EFFECTS OF FLEXIBLE AC TRANSMISSION SYSTEM (FACTS) ON THE PERFORMANCE OF DISTANCE PROTECTION RELAYS

by

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A thesis submitted in partial fulfillment of the requirements of the Staffordshire University for the degree of Master of Philosophy

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Collaborating Establishment: AREVA T&D Ltd (now ALSTOM GRID)

September 2010

Abstract

Flexible AC Transmission Systems (FACTS) are power electronic based devices and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability of power systems. FACTS devices are therefore being increasingly employed in power system networks to satisfy these requirements. An additional requirement to preserve power system stability and security is that the power system protection should be dependable and stable, since existing power system protection devices were designed before the advent of FACTS devices it is therefore necessary to investigate the impact they will have on traditional forms of protection.

The research study examines the effects of STACOM on distance protection relays. The research work aims to validate a particular model of STATCOM for protection study purposes, and to investigate the effects of STATCOM on distance relay.

The objectives set about in this research work are to identify the causes of distance relay mis-operations, to propose corrective actions in order to prevent the mis-operations, and to make recommendations on the area of future research works as an outcome of the research work.

The principle conclusions from this works are, at 220 KV level or at similar levels with system that are solidly-grounded, distance relay will fail to operate correctly for higher fault resistances involved in faults beyond the location of STATCOM. The operating times of the distance relay is also higher whenever STATCOM is in service.

Acknowledgments

The author would like to express his gratitude to his principal supervisor Professor Sarath Tennakoon, for his help and advice throughout the project.

The author would also like to thank his industrial supervisor Dr Anthony Perks from AREVA T&D Substation Automation Solutions UK, for his technical guidance throughout the project.

I would also like to thank my wife and son for their forbearance and tolerance while I was working on the project and during the write up.

The project and course of study presented in this thesis has been funded by AREVA T&D Ltd, Substation Automation Solutions, Stafford. AREVA[1] and I would like to thank the company for the support.

[1] Now ALSTOM GRID

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List of Symbols

ω	Angular Frequency
δ_S	Sending end angle
δ_R	Receiving end angle
AVS	Average Voltage Source
AN,BN,CN,	Selected Phase to Ground phases
AB,BC,CA,	Selected Phase to Phase phases
ABCN,ABC	Selected three Phase and three Phase to Ground
C	Capacitance
CT	Current Transformer
FACTS	Flexible AC Transmission System
FC	Fixed control
FFT	Fast Fourier Transform
F1	Fault location F1: FAULT APPLIED AT 140 km, STATCOM PLACED AT 100 km; (Fault beyond STATCOM location
F2	Fault location F2: FAULT APPLIED AT 165 km, STATCOM PLACED AT 150 km; (Fault beyond STATCOM location)
F3	Fault location F3: FAULT APPLIED AT 50 km, STATCOM PLACED AT 150 km; (Fault before STATCOM location, i.e. faults applied between the relaying point and STATCOM location.)
GTO	Gate Turn-off
I	Current
Iresidual	Residual current
Id	Direct axis current
Iq	Quadrature axis current

I_1	Positive sequence Current
I_0	Zero sequence current
I_2	Negative sequence current
L	Inductance
P	Active Power
Q	Reactive Power
R_L	Resistance of the line
SSSC	Static Synchronous Series Capacitor
STATCOM	Static Synchronous Shunt Compensation
SVC	Static VAR compensator
TCR	Thyristor controlled reactor
TSC	Thyristor switches Capacitor
TSSC	Thyristor switched series capacitor
TCSC	Thyristor controlled series capacitor
V	Voltage
Vbus	Voltage at Power system Bus bar
Vd	Direct axis voltage
$V_{Coupling}$	Coupling Transformer Voltage
V_{AVS}	Voltage of average voltage source
VCO	Voltage Controlled Oscillator
V_S	Sending end Voltage
V_R	Receiving end voltage
Vq	Quadrature axis voltage
V_{source}	Source voltage
VT	Voltage Transformer

W	Work done in a capacitor
X_L	Inductive reactance of the line
X_C	Capacitive reactance of the line
Z	Impedance
Z_L	Impedance of the line
Z_1	Positive sequence Impedance of the line
Z_0	Zero sequence impedance of the line
Z_{mut}	Mutual compensating Impedance
Z_T	Transformer Impedance
Z1	Zone1
Z2	Zone2
Z3	Zone3
Z_{Load}	Impedance of Load
21	Distance relay

1. INTRODUCTION

Global economic development has increased the demand for electrical energy. Coupled with this electricity markets are becoming more competitive and deregulated. Power system networks are also becoming increasingly interconnected so that power system instabilities can have far reaching effects over a wide area. To meet the increasing demand existing transmission networks are frequently being run at maximum transmission capacity and are being challenged to maintain the distribution of increasing power flows. Construction of new transmission lines is problematic because of planning restrictions unless existing rights of way can be utilised. Upgrading of existing lines to transfer power at higher voltage levels also has an associated cost. To meet the increased demand using existing power system networks a more efficient control of power flows to enhance the transmission capability and improve the transient stability limit is needed. Flexible AC Transmission Systems (FACTS) were developed to meet this need.

In addition to improving the efficiency of modern power systems system reliability and dependability are increasingly important to maintain system stability. Factors that can influence these requirements are the performance of power system protection that is installed in the network. The installed power system protection must be dependable, that is it operate for faults within its zone of protection, and is must be stable, that is it must not operate for faults outside its zone of protection. One form of power system protection is provided by a distance relay and because of the way distance protection operates the installation of FACTS devices within their zone of protection present challenges that were not considered when the protection devices were developed. This thesis considers the challenges presented to distance relays but installed FACTS devices within their zone of operation.

One type of FACTS device is a Static Synchronous Compensator (STATCOM). The aim of the research work is to validate the use of an AVS model of STATCOM for protection studies, and to investigate the problems experienced by the distance protection relays due to the presence of a STATCOM in the system.

The objective of the research work is to find out how are the problems caused and to provide recommendations to overcome the problems and to achieve correct operations when STATCOM is employed at the mid point of a transmission line. Further objective of the work is to make recommendations on the areas of future research work.

The aims and objectives are covered in the following sections of the thesis.

The thesis is organised into 11 chapters.

