6-2015

Performance Analysis of Distance Relay on Shunt/Series Facts-Compensated Transmission Line

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PERFORMANCE ANALYSIS OF DISTANCE RELAY ON SHUNT/SERIES
FACTS-COMPENSATED TRANSMISSION LINE

by

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A thesis submitted to the Graduate College
in partial fulfillment of the requirements
for the degree of Master of Science in Electrical Engineering
Electrical and Computer Engineering
Western Michigan University
June 2015

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Flexible Alternating Current Transmission Systems (FACTS) are increasingly being used to enhance the efficiency and reliability of power system networks. FACTS devices can influence the performance of existing protective system components (specifically distance relays) due to the fact that FACTS change power system quantities such as line impedances, voltages, and currents. Distance relay may mal-operate when FACTS devices are connected since they cause some of the tripping characteristics to change. This thesis investigates the impact on distance relay performance due to compensations using two types of FACTS controllers: Static Synchronous Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC). Analytical study on the effects of STATCOM and SSSC on distance relay performance is conducted. A detailed modeling and simulation of digital distance relay with three zones mho characteristics are also presented along with a verification of the proposed models under a variety of fault types and fault locations. Results from the analytical comparative study are confirmed by the simulation results and both corroborate the fact that we need to address distance relay performance under the different modes of operation of STATCOM and SSSC and that a redesign is essential to better face problems such as in over/under reaching.

ACKNOWLEDGMENTS

I would like to express my deepest appreciation to my advisor, Dr. Ikhlas Abdel-Qader, for her help and advice throughout this work. I would like to thank Dr. Johnson Asumadu and Dr. Azim Houshyar for their time and feedback on my thesis, I would also like to thank my friends and classmate fellows who I met during my graduate studies and enjoyed their friendship. Lastly, my special thanks and gratitude go to my parents and my wife for their support and understanding while in graduate school.

Ahmed Kareem Lafta Al-Behadili

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CHAPTER 1

INTRODUCTION

Generating, transmitting, and distributing electrical energy to consumers are achieved through the power grid. The power grid is clearly a very large network with a huge numbers of equipment and transmission lines. A fault, occurrence of any abnormal condition, is still the main threat facing the grid infrastructure. Any fault can impact a much larger area regardless of the small locality of the fault itself.

A fault is technically defined as any abnormal change in one of the power system quantities such as current, voltage, or frequency [1]. The transmission lines are the ones with highest probability for a fault to occur and thus researchers' attention has been focused on them. Transmission lines can be underground cables or overhead cables and they have their own advantages and disadvantages. A fault not only impacts transmission lines but also other parts of the power grid such as generators, transformers, and of course loads [2]. Therefore, appropriate protective relays and circuit breakers are employed to provide as much protection as possible for each section of the power system. Protective Relays are devices trip circuit breaker when fault is detected. The inputs for these devices could be voltage, current, temperature, and frequency and protective relays make comparison with setting point to send tripping signal as the output. The fault is

unavoidable problem in power system network and the customers demand higher levels of reliability, it is essential to it increase the functionality of relays by protecting them.

Recently, researchers aimed to enhance transmission line capability and reliability by interconnecting power electronic control devices to transmission systems. These electronic devices or FACTS (Flexible Alternating Current Transmission System) support the transmission system with capacity enhancement, better power flow control, and increased voltage stability and control. Employing FACTS controllers to transmission and networks systems helps to push the capacity of transmission line close to the thermal limit and aids in reducing the economic and environmental problems from installing new transmission line. Consequently, we have to face emerging problems that may be created by such employments since these devices will directly impact power system quantities, and it can cause mal-operation for pre-existing protective relays installed within the system prior to FACTS deployment [3]. Therefore, it is important to investigate the performance of existing protective relay on FACTS-compensated transmission lines.

1.1   Faults in Transmission Lines

A transmission line fault occurs when the insulation between phases or between phases and ground fails. In this section, I will present a review on faults including common factors causing a fault in section 1.1.1 and fault effects in section 1.1.2.

1.1.1   Causes of Fault in Electrical Power System

Several reasons and events in our daily lives can cause a fault to occur. However, the most common factors are well recognized and are usually classified into two classes based on the causing factors, natural factor and human factors.

A. Natural factors

1. Lighting storm: lighting storm supply high voltage into transmission line and this leads to break down the insulation between phases or phases and ground.

2. High speed wind: the high speed wind move the phases and it leads to reduce the distances between phases or between phases and towers. In this case the fault happens even though there is not contact between them because of the variation in voltage especially at low voltage transmission line.

3. Fire: this factor has direct effect on insulation because it burns the insulation and leads to a fault.

4. Ice or snow: Gathering ice or snow on transmission lines leads to change the conductivity for conductors of transmission line.

5. Earthquakes, falling tree, flying objects are a natural factors that can cause faults in electrical power transmission system and network.

B. Human factors

1. Faulty power or utility pole or tower because of human impact such as in car accidents or physical contact by human.

2. Human error in installing and maintenance work such as inaccurate settings, and faulty connection.

1.1.2 Fault Effects

A- Commercial problems: Fault in electrical power system may cause thermal damage to equipment for both consumers and electrical utilities [4].

B- Continuity of supply: in some power system networks especially the network which has one power source, a fault can cause discontinuity in delivery of electrical energy to consumers.

C- Voltage variation: a good quality in power system depends on the range of voltage supply and it has to be between 114 V and 126 V for consumers that used 120 V, while fault is the main reason to variety in voltage [5].

D- Safety problem: The human life is the most important consideration for designing electrical system. Electrical system should be isolated to avoid killing or injuring people from explosion, fire, arcing, or shock [4].

1.2 Types of Faults

1.2.1 Symmetrical Fault

This type of fault occurs when three phases of transmission line are shorted. The fault current in this type can be calculated from single-phase impedance because the system still balanced as shown in figure 1.1 [6]. The magnitude of fault current is the same for all three phases but with phase shift 120° [7]. (Assuming zero fault impedance)
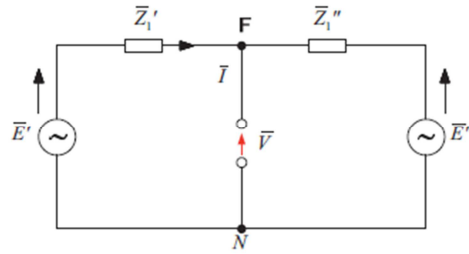
Figure 1.1: Network with fault at point F.

$\overline{E'} \, AND \, \overline{E''}$ are voltage sources

$\overline{Z'} AND \, \overline{Z''}$ are Network impedance

$\overline{V}$ voltage at F befor Fault occurs

$\overline{I}$ current at F befor Fault occurs

$$\overline{V} = \, \overline{E'} - \, \overline{IZ'} = \, \overline{E''} - \, \overline{IZ''} \qquad\qquad (1.1)$$

$$\overline{I}_f = \, \overline{V} \, \frac{(\overline{Z'} + \, \overline{Z''})}{\overline{Z'} \, \overline{Z''}} \qquad\qquad (1.2)$$

1.2.2   Symmetrical Component

There are many types of unsymmetrical system in electrical power system network. The best way to deal with unsymmetrical system is using symmetrical component. The unbalanced voltages and currents in power system can replace them by three separate balanced Symmetrical Components. These vectors sets are described as the positive, negative and zero sequence.

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1- Positive-sequence components are represented as three phasors having same magnitude with $\pm 120^{\circ}$ phase angles and sequence abc, as shown in Figure 1.2 (a).

2- Negative-sequence components are represented as three phasors having same magnitude with $\pm 120^{\circ}$ phase angles and sequence acb, as shown in Figure 1.2 (b).

3- Zero-sequence components are represented as three phasors having same magnitude with zero phase angels, as shown in Figure 1.2 (c).

(a)   (b)   (c)
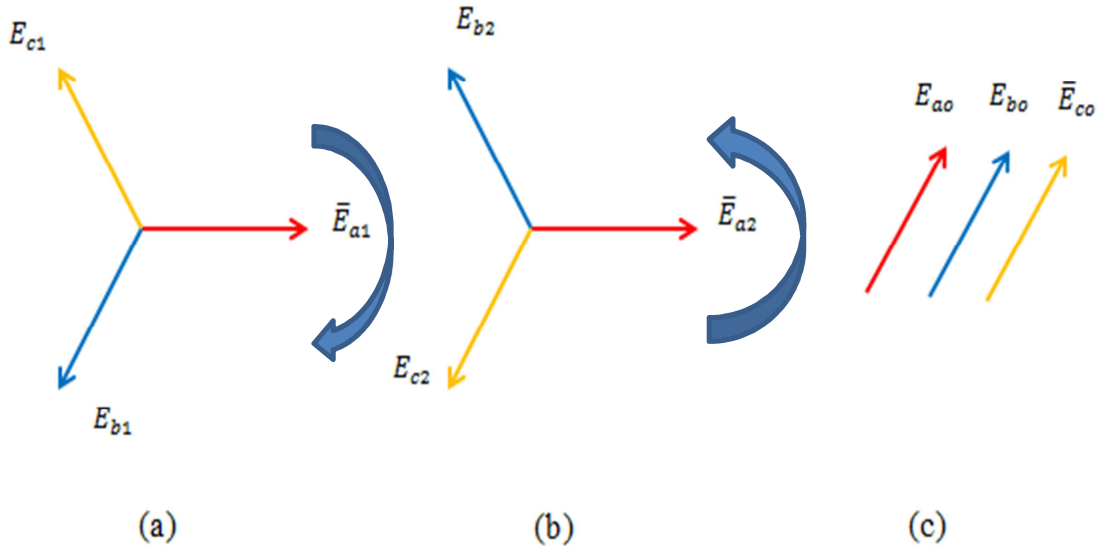
Figure 1.2: (a) Positive-Sequence Components, (b) Negative-Sequence Components, and (C) Zero-Sequence Components

The equations between phase and sequence voltages are given below:

$$\bar{E}_a = \bar{E}_1 + \bar{E}_2 + \bar{E}_0 \tag{1.3}$$

$$\bar{E}_b = a^2\bar{E}_1 + a\bar{E}_2 + \bar{E}_0 \tag{1.4}$$

$$\bar{E}_c = a\bar{E}_1 + a^2\bar{E}_2 + \bar{E}_0 \tag{1.5}$$

Or

$$\bar{E}_1 = \frac{1}{3}(\bar{E}_a + a\bar{E}_b + a^2\bar{E}_c) \tag{1.6}$$

$$\bar{E}_2 = \frac{1}{3}(\bar{E}_a + a^2\bar{E}_b + a\bar{E}_c) \tag{1.7}$$

$$\bar{E}_0 = \frac{1}{3}(\bar{E}_a + \bar{E}_b + \bar{E}_c) \tag{1.8}$$

We can also write these equations in a matrix format as

$$\begin{bmatrix} \bar{E}_a \\ \bar{E}_b \\ \bar{E}_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \times \begin{bmatrix} \bar{E}_0 \\ \bar{E}_1 \\ \bar{E}_2 \end{bmatrix} \tag{1.9}$$

$$\begin{bmatrix} \bar{E}_0 \\ \bar{E}_1 \\ \bar{E}_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \times \begin{bmatrix} \bar{E}_a \\ \bar{E}_b \\ \bar{E}_c \end{bmatrix} \tag{1.10}$$
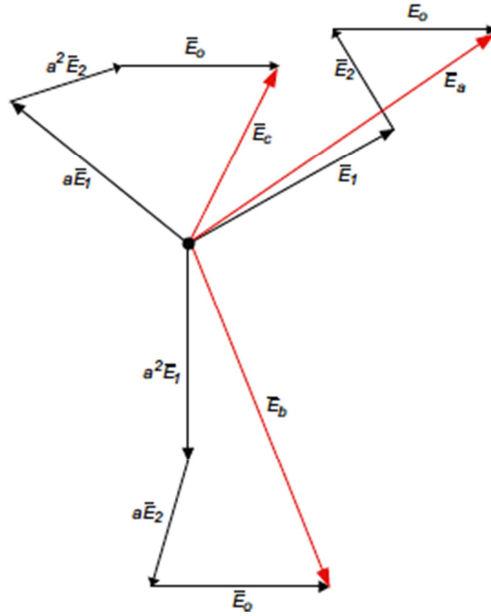
Figure 1.3: Resolution of a system of unbalanced vectors [7].

We can applied equations (1.9) and (1.10) for currents

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \times \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} \qquad (1.11)$$

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \times \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \qquad (1.12)$$

When

$$a = 1 \angle 120°$$

$$a^2 = 1 \angle 240°$$

$$a + a^2 + 1 = 0$$

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \qquad (1.13)$$
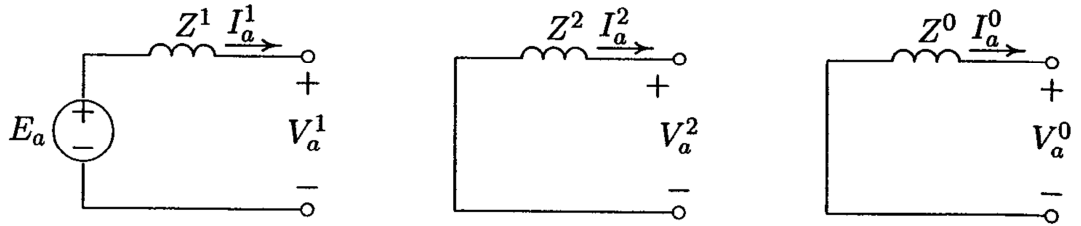
Figure 1.4: Sequence networks: (a) positive-sequence; (a) positive-sequence; (a) positive-sequence (only positive sequence has voltage source) [7].

From figure 1.4 we can write:

$$\overline{V_{a1}} = E_a - \overline{Z_1}\,\overline{I_{a1}} \qquad (1.14)$$

$$\overline{V_{a0}} = 0 - \overline{Z_0}\,\overline{I_{a0}} \qquad (1.15)$$

$$\overline{V_{a2}} = 0 - \overline{Z_2}\,\overline{I_{a2}} \qquad (1.16)$$

1.2.3 Unsymmetrical Fault in Transmission Line

Before fault happens in power system, it is considered as balanced system. The types of fault that may occur in transmission line, in order of frequency of occurrence: single line-to-ground, line-to-line, double line-to-ground, and balanced three-phase fault. The designer put fault impedance on the path of fault current to reduce affecting of fault current on equipment. If there is not impedance, the fault or short circuit will be called a *bolted* fault. These types are called shunt fault because they occur between two points

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(phase and phase or phase and ground). There are other types of fault called series fault such as one-conductor-open, and two-conductors-open [2].
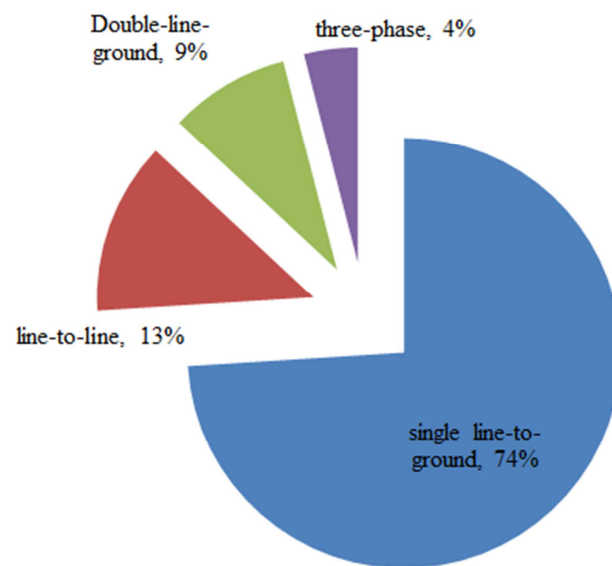
Figure 1.5: Faults probability of occurrence in power transmission systems [5].

1.2.3.1 *Single line-to-ground Fault*

Figure 1.6 shows three-phase generator with a Single line-to-ground Fault at phase *a* through fault impedance.
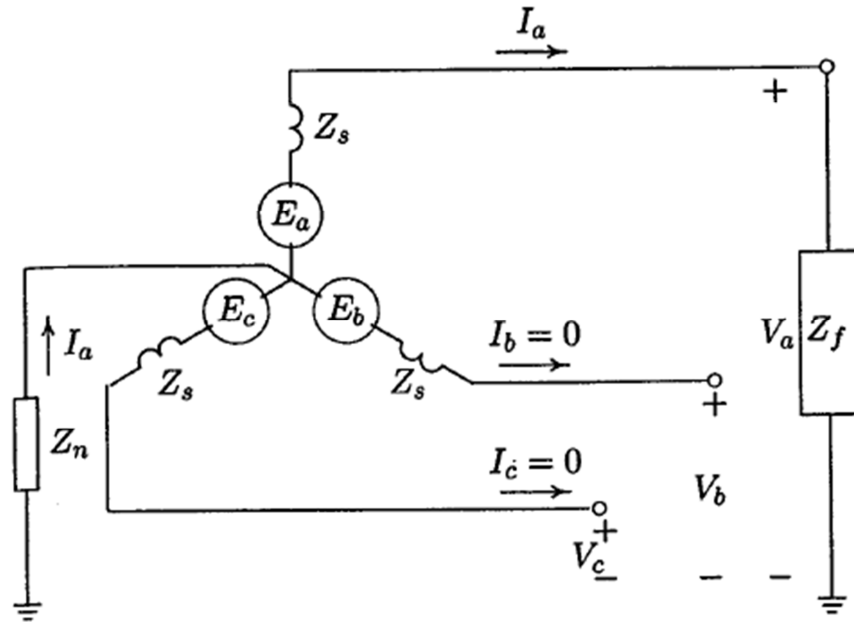
Figure 1.6: Single line-to-ground fault on phase a [7].

$$\overline{V_a} = Z_f \overline{I_a} \tag{1.17}$$

$$\overline{I_b} = 0 \quad , \quad \overline{I_c} = 0 \quad , \quad \text{and} \quad \overline{V_a} = 0$$

From equation (1.9) and (1.12) we get

$$\overline{I_1} = \overline{I_2} = \overline{I_0} = \frac{1}{3}\overline{I_a} \qquad (1.18)$$

$$\overline{V_a} = \overline{V_{a1}} + \overline{V_{a2}} + \overline{V_{a0}} \qquad (1.19)$$

Substituting for $\overline{V_{a1}}$, $\overline{V_{a2}}$, and $\overline{V_{a0}}$ from (1.14,15,and 16) and noting $\overline{I_1} = \overline{I_2} = \overline{I_0}$, we get

$$\overline{V_a} = E_a - \overline{I_{a0}}(\overline{Z_1} + \overline{Z_2} + \overline{Z_0}) \qquad (1.20)$$

Substituting for $\overline{V_a}$ from (1.17) and $\overline{I_a} = 3\overline{I_0}$, we get

$$3Z_f\overline{I_{a0}} = E_a - \overline{I_{a0}}(\overline{Z_1} + \overline{Z_2} + \overline{Z_0}) \qquad (1.21)$$

or

$$\overline{I_{a0}} = \frac{E_a}{(\overline{Z_1}+\overline{Z_2}+\overline{Z_0}+3Z_f)} \qquad (1.22)$$

The fault current is

$$\overline{I_a} = 3\overline{I_{a0}} = \frac{3E_a}{(\overline{Z_1}+\overline{Z_2}+\overline{Z_0}+3Z_f)} \qquad (1.23)$$

We can represent equations (1.18) and (1.22) as a sequence series equivalent circuit as shown in figure (1.7).
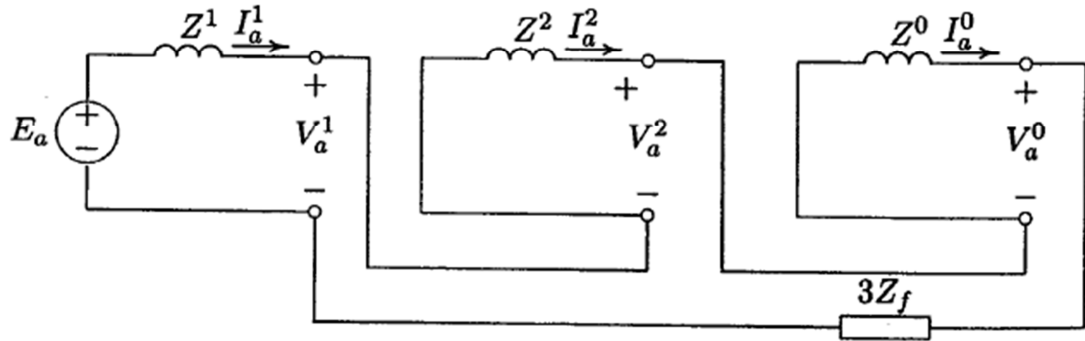
Figure 1.7: Sequence network connection for line to ground [7].

1.2.3.2   Line-to-Line Fault

Figure 1.8 shows three-phase generator with a line to tine fault between phases b and c through fault impedance.

Figure 1.8: Line to line fault between phase b and c [7].

$$\bar{I}_a = 0 \tag{1.24}$$

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$$\overline{I_b} = -\overline{I_c} \tag{1.25}$$

$$\overline{V_b} - \overline{V_c} = Z_f \overline{I_b} \tag{1.26}$$

From equation (1.9) and (1.12) we get the following:

$$\overline{I_{a1}} = -\overline{I_{a2}} \tag{1.27}$$

$$\overline{I_{a0}} = 0 \tag{1.28}$$

$$\overline{V_b} - \overline{V_c} = (a^2 - a)(\overline{V_{a1}} - \overline{V_{a2}}) = Z_f \overline{I_b} \tag{1.29}$$

Substituting for $\overline{V_{a1}}$ and $\overline{V_{a2}}$, from (1.14), (1.15),and (1.16) and noting $\overline{I_{a1}} = -\overline{I_{a2}}$, we get

$$(a^2 - a)[E_a - \overline{I_{a1}}(\overline{Z_1} + \overline{Z_2})] = Z_f \overline{I_b} \tag{1.30}$$

$$[E_a - \overline{I_{a1}}(\overline{Z_1} + \overline{Z_2})] = Z_f \frac{3\overline{I_{a1}}}{(a^2 - a)(a - a^2)} \tag{1.31}$$

where

$$(a^2 - a)(a - a^2) = 3$$

$$[E_a - \overline{I_{a1}}(\overline{Z_1} + \overline{Z_2})] = Z_f \frac{3\overline{I_{a1}}}{(a^2 - a)(a - a^2)} \tag{1.32}$$

$$\overline{I_{a1}} = \frac{E_a}{(\overline{Z_1} + \overline{Z_2} + Z_f)} \tag{1.33}$$

The fault current is

$$\bar{I_b} = -\bar{I_c} = (a^2 - a)\overline{I_{a1}} = -\sqrt{3}\,j\overline{I_{a1}} \qquad (1.34)$$

Equations (1.27) and (1.33) can be represented in an equivalent circuit as shown in figure (1.9).
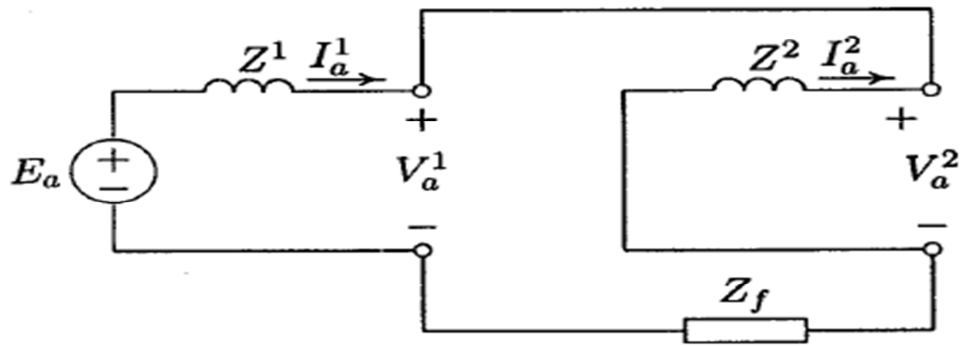
Figure 1.9: Sequence network connection for line to line [7].

