source must supply it, increasing the current from the generator and through power lines. If reactive power is supplied near the load, the line current can be reduced or minimized, reducing power losses and improving voltage regulation at the load terminals. This can be done in three ways: a) with a capacitor, b) with a voltage source, or c) with a current source. In Fig. 2.2(b) a current source device is being used to compensate the reactive component of the load current ( $I_Q$ ). As a result, the system voltage regulation is improved and the reactive current component from the source is reduced or almost eliminated.

If the load needs leading compensation, then an inductor would be required. Also a current source or a voltage source can be used for inductive shunt compensation. The main advantages of using voltage or current source VAR generators (instead of inductors or capacitors) is that the reactive power generated is independent of the voltage at the point of connection.

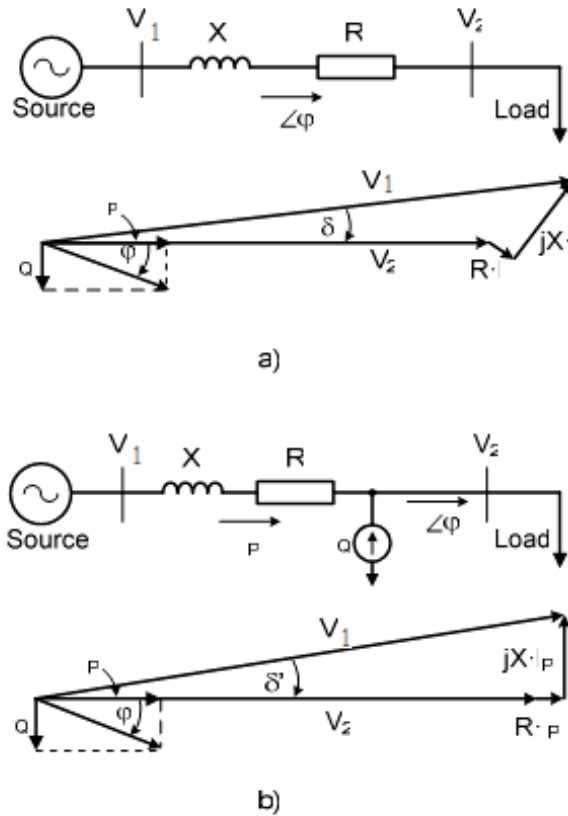


Figure 2.2: Principles of shunt compensation in a radial ac system.

a) Without reactive compensation.

b) Shunt compensation with a current source.

The shunt connected controllers are: Static Synchronous Compensator (STATCOM), Static Synchronous Generator (SSG), Battery Energy Storage System (BESS), Superconducting Magnetic Energy Storage (SMES), Static VAR Compensator (SVC), Thyristor Controlled Reactor (ICR), Thyristor Switched Reactor (TSR), Thyristor Switched Capacitor (TSC), Static VAR Generator or Absorber (SVG), Static VAR System (SYS), Thyristor Controlled Braking Resistor (TCBR). [3][8]

### 2.3.3 Series Compensation

VAR compensation can also be of the series type. Typical series compensation systems use capacitors to decrease the equivalent reactance of a power line at rated frequency. The connection of a series capacitor generates reactive power that, in a self-regulated manner, balances a fraction of the line's transfer reactance. The result is improved functionality of the power transmission system through:

- i) Increased angular stability of the power corridor.
- ii) Improved voltage stability of the corridor.
- iii) Optimized power sharing between parallel circuits.

Like shunt compensation, series compensation may also be implemented with current or voltage source devices, as shown in Figure 2.3. Figure 2.3(a) shows the same power system of figure 2.2(a), also with the reference angle in  $V_2$  and Figure 2.3(b) the results obtained with the series compensation through a voltage source, which has been adjusted again to have unity power factor operation at  $V_2$ . However, the compensation strategy is different when compared with shunt compensation. In this case, voltage  $V_{COMP}$  has been added between the line and the load to change the angle of  $V_2$ , which is now the voltage at the load side. With the appropriate magnitude adjustment of  $V_{COMP}$ , unity power factor can again be reached at  $V_2$ . As can be seen from the phasor diagram of Figure 2.3(b),  $V_{COMP}$  generates a voltage with opposite direction to the voltage drop in the line inductance because it lags the current  $I_p$ .

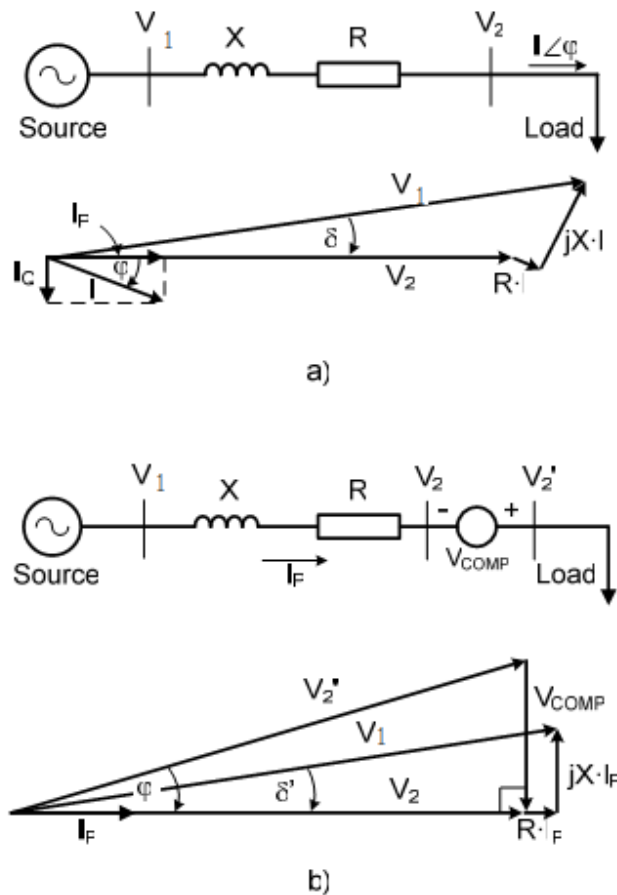


Figure 2.3: Principles of series compensation.

a) The same system of figure 2.2(a) without compensation.

b) Series compensation with a voltage source.

The series connected controllers are: Static Synchronous Series Compensator (SSSC), Interline Power Flow Controller (IPFC), Thyristor Controlled Series Capacitor (TCSC), Thyristor-Switched Series Capacitor (TSSC), Thyristor-Controlled Series Reactor (TCSR), Thyristor-Switched Series Reactor (TSSR). [3][8]

### **2.3.4 Combined Shunt and Series Connected Controllers**

Examples of this type of compensation: Unified Power Flow Controller (UPFC), Thyristor-Controlled Phase Shifting Transformer (TCPST), Interphase Power Controller (IPC). [3]

### **2.4 STATCOM**

One of the many devices under the FACTS family, a STATCOM is a regulating device which can be used to regulate the flow of reactive power in the system independent of other system parameters. STATCOM has no long term energy support on the dc side and it cannot exchange real power with the ac system. In the transmission systems, STATCOM primarily handle only fundamental reactive power exchange and provide voltage support to buses by modulating bus voltages during dynamic disturbances in order to provide better transient characteristics, improve the transient stability margins and to damp out the system oscillations due to these disturbances.

A STATCOM consists of a three phase inverter (generally a PWM inverter) using SCRs, MOSFETs or IGBTs, a DC capacitor which provides the DC voltage for the inverter, a link reactor which links the inverter output to the AC supply side, filter components to filter out the high frequency components due to the PWM inverter. From the DC side capacitor, a three phase voltage is generated by the inverter. This is synchronized with the a.c supply. The link inductor links this voltage to the AC supply side. This is the basic principle of operation of STATCOM.