In chapter 2 a general overview of FACTS devices is presented with a brief description of the various available types of FACTS devices. In chapter 3 the fundamentals of distance protection, present protection practices and the effects of FACTS devices on distance protection relaying are discussed. In this chapter analytical analysis using sequence component network to analyse a particular type of fault in the presence of STATCOM is undertaken. Subsequent chapters describe the development of power system models to investigate the effects of STATCOM on distance protection in order to see whether simulation studies agree with analytical findings and to understand what effects are on the distance protection relays. In chapter 4 the development of an Average Voltage Source model of a STATCOM model using the power system simulator PSCAD/EMTDC is studied. Since the simulations are aimed at determining the effects on the protection equipment it is envisaged that, a fundamental frequency average voltage source model is suitable in terms of less complexity and fast computation. This chapter is aimed at validating the AVS model for distance protection studies, hence study undertaken to understand the behaviour of the AVS model in detail to effects of load changes during steady state conditions and its characteristics behaviour during those changes. In chapter 5 the developed STATCOM model is incorporated into a modelled transmission power system using PSCAD/EMTDC where a distance relay is also modelled into that power system. The aim is to simulate different types of faults at different location before and after the location of AVS model of STATCOM to understand the effects on simulated distance protection relay and also to see whether simulation results agree with analytical findings of chapter 3. From the results of the simulated system, analysis and final observations are made which are included in this chapter. Further, in chapter 6 conclusions are made as an outcome of the research study and proposals for further work are made. References are covered in chapter 7. Appendices are covered from chapter 8 to 11.

2. REVIEW OF FLEXIBLE AC TRANSMISSION DEVICES (FACTS)

2.1. INTRODUCTION

This chapter sets the scene by systematically reviewing the FACTS devices in existence, paving the way for the study of the effects of a particular type of FACTS-based device on distance protection relaying. The chapter starts with the concept of FACTS devices that are used for different power system applications leading to various types of FACTS implementations. A literature survey has been carried out to understand the different types of FACTS devices and the concepts of series and shunt types of FACTS devices. The different types of FACTS devices are conventional thyristor based FACTS devices and the voltage source convertor based FACTS devices. [1],[2],[3],[4],[5],[6],[7],[8],[9]. Two examples are covered; each from series form conventional thyristor based and shunt form conventional based compensation devices. In addition, there is an example from the series form of voltage source based convertor and an example from the shunt form of voltage source based convertor type compensators.

2.2. CONCEPT OF FACTS

In a power system, the transmission of power in a transmission line is mainly dependent on the sending and receiving end voltage levels, the transmission angle and the transmission line reactance.

To increase the power flow through a transmission system, one or more of the above parameters must be changed. For example, the transmission angle can be increased with the use of a phase shifting transformer but such an item of plant is costly to purchase and install, and the transformer losses must be accounted for. Increasing the transmission angle also pushes a power system closer to its stability limit, increasing the likelihood of system instability. Also the transmission voltage level could be increased. However, this would only be economically feasible if permitted by existing tower construction, and it would still be very costly to upgrade system insulation and switchgear. Where such an approach is envisaged in the future, transmission lines could be constructed taking into account future operation at higher voltage levels. Power flow could also be increased by reducing the inductive reactance of the transmission system by installing fixed series capacitors. This was in the past found to be one of the most economical ways of increasing the power flow of the transmission system. [1]

FACTS devices can be broadly applied to increase the power flow or even to change the power flow by having a higher degree of control of the three key parameters of line impedance, phase angle, and voltage magnitude. In addition, FACTS devices are used to increase the stability of the system and to regulate the system voltage.

Let us consider two machine models in a simple power system as shown in Figure 2.1, where locations A and B could be any transmission substations connected by transmission lines.

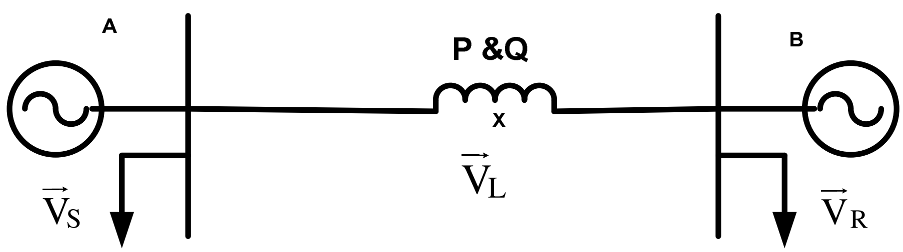


Figure 2.1 Example of a two ended power system

At these locations there may be loads, generation and also interconnecting points, and they are connected by a single transmission line for the purpose of the study. In the figure $\overrightarrow{V_S}$ and $\overrightarrow{V_R}$ are the voltage phasors at buses A and B respectively. Each phasor can be written in the following form:

$$\vec{V}_S = V_S \angle \delta_S \qquad 2.1$$

$$\vec{V}_R = V_R \angle \delta_R \qquad 2.2$$

The transmission angle is then given by,

$$\delta = \delta_S - \delta_R \qquad 2.3$$

This assumes that V_S and V_R are the magnitudes of internal voltages of the two equivalent machines representing the two systems, and the impedance X includes the internal impedance of the two equivalent machines and the transmission line. The impedance X is assumed to be purely inductive with any resistive or capacitive losses ignored.

A high degree of control on the current in the line is achieved by controlling any of the three parameters of impedance, transmission angle and the voltage drop in the line as shown in equation 1.4. The voltage drop in the line is the phasor difference between the two line voltage phasors.

$$\vec{V}_L = \vec{V}_S - \vec{V}_R \qquad 2.4$$

The relationship between active and reactive currents with reference to the voltage phasors V_S and V_R at two ends is shown in Figure 2.2. In the phasor diagram, active and reactive components of the current phasor are shown, as well as the active and reactive components of the voltage phasors. Active power and reactive power at the sending and receiving ends are deduced from the following formulae.