1.2.3.3 Double Line-to-Ground Fault

Figure 1.10 shows three-phase generator with a line to tine fault between phases b and c through fault impedance to ground.
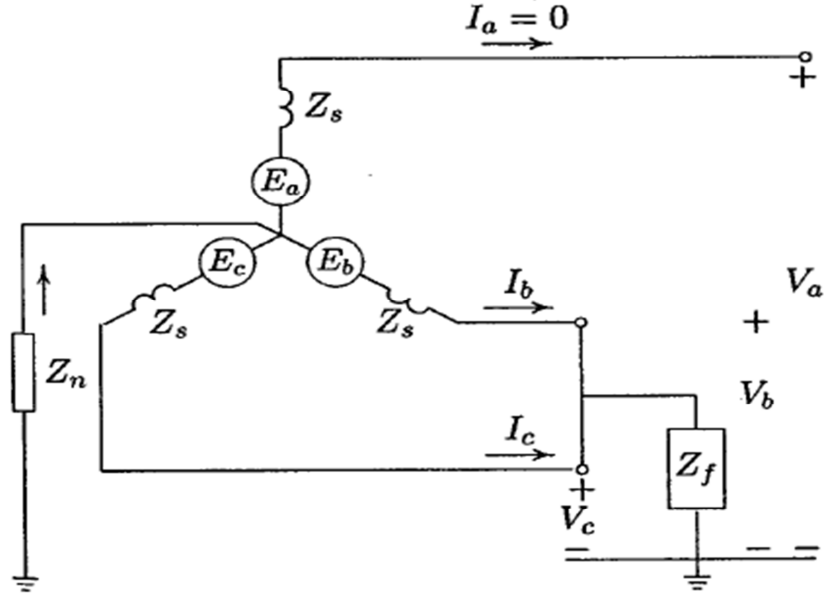
Figure 1.10: Double line-to-ground fault bcg [7].

$$\overline{V_b} = \overline{V_c} = Z_f(\overline{I_b} + \overline{I_c}) \tag{1.35}$$

$$\overline{I_a} = \overline{I_{a1}} + \overline{I_{a2}} + \overline{I_{a0}} = 0 \tag{1.36}$$

$$\overline{V_b} = a^2\overline{V_{a1}} + a\overline{V_{a2}} + \overline{V_{a0}} \tag{1.37}$$

$$\overline{V_c} = a\overline{V_{a1}} + a^2\overline{V_{a2}} + \overline{V_{a0}} \tag{1.38}$$

$$\overline{V_{a1}} = \overline{V_{a2}} \tag{1.39}$$

Substituting for the symmetrical component of currents in (1.35), we get

$$\overline{V_b} = Z_f \, (a^2\overline{I_{a1}} + a\overline{I_{a2}} + \overline{I_{a0}} + a\overline{I_{a1}} + a^2\overline{I_{a2}} + \overline{I_{a0}} \,) = Z_f \, (\, 2\overline{I_{a0}} - \overline{I_{a1}} - \overline{I_{a2}})$$

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$$\overline{V_b} = 3Z_f \overline{I_{a0}} \tag{1.40}$$

Substituting for $\overline{V_b}$ from (1.40) and $\overline{V_{a2}}$ from (1.39) into (1.37), we have

$$3Z_f \overline{I_{a0}} = \overline{V_{a0}} + (a^2 + a)\overline{V_{a1}} = \overline{V_{a0}} - \overline{V_{a1}} \tag{1.41}$$

Substituting for the symmetrical component of voltages in (1.41), we get

$$\overline{I_{a0}} = \frac{E_a - Z_f \overline{I_{a1}}}{\overline{Z_0} + 3Z_f} \tag{1.42}$$

Also, substituting for the symmetrical component of voltages in (1.39), we get

$$\overline{I_{a2}} = \frac{E_a - Z_f \overline{I_{a1}}}{\overline{Z_2}} \tag{1.43}$$

Substituting for $\overline{I_{a0}}$ and $\overline{I_{a2}}$ into (1.36) and solving for $\overline{I_{a1}}$, we get

$$\overline{I_{a1}} = \frac{E_a}{\overline{Z_1} + \frac{\overline{Z_2}(\overline{Z_0} + 3Z_f)}{\overline{Z_2} + \overline{Z_0} + 3Z_f}} \tag{1.44}$$

The fault current is

$$\overline{I_f} = \overline{I_a} + \overline{I_b} = 3\,\overline{I_{a0}} \tag{1.45}$$

Equations (1.42) and (1.44) can be represented in an equivalent circuit as shown in figure (1.11).
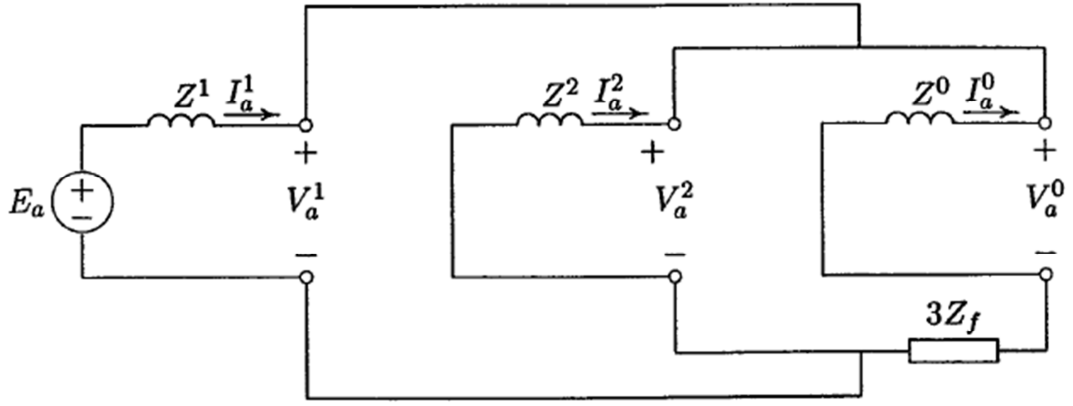
Figure 1.11: Sequence network connection for double line to ground *bcg* [7].

1.3   Protective Relay

The main objective of protective relay is to detect any abnormal change in power system quantities such as voltage and current values and bring it back into operative conditions when possible. When Relay detects the Fault in protective zone, the relay sends signal to circuit breaker to clear and isolate the faulty section. The relays depend on current and voltage and relays cannot afford the high voltage and current, so we have to use current transformer (CT) and voltage transformer (VT) to reduce the magnitude of faulty current and voltage values to avoid damaging the relays. Currently available relays are small in size and high in accuracy and classified in four types. These are:

1- Electromechanical relays.

The earliest relay invented which use electrical and mechanical devices or a combination of both to switch the breaker. When the relay detects the fault, it

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forces mechanical contact using magnetic field to open circuit breaker.

Galvanic isolation between inputs and outputs is a main advantage of this

relay. There are different types of this relay such as attracted armature,

moving coil, induction, thermal, motor operated, and mechanical [6].

2- Static relays

When the first static relay was designed in 1960, it was based on electronic

devices to perform the relay characteristic instead of coils and magnetic field.

The first version it was made by discreet devices such as transistors and

diodes with resistors, capacitors and inductors. The advantages of this relay

are: smaller size, more accurate, and is easier to change the characteristics of

the relay [6].

3- Digital relays

Digital relay is an advanced relay that uses analog to digital conversion of

all measured quantities. Also, it uses microprocessor to implement the

protection algorithm. This process uses counting technique or Discrete Fourier

Transforms (DFT) to implement the algorithm. The digital relay has hardware

and software components. In addition, it can be used as a part with another

type of relays by simply downloading the software to the RAM or EEPROM.

It has the ability to function offline for testing purposes. Typically, the

quantities used to detect faults are current, voltage, impedance, and phase of

the protected transmission line. The disadvantage of this relay is it takes a longer time to process when compared with static relays [6].

4- Numerical relays

Numerical relays are the advanced version of digital relay. They use one or more digital signal processors (DSP) optimized for real time signal processing, running the mathematical algorithms for the protection functions. This relay is made as lower cost and size of microprocessors, memory and I/O circuitry leads to a single item of hardware for a range of functions. Also, the process in this relay faster than digital relay because the Discreet Signal Processing can run in parallel [6].

1.4   Protection of Transmission Line

Transmission lines operate at voltage levels from 69 kV to 765 kV. The level of voltage in transmission line is one of the most important factors considered in selecting the protective approaches to be used. Overcurrent protection of distribution radial feeders, distance protection of transmission lines, and differential protection of transmission lines are the most protective relay types in transmission lines [8].

1.4.1   Overcurrent Protection of Distribution Feeders

Protection of distribution feeder in transmission line depends on the principle operation of overcurrent relay. The magnitude of fault current varies according to the fault position. The fault currents are the highest when fault occurs close to the source, and

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its value will decay when the distance between fault location and the source increases. The principle operation of overcurrent relay depends on the magnitudes of fault currents [8]. The following are the data required for a relay setting [6]:

1- A one-line diagram of the power system includes the type and rating of the protection devices.

2- The impedances in ohms, per cent or per unit, of all power transformers, rotating machine and feeder circuits

3- The maximum and minimum values of short circuit values of the fault currents.

4- The maximum load current through protection devices.

5- The starting current and their times of induction motors.

6- The transformer inrush, thermal withstands and damage characteristics.

7- Decrement curves showing the rate of decay of the fault current supplied by the generators

8- Performance curves of the current transformers.

1.4.2   Distance Protection of Transmission Line

A distance relay is able to detect a fault in transmission line depends on the impedance of transmission line which is a function of length of transmission line or power system cable. The reach point in distance relay comes from the resistance and capacitance per Kilometer which is known for specification of each conductor in transmission line. The change in determine impedance because the fact that current will

increase and voltage decrease when fault occurs. Therefore, the impedance will decrease according to ohm's law (Z= V/I), and when distance relay compare this value with per-set value, it will be able to detect the fault and its location. The distance relay can only detect fault for area between the reach points and relay location, so it's necessary to select the right reach point for distance relay on length transmission line [9]. Distance relay will discuss with more details in chapter 4.
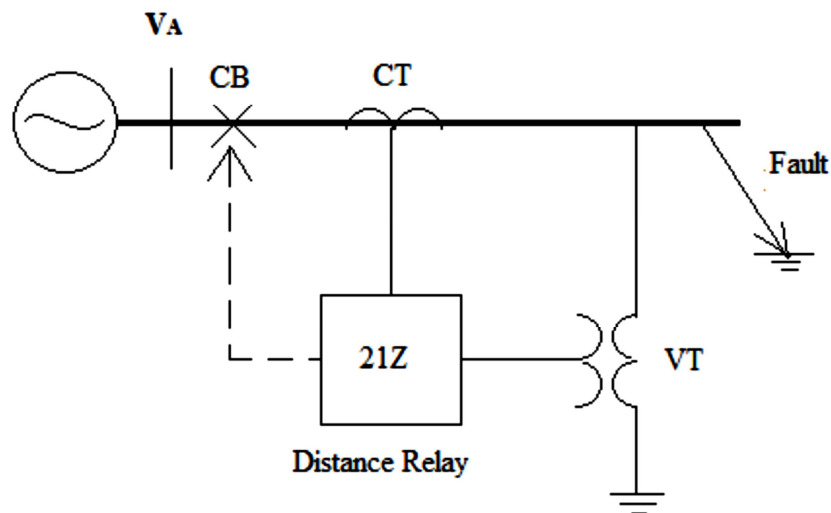
Figure 1.12: Basic distance protection scheme [10].

In the fig.1.12, the distance relay takes the voltage and current from voltage transform (VT) and current transform (CT). Then, calculate the apparent impedance, and compare this value with setting value (reach point) to detect fault in transmission line

1.4.3   Directional Relay for High-Voltage Transmission Line

Unlike the distance relay, the directional relay need to receive information from both ends, and transfer the information using a communication channel. That because the effect of current in-feed in transmission line which leads to wrong decision for relay based on one end information.

Relaying zones used for implementation of a blocking directional relay are shown in Figure (1.12). Each relay has a forward overreaching (FO) and a backward reverse (BR) setting. The FO setting is selected so that the relay can sense the faults occurring in the forward direction, overlooking the region from the relay position toward the adjacent line terminal and beyond. The BR setting is selected so that the relay can sense the faults occurring in a backward direction, causing a reversal of power flow. If the relay R1 (At location A) has sensed the fault at location X1 in zone FO, which is behind the relay R2 (At location B) of the line, then the relay is blocked by relay R2 from operating. On the other hand, when relay R2 senses a fault at location X1 in a BR zone end, can communicate to R1 not to trip by sending a blocking signal. If a fault occurs at a location between the two relays (as in location X2), the blocking signal will not be sent and both relays will operate simultaneously.
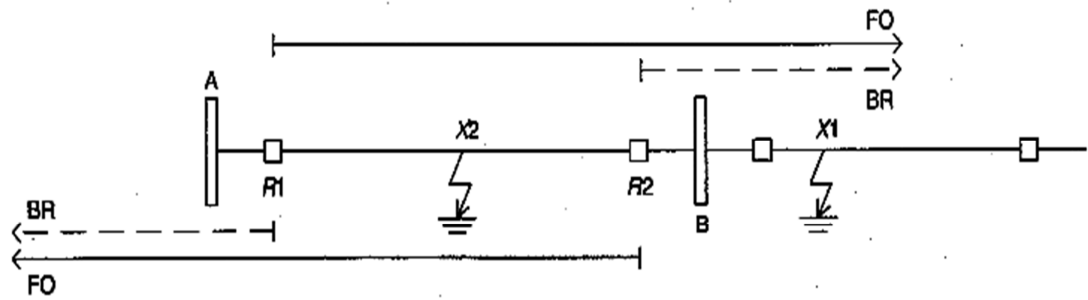
Figure 1.13: A schematic showing the blocking principle of relaying with fault directionality discrimination.

1.4.4   Differential Relay of High-Voltage Transmission Line

This type of relay use to protect transmission lines when the high-voltage transmission lines are not sufficiently protected using the other types. Differential relay make the decision by comparing the measurements from two ends. It is provide 100% protection of transmission lines with minimal effect caused by the rest of system. For this reason, differential relay used to protect high-voltage transmission line that have a strategic importance or have difficult application such as series compensator or radial system configuration. It can be classified according to the type of the communication media and the type of the measurement compared. Metallic wire, leased telephone lines, microwave radio, and fiber-optic cables are most communication media used in differential relay. The comparison inside the relay either phase comparison or both ends directly compared. It may convert the currents into square waves or composite waveform

converted into binary to use for phase comparison. In case of both ends directly

compared, it samples of each current transmitted to other or convert each current into

sequence current and composite signals from both side. The material which use in

communication channels and comparison methods make the differential relay more

expensive than other type and that is considered as a disadvantage for this relay [**8**].

1.5   Thesis Statement

The distance relay performance is impacted by interconnecting new devices in the

protected transmission line. It is very important that the distance relays do not mal-

operate under system fault conditions as this will result in the loss of stability or the

security of the system. This thesis presents a comparative study on the performance of

distance protection relays when integrated within protect compensated transmission lines.

We show two compensation techniques, that is the shunt and series connected Flexible

AC Transmission System (FACTS) Controllers.

1.6   Objective of this Research

1- Analytical study for the effect of series and shunt controller on the performance of
distance relay.

2- Designing a distance relay to detect and classify all types of fault at varying fault
locations and show the ability to determine the fault location.

3- Draw the impedance trajectory for different fault type and locations with and without FACTS controllers.

4- Compares the result of the effect of series and shunt controller on the performance of distance relay.

1.7   Thesis Outline

The thesis is organized in six chapters. Chapter 1 provides an introduction and background information on power transmission system protection, on faults in transmission system, and on protective relays. Chapter 2 covers my results on the pertinent literature consulted, introduction on the concept and application of FACTS Controllers, and the principle operation of series (SSSC) and shunt (STATCOM) controllers. The impact of STATCOM and SSSC on the performance of distance relay is studied analytically in chapter 3. In Chapter 4, I provide a detailed description of the distance relay modeling using MATLAB/SIMULINK tools while in Chapter 5 implementation issues and simulation results are presented. Finally, in Chapter 6 concludes the thesis and indicate the possible future work.

CHAPTER 2

PERTINENT LITERATURE AND BACKGORUND

2.1   Pertinent Literature

In the presence of FACTS devices in the fault loop, the voltage and current values

at distance relay locations will be changed in both steady and transient state and the

impedance seen by distance relay will be affected. Many researchers investigated the

FACTS devices impact on performances of distance relays.

Zhou et al. [11] presented the apparent impedance calculation for single line to

ground fault based on symmetrical components of voltages and currents at relay location.

Their simulation results have shown the impact Static Synchronous Shunt Compensator

(STATCOM) on measured impedance for single line to ground and double line fault with

capacitive and inductive compensation. They found that the apparent impedance will

increase when the STATCOM generates reactive power and decrease if the STATCOM

consumes reactive power, and when the fault location increased, the error in measuring

impedance and the influence ratio of STATCON will increase. Effects of two types of

shunt controller FACTS devices, namely the static synchronous shunt compensator and

static VAR compensator, were reported in Sidhu et al. [12]. In their work, shunt

controllers were presented as shunt reactance to calculate the transmission line

impedance and they used artificial neural network for detecting and classifying the faults.

SVC and STATCOM can cause under-reach and incorrect phase selection. Also, this work discussed the over-reach phenomena caused by employing STATCOM in weak systems only. The results showed the distance relay is not the best relay in a mid-point STATCOM connected transmission line. In addition, STATCOM caused incorrect phase selection and increased the operation time of distance relay.

In Zhang et al. [13] , new setting rule of the zones of distance relay to mitigate STATCOM effects when it's connected in a mid-point. The suggested setting rules are based on the simulation results to mitigate the error in impedance measurement. Different setting rules for under-reach and over-reach are proposed in this work. Impedance relay based on digital distance relay algorithm using MATLAB/SIMULINK environment is presented in Alapati and Prasad work [14] and they presented a mathematical model of STATCOM. The analytical and simulation results showed the impact of STATCOM on distance relay for single line to ground fault. According to their results, the distance relay will not operate because the impedance trajectory shown the fault out of protected area. In Hemasundra et al. [15], detailed modeling of distance relay and STATCOM are presented using PSCAD/EMTDC. Different fault types and location are simulated with different operation mode of STATCOM. The simulation results showed the under-reach and over- reach problems resulted from injected reactive power to the system. The locations of STATCOM and distance relay have a significant effect on apparent impedance seen by protective relay.

Kazemi et al. [16] discussed the distance relay mal-operation when applied to protected transmission line that has static synchronous series compensator (SSSC).

Mathematical calculations for apparent impedance in presence of SSSC in transmission line under different fault types are studied. They reported that SSSC injected voltage caused a variation in the values of measured impedance. The work in [17] has presented detailed model of SSSC and its control. Analytical study based on voltages and currents symmetrical components for single phase to ground fault to show the impact of SSSC on distance relay performance is investigated. The simulation results showed that the error in apparent resistance increased in capacitive mode more than in inductive mode and the apparent reactance error increased in inductive mode more than in the capacitive mode. The apparent resistance and reactance increase in presence SSSC and the impact of SSSC is smaller for farther A-G faults. New equivalent symmetrical components of a 48-pulse SSSC and apparent impedance calculations for phase to ground and phase to phase fault are presented in [18]. The simulation results showed the apparent resistance and reactance values were increased in both capacitive and inductive compensation mode due to the effect of coupling transformer leakage impedance.

Khederzadeh et al. [19] presented the impact of VSC-Based multiline FACTS controller on performances of distance relay. Single phase to ground and phase to phase fault with multiline FACTS controller are studied analytically. The simulation results showed the distance relay mal-operate when power flow controlled in the system using multiple line FACTS controller such as generalized unified power-flow controller (GUPFC). In the work [20], a comparison between apparent impedance for uncompensated and compensated line with UPFC based on new pi-model is presented. Detailed modeling of UPFC during power swing condition and impact of different

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operation mode of a UPFC are investigated. The simulation results showed that the impedance circle increased in STATCOM operation mode and inductive mode of SSSC while the impedance circle decreased in capacitive mode of SSSC. Also, the speed of impedance trajectory movement increase with differ operation mode of UPFC.

It should be noted that most reported work showed the impact of one type of FACTS devices on distance relay for single phase to ground fault. Also noteworthy is the fact that employing STATCOM as shunt reactance resulted in a disagreement between the analytical and simulation results [13]. In fact, this is a possibility since the magnitude of the compensating reactance should not be equal (or less than) the line reactance to avoid reaching resonance and over-reach which may be caused by capacitive mode operation of STATCOM. These situations or operation conditions did not occur in simulations. In this thesis, a detailed modeling of digital distance relay is presented and we verified the proposed model under a variety of fault types and fault locations. Impact of shunt FACTS controller (STATCOM) and series FACTS controller (SSSC) on performances of distance relay are analytically investigated. In the rest of this chapter, an introduction and application of the FACTS controllers are presented.