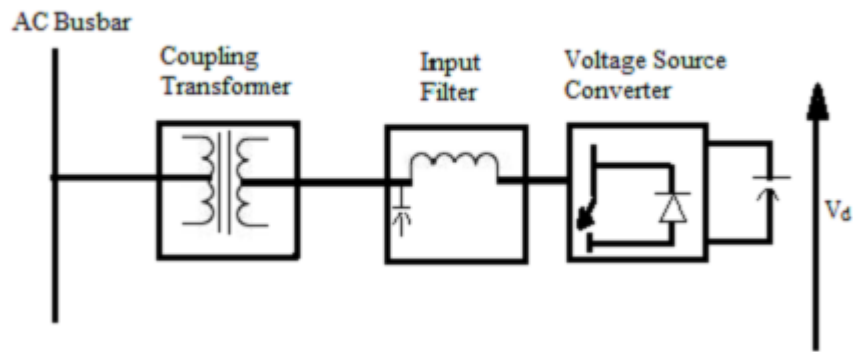


Figure 2.4: Static Synchronous Compensator (STATCOM)

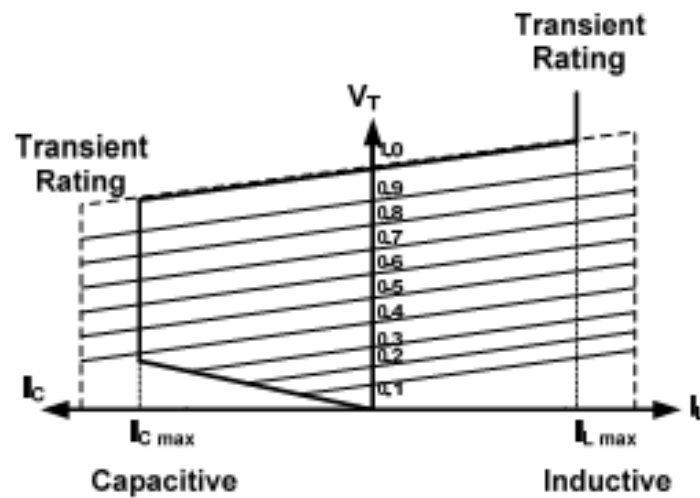


Figure 2.5: V-I characteristic of STATCOM

For two AC sources which have the same frequency and are connected through a series inductance, the active power flows from the leading source to the lagging source and the reactive power flows from the higher voltage magnitude source to the lower voltage magnitude source. The phase angle difference between the sources determines the active power flow and the voltage magnitude difference

between the sources determines the reactive power flow. Thus, a STATCOM can be used to regulate the reactive power flow by changing the magnitude of the VSC voltage with respect to source bus voltage. [2][8]

## **2.5 Effect of STATCOM on Distance Relay Protection**

The basic principles of distance relay protection is based on dividing the voltage at the relaying point by the measured current. The apparent impedance is compared with the reach point impedance to decide wither the fault is internal or external. The relay calculates the apparent impedances of the fault loops which then are compared against impedance limits that are determined by the relay settings. The reactive power injected by STATCOM into power system cause significant changes in magnitude of the current flowing in the transmission line and hence affects the calculated impendence seen by the relay.

The measured current at beginning of the line decreases when STATCOM injects current into the system and increases when STATCOM draws current from the system. The distance relay operation is affected when shunt FACTS devices is installed, for example a fault at point in transmission line without STATCOM will activate the distance relay, while the same fault when STATCOM is insulated will not activate the relay.

The error in apparent impedance is due to the shunt-FACTS and proportional to the fault location and the ratio of the current in the shunt FACTS device and the relay. The distance relay will see higher impedance when the STATCOM injects reactive power into system, and this leads to under reach condition. While the relay will see smaller impedance when the STATCOM absorbs reactive power from the system, in this case the relay considering fault at a closer location than the actual fault location and results in over reach condition. [5]

# **CHAPTER THREE**

## **MATHEMATICAL MODELLING**

### **3.1 Introduction**

This chapter presents the mathematical model of a three phase static VAR compensator (STATCOM) that uses a pulse width modulated (PWM) VSC connected to a dc capacitor, and the mathematical model of distance relay when the faults is occurred in the transmission line and STATCOM presented in the transmission line, the effect of STATCOM on distance relay is described, the computations of measured impedance in faults also are described.

### **3.2 Mathematical Modeling of STATCOM**

Static compensators or inverter circuit are mostly designed for voltage support of three phase balanced system. On transmission level, systems are normally balanced, but it is not the case during fault conditions of the distribution system. In three phase balanced system STATCOM produce a set of balanced reactive currents so that instantaneous power flow in STATCOM or from STATCOM is always zero.

Physically, compensator based on a three phase inverter circuit interconnects all the phases of thee phase ac system, providing full path for the exchange of reactive power between them. This type of exchange is disturbed during unbalanced operation of the ac system. In this case each phase of the inverter must provide unequal voltage. If PWM strategy of the control is used, it is possible to change phase voltages by changing control signals and keeping dc voltage constant.

The value of dc reference voltage will determine the rating of the inverter and inverter will always draw some active power from the ac system to cover for its losses and keep the dc bus voltage constant.

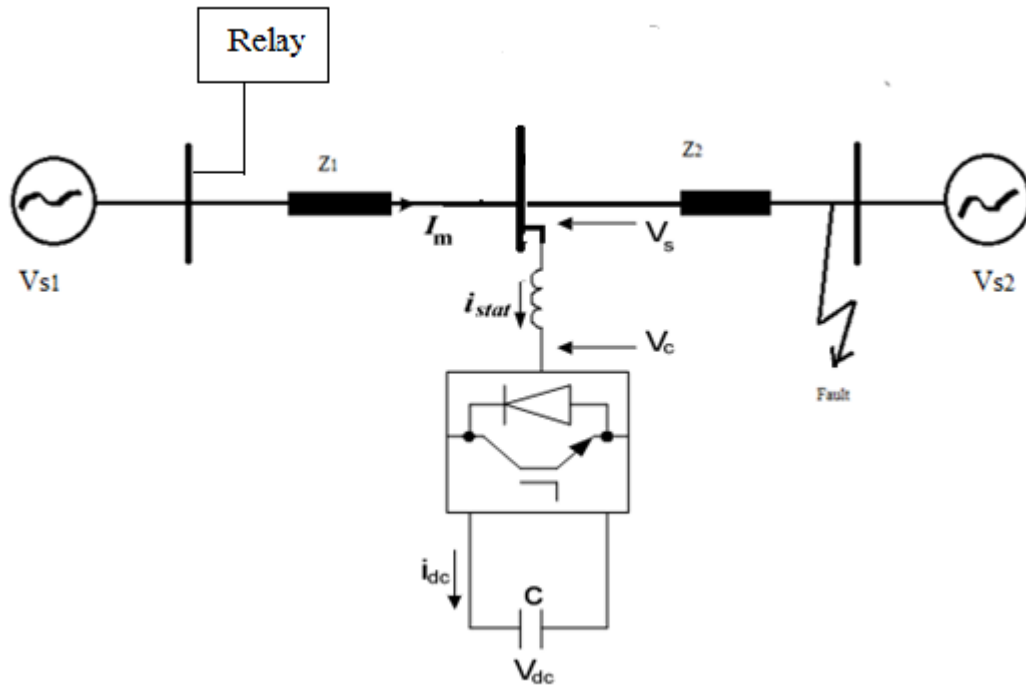


Figure 3.1: Typical transmission line system

The STATCOM is assumed to operate within its reactive power rating to maintain the voltage at its location under all operating conditions.