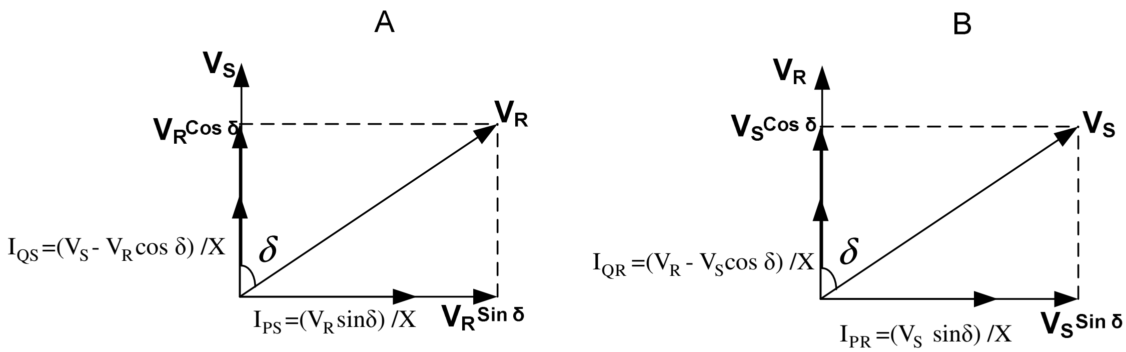


Figure 2.2 Active and reactive power flow and active reactive current flow vector representation

The active component of current flow (I_{PS}) at A is:

$$I_{PS} = (V_R \sin\delta) / X$$

The reactive component of the current flow (I_{QS}) at A is:

$$I_{QS} = (V_S - V_R \cos\delta) / X$$

Thus, the active power (P_S) flowing from A is:

$$P_S = V_S (V_R \sin\delta) / X \qquad 2.5$$

And the reactive power (Q_S) at A is:

$$Q_S = V_S (V_S - V_R \cos\delta) / X \qquad 2.6$$

Similarly, the active component of the current flow (I_{PR}) at B is:

$$I_{PR} = (V_S \sin\delta) / X$$

The reactive component of the current flow (I_{QR}) at B is:

$$I_{QR} = (V_R - V_S \cos\delta) / X$$

Thus, the active power (P_R) at the V_R end is:

$$P_R = V_R (V_S \sin\delta) / X \qquad 2.7$$

And the reactive power (Q_R) at the V_S end is:

$$Q_R = V_R (V_R - V_S \cos\delta) / X \qquad 2.8$$

It can be seen from equations 1.5 and 1.7 that the active power P_S is equal to active power P_R.

If there are no active power losses in the line:

$$P_S = P_R = P \qquad 2.9$$

Thus, varying the value of X varies P, Q_S, and Q_R in accordance with equations 2.5, 2.6, 2.7 and 2.8 respectively.

As is seen from the above formulae, if the angle between the two bus voltages is small, the current flow largely represents the active power flow. Increasing or decreasing the inductive impedance of the line greatly affects the active power flow.

The current flow between the two voltage source ends can be expressed by the following equation:

$$I = \frac{\overrightarrow{V_S} - \overrightarrow{V_R}}{jX} = \frac{\overrightarrow{V_L}}{jX} = \frac{\overrightarrow{V_L}}{X} e^{-j\pi/2}$$ Where $e^{j\theta} = \cos\theta + j\sin\theta$ and $\theta = \frac{\pi}{2}$

2.10

Where V_L is the voltage drop in the line.

Thus the current flow could be expressed as leading or lagging the driving voltage by 90 degrees.

Figure 2.3 shows the current flow perpendicular to the driving voltage as a phasor diagram.

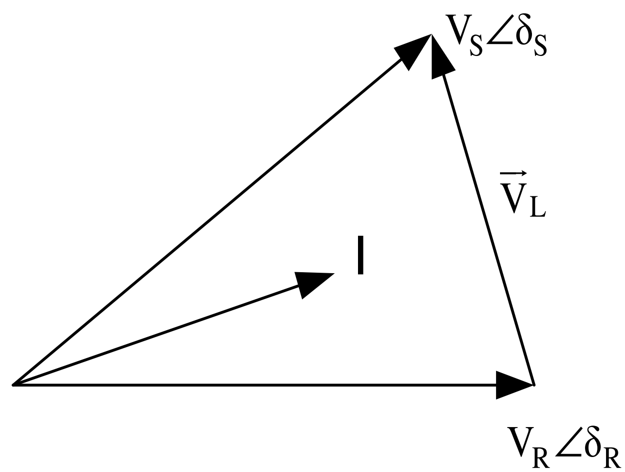


Figure 2.3 Voltage and Current Phasors

Thus impedance control, which provides current control, can be the most effective means of controlling the power flow as the current flow in the line is either leading or lagging the voltage drop in the line by 90 degrees.

Figure 2.4 shows the half sine wave curve of active power increasing to a peak value as angle δ increases from 0 degrees to 90 degrees:

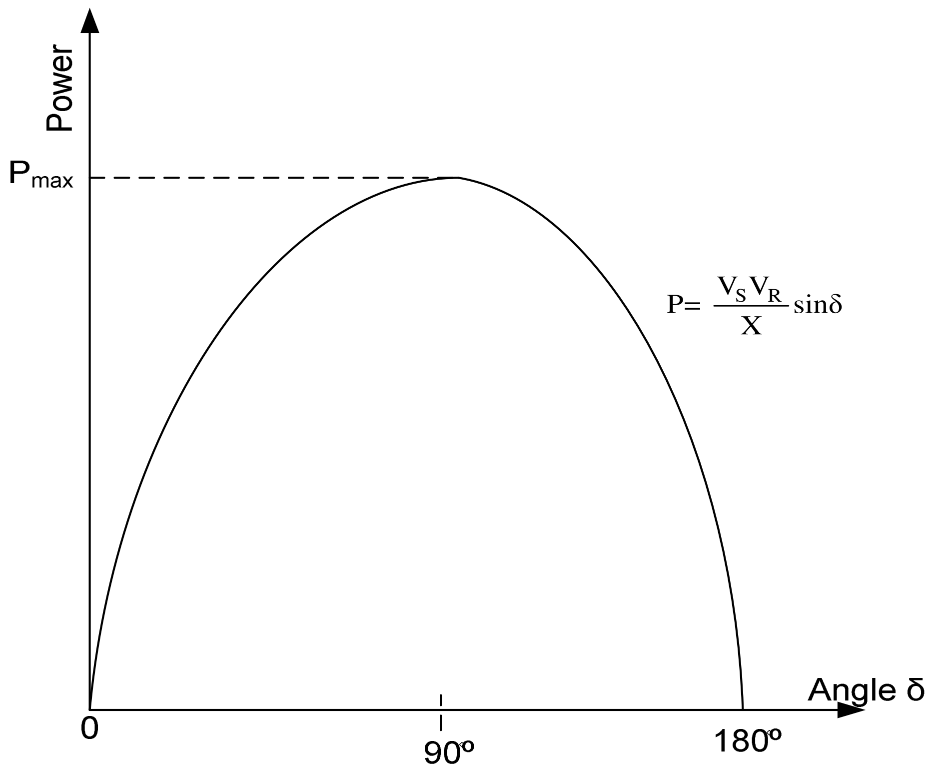


Figure 2.4 Power angle curves for different values of X

Power then falls with further increases in angle, and finally to zero at δ =180 degrees. Here is where we start to appreciate the presence of FACTS devices in the system, that without high-speed control of any of the parameters V_S, V_R, δ , X, and V_L (V_S - V_R) the transmission line can be utilised only to a level well below that corresponding to 90 degrees. This is necessary to maintain an adequate margin needed for transient and dynamic stability and to ensure that the system voltage does not fall below an acceptable level, following an outage of the largest generator or the loss of a transmission line. An increase or decrease in the value of X results in a decrease or increase respectively in the power flow P, shown by the height of the curve. Power and current flow can also be controlled by regulating the magnitude of voltage phasor V_S or V_R. A small change in the magnitudes of V_S or V_R causes a small change in the magnitude of the driving voltage V_S-V_R but a large change in the angle of (V_S - V_R) as shown in Figure 2.5. Hence the regulation of either of the voltage magnitudes V_S or V_R has more of an influence on the reactive power flow (shown in Figure 2.5) than on the active power flow. [1], [2]. The figure shows how the two current phasors correspond to the two driving voltage phasors.

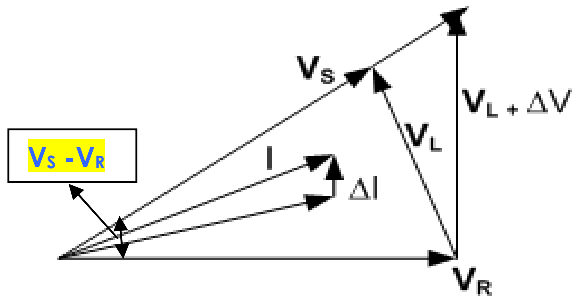


Figure 2.5 Voltage magnitude regulation for reactive power change.

Thus current flow and therefore the power flow can be changed by injecting a voltage in series with the line. Figure 2.6 shows that the injected voltage is in phase with the driving voltage but is injected in quadrature with the current. Therefore the injected voltage directly affects the magnitude of the current flow and hence affects the reactive power flow, and with small angles influences the active power flow.

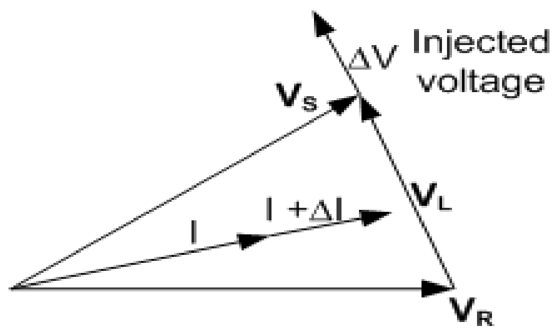


Figure 2.6 Injected voltage in perpendicular to line current (mostly changing active power)

Alternatively a voltage can be injected that will change the magnitude and angle of the driving voltage. It is seen that by varying the magnitude and angle of the injected voltage both the reactive and active power flow could be controlled. This is shown in Figure 2.7.

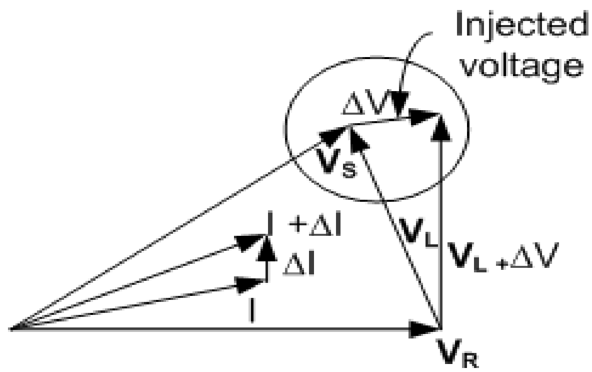


Figure 2.7 Variable magnitude and phasor relationship of injected voltage with the line voltage

Thus voltage injection methods form an important portfolio of FACTS controllers. The two main objectives of FACTS are to:

a) Increase the transmission capacity of the lines

b) Control power flow over designated transmission routes

2.3. FACTS TECHNIQUES

FACTS are broadly classified into four different categories based on the type of application [1], [2], [4], [5]:

1. Series devices
2. Shunt devices
3. Combined series-series devices
4. Combined series-shunt devices

2.3.1. Series Devices

Series devices are power electronic based variable source of mains frequencies, sub-synchronous frequencies and harmonic frequencies.

In principle all series devices inject a voltage in series with the line. For example, variable impedance multiplied by the current flowing through it represents an injected variable series voltage in the line. As long as the voltage is in phase quadrature with the line current, the series controller only supplies or consumes variable reactive power. Any other phase relationship will involve real power being supplied or consumed.

2.3.2. Shunt Devices

As in the case of series devices, shunt controllers may be of variable impedance, variable source, or combinations of these. In principle, shunt devices inject current into the system at the point of connection. Variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt controller only supplies or consumes variable reactive power. Any other phase relationship involves supply or consumption of real power.

2.3.3. Combined Series-Series Devices

Combined series-series devices are normally referred to as interline power flow controllers which are a combination of separate series devices controlled in a coordinated manner. Combined series–series devices have the ability to balance both real and reactive power flows in the lines

When the DC terminals of all the controller converters are connected together for real power transfer they are called Unified Power Flow Controllers (UPFC).

2.3.4. Combined Series-Shunt Devices

Combined Series-shunt devices are a combination of separate shunt and series devices which are controlled in a coordinated manner. In principle, combined shunt and series devices inject current into the system with the shunt part of the controller, and voltage in series in the line with the series part of the controller.

2.4. TYPES OF FACTS DEVICES

There are two distinctly different approaches to realization of FACTS devices, the first is based on conventional thyristor technology and the second is by using voltage source convertors [1], [2], [4], [5].

Different types of FACTS devices that are available are listed in Table 2.1.