2.2   Background on Flexible AC Transmission System

The FACTS is power electronic based devices used to improve the quality of power system and increase power transfer in transmission system. FACTS devices have an ability to control transmission system parameter such as voltage, current, impedance, and phase angle to maintain the system in the highest level of reliability. FACTS technology

is a collection of controllers can be applied individually or in coordination with other and can be classified into four types as follows [**3**]:

- Series Controllers: these can be series capacitor or reactor or a power electronic based variable source. Series Controllers inject voltage in series in phase angle 90 degree with line current. Due to the quadrature angle between the voltage and current, Series Controllers only generate or absorb reactive power. Examples of series controllers are Static Synchronous Series Compensator (SSSC), GTO Thyristor-Controlled Series Capacitor (GCSC), Thyristor-Switched Series Capacitor (TSSC), Thyristor-Controlled Series Capacitor (TCSC).

- Shunt Controllers: they may be variable impedance, variable source or combination of these. They injected current into the system at the connecting point in phase angle 90° with the line voltage. Shunt Controllers only generate or absorb reactive power due to the injected current in phase quadrature with line voltage. Examples of Shunt Controllers are Static Synchronous compensator (STATCOM), Static Synchronous Generator (SSG), Static Var Compensator (SVC).

- Combined Series-Series Controllers: these are a combined two or more separate series controllers, and used in a coordinated manner in a multiline transmission system. They compensate the reactive power in each line, and also exchange the real power the power link. These controllers balance the real and reactive power

in the lines and increase transmission system's capability. An example of Combined Series-Series Controllers is Interline Power Flow Controller (IPFC).

- Combined series-shunt Controllers: this type of controllers could be a combination of shunt or series controllers. They inject voltage in series in the line by the series controller part and inject current into the system via the shunt controller part. When series and shunt controllers connect together via power link, the real power will exchange between them. An example of Combined Series-Shunt Controllers is the unified Power Flow Controller (UPFC).

Series controllers affect directly on the voltage, current, and power flow, therefore using series-connected for controlling current/power flow and damping oscillations is much useful than shunt connected. Shunt controllers is the best FACTS controller for voltage control and voltage oscillations around the point of connection. The series controllers can be used for some shunt applications and vice versa. Regulating voltage at substation bus using shunt controller is more effective while compensating voltage drop in transmission system by injecting voltage in series is lower cost. In multiline transmission system, we can connect a separate series controller in each line or connect as shunt controller at the substation. The series controller connection needs to have smaller MVA rating than Shunt controller. Also, any type of shunt controllers does not control the power flow in transmission system. Because of these reasons, companied shunt and series controller is the best to control all of operational parameters of transmission system such as line impedance, voltage magnitude and phase [21].

There are many benefits from using FACTS technology such as:

➤ Increasing existing transmission lines capabilities

➤ Regulating voltage of transmission lines

➤ Improving transient and steady-state stability

➤ Improving damping of power oscillation

➤ Correcting power factor

➤ Eliminating current harmonic

➤ Improving HVDC-link performance [**12**]- [**22**].

2.3   Static Synchronous Compensator (STATCOM)

Static Synchronous Compensator (STATCOM) is one of the shunt type FACTS controllers and it can be based on a voltage-sourced or current-sourced converter. The STATCOM converts the input voltage (V_{dc}) into three phase output voltages with desired amplitude, frequency, and phase. In other words, the output voltage of the inverter must be in synchronous operation with the system voltage under any condition.

The best location of STATCOM is an application dependent. For example, the best location for STATCOM is at the midpoint of a transmission line connecting two systems because the voltage sag is the largest at the midpoint while the best location for a radial feed to a load system would be at the load end. STATCOM generates or absorbs reactive

power to control power system parameters and maintain them within an acceptable level [**3**].

Figure 2.1 shows the STATCOM for a voltage-sourced converter. The STATCOM will be in capacitive mode, generating reactive power to the ac system, and the current (I_{sh}) flows from the converter to ac system when the amplitude of output voltage (V_o) is greater than the ac system voltage (V_{ac}). If the amplitude level of converter output voltage is less that the ac system voltage, the current will flow from the ac system to the converter and the STATCOM will be in inductive mode (absorbing reactive power from the ac system) [**23**]. A multilevel inverter is appropriate converter to design STATCOM due to the fact that the output voltage of the inverter must be very close to sinusoidal waveform [**24**]. In this work, four 12-pulse three-level Gate turn-off Thyristor (GTO) inverters are used to convert the dc voltage into mostly sinusoidal three phase output voltages.
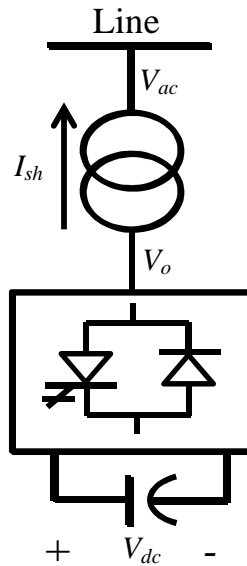
Figure 2.1 : STATCOM based on voltage-sourced converter

2.4   Static Synchronous Series Compensator (SSSC)

Static Synchronous Series Compensator is the one of series type FACTS controllers and it can be based on a voltage-sourced or current-sourced converter. SSSC is connected in series with transmission line through a coupling transformer as shown in figure 2.2. SSSC convert the input voltage (v_{dc}) to the three phase output voltage lags or leads line current with 90 degree. The outputs of the convertor are three phase voltages at fundamental frequency with controllable amplitude and phase angle. SSSC is able to exchange real power when its dc terminals connected to external dc source or energy storage [3].
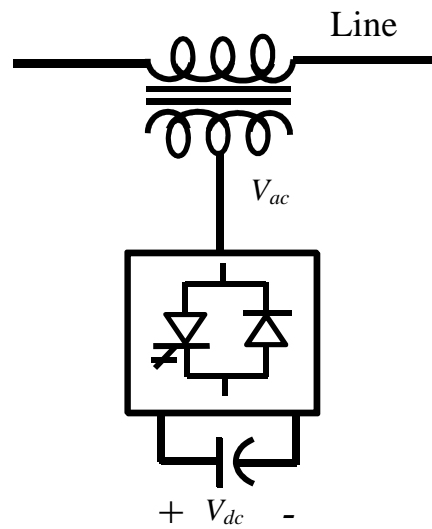
Figure 2.2: Static Synchronous Series Compensator based on a voltage-sourced converter

When the injected voltage leads the line current, the SSSC provide series capacitive compensation of line current. In this case, the line impedance will decrease and the transmitted power in transmission system will increase. The SSSC provide series inductive compensation of line current, if the injected voltage lags the line current. In inductive compensation, the line impedance will increase and the transmitted power in transmission system will decrease [25].

CHAPTER 3

APPARENT IMPEDANCE ANALYSIS

3.1   Apparent Impedance calculation at Relay Location

The measured impedance seen by distance relay should be equal to actual

impedance of the transmission line. It is calculated by dividing the voltage and current at

relay location (V_R / I_R). The voltage and current at relay point will be different for each

type of fault as shown in table 3.1 [26].

Table 3.1: Voltage and Current Signals at Relay Point

Fault type	V_R	I_R
AG	V_{an}	$I_a + KI_O$
BG	V_{bn}	$I_b + KI_O$
CG	V_{cn}	$I_c + KI_O$
AB/ABG	$V_{an} - V_{bn}$	$I_a - I_b$
AC/ACG	$V_{an} - V_{cn}$	$I_a - I_c$
BC/BCG	$V_{bn} - V_{cn}$	$I_b - I_c$
ABC/ABCG	V_{an} OR V_{bn} OR V_{cn}	I_a OR I_b OR I_c

Where:

A, B, C indicates faulty phase, G indicates Ground.

I_a, I_b, I_c indicates current phases.

V_{an}, V_{bn}, V_{cn} indicates voltage phases.

$K = (Z_O - Z_1) / Z_1$, residual compensation factor.

$I_O = (I_a + I_b + I_c)/3$: zero-sequence current

Z_O, Z_1 zero-sequence impedance , positive-sequence impedance respectively.

Note: in three phase fault, the phase voltage and current must be for the same phase. If V_R equal to V_{an}, the I_R must be equal to I_a.

We can draw an equivalent circuit for the section between relay and fault location as shown in figure 3.1.
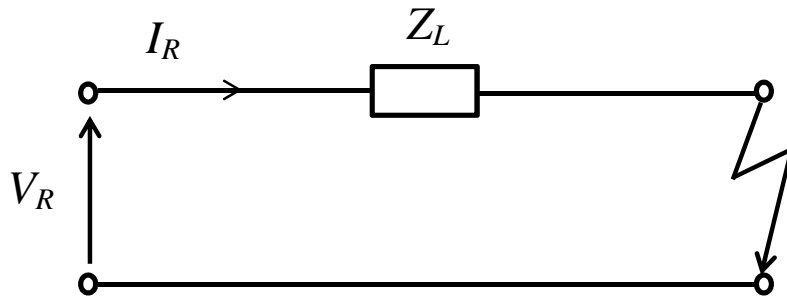
Figure 3.1: Equivalent circuit during a fault loop with zero fault resistance

In figure 3.1 we have

V_R, I_R: voltage and current at Relay location

Z_L: The actual impedance of transmission line

From Figure 3.1 will get

$$Z_L = \frac{V_R}{I_R}$$
(3.1)

3.2   Measured Impedance in STATCOM Compensated Transmission Line

        The STATCOM is connected in parallel in transmission line to regulate the

voltage at the connecting point. It is represented as current source due to the fact of it

injecting or consuming current, and it will separate the transmission line into two parts as

shown figure 3.2. This study shows how the STATCOM clearly affect the measured

impedance when it is employed within the fault loop. The error in measuring impedance

due to different locations and different operating modes of STATCOM will be discussed

analytically in this section.
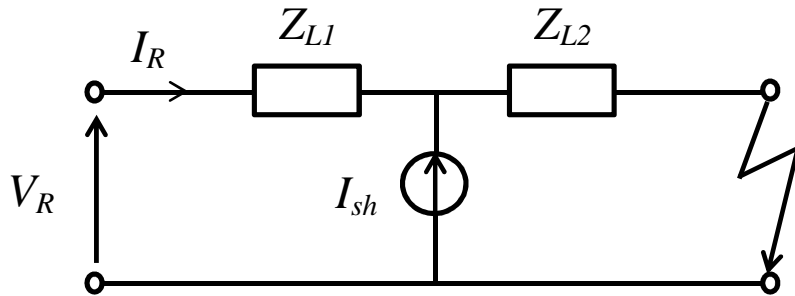
Figure 3.2: Transmission line with midpoint STATCOM equivalent circuit during a fault
loop.

In Figure 3.2, we have

I_{sh}: STATCOM shunt current

$Z_{L1} = (1-d) Z_L,$

$Z_{L2} = d\ Z_L$

d is a coefficient calculated from the ratio of the distance between fault location and STATCOM location to the distance between fault location and relay location.

By converting the current source to voltage source shown in Figure 3.2, we can measure the apparent impedance of transmission line as follows:

$$V_R = V_{ZL1} + I_{sh}\ Z_{L2} + V_{ZL2} \tag{3.2}$$

Dividing equation (3.2) by I_R, will have

$$\frac{V_R}{I_R} = \frac{V_{ZL1}}{I_R} + \frac{I_{sh}\ Z_{L2}}{I_R} + \frac{V_{ZL2}}{I_R} \tag{3.3}$$

Substitute $V_R/I_R = Z_{app}$, $V_{ZL1}/I_R = Z_{L1}$, $V_{ZL2}/I_R = Z_{L2}$ into equation (3.3), the apparent impedance of transmission line will be

$$Z_{app} = Z_{L1} + Z_{L2} + \frac{I_{sh}}{I_R} Z_{L2} \tag{3.4}$$

Also

$$Z_{L1} + Z_{L2} = Z_L \quad \text{(the actual impedance of transmission line)}$$

$Z_{L2} = d\ Z_L$

$$Z_{app} = Z_L + \frac{I_{sh}}{I_R}(dZ_L) \tag{3.5}$$

From equation 3.5, the amount of error for measuring impedance ($\frac{I_{sh}}{I_R}(dZ_L)$) is affected

by two factors: 1) compensation ratio (Cr = $\frac{I_{sh}}{I_R}$) and 2) the distance between the fault

location and STATCOM location.

The compensation ratio is used to identify STATCOM three operation modes:

- Cr > 0, represents STATCOM in capacitive mode and the direction of (I_{sh})is

  from STATCOM to ac system. The apparent impedance seen by distance relay

  will be greater than the actual impedance.

- Cr < 0, represent the STATCOM in inductive mode and the direction of (I_{sh})is

  from ac system to STATCOM. The apparent impedance seen by distance relay

  will be smaller than the actual impedance.

- Cr = 0, represent that there is not exchange reactive power between STATCOM

  and ac system. The apparent impedance seen by distance relay will be equal to the

  actual impedance.

Figure 3.3 shows the error in impedance measurements due to STATCOM operation

modes When the SATATCOM in capacitive mode (Cr > 0), the impedance is greater than

the actual impedance and the distance relay in under-reach operation mode. The over-

reach operation mode of distance relay is caused by inductive mode of STATCOM (Cr <

0). Also, it is clear that the apparent impedance is equal to the actual impedance (d =0)

when fault occurs before STATCOM location
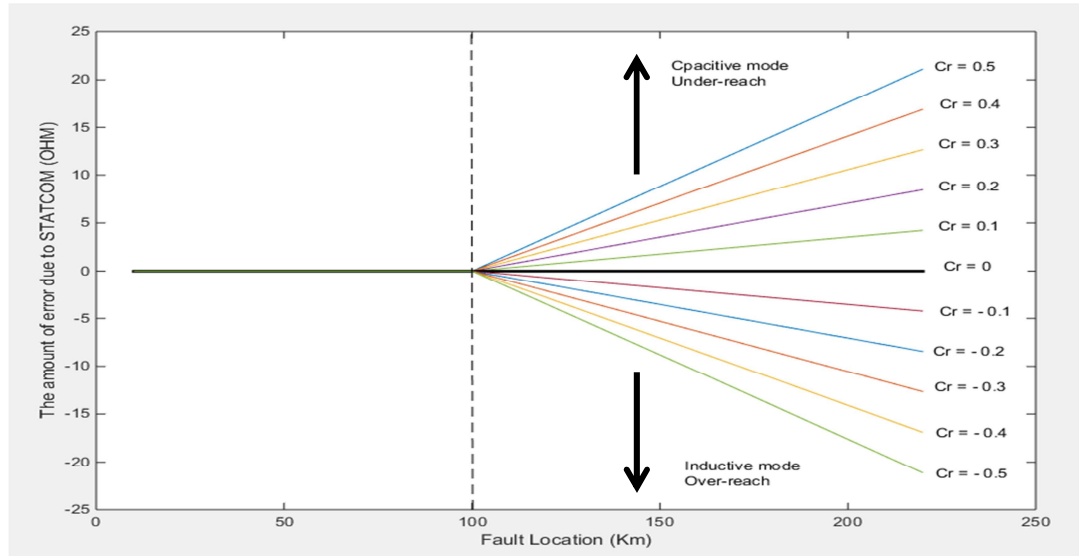
Figure 3.3: The error in impedance measurement for different fault location and different mode of STATCOM, The STATCOM installed at 100 km.

3.3 Measured Impedance in SSSC Compensated Transmission Line

The SSSC is one of most important FACTS controllers used to control the power and current flow in transmission system. In the normal SSSC, the ac output voltage of inverter leads or lags the line current by 90 degree. The SSSC is a variable voltage source connected in series with transmission line and like STATCOM, SSSC break the transmission line in to two parts as shown in figure 3.4.
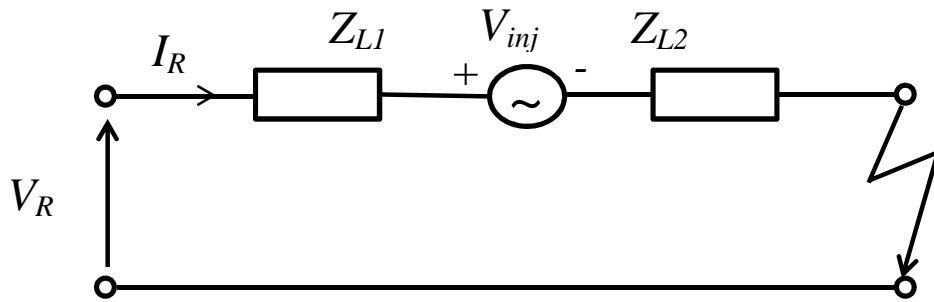
Figure 3.4: Equivalent circuit during a fault loop with SSSC.

Where

$V_{inj:}$ SSSC injected voltage

From figure 3.4, we get

$$V_R = V_{ZL1} - V_{inj} + V_{ZL2} \tag{3.6}$$

Dividing equation (3.6) by I_R, will have

$$\frac{V_R}{I_R} = \frac{V_{ZL1}}{I_R} - \frac{V_{inj}}{I_R} + \frac{V_{ZL2}}{I_R} \tag{3.7}$$

Substitute $V_R/I_R = Z_{app}$, $V_{ZL1}/I_R = Z_{L1}$, $V_{ZL2}/I_R = Z_{L2}$ into equation (3.7), the apparent

impedance of transmission line will be

Also

$Z_{L1} + Z_{L2} = Z_L$ (The actual impedance of transmission line)

$$Z_{app} = Z_L - \frac{V_{inj}}{I_R} \qquad\qquad (3.8)$$

Substitute $I_R = \frac{V_R - V_{inj}}{Z_L}$ in equation (3.8), the apparent impedance will be

$$Z_{app} = Z_L - \frac{V_{inj}}{V_R - V_{inj}} Z_L \qquad\qquad (3.9)$$

From equation 3.9, the amount of error for measuring impedance will be ($\frac{-V_{inj}}{V_R - V_{inj}} Z_L$).

The compensation ratio ($Cr = \frac{-V_{inj}}{V_R - V_{inj}}$) is used to identify SSSC three operation modes:

- Cr < 0 represents SSSC in capacitive mode and the injected voltage leads the line current. The apparent impedance seen by distance relay will be smaller than the actual impedance.

- Cr > 0, represent the SSSC in inductive mode and the injected voltage lags the line current. The apparent impedance seen by distance relay will be greater than the actual impedance.

–   Cr = 0, represent that there is not exchange reactive power between SSSC and ac system. The apparent impedance seen by distance relay will be equal to the actual impedance.

Figure 3.5 shows the apparent impedance due to SSSC operation modes. When the SSSC in capacitive mode (Cr < 0), the impedance is smaller than the actual impedance and the distance relay in over-reach operation mode. The under-reach operation mode of distance relay is caused by inductive mode of STATCOM (Cr > 0). Also, it is clear that the apparent impedance is equal to the actual impedance, when fault occurs before SSSC location.
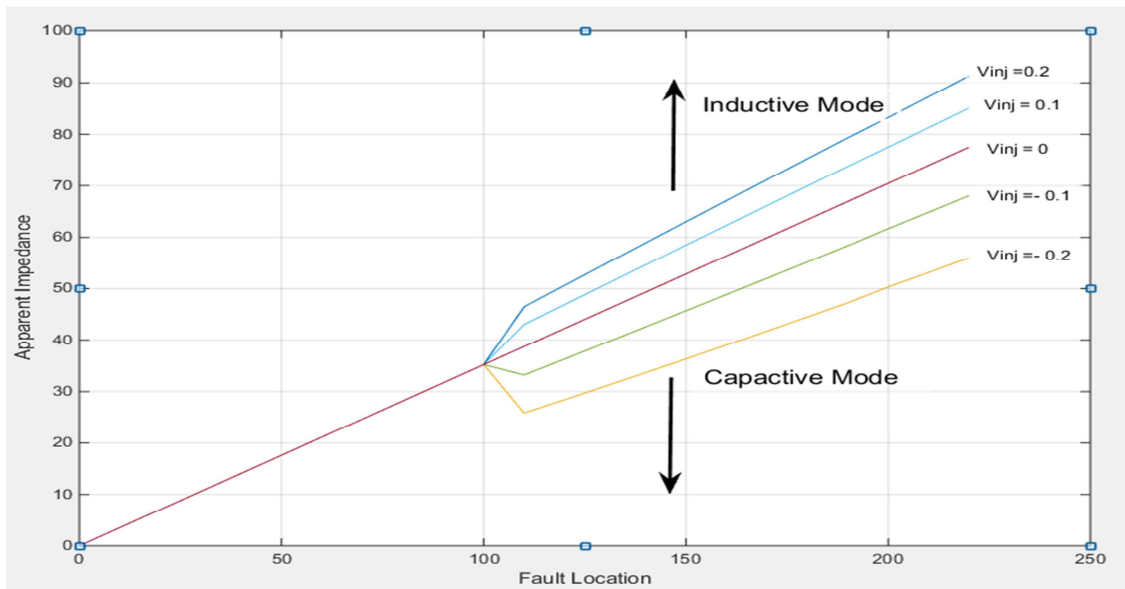

Figure 3.5: The apparent impedance seen by distance relay for different fault location and different mode of SSSC, The SSSC installed at 100 km.

CHAPTER 4

PROPOSED METHODOLOGY: MODELING OF DISTANCE RELAY IN
TRANSMISSION LINE

4.1   Introduction

MATLAB/SIMULINK package is a powerful package offers a good environment
to model and simulate a variety of Digital Protective Relays. MATLAB/SIMULINK
libraries content almost all power system requirements such as three phase sources,
transformers, transmission lines, three phase load. In addition, it includes many other
items which help to implement Digital Relay Protection such as Voltage Transformer
(VT), Current Transformer (CT), voltage and current measurements, and three phase fault
maker. Logical components and signal processing libraries, Analog to Digital converter,
Filters, phasor estimation, which are provided by Simulink toolbox are used to modeling
digital protective relay [**3**].

Measurements of the voltage and current for each phase (V_{an}, V_{bn}, V_{cn}, I_a, I_b, I_c) at
the relay location and computing of impedance according to fault type used enabled us to
models of the distance relay. Comparing the measured impedance with impedance setting
values for each zone allows for a fault or no faults to be declared and provided its zone
information if any. The distance relay model also allows for an activation of a tripping

signal which is transmitted to the suitable circuit breaker to isolate the faulty zone from the rest of the system or network. Therefore, I focus on distance relay model using MATLAB/SIMULINK package in this chapter.

4.2 Modeling Distance Relay Requirement

In the MATLAB/SIMULINK, each subsystem is established separately and they are connected together to compose the larger power transmission system. This feature allows us to test each subsystem individually and thus simulations of the larger system can be more forward. The subsystems we proposed are based on the main functions of a typical digital distance relay [27]. These are:

1- Fault detection and classification.