The schematic diagram of a STATCOM is shown in Figure 3.1. The reactive power and power are flow between the VSC converter and the ac net work can be expressed as:

$$Q = \frac{V_c V_s \cos(\delta_c - \delta_s)}{X_t} - \frac{V_c^2}{X_t} \quad (3.1)$$

$$P = \frac{V_c V_s \sin(\delta_c - \delta_s)}{X_t} \quad (3.2)$$

where,  $V_c$ ,  $V_s$ ,  $\delta_c$  and  $\delta_s$  are converter voltage, the point of common coupling voltage, converter voltage phase angle and the point of common coupling voltage angle phase respectively and  $X_t$  is the leakage inductance of the coupling transformer. The reactive power exchange between the converter and the AC system can be controlled by varying the amplitude of converter voltage ( $V_c$ ) according to:

1. If  $V_c > V_s$  then a lagging current results and the STATCOM acts as an inductor consumer.
2. If the amplitudes are equal no reactive power exchange takes place.
3. If  $V_c < V_s$  then a leading current results and the STATCOM acts as a capacitor supplier.

The main advantage of STATCOM compared to ordinary static VAR compensator (SVC) and its ability to provide more capacitive reactive power during faults, or when the system voltage drops abnormally is shown in V-I characteristic in Figure 3.2.

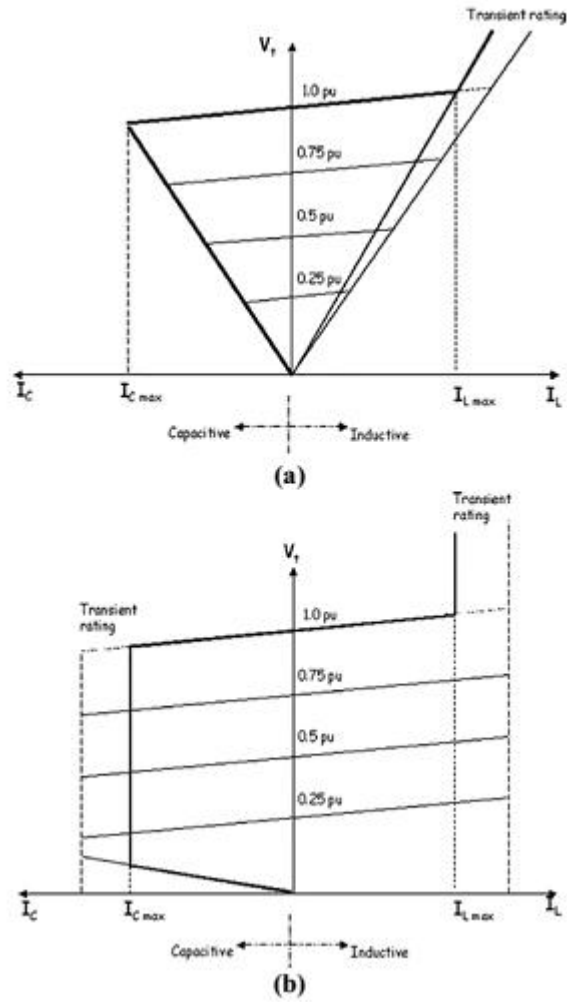


Figure 3.2: V-I characteristic (a) of the SVC (b) of STATCOM

The STATCOM can provide full capacitive output current at any system voltage, practically down to zero. [6]

### 3.2.1 Mathematical Model For VSC Control System

According to mathematical model of STATCOM, the dynamic model of 6-pulse STATCOM in Fig.3 can be described as equation (3.3)

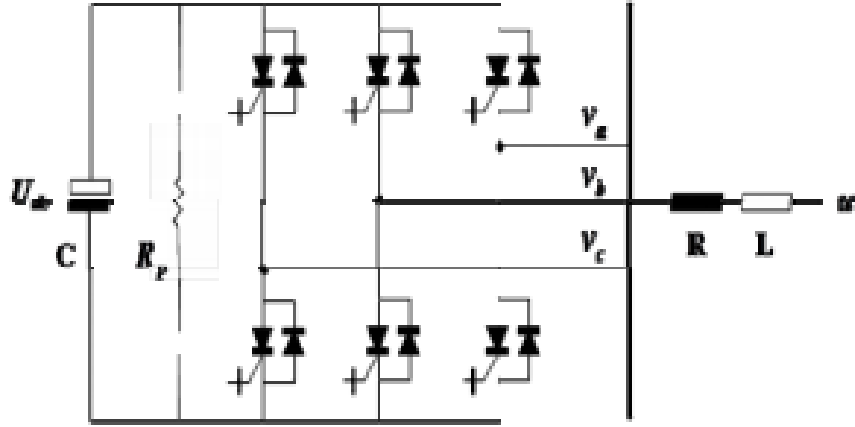


Figure 3.3: Basis circuit of two-level 6 pulse STATCOM

$$L \frac{di_{abc}}{dt} + Ri_{abc} = u_{abc} - v_{abc} \quad (3.3)$$

The three phase voltage equations can be rewritten as following:

$$L \frac{di_a}{dt} + Ri_a = u_a - v_a \quad (3.4)$$

$$L \frac{di_b}{dt} + Ri_b = u_b - v_b \quad (3.5)$$

$$L \frac{di_c}{dt} + Ri_c = u_c - v_c \quad (3.6)$$

Equations (3.4, 3.5, and 3.6) can be transformed to synchronously rotating reference frame using the Park's transformation, as in (3.7)

$$f_{dq}^e = T(\theta) f_{abc} \quad (3.7)$$

Where  $T(\theta)$  is the matrix of converting three-phase ABC frame into the synchronous reference frame involved with the d and q components when it is not considered the zero components.

$$T(\theta) = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2}{3}\pi) & \cos(\theta + \frac{2}{3}\pi) \\ -\sin \theta & -\sin(\theta - \frac{2}{3}\pi) & -\sin(\theta + \frac{2}{3}\pi) \end{bmatrix} \quad (3.8)$$

The voltage equations from three phase ABC frame are transformed to synchronously rotating reference frame by multiplying them with the converting matrix  $T(\theta)$ .

$$T(\theta) u_{abc} = L T(\theta) \frac{di_{abc}}{dt} + R T(\theta) i_{abc} + T(\theta) v_{abc} \quad (3.9)$$

Substituting (3.7) into (3.9) and rearrange, the voltage equations can be described as:

$$u_{dq}^e = L T(\theta) \frac{d(T^{-1}(\theta) i_{dq}^e)}{dt} + R i_{dq}^e + v_{dq}^e \quad (3.10)$$

Using chain rule and the result of  $T(\theta) \frac{d}{dt} T^{-1}(\theta)$  voltage equation for real part in d-axis and for imaginary part in q-axis are:

$$u_d^e = L \frac{di_d^e}{dt} + Ri_d^e + v_d^e - \omega Li_q^e \quad (3.11)$$

$$u_q^e = L \frac{di_q^e}{dt} + Ri_q^e + v_q^e + \omega Li_d^e \quad (3.12)$$

Where  $\omega$  is system frequency. The magnitude of converter voltage can be proportional to the DC voltage across the capacitor; the relationships for d q axis can be described as:

$$v_d = mu_{dc} \cos(\delta) \quad (3.13)$$

$$v_q = mu_{dc} \sin(\delta) \quad (3.14)$$

Where m is coefficient related to the type of converter. It means the ratio of DC voltage and magnitude to phase voltage at converter. The power balance equation of the converter is:

$$P = u_{dc} i_{dc} = u_{dc} C \frac{du_{dc}}{dt} = \frac{3}{2} (v_d i_d + v_q i_q) \quad (3.15)$$

Using equations (3.13, 3.14) and (3.15), the dc current is

$$i_{dc} = \frac{3}{2} m (i_d \cos \delta - i_q \sin \delta) \quad (3.16)$$

Equation (3.11), (3.12) and (3.26) form a state equation for STATCOM

$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \\ u_{dc} \end{bmatrix} = \begin{pmatrix} -\frac{1}{T_1} & \omega & -\frac{m}{L} \cos \delta \\ -\omega & -\frac{1}{T_1} & \frac{m}{L} \sin \delta \\ \frac{3m}{2C} \cos \delta & -\frac{3m}{2C} \sin \delta & -\frac{1}{T_2} \end{pmatrix} \begin{bmatrix} i_d \\ i_q \\ u_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix} \quad (3.17)$$