Thyristor Controlled Reactor (TCR)

Thyristor Switched Reactor (TSR)

Thyristor Controlled Capacitor (TCC)

Thyristor Switched Capacitor (TSC)

Table 2.1 Available FACTS devices

Conventional Thyristor technology based FACTS devices (as shown in Figure 2.8)	**Voltage source convertors based FACTS devices**
Static shunt compensator of the following types: thyristor controlled reactor (TCR) thyristor switched reactor (TSR) thyristor switched capacitor (TSC) Fixed capacitor-thyristor controlled reactor (FC-TCR) thyristor switched capacitor & thyristor controlled reactor (TSC-TCR)	Static synchronous shunt compensator (STATCOM)
Static series compensators of the following types: thyristor switched series capacitor (TSSC) Fixed capacitor in parallel with thyristor controlled reactors (FC-TCR).	Static synchronous series compensator (SSSC)
Thyristor controlled phase shifters.	Unified power flow controllers

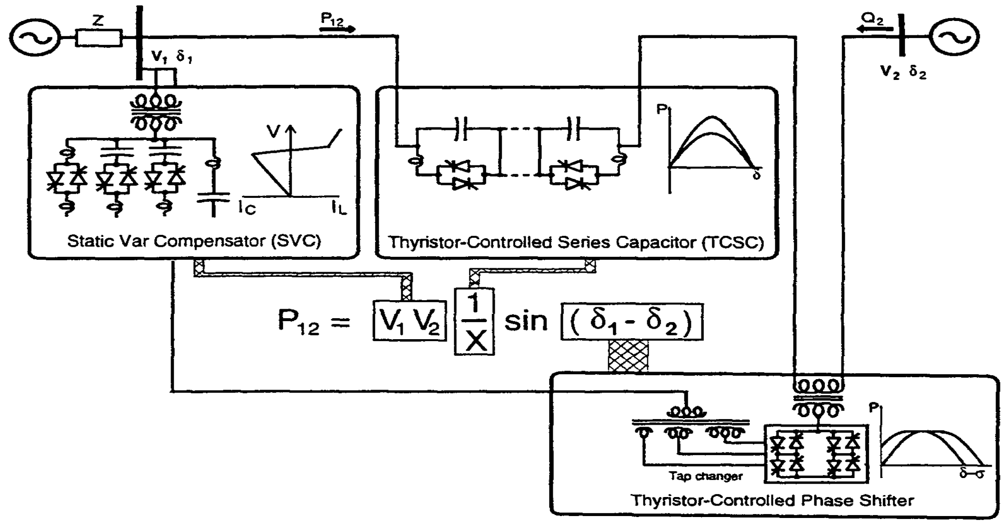


Figure 2.8 Conventional Thyristor based FACTS devices for different application [2]

In the following sections, two of the shunt and series compensators of the two different approaches of FACTS devices are studied.

2.5. CONVENTIONAL THYRISTOR BASED FACTS DEVICES

2.5.1. STATIC VAR COMPENSATORS (Shunt compensation): Thyristor switched capacitor and Thyristor controlled reactor

A typical shunt connected Static VAR Compensator (SVC) is composed of Thyristor Switched Capacitors and Thyristor Controlled Reactors, shown in Figure 2.9 [1]

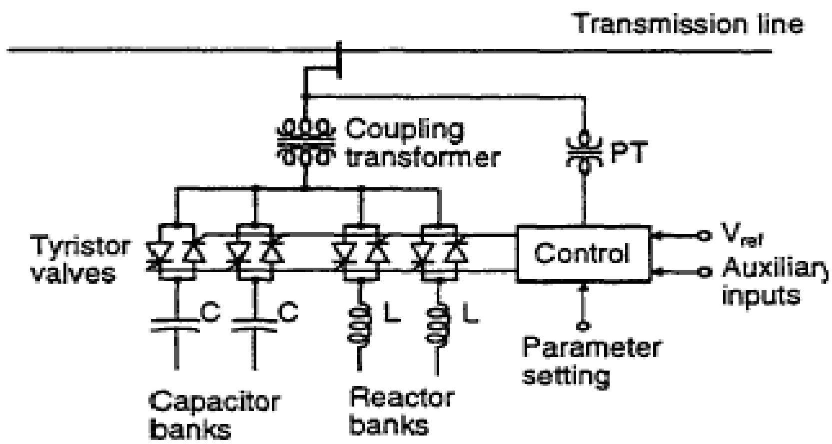


Figure 2.9 Static VAR Compensator employing thyristor switched reactors and thyristor controlled reactors

With proper coordination of the capacitor switching and reactor control, the VAr output can be varied continuously between the capacitive and inductive ratings of the equipment. The compensator is normally operated to regulate the voltage of the transmission system at a selected point. The V-I characteristic of the SVC is shown in Figure 2.10. It indicates that regulation with a given slope around the nominal voltage can be achieved in the normal operating range defined by the maximum capacitive and maximum inductive currents of the SVC.

However the maximum obtainable capacitive currents decrease linearly with the system voltage since the SVC becomes a fixed capacitor when the maximum capacitive output is reached.

Therefore the voltage support capability of the conventional Thyristor Controlled Compensator rapidly deteriorates with the decreasing system voltage.

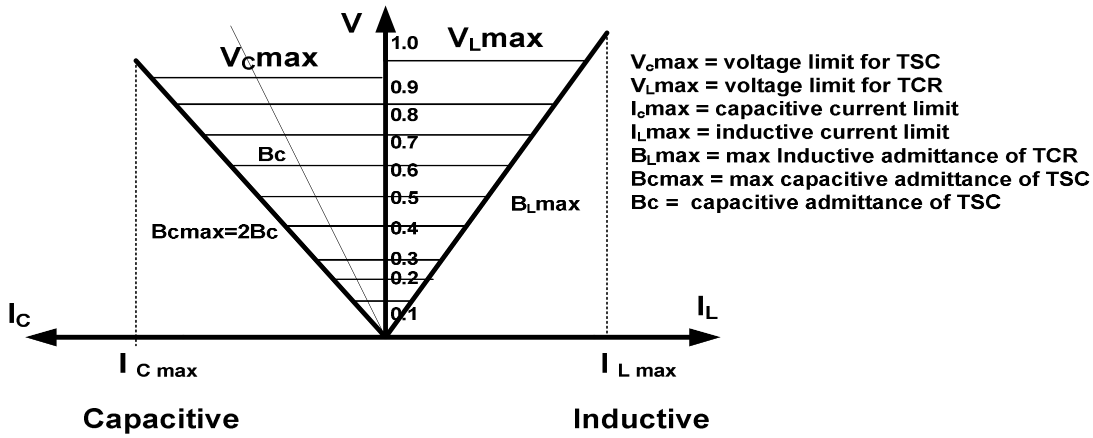


Figure 2.10 Operating V-I area of the TSC-TCR type VAr generator with two thyristor-switched capacitor banks

2.5.2. STATIC VAR COMPENSATORS (Shunt compensation): Fixed capacitor and Thyristor controlled reactor

A basic VAr generator arrangement using a fixed capacitor (permanently connected) with a thyristor controlled reactor is shown in Figure 2.11. [1]