2- Apparent impedance measurement.

3- Zone detection.

4- Tripping signal.

4.2.1 Fault Detection and Classification

`   Designing Fault detection and classification is very important in distance relay to avoid unnecessary tripping of circuit breakers. Appropriate selection for fault types will minimize errors such as in cases where a tripping of three phase results when only one phase clearance is required. Also, it is necessary to calculate the apparent impedance because every types of fault has own impedance algorithm.

The following steps are used in the design of a subsystem:

1- Measuring the current for each phase at relay location using Three-Phase V-I Measurement block.

2- Comparing the fault current with pre-fault current for each phase using *If and If Action* subsystems. The output of the comparator will be one at the time that the current exceeds the pre-fault current (reference current).
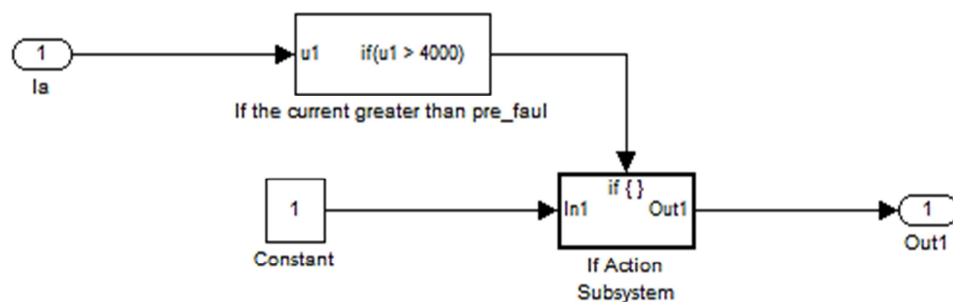

Figure 4.1: Fault comparator structure

3- Classifying the fault type using logical components based method since the output of comparator is binary. Table 4.1 shows the possible inputs and desired outputs (fault type) cases. Then, we can find the type of fault by resolving input data by using Karnaugh-Maps or other technique [28].

Table 4.1 : Inputs and Desired Outputs for Fault Detection and Classification Subsystem

I_a	I_b	I_c	I_G	AG	BG	CG	ABG	AB	BCG	BC	ACG	AC	ABCG	ABC
0	0	1	1	0	0	1	0	0	0	0	0	0	0	0
0	1	0	1	0	1	0	0	0	0	0	0	0	0	0
0	1	1	1	0	0	0	0	0	1	0	0	0	0	0
0	1	1	0	0	0	0	0	0	0	1	0	0	0	0
1	0	0	1	1	0	0	0	0	0	0	0	0	0	0
1	0	1	1	0	0	0	0	0	0	0	1	0	0	0
1	0	1	0	0	0	0	0	0	0	0	0	1	0	0
1	1	0	1	0	0	0	1	0	0	0	0	0	0	0
1	1	0	0	0	0	0	0	1	0	0	0	0	0	0
1	1	1	1	0	0	0	0	0	0	0	0	0	1	0
1	1	1	0	0	0	0	0	0	0	0	0	0	0	1

For example, to find AG fault using Karnaugh-Maps methods, we generate

SO

Then $AG = Ia.\overline{Ib}.\overline{Ic}$ this means indicator phase A to ground fault result from

$I_a\ AND\ (NOT\ (I_b))\ AND(NOT(I_c))$

We can implement this equation using logical components in MATLAB/SIMULINK.
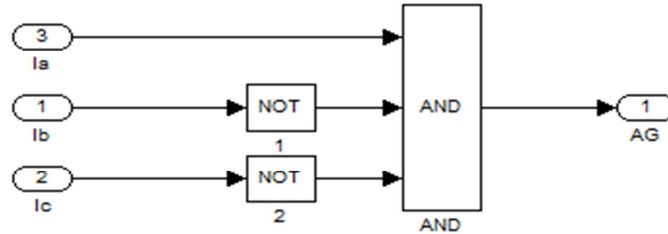
Figure 4.2: Fault detection and classification block for AG fault using logical components

All other fault types were also implemented and results are summarized in Table 4.2.

Table 4.2: Fault Classification Based on Digital Components

Types of fault	Digital input signals
AG	I_a AND (NOT I_b) AND (NOT I_c) AND I_G
BG	(NOT I_a) AND I_b AND (NOT I_c) AND I_G
CG	(NOT Ia) AND (NOT I_b) AND I_c AND I_G
AB	I_a AND I_b AND (NOT I_c) AND (NOT I_G)
ABG	I_a AND I_b AND (NOT I_c) AND I_G
AC	I_a AND (NOT I_b) AND I_c AND (NOT I_G)
ACG	I_a AND (NOT I_b) AND I_c AND I_G
BC	(NOT Ia) AND I_b AND I_c AND (NOT I_G)
BCG	(NOT Ia) AND I_b AND I_c AND I_G
ABC	I_a AND I_b AND I_c AND (NOT I_G)
ABCG	I_a AND I_b AND I_c AND I_G

Figure.4. 4and figure 4.5 show the fault detection and classification subsystem.

The inputs of this subsystem are phase currents and the outputs are the signals which will

determine which impedance algorithm for the apparent impedance calculation for each

type of possible fault. Table 4.2 presents the methods used with each fault type.
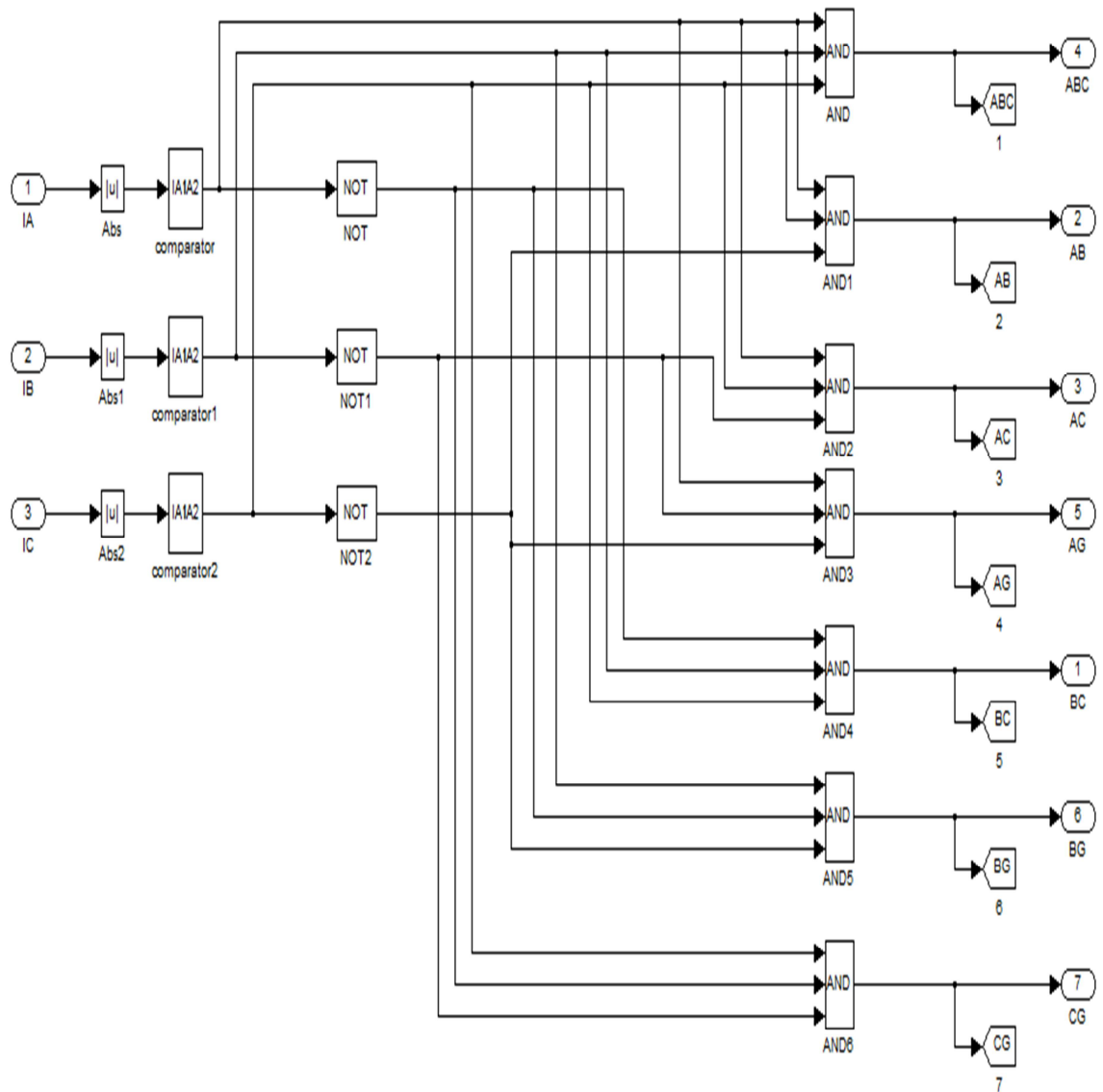

Figure 4.3: Fault detection and classification block (ignored grounding because it is
unnecessary to select impedance algorithm because the fault with or without ground has
same impedance algorithm)
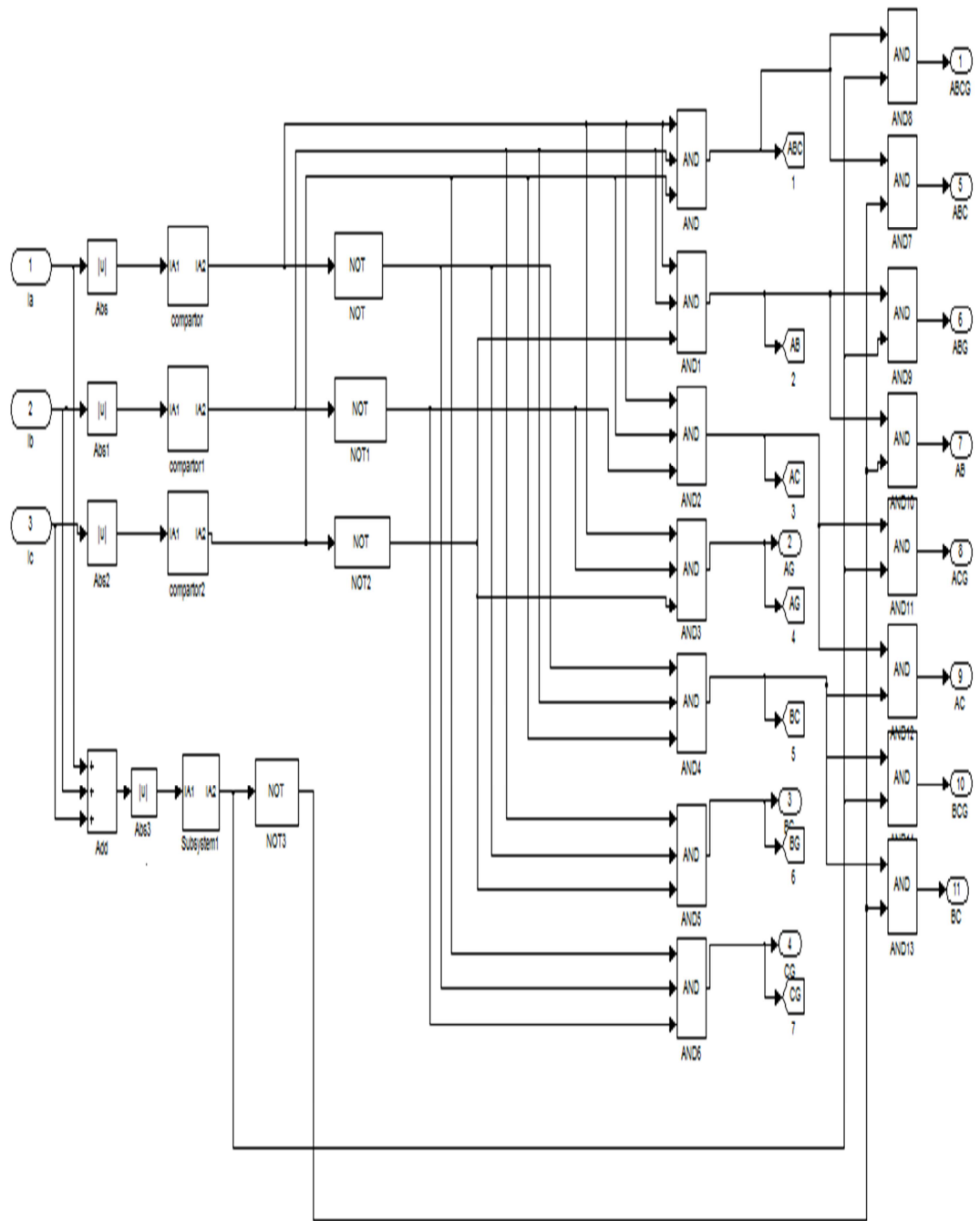
Figure 4.4: Fault detection and classification block, this figure is also available in appendix A

Figure 4.5: Overall fault detection and classification

4.2.2   Apparent Impedance Measurement

Apparent impedance measurement block includes all impedance algorithms to calculate the apparent impedance by measurement the voltages and currents at relay location. The output signal from fault detection and classification block select which impedance algorithm must be used.

Table 4.3 shows the impedance algorithm for various types of fault.

Table 4.3: Fault Impedance Calculation on Difference Faults

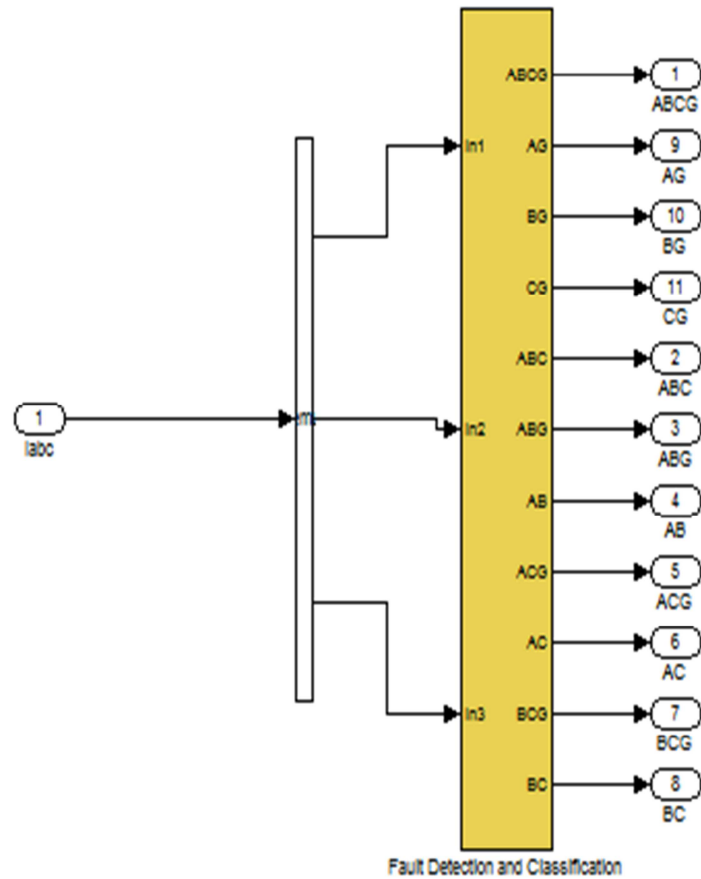| Fault type	Algorithm
AG	$V_{an} / (I_a + KI_O)$
BG	$V_{bn} / (I_b + KI_O)$
CG	$V_{cn} / (I_c + KI_O)$
AB/ABG	$(V_{an} - V_{bn}) / (I_a - I_b)$
AC/ACG	$(V_{an} - V_{cn}) / (I_a - I_c)$
BC/BCG	$(V_{bn} - V_{cn}) / (I_b - I_c)$
ABC/ABCG	(V_{an} / I_a) OR (V_{bn} / I_b) OR (V_{cn} / I_c)

Where:

A, B, C indicates faulty phase, G indicates Ground.

I_a, I_b, I_c indicates current phases.

V_{an}, V_{bn}, V_{cn} indicates voltage phases.

$K = (Z_O - Z_1) / 3Z_1$, residual compensation factor.

$I_O = (I_a + I_b + I_c)/3$: zero-sequence current

Z_O , Z_1 zero-sequence impedance , positive-sequence impedance respectively

Apparent impedance measurement block receive the voltages and currents in discrete form from V-I measurement and process these inputs to get the magnitude and phase angle for each input which are required to calculate the apparent impedance.

The processes in this block are;

1- Extract the input vector into three separate signals using DEMUX block.

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2- Convert the complex input signal into magnitude and phase angle.

3- Use the impedance algorithm.

4- Convert the calculated impedance from magnitude and angle into real
(transmission line resistance) and imaginary (transmission line reactance).

5- Send the outputs to Work Space to use them for drawing the impedance trajectory
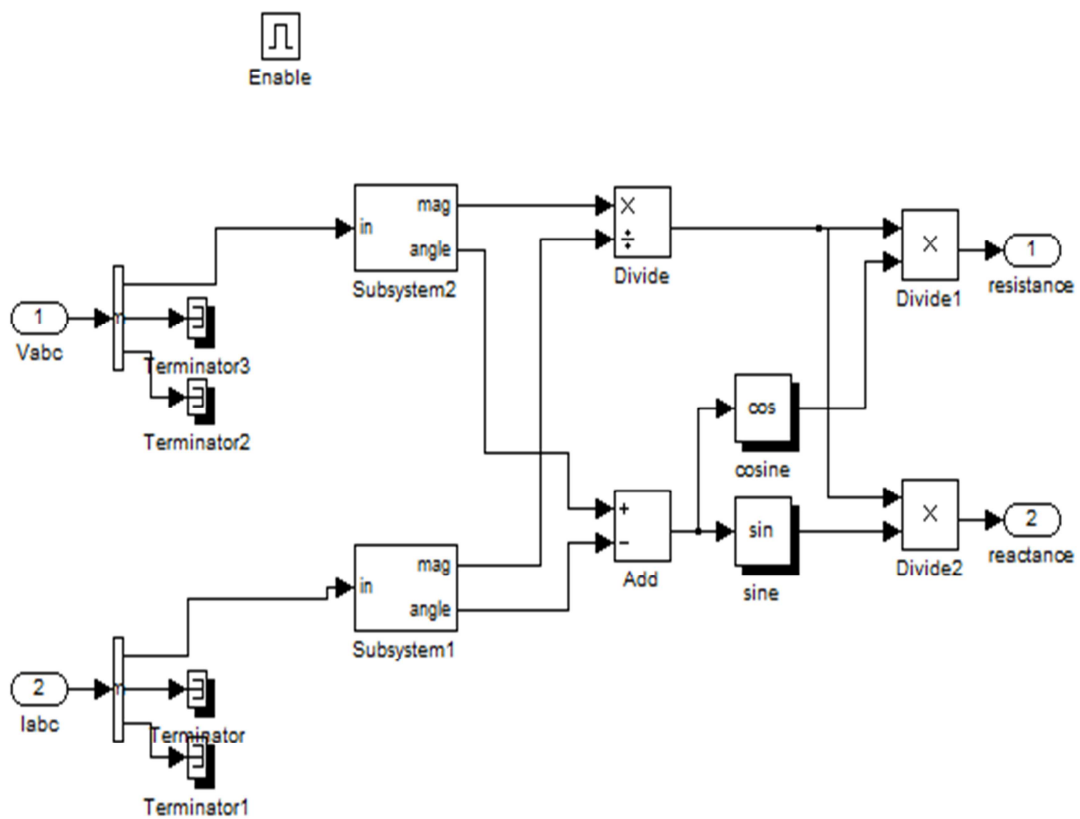
Figure 4.6: Apparent impedance model for three-phase fault
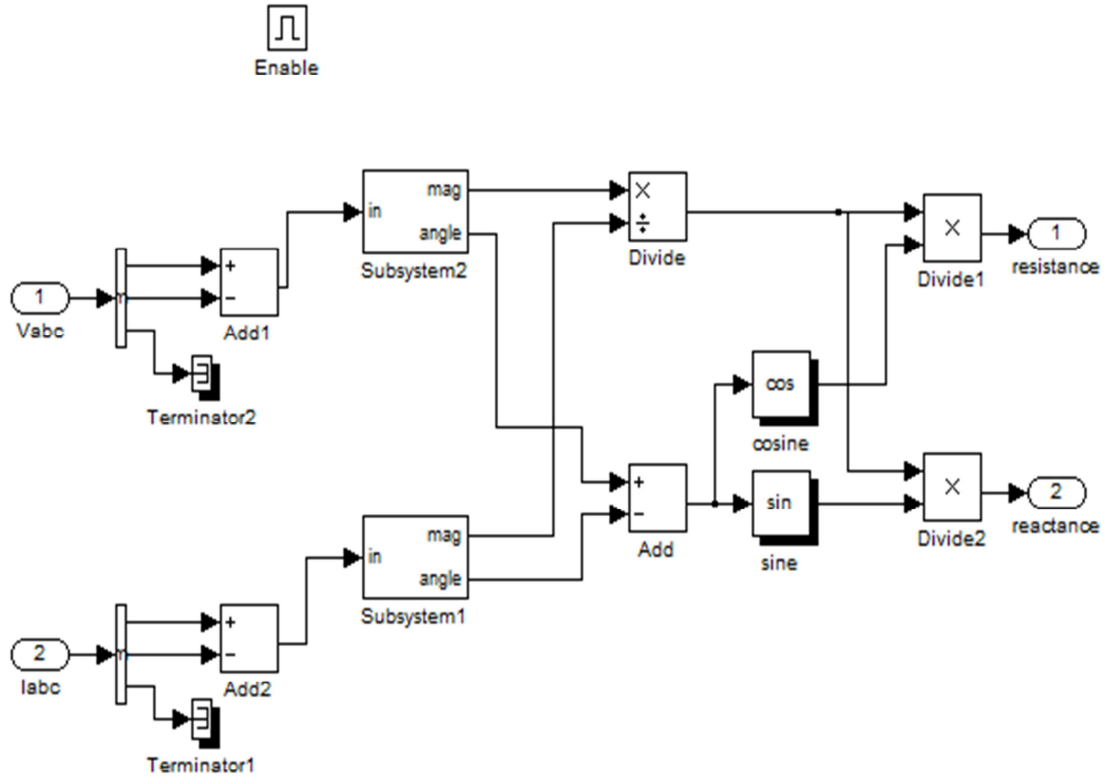
Figure 4.7: Apparent impedance model for DLG (fault between phase A and B)
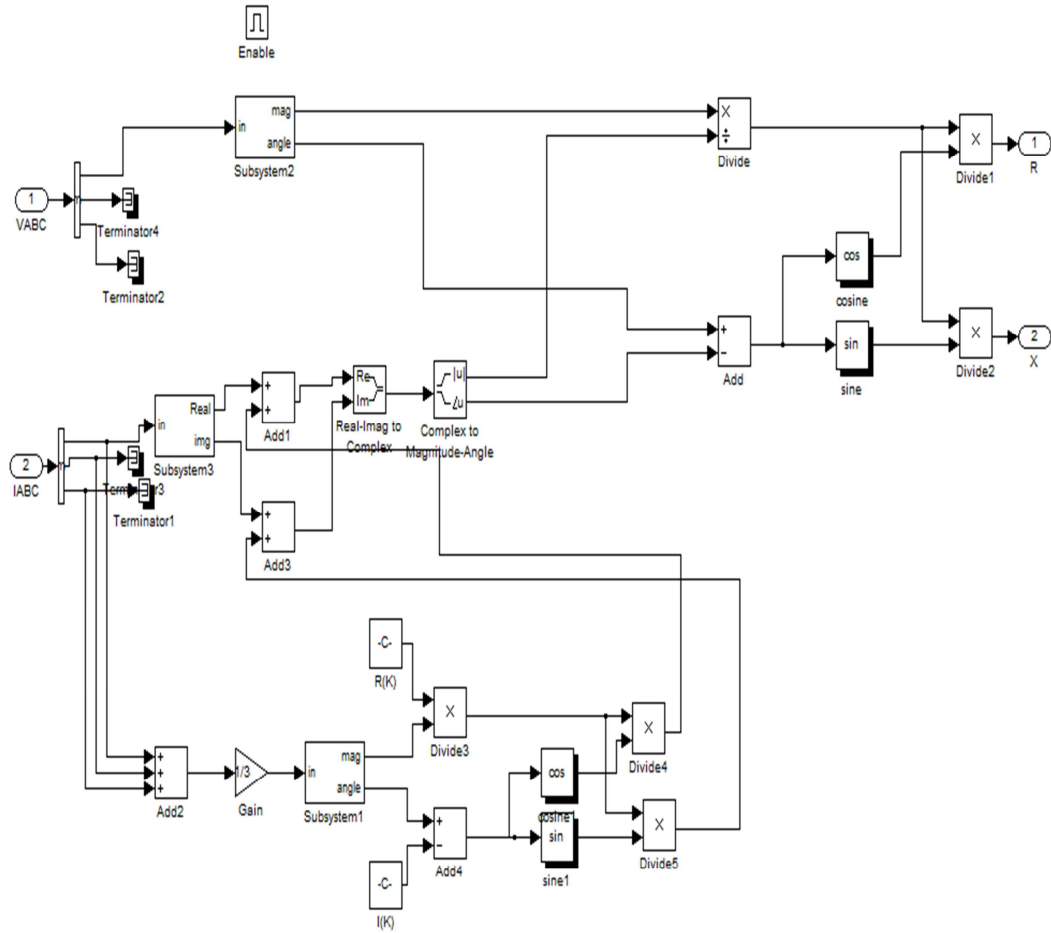
Figure 4.8: Apparent impedance model for SLG (at phase A), this figure is also available in appendix