Where  $T_1 = \frac{L}{R}$ ,  $T_2 = R_p C$

Using linearization of equation (3.17) around the operating firing angle and neglecting the second and higher order terms, a set of linear equations as expressed as in (3.18). [6]

$$\frac{d}{dt} \begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta u_{dc} \end{bmatrix} = \begin{pmatrix} -\frac{1}{T_1} & \omega & -\frac{m}{L} \cos \delta \\ -\omega & -\frac{1}{T_1} & \frac{m}{L} \sin \delta \\ \frac{3m}{2C} \cos \delta & -\frac{3m}{2C} \sin \delta & -\frac{1}{T_2} \end{pmatrix} \begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta u_{dc} \end{bmatrix} + \begin{pmatrix} \frac{1}{L} & 0 & \frac{m}{L} \sin \delta u_{dc0} \\ 0 & \frac{1}{L} & \frac{m}{L} \cos \delta u_{dc0} \\ 0 & 0 & -\frac{3m}{2C} (\sin \delta_0 i_{d0} + \cos \delta_0 i_{q0}) \end{pmatrix} \begin{bmatrix} \Delta u_d \\ \Delta u_q \\ \Delta \delta \end{bmatrix} \quad (3.18)$$

### 3.3 Mathematical Modeling Of A Relay

For the analysis associated with the operation of a distance relay, the power system shown in figure 3.4 is used, the relay is installed on the right side of Bus S. The apparent impedance calculation is based on symmetrical component transformation using power frequency components of voltage and current signals measured at relay point.

When a single phase to ground fault occurs at the right side of STATCOM and the distance is  $n \cdot L$  from the relay point, the positive, negative and zero sequence networks of the system during the fault can be shown as shown in figure 3.4.

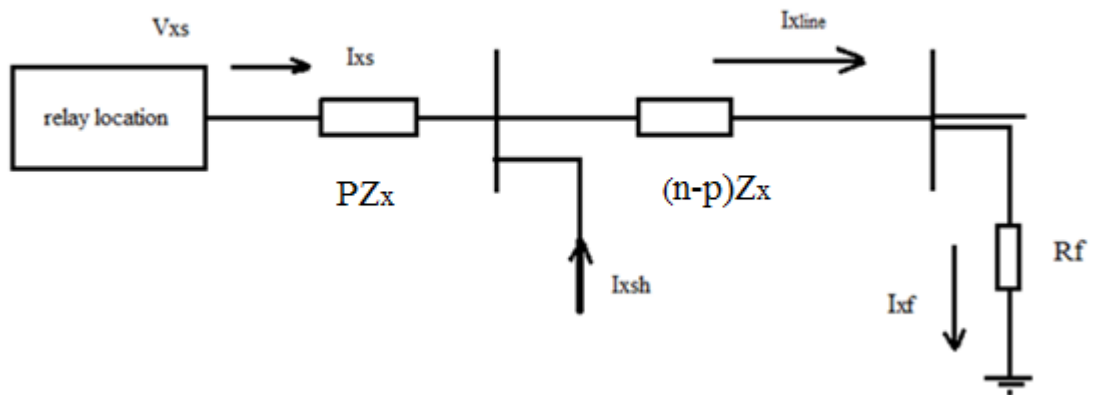


Figure 3.4: The sequence network of single phase fault

The same circuit will be considered for positive, negative and zero sequence networks. For the positive sequence network the notation 'x' equals to 1, for negative sequence network it will be '2', and for zero sequence network it is equal to '0'. Using these notations for the three sequence networks the following equations are obtained.

The sequence voltages at the relay point can be expressed as follows:

$$V_{1s} = I_{1s} pZ_1 + I_{1LINE} (n-p) Z_1 + R_f I_{1f} \quad (3.19)$$

$$V_{2s} = I_{2s} p Z_1 + I_{2LINE} (n-p) Z_1 + R_f I_{2f} \quad (3.20)$$

$$V_{0s} = I_{0s} p Z_1 + I_{0LINE} (n-p) Z_0 + R_f I_{0f} \quad (3.21)$$

$$I_{1LINE} = I_{1s} + I_{1sh} \quad (3.22)$$

$$I_{2LINE} = I_{2s} + I_{2sh} \quad (3.23)$$

$$I_{0LINE} = I_{0s} + I_{0sh} \quad (3.24)$$

where  $V_{1s}$ ,  $V_{2s}$  and  $V_{0s}$  are the sequence phase voltages at the relay location,  $I_{1s}$ ,  $I_{2s}$  and  $I_{0s}$  are the sequence phase currents at the relay location,  $I_{1line}$ ,  $I_{2line}$  and  $I_{0line}$  are the sequence phase currents in the transmission line,  $I_{1f}$ ,  $I_{2f}$  and  $I_{0f}$  are the sequence phase currents in the fault,  $I_{1sh}$ ,  $I_{2sh}$  and  $I_{0sh}$  are the shunt sequence phase currents injected by STATCOM,  $Z_1$  and  $Z_0$  are the sequence impedance of the transmission line, 'p' is the per unit distance of relay location, 'n' is the per unit distance of a fault from the relay location.

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

$$V_s = n I_s Z_1 + n I_{0s} (Z_0 - Z_1) + I_{sh} (n-p) Z_1 + (n-p) I_{sh0} (Z_0 - Z_1) + I_f R_f \quad (3.25)$$

Where

$$V_s = V_{1s} + V_{2s} + V_{0s} \quad (3.26)$$

$$I_s = I_{1s} + I_{2s} + I_{0s} \quad (3.27)$$

$$I_{sh} = I_{1sh} + I_{2sh} + I_{0sh} \quad (3.28)$$

Single phase to ground fault, the apparent impedance of distance relay can be calculated using the equation below:

$$Z = V_R / (I_R + ((Z_0 - Z_1) / Z_1) * I_{R0}) = V_R / I_{\text{relay}} \quad (3.29)$$

Where  $V_R$ ,  $I_R$  phase voltage and current at relay point  $I_{R0}$  zero sequence phase current  $I_{\text{relay}}$  The relaying current If this traditional distance relay is applied to the transmission system with STATCOM, the apparent impedance seen by this relay can be expressed as:

$$Z = n Z_1 + (I_{sh} / I_{\text{relay}}) (n-p) Z_1 + (I_f / I_{\text{relay}}) R_f \quad (3.30)$$

It is clear from equation (3.30) that if only a solid single phase to ground fault is considered, the equation becomes:

$$Z = n Z_1 + (I_{sh} / I_{\text{relay}}) (n-p) Z_1 \quad (3.31)$$

The impact of STATCOM on the apparent impedance calculation for an impedance relay in a transmission line can be obtained using these equations. [7]

### 3.4 Mathematical Review For The Effect Of STATCOM On Distance Relay

The reactive power injected by STATCOM into power system cause significant changes in magnitude of the current flowing in the transmission line and hence affects the calculated impedance seen by the relay. The current ( $I_m$ ) which is seen by the distance relay located at the beginning of the transmission line is defined as:

$$I_m = I_{\text{statcom}} + I_L \quad (3.32)$$

Where,  $I_m$  is current from generation side,  $I_L$  load side current and  $I_{\text{statcom}}$  is STATCOM current.