The current in the reactor is varied by delaying the firing angle (α) control of the thyristor. The overall VAr demand versus VAr output characteristics of the fixed capacitor-thyristor controlled reactor type VAr generator is shown in Figure 2.12. As seen from the diagram, the constant capacitive VAr generation (Q_C) of the fixed capacitor is opposed by the variable VAr absorption (Q_L) of the thyristor controlled reactor, to yield the total VAr (Q) output. At maximum capacitive VAr output, the thyristor controlled reactor is off, which is when the firing angle (α=90 degrees). To decrease the capacitive output of the TSC, the current in the reactor is increased by decreasing the firing angle α. At zero VAr output, the capacitive and inductive currents become equal so the capacitive and inductive VArs cancel out. With a further decrease of angle α, the inductive current becomes larger than the capacitive current, resulting in a net inductive VAr output. At zero firing angle, the thyristor-controlled reactor conducts current over the full 180 degree interval, resulting in maximum inductive VAr output that is equal to the difference between the VArs generated by the capacitor and those absorbed by the fully conducting reactor.

The Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR) can be considered as a controllable reactive admittance which, when connected to the AC system, faithfully follows an arbitrary reference input signal (reactive admittance or current). The V-I characteristics of the FC-TCR is defined by the maximum attainable capacitive and inductive admittances and by the voltage and current ratings of the power components (capacitor, reactor and thyristor). The V-I characteristics of Fixed capacitor thyristor controlled reactor is shown in Figure 2.13

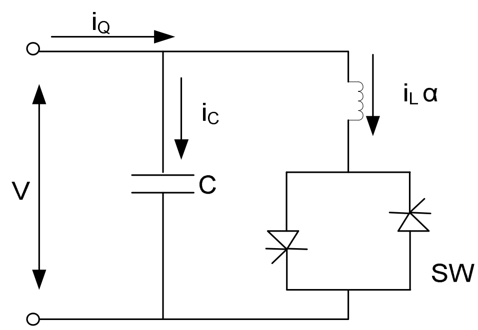


Figure 2.11 Fixed Capacitor-Thyristor controlled reactor type static VAr generator

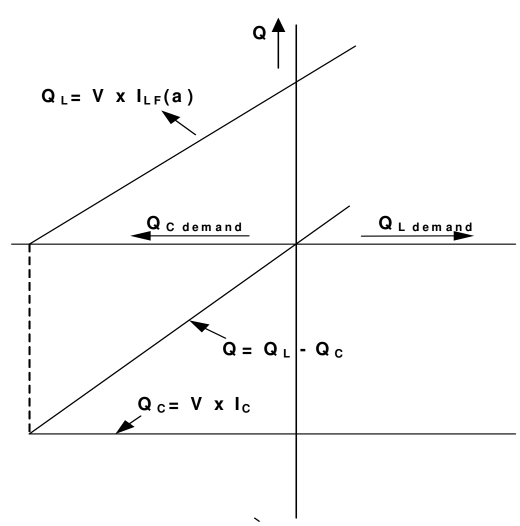


Figure 2.12 Fixed Capacitor-Thyristor controlled reactor type VAr generator - VAr demand versus VAr output characteristics

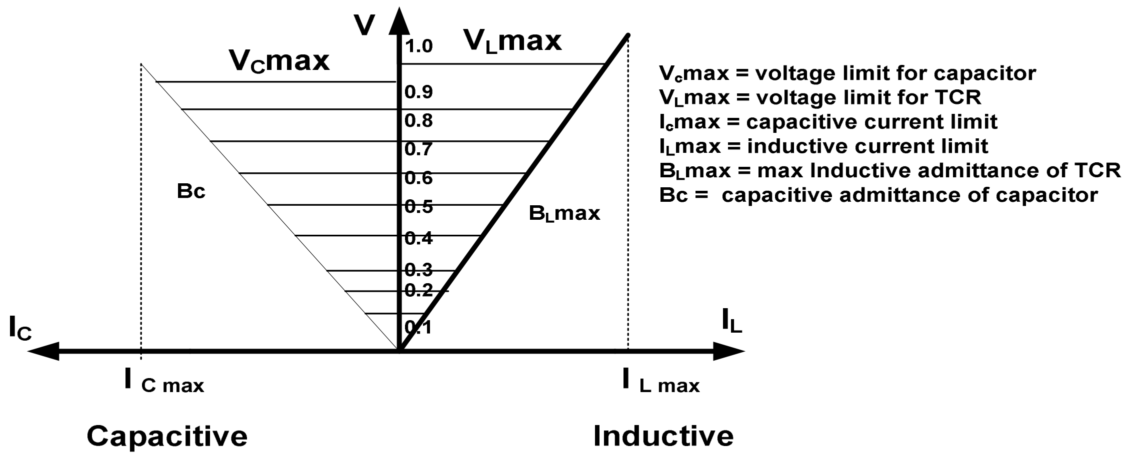


Figure 2.13 Operating V-I area of the FC-TCR type VAr generators

Comparisons of Static VAR Compensators (only Thyristor controlled and switched shunt capacitor / reactors Compared here) are shown in Table 2.2.

Table 2.2 Comparison between different types of conventional thyristor based FACTS shunt compensation devices

VAR Generator	TCR-FC	TSC-TSR	TCR-TSC
Type	Controlled Impedance	Controlled Impedance	Controlled Impedance
V-I and V-Q characteristics	Maximum compensation current is proportional to system voltage. Maximum Capacitive VAr output decreases with square of voltage decrease.	Maximum compensation current is proportional to system voltage. Maximum Capacitive VAr output decreases with square of voltage decrease.	Maximum compensation current is proportional to system voltage. Maximum Capacitive VAr output decreases with square of voltage decrease.

VAR Generator	TCR-FC	TSC-TSR	TCR-TSC
Loss vs. output	High losses at zero output. Losses decrease smoothly with capacitive output and increase with inductive output.	Low losses at zero output. Losses increase in steps with capacitive output.	Low losses at zero output. Losses increase in steps with capacitive output and smoothly with inductive output.
Harmonic generation	Internally high. Requires significant filtering	Internally very low. Resonances (and current limitations) may necessitate tuning reactors	Internally low (small p.u TCR). Requires filtering
Maximum theoretical delay	Half-cycle	One cycle	One cycle
Transient behaviour under system voltage disturbances	Poor. FC causes transient over-voltages in response to step disturbances.	Can be neutral. Capacitors can be switched out to minimize transient over voltages.	Can be neutral. Capacitors can be switched out to minimize transient over voltages.