Figures(4.6), (4. 7), and (4.8) show the apparent impedance measurement subsystems for three-phase fault, double line fault, and single line to ground fault respectively. These blocks are built by using Enable Subsystem Block, which works when it receives an enabling signal. Figure 10 shows the overall apparent impedance block.

Figure 4.9: Overall apparent impedance measurement subsystem, this figure is also available in appendix

4.2.3 Zone Detection

According the principle operation of distance relay, the transmissions line is divided into several zones. Practical distance relay has three zones [6], but we can divide the transmission line into five zones. If distance relay indicate the fault in zone 1, distance relay will send 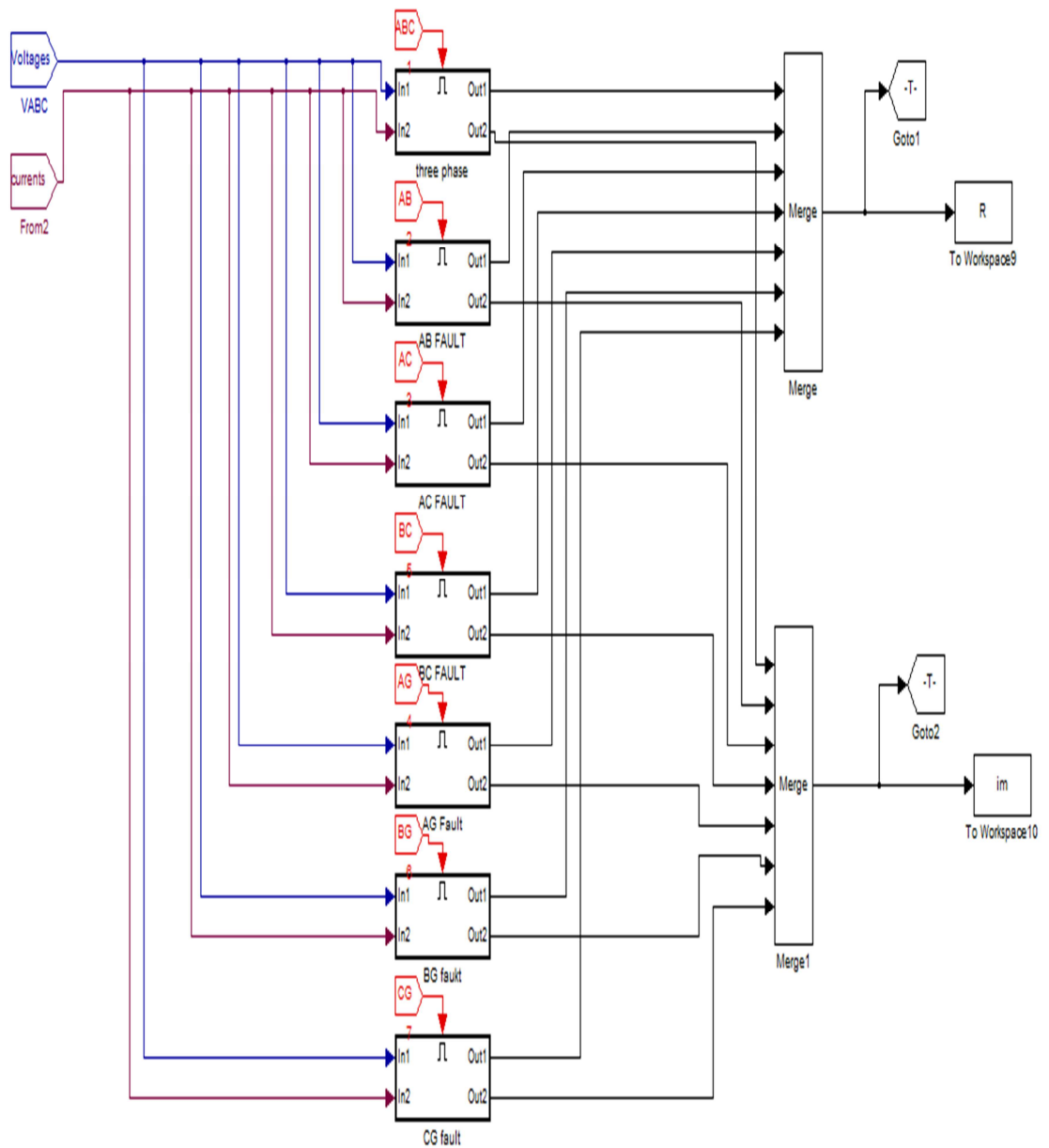tripping signal into circuit breaker immediately, while there is a time delay if the fault in zone 2 or zone 3. Many factors select the number of zones and the tripping delay such as power system configuration and coordination the distance relay with other protected relay.

Figure 4.10 shows the zone detection subsystem produced using MATLAB/SIMULING. This block received the input signal from apparent impedance measurement block, and the output is the number of zone

Table 4.4: Setting Point of Three Zones Distance Relay

Zones	Setting Point
Zone1	Cover 80% to 85% of protect line
Zone2	120% of protect line
Zone3	220% of protect line

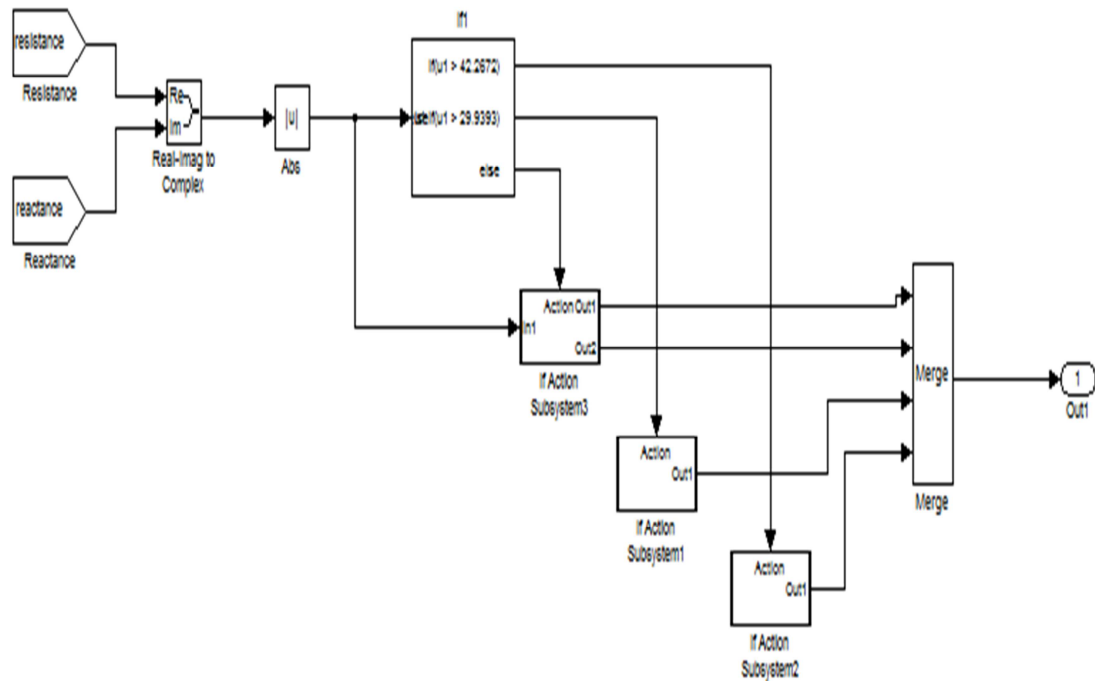Figure 4.10: Zone detection subsystem

4.2.4 Tripping Signal

This subsystem received the number of zone from zone detection subsystem and the operation in this subsystem is delaying tripping signals as shown in figure 4.11.

Table 4.5: The Typical Time Delay for Three Zones Distance Relay

Zones	Time Delay
Zone1	0ms (instantaneously)
Zone2	250ms
Zone3	800ms
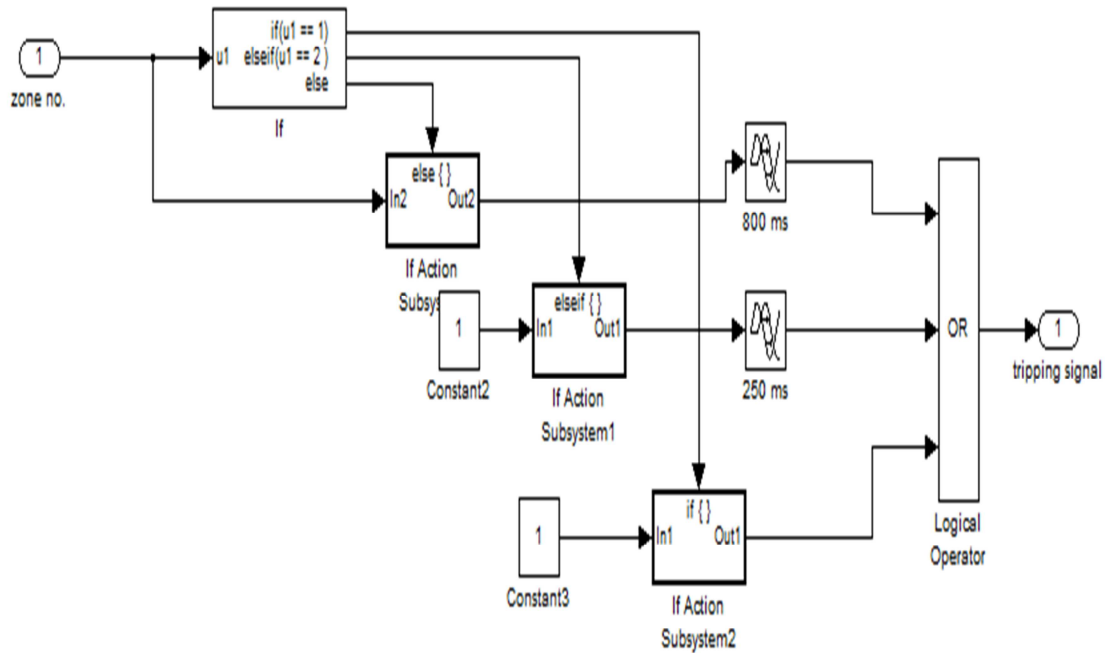
Figure 4.11: Our model for the tripping signal subsystem. The input is the number of zone to isolate and the output is the tripping signal.

4.3   MHO Characteristics

Mho characteristic is an important to understand the behavior of distance relay, and it is considered as a final stage of distance relay. This characteristic is drawn by using M-file MATLAB, and it shows the related between the resistance and the reactance of transmission line. Every circle in the shape represents the setting impedance for each zone which has to be calculated first.
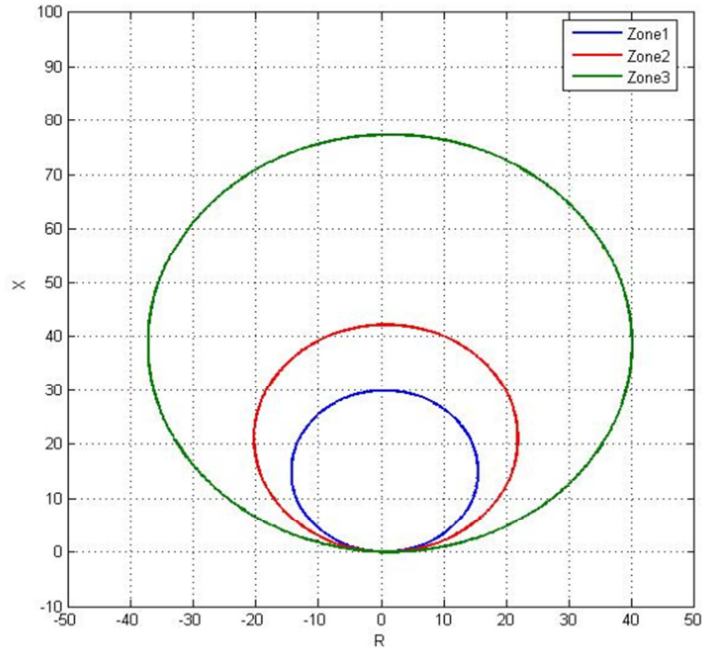
Figure 4.12: Three zones Mho Characteristics, the X-axis is transmission line resistance

in (Ω), R, and the Y-axis is the transmission line reactance in (Ω), X.

4.4   The Complete System Distance Relay Model

Fig 4.13 shows the whole modeling of distance relay block is built by

MATLAB/SIMULING. The inputs of distance relay are phase voltages and

currents, and the outputs are fault types indicators, zone indicator, the values of

transmission line resistance and reactance to use later for drawing impedance

trajectory, and tripping signal.
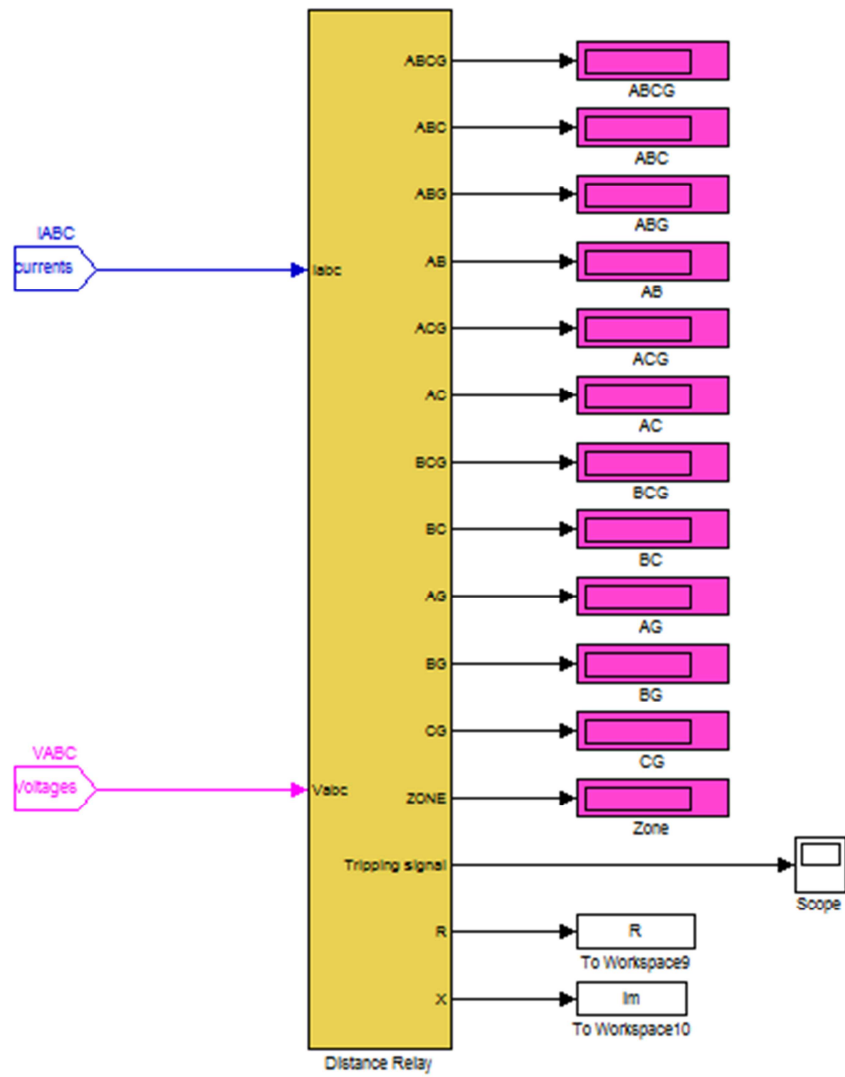
Figure 4.13: Distance relay model showing its inputs are the currents and voltages measured at relay location and outputs are fault types indicators, tripping signals, and transmission line resistance and reactance

CHAPTER 5

EXPERIMENTAL RESULTS AND ANALYSIS

5.1   Power System Parameters

As a case study, simulation is modeled on a 500KV single circuit transmission lines,

300 km in length, connected to a source at one end as shown in figure 5.1. This system

simulated with MATLAB/SIMULINK package.
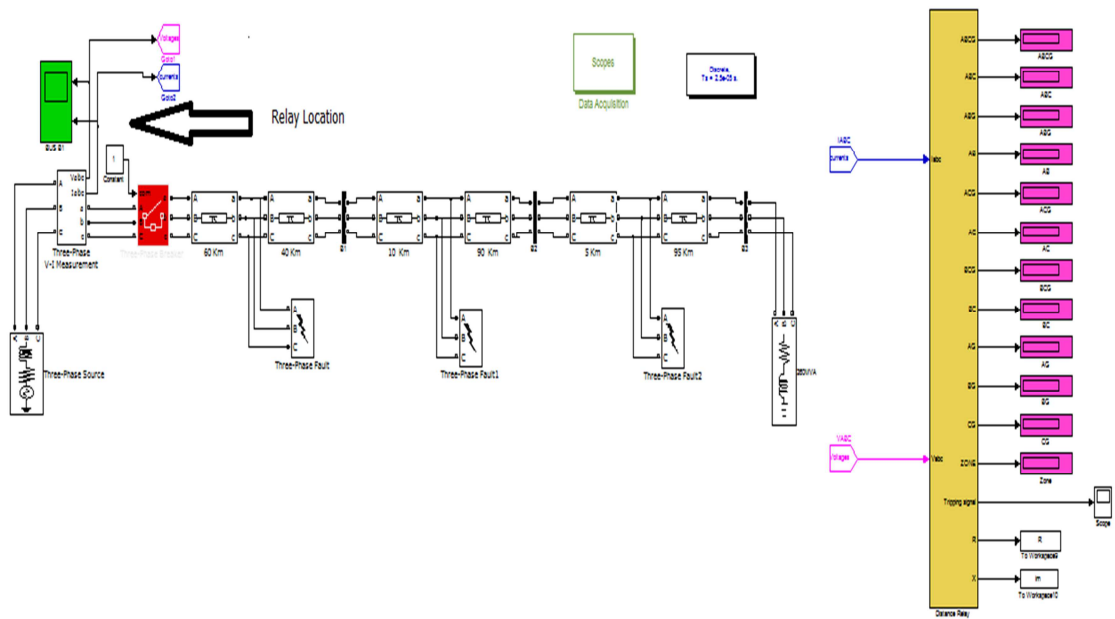
Figure 5.1: Simulation power system in MATLAB/SIMULINK, this figure is also
available in appendix

1- Three-Phase Source Data

The Three-Phase Source block implements a balanced three-phase voltage source with internal R-L impedance. The three voltage sources are connected in Y with a grounded neutral. The source data are given in Table 5.1.

Table 5.1: Source Data

Parameter	Data
Phase –to –Phase rms voltage (V)	500 KV
Positive sequence source resistance	0.8929 ohms
Positive sequence inductance	16.58 mH
Base voltage (Vrms ph-ph):	500 KV
Power system frequency	60 Hz

2- Three-Phase Transmission line Data

The Three-Phase PI Section Line block used to implement a balanced three-phase transmission line. The transmission line data are given

in Table 5.2.

Table 5.2: Transmission Line Data

Parameter	Data
Positive sequence resistance	0.01273 Ω/km
Zero sequence resistance	0.3864 Ω/km
Positive sequence inductance	0.9337 mH/km
Zero sequence inductance	4.1264 mH/km

3- Three-Phase Load

The Three-Phase Series RLC Load block used to implement a three-phase balanced load as a series combination of RLC elements. Three-Phase Load is connected in Y with a grounded neutral. Three-Phase Load data are given in Table 5.3.