According to (3.32) the measured current at beginning of the line decreases when STATCOM injects current into the system and increases when STATCOM draws current from the system. The distance relay operation is affected when shunt FACT devices is installed, for example a fault at point in transmission line without STATCOM will activate the distance relay, while the same fault when STATCOM is insulated will not activate the relay. The error in the apparent impedance introduced as a result of the STATCOM and the fault resistance in phase to ground and phase to phase faults are given as:

$$Z = \frac{V_{XG}}{I_X + \frac{Z_0 - Z_1}{Z_1} I_{res}} + Z_{error} = \frac{V_{XG}}{I_X + KI_{res}} + Z_{error} \quad (3.33)$$

$$\begin{aligned} Z &= \frac{V_{AG} - V_{BG}}{I_A - I_B} + Z_{error} = \frac{V_{AG} - V_{CG}}{I_A - I_C} + Z_{error} \\ &= \frac{V_{CG} - V_{AG}}{I_C - I_A} + Z_{error} \end{aligned} \quad (3.34)$$

Where  $K = (Z_0 - Z_1)/Z_1$  and  $Z_{error}$  is the error measured impedance when the STATCOM is connected. The error in apparent impedance is due to the shunt-FACTS and proportional to the fault location and the ratio of the current in the shunt FACTS device and the relay. The distance relay will see higher impedance when the STATCOM injects reactive power into system, and this leads to under reach condition. While the relay will see smaller impedance when the STATCOM absorbs reactive power from the system, in this case the relay considering fault at a closer location than the actual fault location and results in over reach condition. [5]

# CHAPTER FOUR

## SIMULATION AND RESULTS

### 4.1 Introduction

With the updated versions of MATLAB/SIMULINK, the model development of power system components is onward to perfection. The excellent advantages that MATLAB has make MATLAB/SIMULINK a convenient and interactive tool for both numerous analysis and simulation.

### 4.2 System Lay-Out

The power grid consist of two synchronous machines (5000MVA, 1000MVA), three bus bars, static VAR compensation (STATCOM) based on voltage source converter ,STATCOM output current (inductive or capacitive) can be controlled independent of the AC system voltage. , and also consist of two transformers (5000MVA 13.8kV/500kV, 1000MVA 13.8kV/500kV), and two transmission lines 350KM, 60HZ, 500KV each, with the following parameters:

Table 4.1: Parameters of the transmission line

$R_0=0.2758 \Omega/\text{Km}$	$L_0=3.220*10^{-3} \text{ H/Km}$	$C_0=8.297 \text{ nF/Km}$
$R_1=0.01755 \Omega/\text{Km}$	$L_1=0.8737*10^{-3} \text{ H/Km}$	$C_1=13.33 \text{ nF/Km}$

The whole system is simulated using MATLAB/SIMULINK as shown in Figure 4.1. STATCOM is located at the midpoint of the line (bus B2) and has a rating of +/- 100MVA. This STATCOM is a phasor model of a typical three-level PWM STATCOM. The STATCOM having a DC link nominal voltage of 40kV with an equivalent capacitance of 375 $\mu$ F. On the AC side, its total equivalent impedance

is 0.22 Pu on 100 MVA. This impedance represents the transformer leakage reactance and the phase reactor of the IGBT Bridge of an actual PWM STATCOM. Distance relay is located at (bus B1). Zone 1 setting is 85% of the total line length.

System is tested when the fault is occurred at 75% of transmission line length and at the end point on the transmission line. Tests are made for the system without STATCOM and with STATCOM.

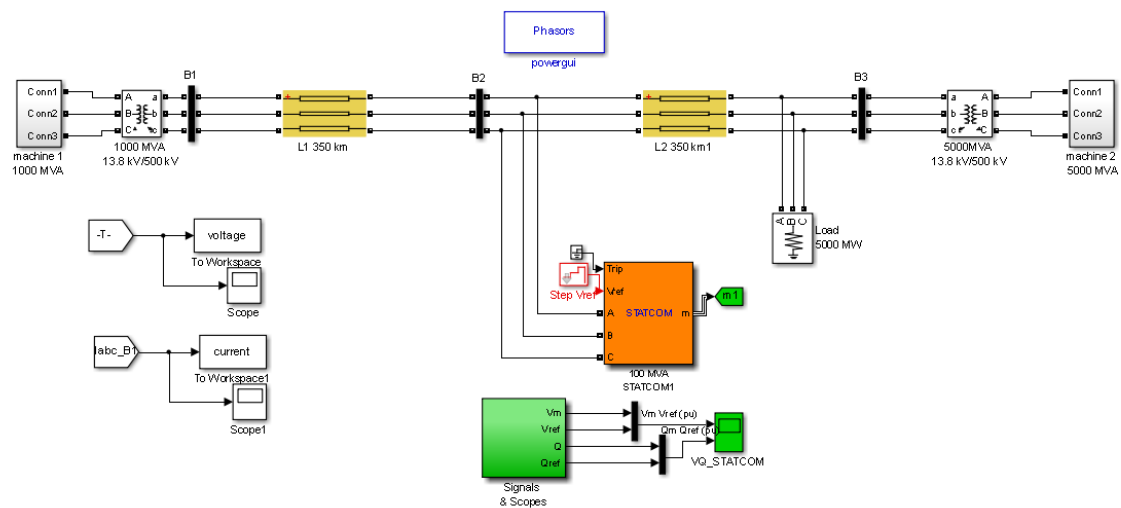


Figure 4.1: System lay-out

## 4.3 Results

The effect of STATCOM on distance relay operations has been investigated. Several case studies are demonstrated including line to ground, phase to phase to ground, and three-phase to ground faults inside and outside the protected zone of the distance relay. In order to include STATCOM in the loop of the impedance seen by distance relay the fault is applied beyond the STATCOM. The distance

relay operation is examined in all cases when the transmission line is equipped with and without STATCOM.

### **4.3.1 Single Phase to Ground Fault**

phase A to ground fault occurs at 525km (%75) of the line beyond relay location with the STATCOM injecting current into the point of common coupling in order to control the line voltage. The apparent impedance trajectories of the transmission line with and without connecting STATCOM together with the distance relay characteristic is shown in Figure 4.2.

Figure 4.2 shows that the value of measured impedance or apparent impedance when STATCOM is presented is higher than the apparent impedance when STATCOM is unconnected since the case under reach. Figure 4.3 shows the apparent impedance trajectories of the transmission line with and without connecting STATCOM together with the distance relay characteristic when the phase fault occurs in the end of the line, the apparent impedance of two cases in out of zone.

### **4.3.2 Phase To Phase (A-B) To Ground Fault**

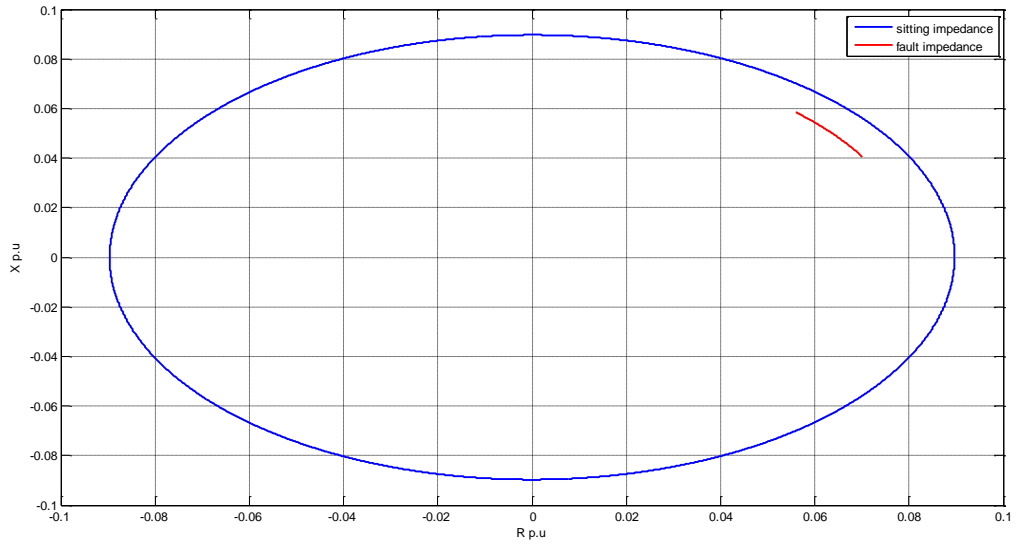
phase A to phase B to ground fault occurs at 525km (%75) of the line at beyond relay location with the STATCOM injecting current into the point of common coupling in order to control the line voltage. The apparent impedance trajectories of the transmission line with and without connecting STATCOM together with the distance relay characteristic is shown in Figure 4.4. It's clear that the value of measured impedance or apparent impedance when STATCOM is presented is higher than the apparent impedance when STATCOM is unconnected since the case under reach.