2.5.3. STATIC SERIES COMPENSATORS: (Thyristor switched series capacitors)

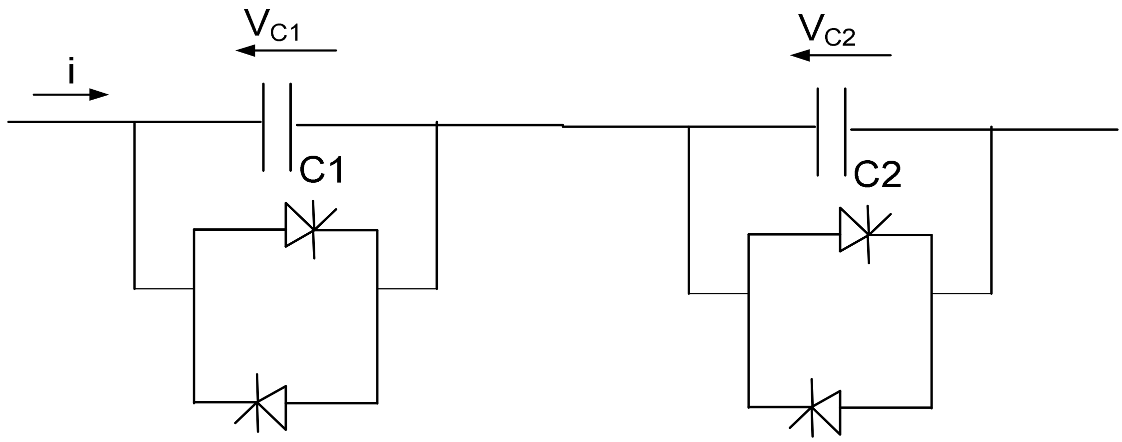


Figure 2.14 Thyristor Switched Series Capacitor

The basic circuit of the Thyristor Switched Series Capacitor (TSSC) is shown in Figure 2.14. It consists of a number of capacitors, each shunted by an appropriately rated bypass valve composed of a string of reverse parallel connected thyristors, in series. The operating principle of the TSSC is straight forward; the degree of series compensation is controlled in a step like manner by increasing or decreasing the number of series capacitors inserted. A capacitor is inserted by turning off, and it is bypassed by turning on the corresponding thyristor.

A thyristor turns off when the current crosses zero. Thus a capacitor can be inserted into the line by the thyristor only at the zero crossings of the line current. Since the insertion takes place at line current zero, a full-cycle of the line current charges the capacitor from zero to maximum and the successive, opposite polarity half-cycle of the line current discharges it from this maximum to zero, as shown in Figure 2.15. As can be seen, the capacitor insertion at line current zero, necessitated by the switching limitation of the thyristor, results in a DC offset voltage which is equal to the amplitude of the AC capacitor voltage. To minimise the initial surge current in the valve, and the corresponding circuit transient, the thyristor should be turned on for bypass only when capacitor voltage is zero. [1]

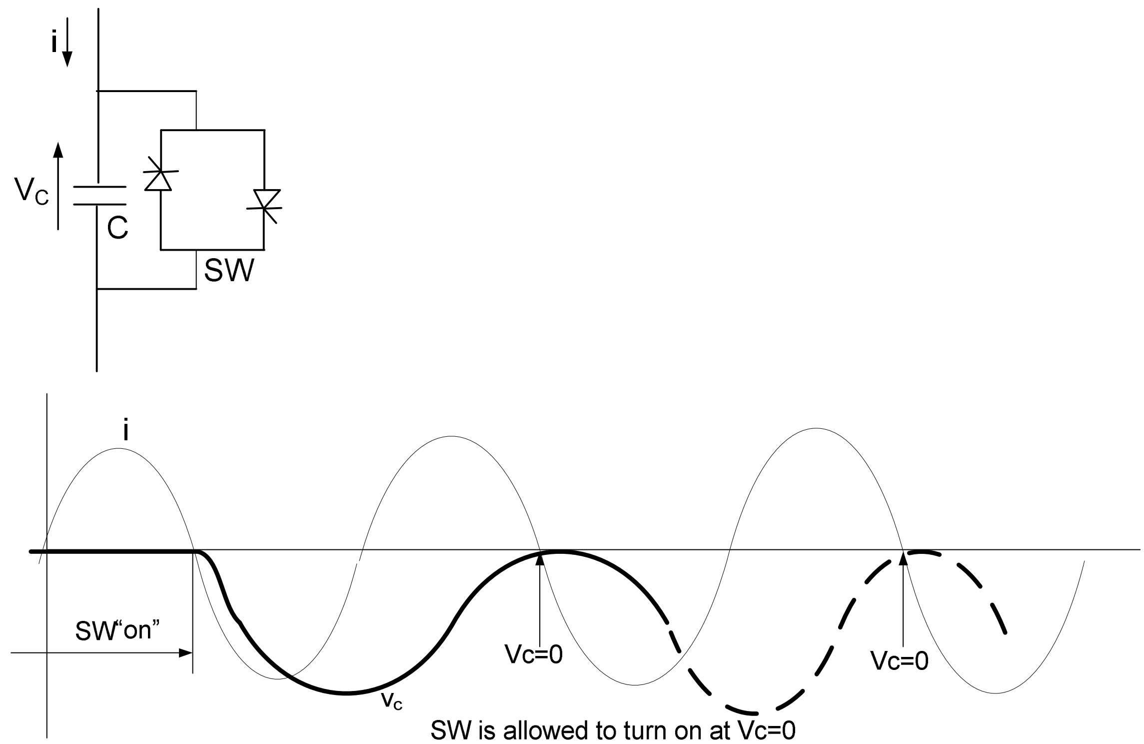


Figure 2.15 Capacitor offset voltage resulting from restriction of inserting at zero line current

The TSSC can be operated in two modes of control. The first is the voltage compensation mode and the second is the impedance compensation mode. The V-I characteristics of the TSSC with two series connected compensator modules, operated to control the compensating voltage as per the first mode, is shown in Figure 2.16. For this mode of compensation the reactance of the capacitor banks is chosen to produce, on average, the rated compensating voltage $V_{C(\max x)} = 2X_C I_{\min}$ in the face of decreasing line current over a defined interval $I_{\min} \le I \le I_{\max}$. When the current I_{min} is increased towards I_{max}, the capacitor banks are progressively bypassed by the related thyristors to reduce the overall capacitive reactance in steps and thereby maintain the compensating voltage with increasing line current.