Table 5.3: Three-Phase Load Data

Parameter	Data
Nominal phase-to-phase voltage	500 KV
Nominal frequency	60 Hz
Active power P	208 MW
Inductive reactive power QL	156 MW
Capacitive reactive power Qc	0 MW

4- Distance Relay Zone Settings

The setting zones of distance relay are calculated from the values of the positive

sequence resistance and inductance in transmission line as shown in table 5.4.

Table 5.4: Three Zones Setting Impedance

Zones	Setting	Values(Ω)
Zone1	85%TL1(85km)	29.9393∠87.9288
Zone2	TL1+20%TL2(120km)	42.2672∠87.9288
Zone3	TL1+TL2+20%TL3(220km)	77.4899∠87.9288

5.2   Simulation Results and Discussion

To study the impact of STATCOM and SSSC on performance of distance relay, we

used 48-puls STATCOM and SSSC were designed by MATLAB/SIMULINK

environment and they have many applications like regulate voltage by setting the desired

reference voltage, fix the reactive power, and fix the reactive current [**29**]. The FACTS

devices installed at 100 km of transmission line as shown in figures 5.2 and 5.3.
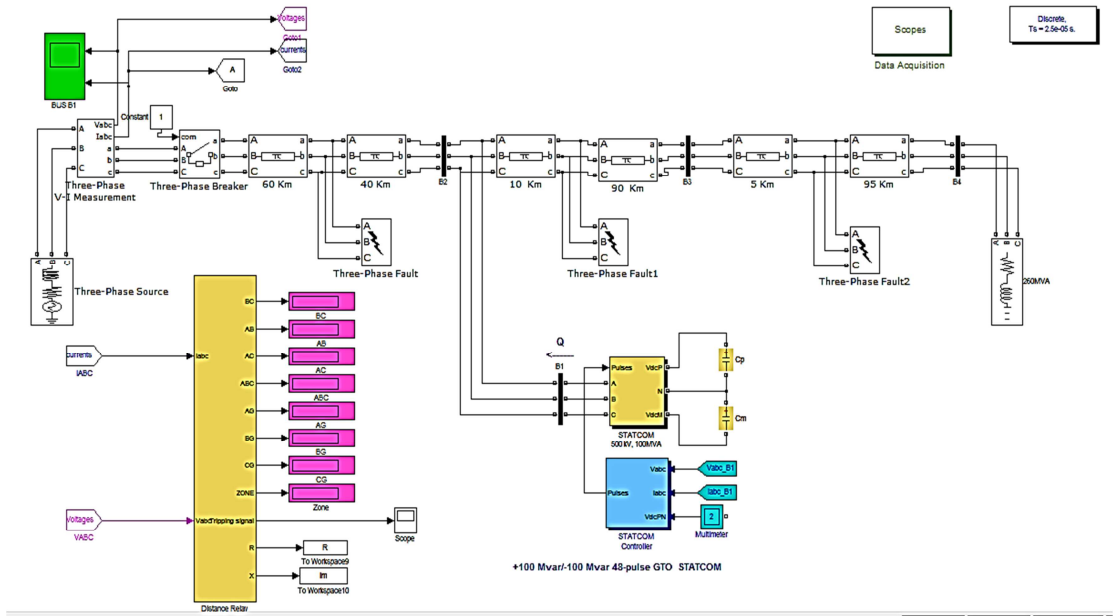
Figure 5.2: Simulation power system with STATCOM, this figure is also available in appendix
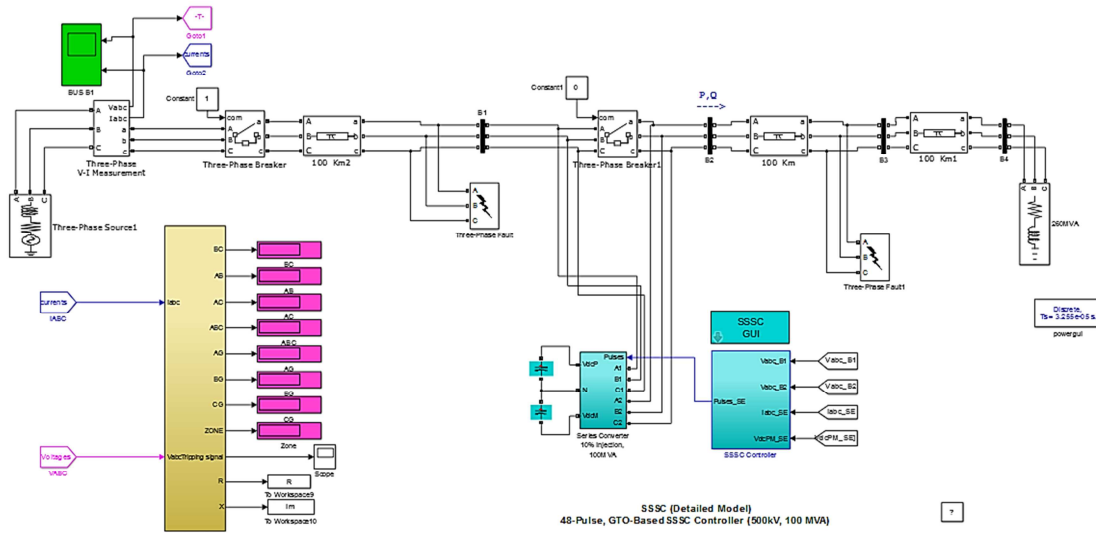

Figure 5.3: Simulation power system with STATCOM, this figure is also available in appendix

The following procedure is used for the simulation of the system under study:

1- Run the model without FACTS devices

2- Run the model with STATCOM controller with different operation mode

3- Run the model with SSSC controller with different operation mode

4- Generate the impedance trajectory for 1,2,3

5- Compare and discuss the results in 4

5.2.1 Single line to ground fault

Single line to ground fault is the most common fault in transmission lines. AG, BG, and CG are simulated using different locations. The impedance trajectory for any single line to ground fault is the same, therefore, AG fault will be presented as an example in this thesis.
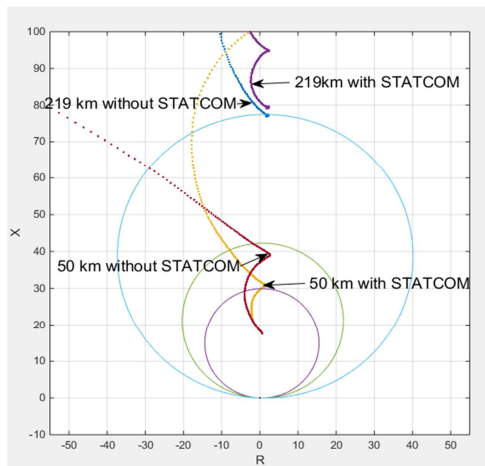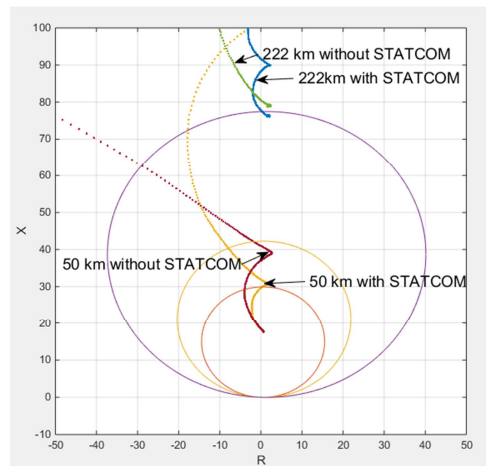
(a)   (b)

Figure 5.4: Impedance trajectory for phase A to ground fault without and with STATCOM installed at 100 km, (a) STATCOM in capacitive mode, (b) STATCOM in inductive mode.

(a)   (b)
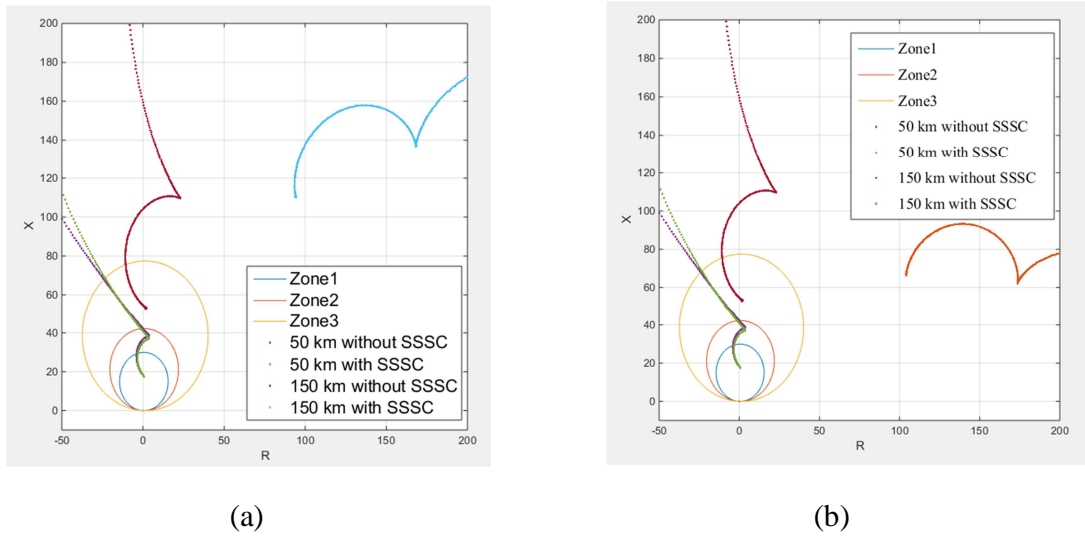
Figure 5.5: Impedance trajectory for phase A to ground fault without and with SSSC installed at 100 km, (a) SSSC in capacitive mode, (b) SSSC in inductive mode.

When a fault occurs before FACTS location (such as a fault at 50 km), the apparent impedance seen by distance relay is equal to the actual impedance regardless of the type and operation mode of FACTS devices as shown in figures (5.4) and (5.5). In case of a fault at 219 km with capacitive compensation, the fault occurs in zone

3 but the impedance trajectory shows the fault is out of protected area of zone 3(220km) as shown in figures 5.4 (a). When a Fault is at 222 km with inductive compensation, the fault occurs out of protected area for zone 3 but the impedance trajectory shows the fault is in zone 3 as evident from figures 5.4 (b).

Figure 5.5 shows the impedance trajectory without and with SSSC for both capacitive and inductive modes. Distance relay will not operate because the apparent impedance for fault occurs after SSSC location is out the protected area of zone 3. The impedance seen by distance relay is much larger than actual impedance due to the value of zero-sequence current as shown in table 5.5.

Table 5.5: The Effective Parameters of Measuring Apparent Impedance During Single Line to Ground Fault

Fault Location	Without			With Inductive SSSC			With Capacitive SSSC		
	$I_{A,m}$ A	$I_{O,m}$ A	V_{Ag} V	$I_{A,m}$ A	$I_{O,m}$ A	V_{Ag} V	$I_{A,m}$ A	$I_{O,m}$ A	V_{Ag} V
50 km	10K	2900	35 K	10k	2900	35 kv	10k	2900	35 k
150 km	4000	1000	38.5K	2740	82	39.3K	3600	86.67	39.7K
219 km	2870	687	39K	2620	80	39.5K	2760	80	39.9K

where

$I_{A,m}$: Maximum value of phase A current

$I_{O,m}$: Maximum value of Zero current

V_{Ag}: Maximum value of phase A Voltage.

Note that the impedance formula used to calculate the apparent impedance is

V_{an} / (I_a + KI_O)

We use Figures 5.6 and 5.7 to present the different measured impedance values as seen by distance relay with and without STATCOM and the impact SSSC has on distance

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relay for different fault locations respectively. Both figures are for phase A to ground

fault enforced every 10 km for both capacitive and inductive compensation.
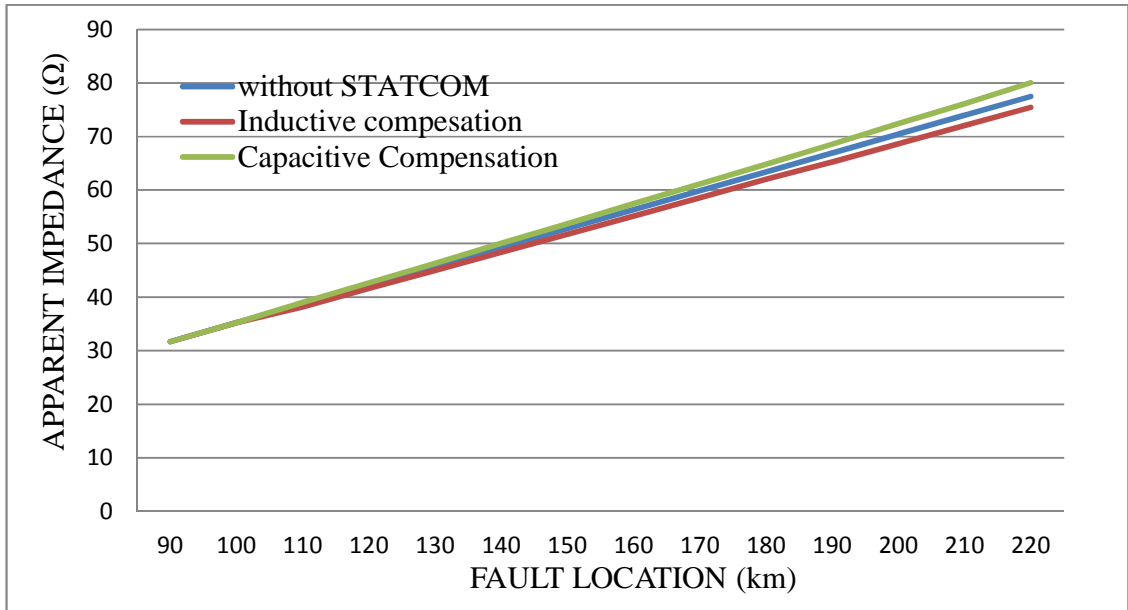

Figure 5.6: Apparent impedance measurement for different fault locations and a variety of STATCOM operation modes for AG fault.
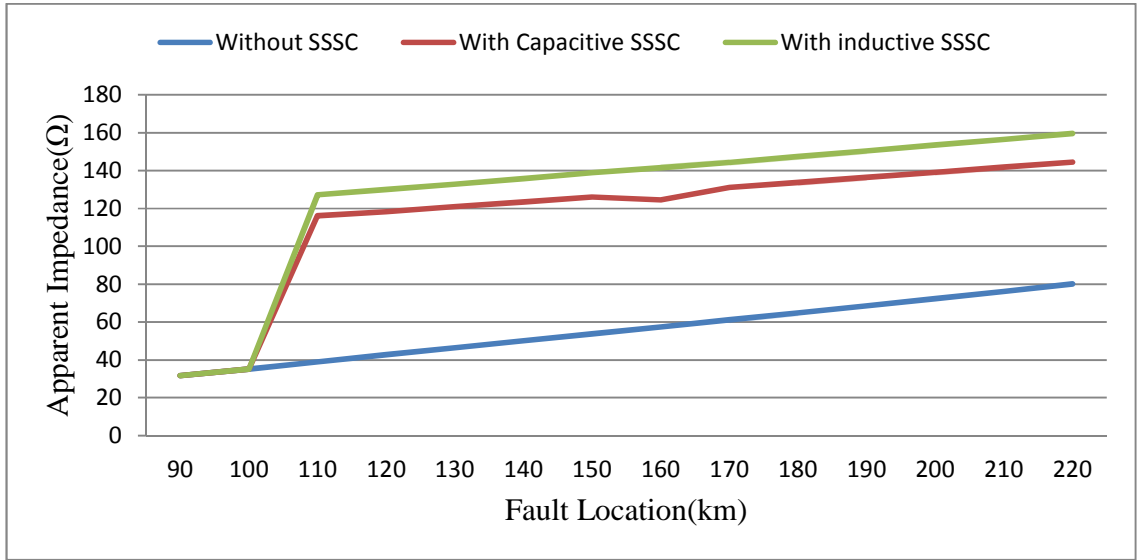
Figure 5.7: Apparent impedance measurement for different fault locations and a variety of SSSC operation modes for AG fault.

Analyzing the results of single line to ground fault, one can deduce the following:

1- The STATCOM and SSSC impact the measuring impedance when they are located within the fault loop.

2- In STATCOM compensated transmission line, the apparent impedance seen by distance relay will be greater than the actual impedance (under-reach) in case of capacitive compensation, and it will be smaller than actual impedance (over-reach) in case of inductive compensation.

3- In SSSC compensated transmission line, the apparent impedance seen by distance relay will be greater than the actual impedance (under-reach) in both capacitive and inductive compensation.

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4- The fault location has a significant effect on the error value of measuring impedance in case of STATCOM while it has minimal effect on it in case of SSSC.

5.2.2 Line to Line and Double Line to Ground fault

In a very similar manner to single line to ground fault, we applied double line fault before and after FACTS locations to show the impact of these devices on distance relay performance. AB, ABG, BC, BCG, AC, and ACG fault types are simulated and results also in similar impedance trajectory.
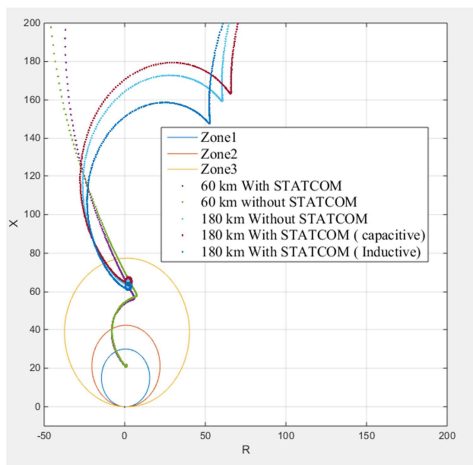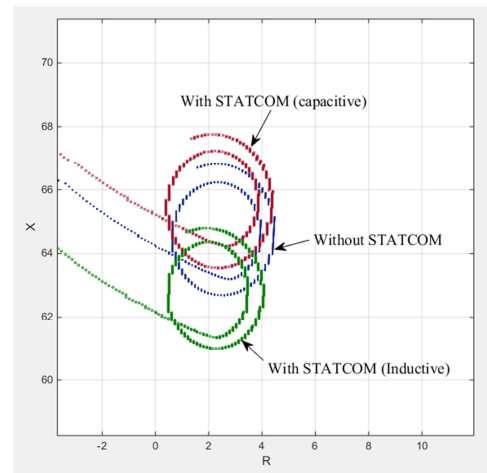
(a)   (b)

Figure 5.8: Impedance trajectory for double line fault without and with STATCOM for both inductive and capacitive mode, (a) fault applied before (60km) and after (180km) STATCOM location, (b) Zoomed picture for fault at 180km.

Figure 5.9: Impedance trajectory for double line fault without and with SSSC for both inductive and capacitive mode, (a) fault applied before SSSC location at 90km, (b) fault applied after SSSC location at 160km

The apparent impedance for double line and double line to ground fault is equal to the actual impedance when fault occurs before FACTS devices as shown in figures 5.8(a) and 5.9(a). In case of STATCOM compensated transmission line, the apparent impedance is larger than the actual impedance (under-reach) for capacitive operation mode of STATCOM. Over-reach can appear when the ST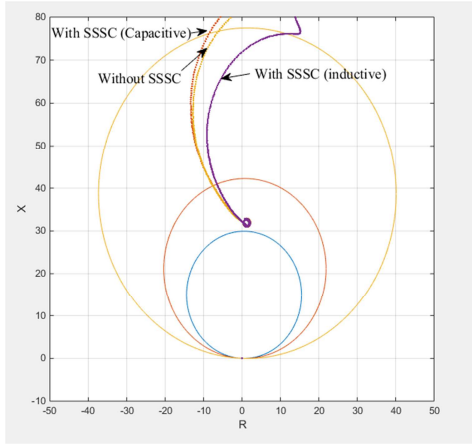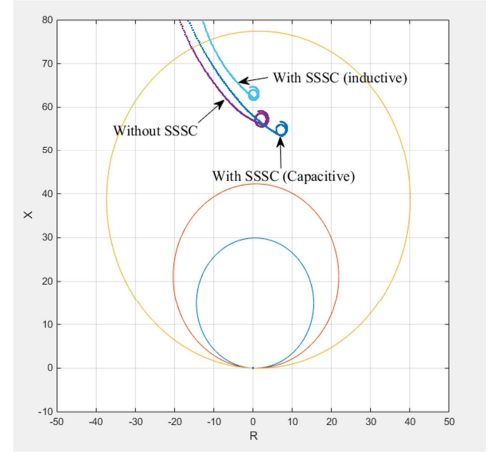ATCOM is in inductive mode because the apparent impedance is smaller than the actual impedance as shown in figure 5.8(b).

Figure 5.9(b) shows the fault occurs after SSSC location and how the measured impedance affected in series compensated transmission line. The apparent impedance seen by distance relay is larger than actual impedance and the distance relay will operate in under-reach condition when the SSSC consume reactive power (inductive mode). In case of generating reactive power (capacitive mode), the apparent impedance is smaller the actual impedance and distance relay will operate in over-reach condition.