Figure 4.5 shows the apparent impedance trajectories of the transmission line with and without connecting STATCOM together with the distance relay characteristic when the phase to phase fault occurs in the end of the line, the apparent impedance of two cases in out of zone.

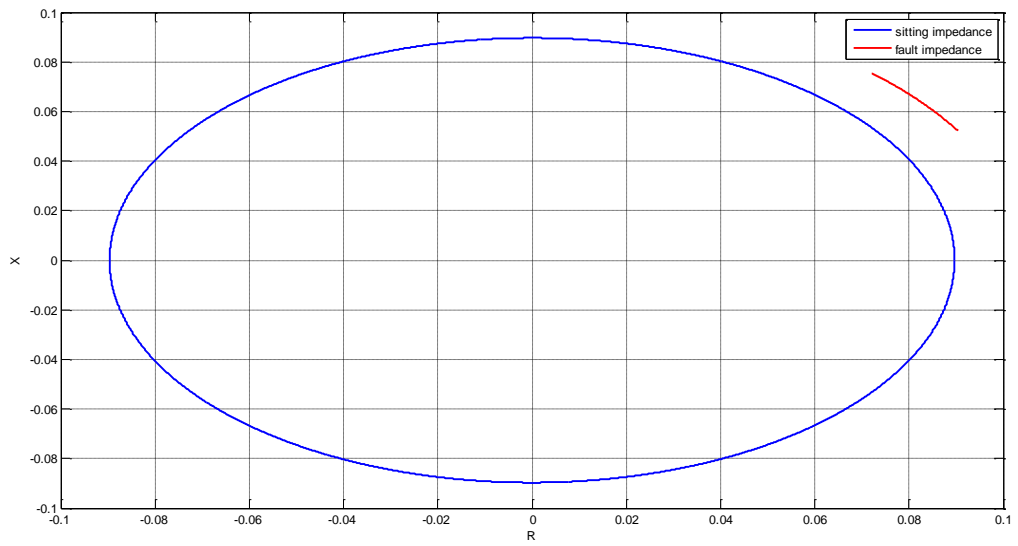
### **4.3.3 Three phase to Ground Fault**

A three phase to ground fault occurs at 525km (%75) of the line at beyond relay location with the STATCOM injecting current into the point of common coupling in order to control the line voltage. The apparent impedance trajectories of the transmission line with and without connecting STATCOM together with the distance relay characteristic is shown in Figure 4.6, it shows that the value of measured impedance or apparent impedance when STATCOM is presented is higher than the apparent impedance that STATCOM is unconnected since the case under reach.

Figure 4.7 shows the apparent impedance trajectories of the transmission line with and without connecting STATCOM together with the distance relay characteristic when the phase to phase fault occurs in the end of the line, the apparent impedance of two cases in out of zone.

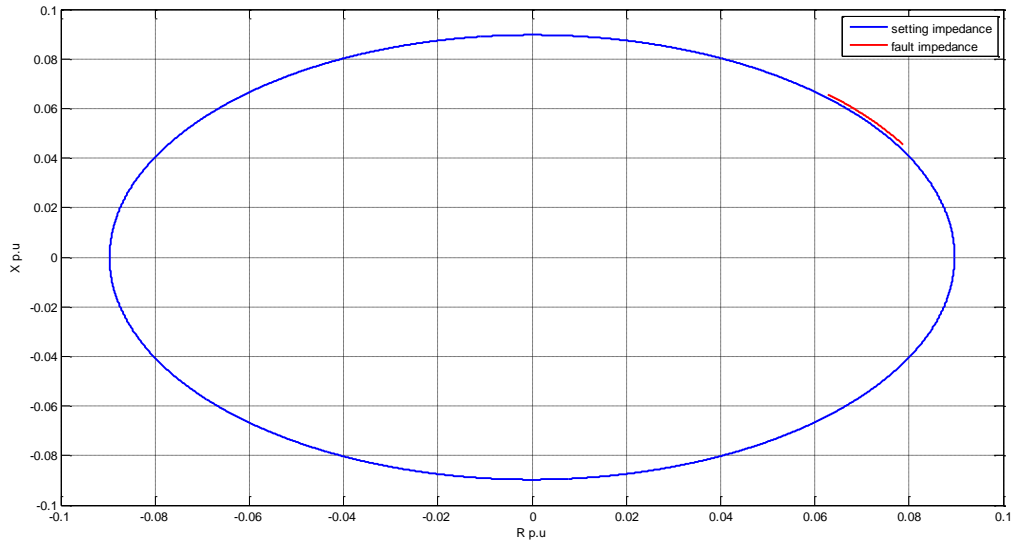


(a)

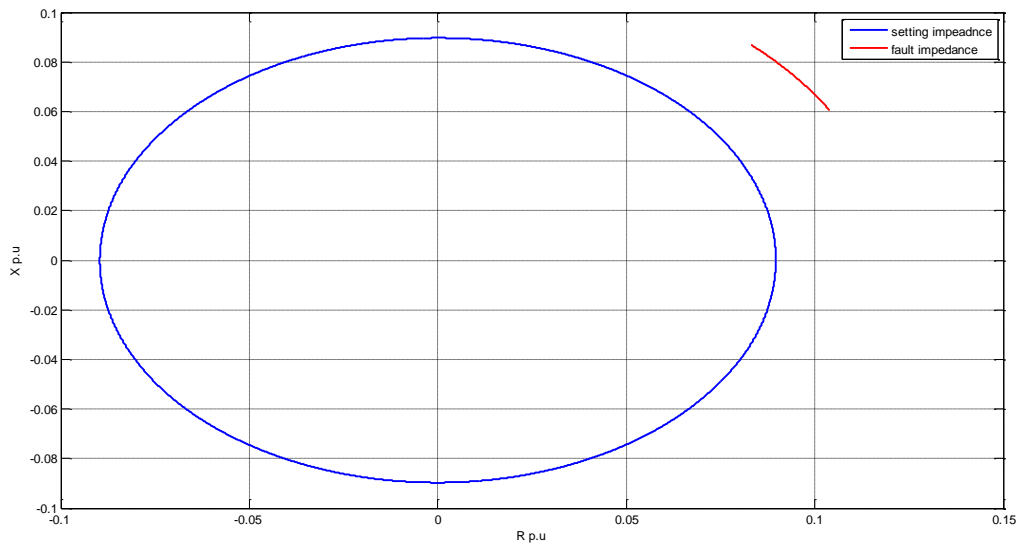


(b)

Figure 4.2: Phase A to ground fault at %75 length (a) without STATCOM (b) with STATCOM