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The amount of error of measuring impedance due to the effect of FACTS devices will increase when the distance between fault location and FACTS controller location is increased as shown in figures 5.10 and 5.11.
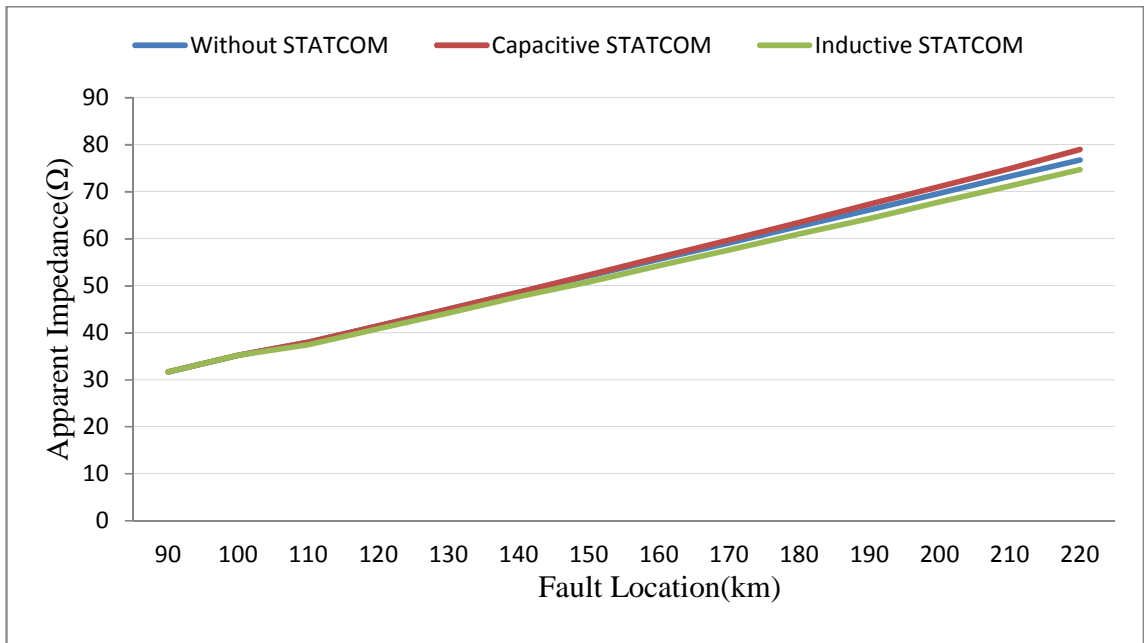

Figure 5.10: Apparent impedance measurement for different fault locations and a variety of STATCOM operation modes for ABG fault.

Figure 5.11: Apparent impedance measurement for different fault locations and a variety of SSSC operation modes for ABG fault.

5.2.3   Three Phase Fault and Three Phase Fault with Ground

The impedance trajectory for three phase fault occurs between the FACTS and distance relay location are the same regardless the type and operation mode of FACTS controller as shown in figures 5.12(a) and 5.13(a). The apparent impedance will be larger than actual impedance in capacitive mode of shunt controller or inductive mode of series controller as shown in figures 5.12(b) and 5.13(b). The error in measured impedance in case of series compensated transmission line is much larger than in the case of the shunt compensated transmission line. When the distances between fault and FACTS locations are increased, the error in measured impedance will also increase as shown in figures 5.14 and 5.15.

(a)   (b)

Figure 5.12: Impedance trajectory without and with different operation mode of
STATCOM, (a) fault applied before STATCOM location at 80km, (b) fault applied after
STATCOM location at 200km
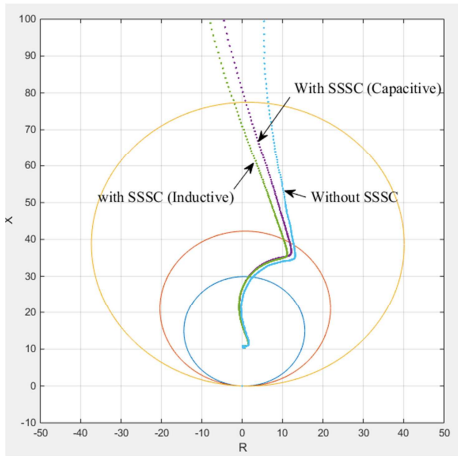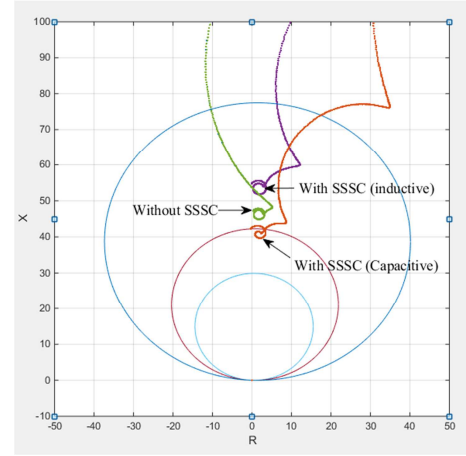
(a)   (b)

Figure 5.13: Impedance trajectory without and with different operation mode of SSSC,
(a) fault applied before SSSC location at 30km, (b) fault applied after SSSC location at
130km

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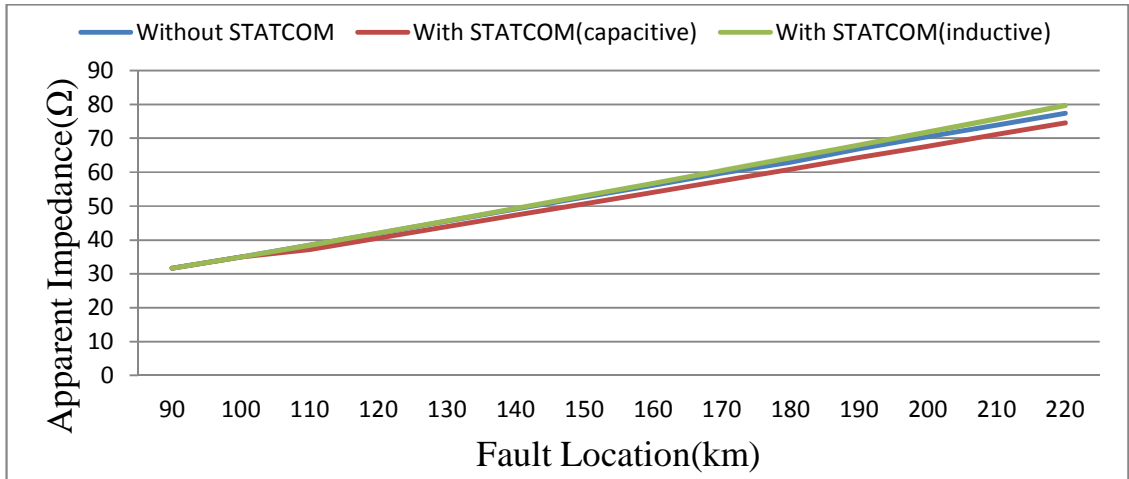
Figure 5.14: Apparent impedance measurement for different fault locations and a variety of STATCOM operation modes for ABCG fault.
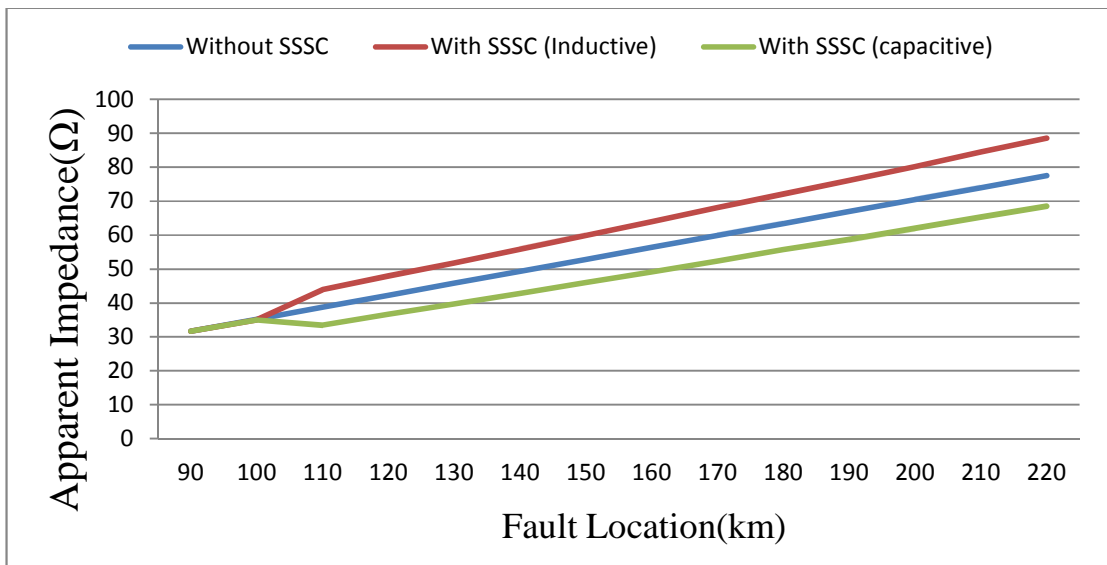
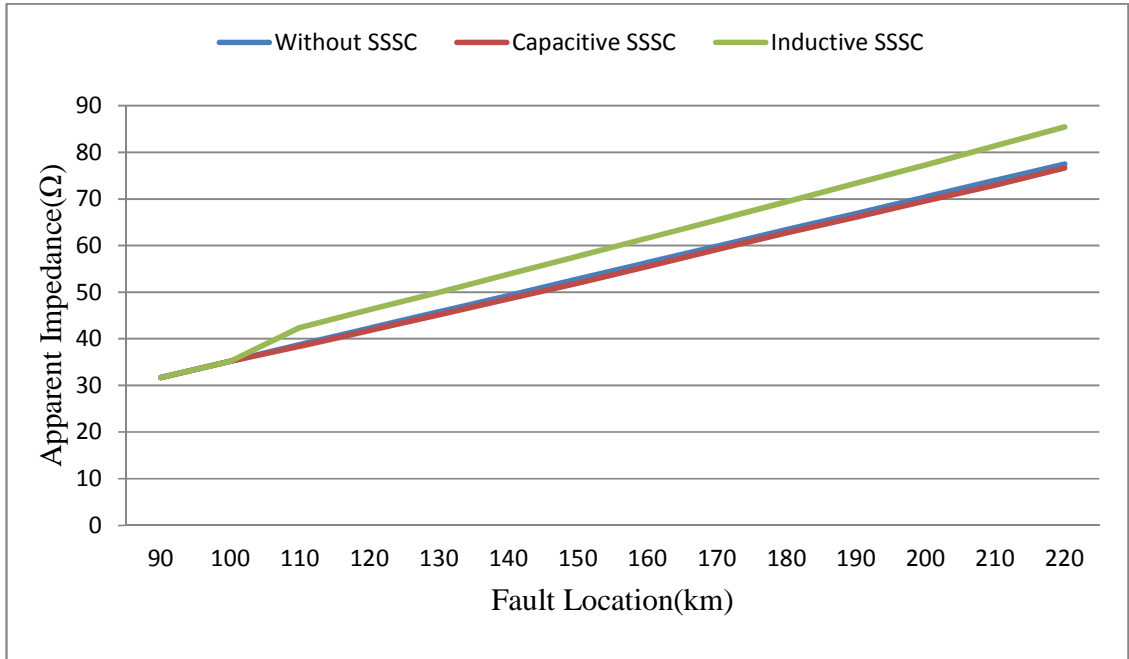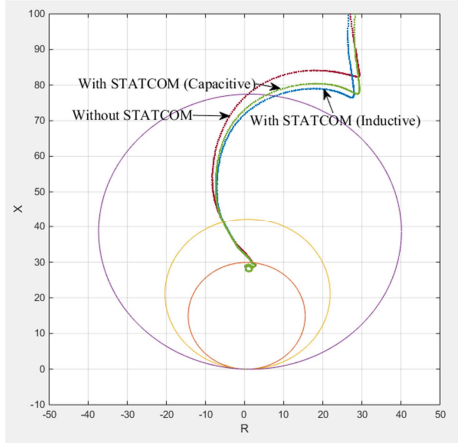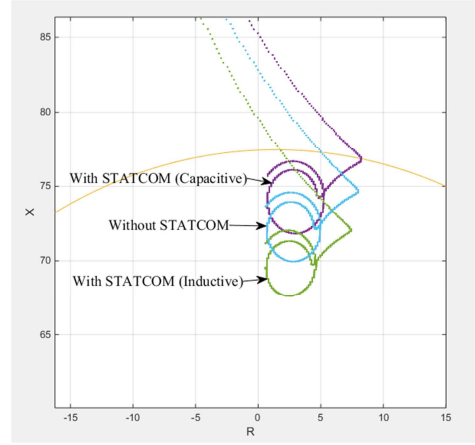Figure 5.15: Apparent impedance measurement for different fault locations and a variety of SSSC operation modes for ABCG fault.

CHAPTER 6

CONCLUSION AND FUTURE WORK

Flexible AC Transmission Systems (FACTS) devices have been widely used in
the last two decades to improve power system stability, increase controllability and
flexibility of transmission system, and to increase efficiency of transmitted power in
existing transmission lines. Based on the principle of operation of FACTS controllers, the
power system quantities such as voltages, currents and impedances are affected and
change rapidly when compensated. It is, therefore, important to investigate the impact of
FACTS Controllers on the power system protective system.

In this thesis, shunt (STATCOM) and series (SSSC) controllers' impact on the
performance of distance relays are studied analytically. Detailed modeling of distance
relay using MATLAB/SIMULINK environment is presented. Different fault types and
locations with different FACTS controllers' types and operation modes are simulated.
The analytical and simulation results in this thesis yield the following conclusions:

1- The proposed distance relay is tested without connecting FACTS controllers
   under different fault types and locations. The simulation results have shown the
   ability to detect and classify any fault type and high level of accuracy to
   determine fault location.

2- When the fault occurs between the relay and FACTS location, the apparent
   impedance will not change and it will be equal to actual impedance regardless of
   the types and operation modes of FACTS controller.

3- In case of single line to ground fault with SSSC compensator, the distance relay
   will not operate (under-reach) for both capacitive and inductive operation modes.
   The apparent impedance seen by distance relay is much larger than actual
   impedance due to the zero sequence component of the injected voltage of a SSSC.

4- In case of STATCOM compensated transmission line, under-reach phenomena of
   distance relay caused by capacitive operation mode of STATCOM, and over-
   reach caused by inductive operation mode of STATCOM. There is no significant
   difference of the error in measuring impedance for different fault types.

5- In case of DLG fault with SSSC compensator, the apparent reactance decreased
   and the apparent impedance increased in capacitive operation mode. In inductive
   compensating the apparent reactance increased and the apparent resistance
   decreased. The effect of inductive operation mode of a SSSC is more severe
   compared to that of capacitive mode which results in more cases of relay mal-
   operation.

6- The apparent impedance is larger than actual impedance for inductive
   compensating and is smaller than actual impedance for the capacitive
   compensating when SSSC was employed under a three phase fault.

7- In all fault case studies, the error in the measured impedance seen by distance
   relay increases as the fault location varies from FACTS location to the end of the

relay reach line. Moreover, the effect of fault location on the measured impedance in case of STATCOM is higher than that in SSSC.

In general, the effect of SSSC is more severe than STATCOM on distance relay performance especially in most common fault type (Single Line to Ground). The typical distance relay is not the best protective relay for FACTS compensated transmission line. Concerning recommendation for future work, I would like to suggest the following:

1- The proposed work can be extended by applying similar techniques to the transmission lines compensated by other FACTS devices such as Interline Power Flow Controller (IPFC) and Unified Power Flow Controller (UPFC).

2- Design a new scheme for distances relays that has the ability to change the setting rule of the zones according to the effects of FACTS controllers on power system quantities that is we must design an *adaptive* relay protective system.

3- Investigate the impact of FACTS controllers in real time to address the effects of FACTS controller on tripping time delay since the delayed operation of distance relay can negatively affect system stability. This work could be conducted using real time simulation software such as NETOMAC (Network Torsion Machine Control), EMTDC (Electromagnetic Transients including DC), or any other real time simulation software.

BIBLIOGRAPHY

[1] Russell C. Mason, *The Art and Science of Protective Relaying*. New York, United States of America: Wiley, 1956.

[2] J. Duncan Glover, Mulukutla S. Sarma, and Thomas J. Overbye, *Power System Analysis and Design*, 5th ed.: CENGAGE Learning, 2011.

[3] Narain G Hingorani and Laszlo Gyugyi, *Understanding FACTS Concepts and Technology of Flexible AC Transmission systems*. Los Atlos Hills, CA: Willey, 1999.

[4] *242-2001 - IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (IEEE Buff Book)*. The United States of America: The Institute of Electrical and Electronics Engineers, Inc, 2001.

[5] Qais Hashim Alsafasfeh, "Pattern Recognition for Fault Detection, Classification, and Localization in Electrical Power Systems," Western Michigan University, Ann Arbor, Ph.D. 3424508, 2010.

[6] Alstom, *Network Protection & Automation Guide*.: ALSTOM, 2011.

[7] Hadi Saadat, *Power System Analysis*, 3rd ed. The United States: PSA, 2010.

[8] Mladen Kezunovic, *Fundamental of Power System Protection*. Texas, The United Stats of America: Academic Press., 2005.

[9] Gerhard Ziegler, *Numerical Distance Protection Principle and Applications*, 2nd ed., Berlin and munchen Siemens Aktiengesellschaft, Ed. Erlangen, Germany: Publicis Corprate Publishing, 2006.

[10] Muhd Hafizi Idris, Surya Hardi, and Mohd Zamri Hasan, "Teaching Distance Relay Using Matlab/Simulink Graphical User Interface," *Malaysian Technical Universities Conference on Engineering & Technology* , vol. 53, pp. 264-270, 2012.

[11] X. Y. Zhou, H. F. Wang, R. K. Aggarwal, and F. Beaumont, "The Impact of STATCOM on Distance Relay," in *15th Power Systems*, Liège, Belgium, 2005, pp. 1-7.

[12] Tarlochan Singh Sidhu, Rajiv K Varma, Pradeep Kumar Gangadharan, Fadhel Abbas Albasri, and German Rosas Ortiz, "Performance of Distance Relays on Shunt—FACTS Compensated Transmission Lines," *Power Delivery, IEEE Transactions.*, vol. 20, no. 3, pp. 1837 - 1845, June 2005.

[13] Wen-Hao Zhang, Seung-Jae Lee, Myeon-Song Choi, and Shigeto Oda, "Considerations on distance relay setting for transmission line with STATCOM," in *Power and Energy Society General Meeting, 2010 IEEE*, Minneapolis, MN, 2010, pp. 1 - 5.

[14] Sriteja Alapati and Durga prasad, "Effect of Statcom on Distance Relay Performance in a Transmission Line," *International Journal of Computer and Electrical Engineering*, vol. 4, no. 4, pp. 489-492, August 2012.

[15] Dannana Hemasundar, Mohan Thakre, and V S Kale, "Impact of STATCOM on distance relay - Modeling and simulation using PSCAD/EMTDC," in *IEEE*, Bhopal, 2014, pp. 1 - 6.

[16] A. Kazemi, S. Jamali, and H. Shateri, "Distance Relay Mal-Operation due to Presence of SSSC on Adjacent Lines in Inter Phase Faults," in *Region 5 Conference, 2008 IEEE*, Kansas City, MO, 2008, pp. 1-6.

[17] M. Khederzadeh, A. Ghorbani, and A. Salemnia, "Impact of SSSC on the digital distance relaying," in *Power & Energy Society General Meeting, 2009. PES '09. IEEE*, Calgary, AB, 2009, pp. 1 - 8.

[18] A. Shojaei and S. M. Madani, "Analysis of Measured Impedance by Distance Relay in Presence of SSSC," in *Power Electronics, Machines and Drives (PEMD 2010), 5th IET International Conference*, Brighton, UK, 2010, pp. 1 - 6.

[19] M. Khederzadeh and A. Ghorbani, "Impact of VSC-Based Multiline FACTS Controllers on Distance Protection of Transmission Lines," *Power Delivery, IEEE Transactions* , vol. 27, no. 1, pp. 32 - 39, January 2012.

[20] Z. Moravej, M. Pazoki, and M. Khederzadeh, "Impact of UPFC on Power Swing Characteristic and Distance Relay Behavior," *Power Delivery, IEEE Transactions* , vol. 29, no. 1, pp. 261 - 268, February 2014.

[21] M. Khederzadeh, "UPFC operating characteristics impact on transmission line distance protection," in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, Pittsburgh, PA, 2008, pp. 1 - 6.

[22] Dominik Szabo, Michal Regul'a, Roman Bodnar, and Juraj Altus, "Control of a SVC for Power Factor Correction," in *ELEKTRO*, Rajecke Teplice, 2014, pp. 379 - 382.

[23] Sankara Subramanian, Anthony Perks, Sarath B Tennakoon, and Noel Shamunas, "Protection Issues Associated with the Proliferation of Static Synchronous Compensator (STATCOM) Type Facts Devices in Power Systems," in *IEEE*, Newcastle-upon-Tyne, 2006, pp. 846 - 850.

[24] Pedram Sotoodeh and Ruth Douglas Miller, "Design and Implementation of an 11-Level Inverter With FACTS Capability for Distributed Energy Systems," *Emerging and Selected Topics in Power Electronics, IEEE Journal*, vol. 2, no. 1, pp. 87 - 96, November 2013.

[25] Therese Uzochukwuamaka Okeke and Ramy Georgious Zaher, "Flexible AC Transmission Systems (FACTS) ," in *New Concepts in Smart Cities: Fostering Public and Private Alliances (SmartMILE), 2013 International Conference on*, Gijon, 2013, pp. 1 - 4.

[26] Abdlmnam A Abdlrahem and Hamid H Sherwali, "Modelling of Numerical Distance relays using MATLAB," in *Industrial Electronics & Applications, 2009. ISIEA 2009. IEEE Symposium*, Kuala Lumpur, 2009, pp. 389 - 393.

[27] Roland Priemer, *MATLAB for Electrical and Computer Engineering Students and Professionals with Simulink*. New Jersey, United States of America: Scitech, 2013.

[28] Allan R. Hambley, *Electrical Engineering Principles and Applications* , 2nd ed. New Jersey, United Stats of America: Prentice Hall.

[29] (2014, November) MathWorks. [Online]. http://www.mathworks.com/

[30] Omar G Merhel, Hassan B Elfetori, and Abdallah O Hawal, "Impact of STATCOM on distance relay - Modeling and simulation using PSCAD/EMTDC," in *SDIWC*, 2013, pp. 132-137.

[31] LIU Qing, WANG Zeng-ping, and ZHANG Yuan, "Study on a novel method of distance protection in transmission line with STATCOM," in *IEEE*, Chengdu, 2010, pp. 1 - 5.

[32] Thanakorn Penthong and Komsan Hongesombut, "An Efficient Method of Automatic Distance Relay Settings for Transmission Line Protection," in *IEEE*, Xi'an, 2013, pp. 1 - 4.

[33] Gorakshanath Abande, M.F. A.R. Satarkar, Mohan Thakre, V.S. Kale, and Ganesh patil, "Impact analysis of STATCOM on Distance Relay," *IEEE International Conference on Innovations in Engineering and Technology (ICIET'14)*, vol. 3, no. 3, pp. 90-97, March 2014.

[34] Fadhel A Albasri, Tarlochan Singh Sidhu, and Rajiv K Varma, "Performance Comparison of Distance Protection Schemes for Shunt-FACTS Compensated Transmission Lines," *Power Delivery, IEEE Transactions*, vol. 22, no. 4, pp. 2116 - 2125, October 2007.

[35] Mahfoud Chafa, Hamid Bentarzi, Abderrahmane Ouadi, Abdelkader Zitouni, and Abdelmadjid Recioui, "PC based Testing System for Protective Relay," in *Power Engineering, Energy and Electrical Drives (POWERENG), 2013 Fourth International Conference*, Istanbul, 2013, pp. 939 - 943.

[36] Mojtaba Khederzadeh, "Vulnerability analysis of transmission lines based on the performance of Mho relays and series/shunt compensation systems," in *Universities Power Engineering Conference, 2007. UPEC 2007. 42nd International*, Brighton, 2007, pp. 328 - 332.

[37] S. Dechphung and T. Saengsuwan, "Three Zones Adaptive Characteristic of the Mho Distance Relay by KU Method," in *Sustainable Energy Technologies, 2008. ICSET 2008. IEEE International Conference*, Singapore, 2008, pp. 1206 - 1210.

[38] Sandro G. Aquiles Perez, "Modeling relays for power system protection studies," he University of Saskatchewan (Canada), Ph.D. NR18172, 2006.

[39] Mohamed Salah Kamel Elsamahy, "Impacts of Midpoint Facts Controllers on the Coordination Between Generator Phase Backup Protection and Generator Capability Limits," The University of Saskatchewan (Canada), Saskatoon, Saskatchewan ,

Ph.D. NR92092, 2011.

[40] Mohamed M. Ismail and M. A. Moustafa Hassan, "Distance Relay Protection for Short and Long Transmission line," in *Modelling, Identification & Control (ICMIC), 2013 Proceedings of International Conference on*, Cairo, 2013, pp. 204 - 211.

[41] Arvind Pahade and Nitin Saxena, "Transient stability improvement by using shunt FACT device (STATCOM) with Reference Voltage Compensation (RVC) control scheme," *International Journal of Electrical, Electronics and Computer Engineering*, vol. 2, no. 1, pp. 7-12, December 2012.

[42] Yashasvi B, Vidushi K, and Ramesh P, "Simulation of Mho Charcacteristics for Transmission Line Protection Usind PSCAD," *International Journal of Research in Engineering & Applied Sciences*, vol. 2, no. 2, pp. 540-550, February 2012.

[43] Shameem Ahmad, Fadi M. Albatsh, Saad Mekhilef, and Hazlie Mokhlis, "An Approach to Improve Active Power Flow Capability by Using Dynamic Unified Power Flow Controller," in *Innovative Smart Grid Technologies - Asia (ISGT Asia), 2014 IEEE*, Kuala Lumpur, 2014, pp. 249 - 254.

[44] C. L. Wadhwa, *Electrical Power Systems*. Delhi, India: New Academic Science, 2012.

[45] MO-yuen Chow and Leroy S. Taylor, "Analysis and Prevention of Animal-Caused Faults in Power Distribution Systems ," *IEEE Transactions on Power Delivery*, vol. 10, no. 2, pp. 995 - 1001, April 1995.

[46] Barry W. Kennedy, *Power Quality Primer*, Scott Grillo and Gerry Fahey, Eds. United States of America: McGraw-Hill, 2000.

[47] Hamed Abdollahzadeh, Babak Mozafari, Arash Tavighi, and José Martí, "Impact of shunt capacitance of a SSSC-compensated transmission line on performance of distance relays," in *Power and Energy Society General Meeting (PES), 2013 IEEE*, Vancouver, BC, 2013, pp. 1 - 5.
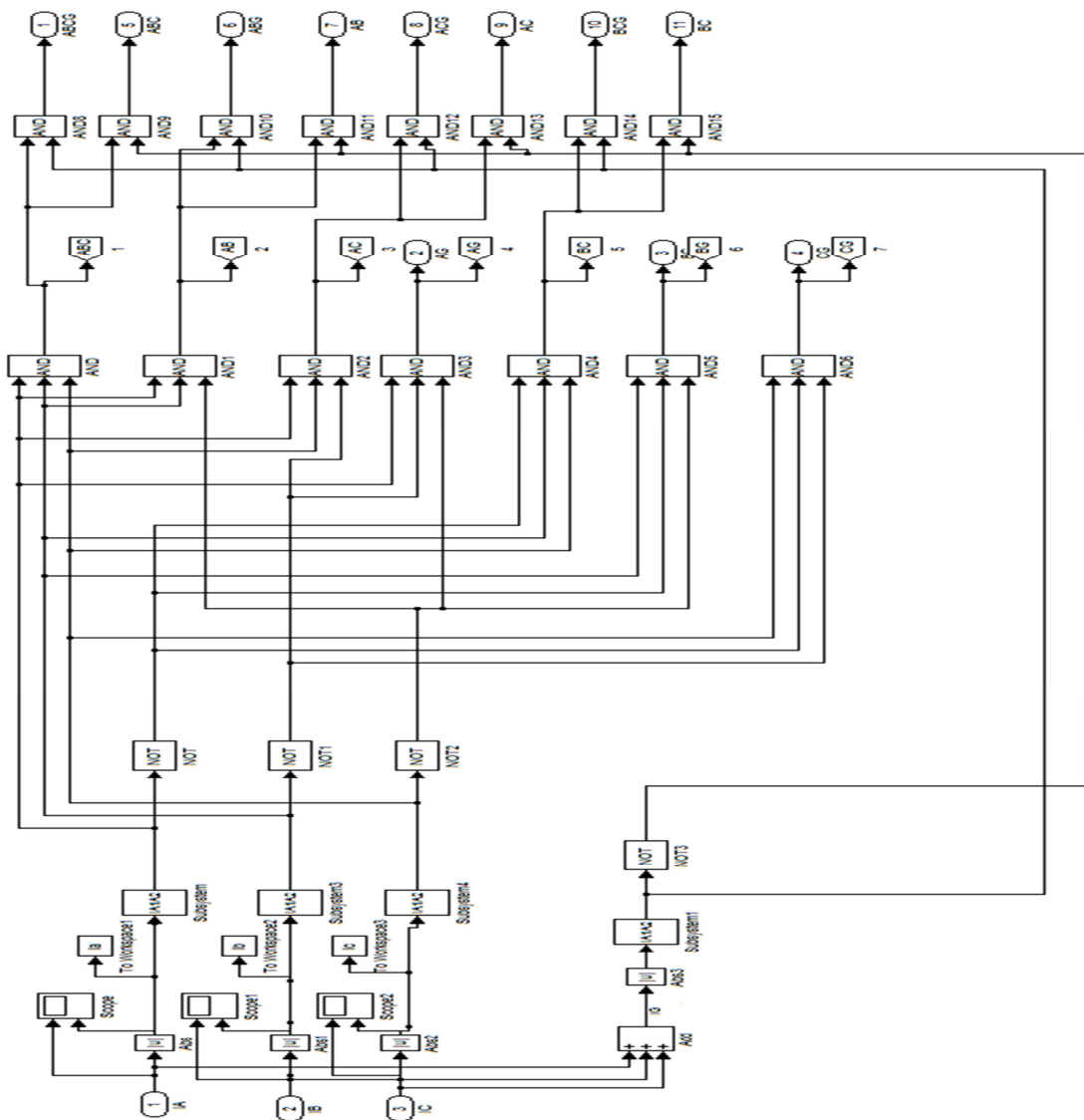
APPENDIX

System Diagrams

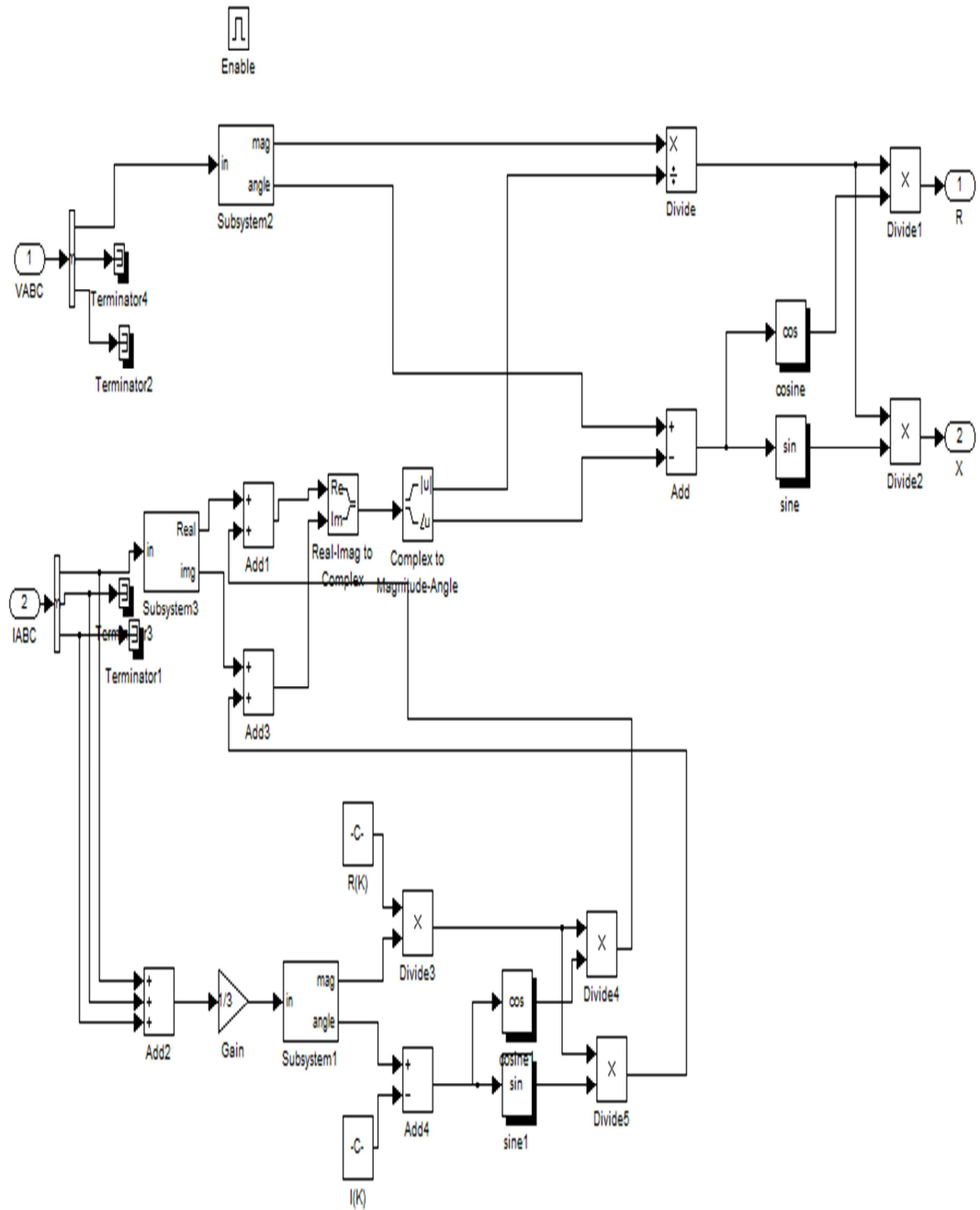Figure A.1: Fault detection and classification block.
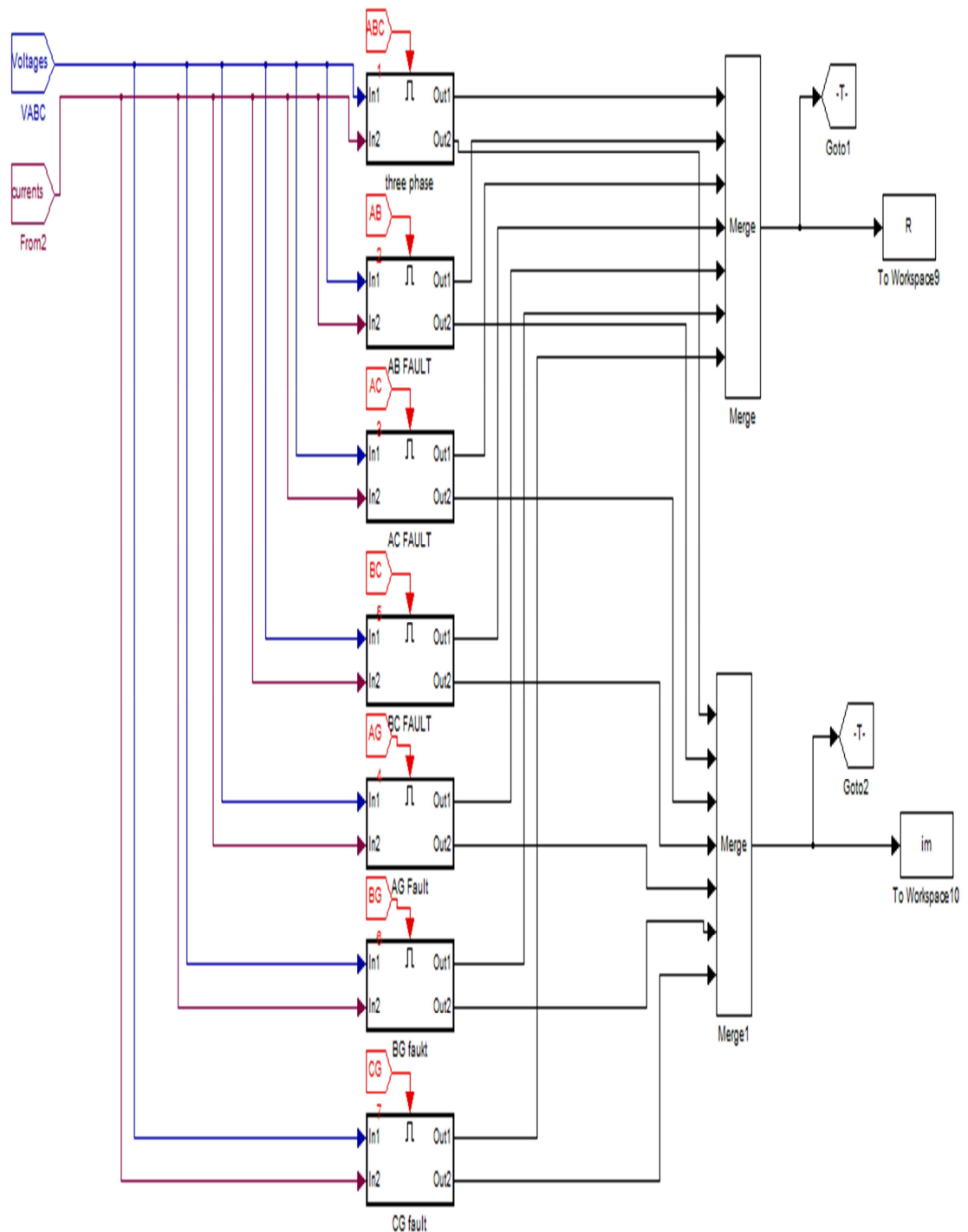
Figure A.2: Apparent impedance model for SLG (at phase A)

Figure A.3: Overall apparent impedance measurement subsystem

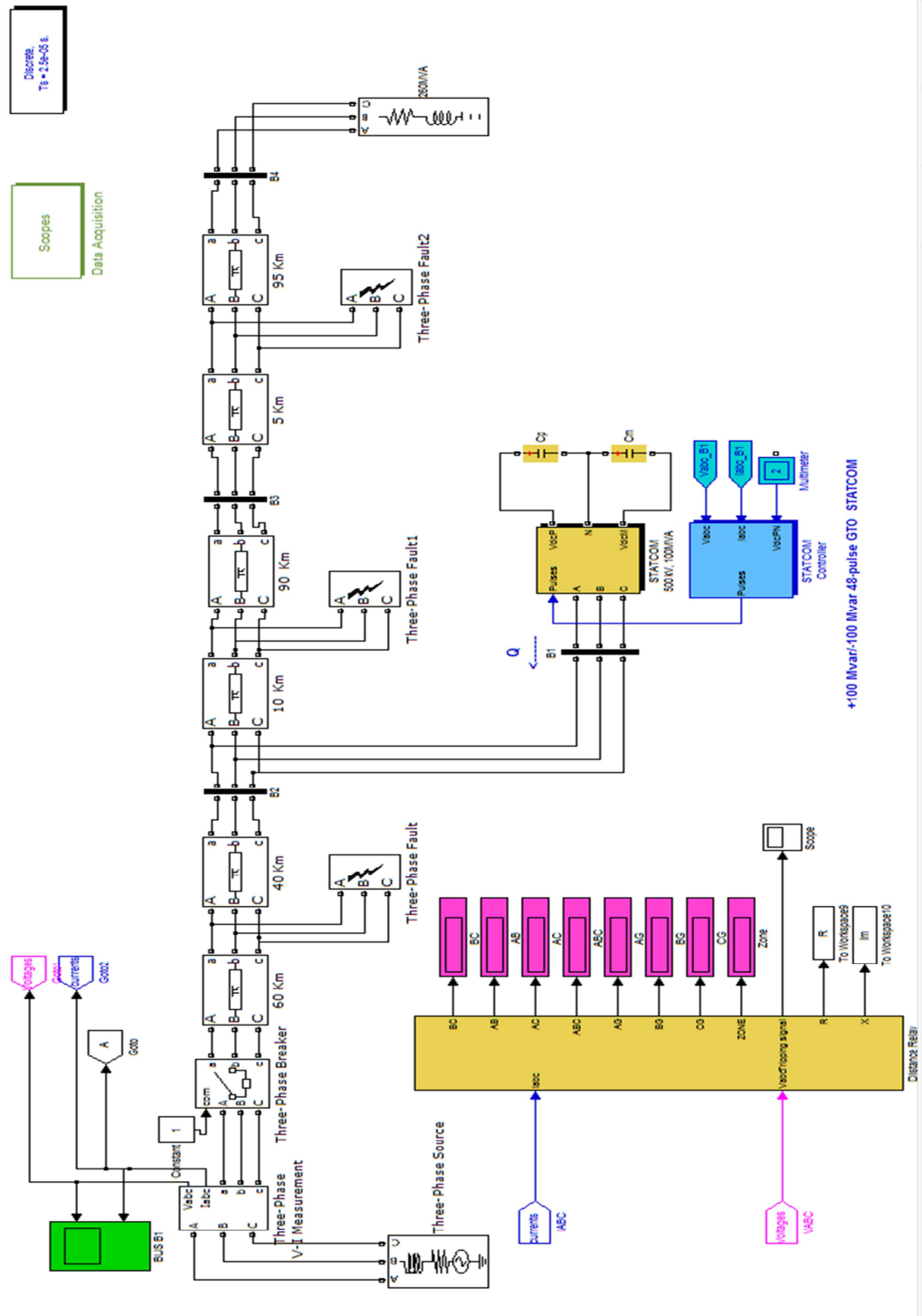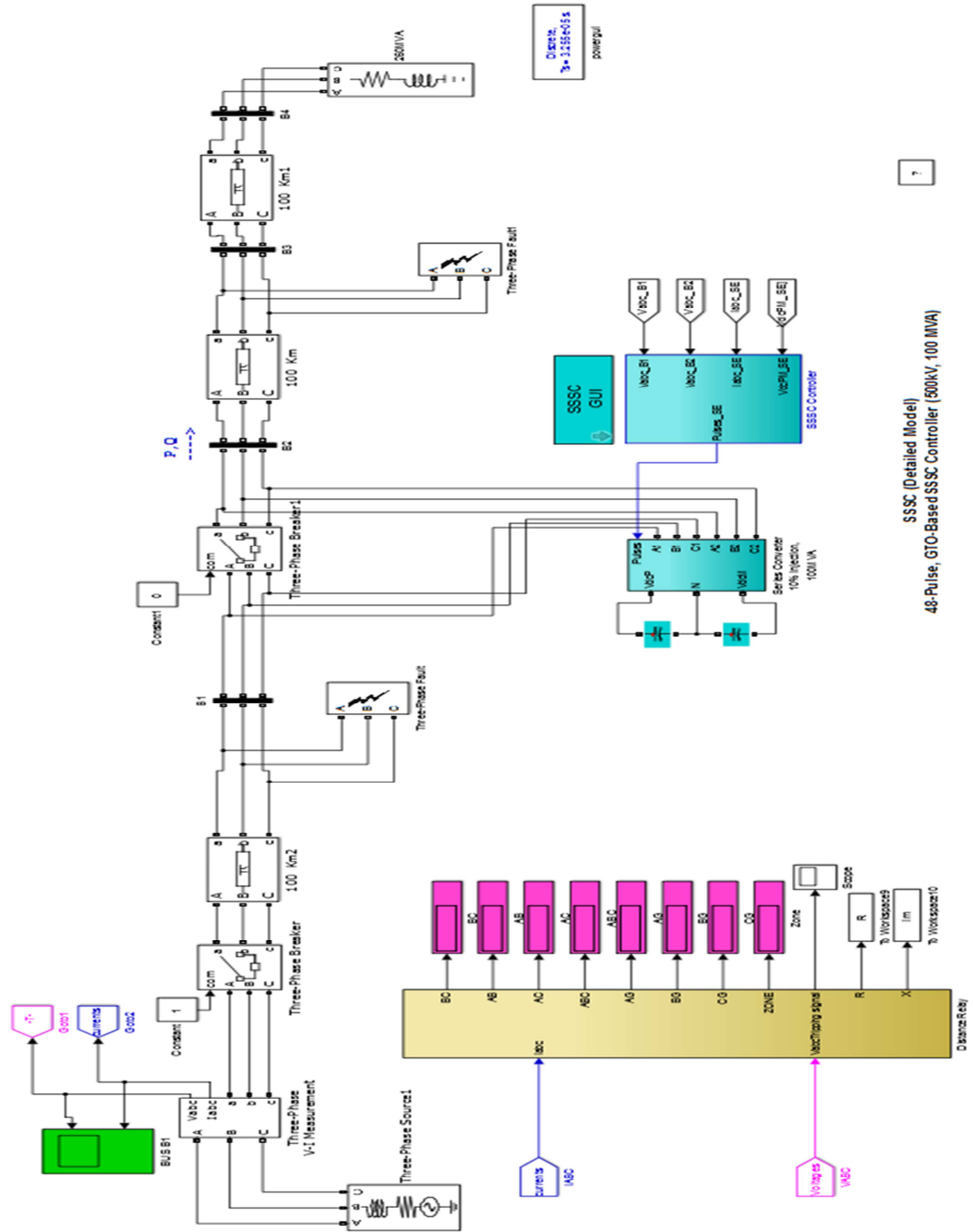Figure A.4: Simulation power system in MATLAB/SIMULINK

Figure A.5: Simulation power system with STATCOM

Figure A.6: Simulation power system with SSSC