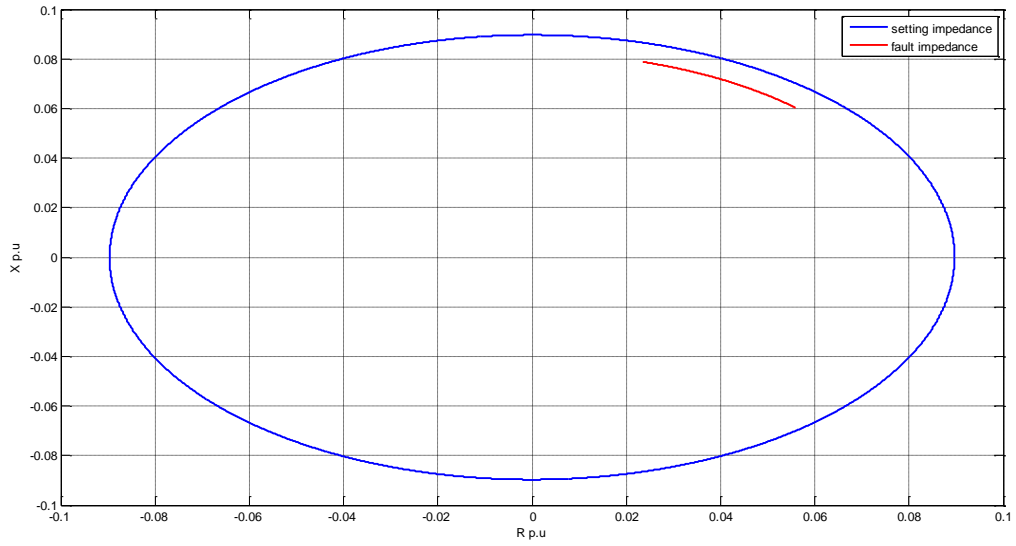


(a)

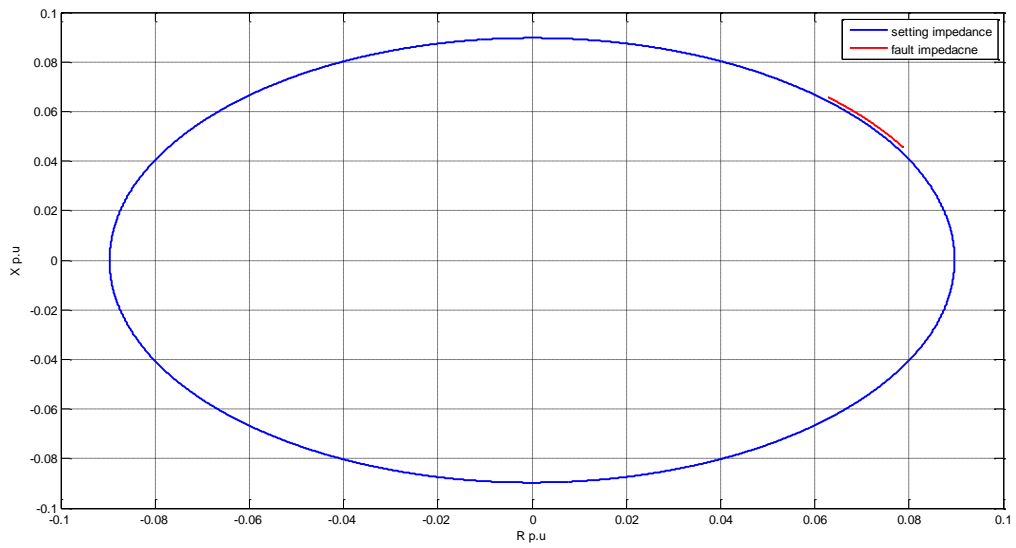


(b)

Figure 4.3: Phase A to ground fault at the end of the line (a) without STATCOM  
(b) with STATCOM

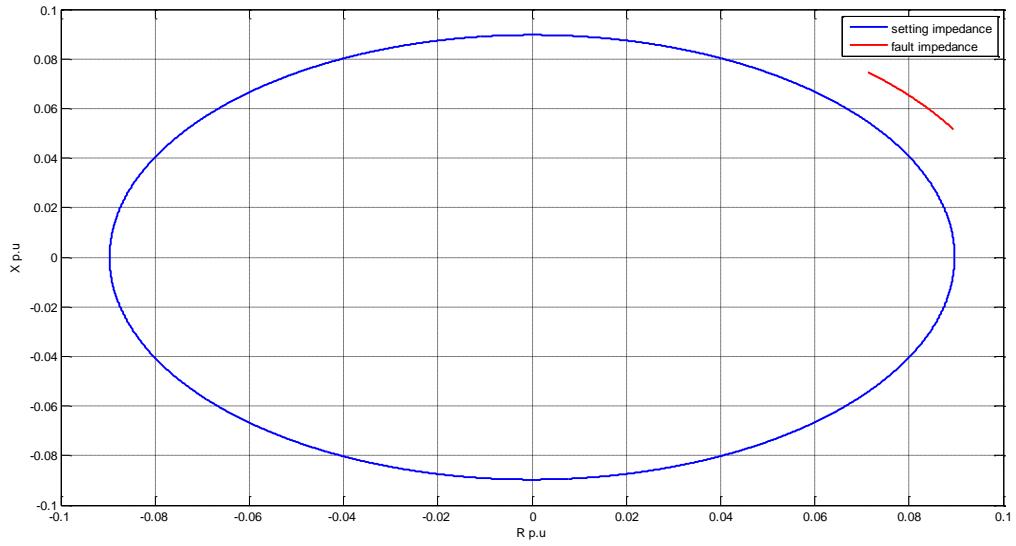


(a)

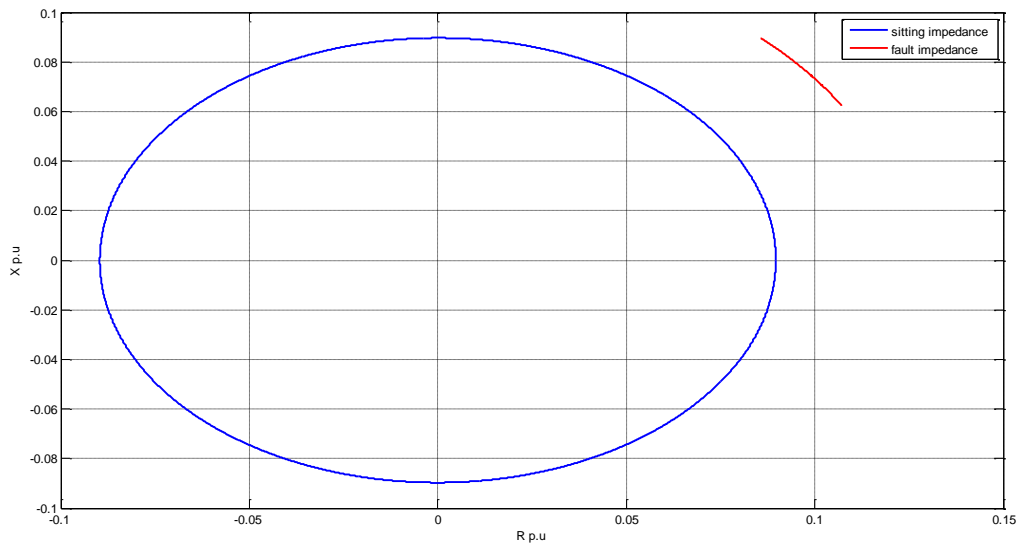


(b)

Figure 4.4: Phase to phase (A-B) to ground fault at %75 length (a) without STATCOM (b) with STATCOM

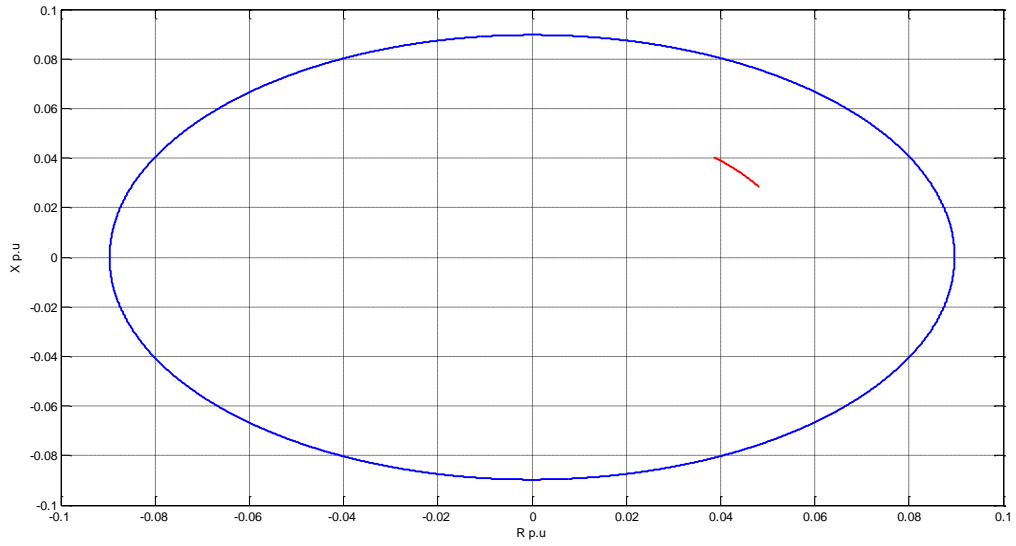


(a)

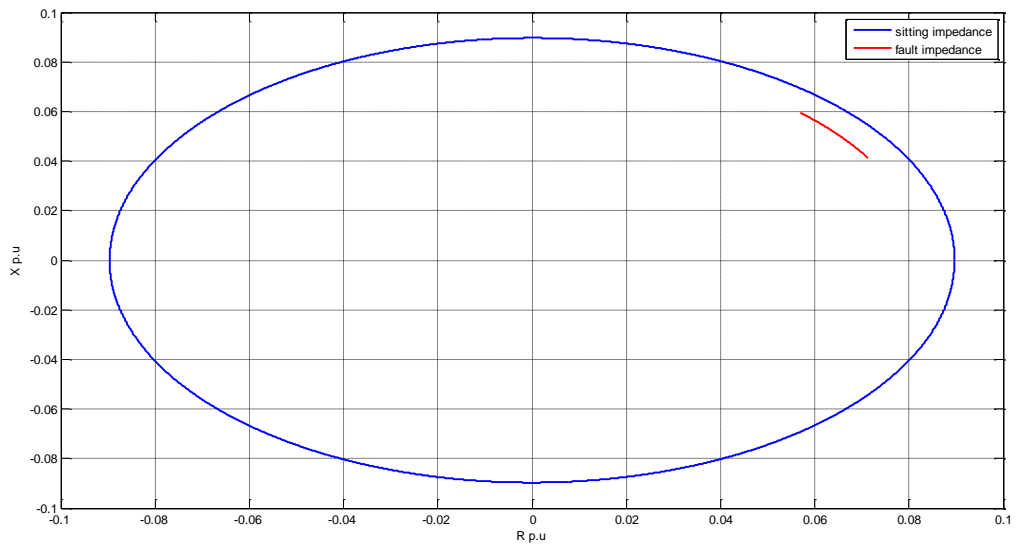


(b)

Figure 4.5: Phase to phase (A-B) to ground fault at the end of the line (a) without STATCOM (b) with STATCOM

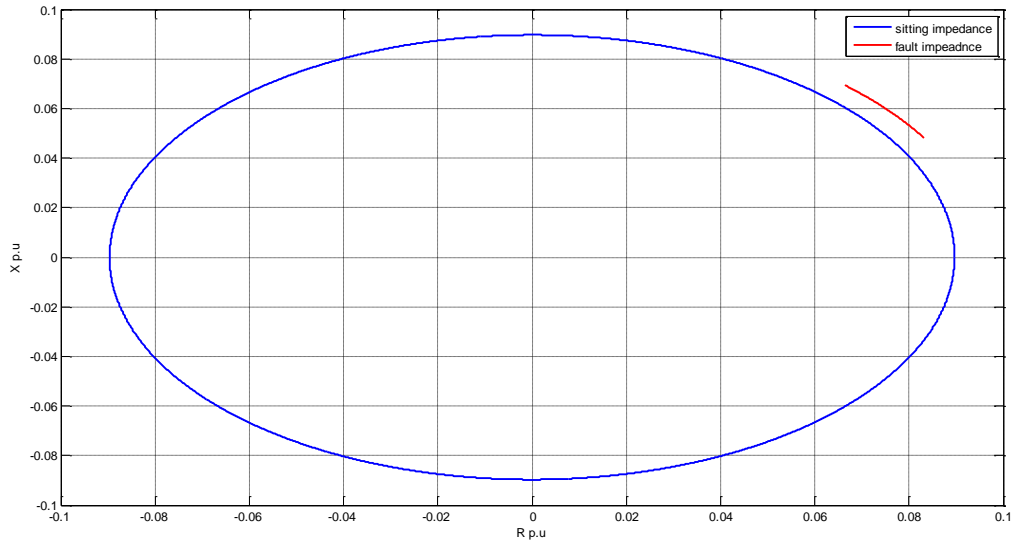


(a)

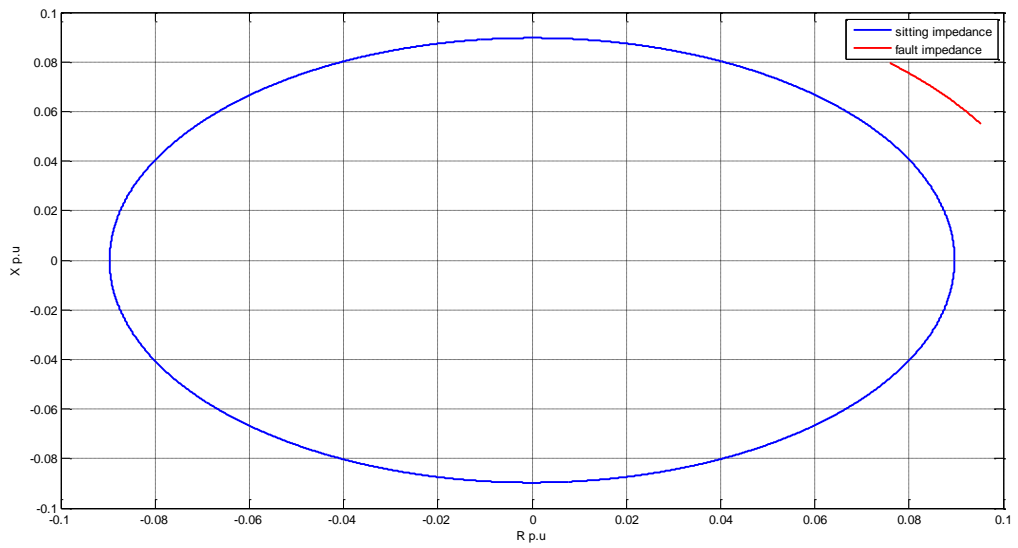


(b)

Figure 4.6: Three phase to ground fault at % 75 lengths (a) without STATCOM  
(b) with STATCOM



(a)



(b)

Figure 4.7: Three phase to ground fault at the end of the line (a) without STATCOM (b) with STATCOM

# CHAPTER FIVE

## CONCLUSION AND RECOMMENDATIONS

### 5.1 Conclusions

After the study is done, and the calculation of the apparent impedance of system with STATCOM is outlined, it's clear that installation of STATCOM in the power system affects the performance of the distance relay. if the fault occurs, the relay may trip for external and may not respond for internal fault if the STATCOM is absorbing or injecting reactive power into the system. The simulation results also show clearly the impact of STATCOM on distance relay performance.

### 5.2 Recommendations

From the present study it is confirmed the distance relay measurements are affected when STATCOM is provided for the power system. It's recommended to:

1. Study the effect of the other types of shunt connected facts devices, and also the series connected types on the protective devices.
2. Using backup protection to cover the failure of the distance protection when STATCOM device is in use.

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