In the reactance control mode, the TSSC is applied to maintain maximum rated compensating reactance at any line current up to the rated maximum as shown in Figure 2.17. In this compensation mode the capacitive reactance is chosen to provide the maximum series compensation at rated current $2X = \frac{V_{C(\max)}}{I_{\max}}$, which the TSSC can vary in steps by bypassing one or more capacitor banks.

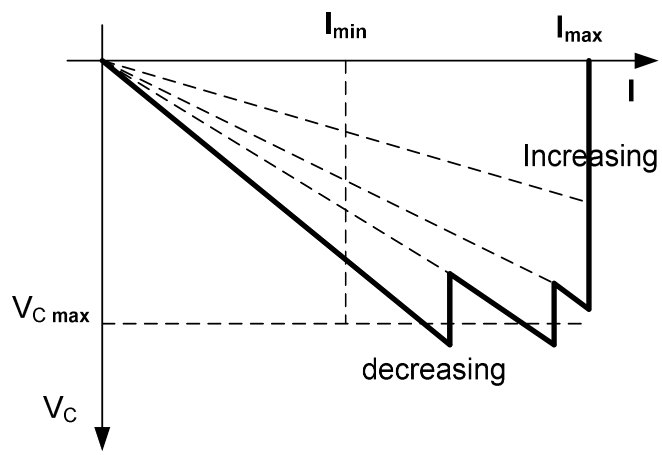


Figure 2.16 Attainable compensating voltage Vs line current characteristics of TSSC when operated in Voltage control mode

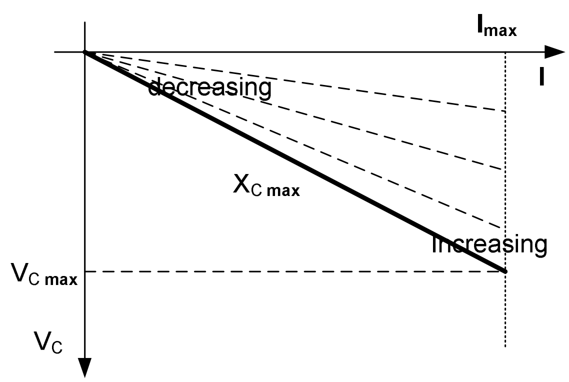


Figure 2.17 Attainable compensating voltage Vs line current characteristics of TSSC when operated in reactance control mode

2.5.4. STATIC SERIES COMPENSATORS: (Thyristor controlled series capacitors)

The basic Thyristor Controlled Series Capacitor (TCSC) consists of a series compensating capacitor shunted by a thyristor controlled reactor. In a practical TCSC implementation as shown in Figure 2.18, several such basic compensators may be connected in series to obtain the desired voltage rating and operating characteristics. This arrangement is similar to that of the TSSC and, if the impedance of the reactor, X_L, is sufficiently smaller than that of the capacitor $X_{C,}$ it can be operated in an on/off manner like the TSSC. The basic idea behind the TCSC scheme is to provide a continuously variable capacitor by partially cancelling the effective compensating capacitance of the TCR. At the fundamental frequency, the TCR could be continuously variable reactive impedance, controllable by a delay angle, the steady-state impedance of the TCSC is that of a parallel LC circuit, consisting of fixed capacitive impedance, X_C and a variable inductive impedance $X_{L,}$ equation 2.9 shows the equivalent impedance of TCSC.

$$X_{TCSC} = \frac{X_C X_L}{X_L + X_C} \qquad 2.9$$

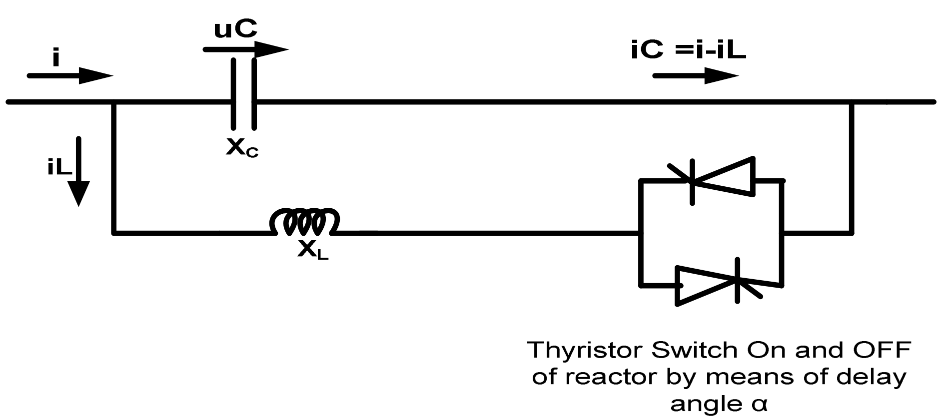


Figure 2.18 Fixed Capacitor Thyristor Controlled Reactor

$$\lambda = \sqrt{\frac{-X_C}{X_L}} \qquad 2.10$$

Where,

$$X_C = \frac{-1}{\omega C} \qquad 2.11$$

and

$$X_L = \omega L \qquad 2.12$$

For an LC circuit the resonant frequency is given by

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad 2.13$$

Substituting equations 2.11and 2.12 in the equation 2.10 we get

$$\lambda = \frac{f_r}{f} = \frac{1}{\omega\sqrt{LC}} \qquad 2.14$$

Reasonable values for λ fall in the range of 2 to 4.

A parameter to describe the TCSC main circuit is λ which is the ratio (f_r / f) of the resonant frequency(f_r) and the network frequency(f), and is a real number as the (-) sign gets cancelled while substituting equation 2.10 in 2.11.

As discussed earlier there are different modes of operation of the TCSC depending on the trigger position of the thyristor.

These operating modes of the TCSC are characterized by a factor called the boost factor.

$$K_B = \frac{X_{TCSC}}{X_C} \qquad 2.15$$

where X_{TCSC} is the apparent reactance:

$$X_{TCSC} = \frac{U_C}{I} \qquad 2.16$$

Where U_c is the voltage measured across the capacitor and I is the current injected into the circuit.

Blocking Mode

In this mode the thyristor remains non-conducting as it is not triggered. The situation is like an inductor connected in series with a switch, which is in the open position. Hence the line current passes only through the capacitor bank $X_{TCSC} = X_C$ so the boost factor is equal to one. In this mode the TCSC performs like a fixed series capacitor.

Bypass Mode

Bypass mode is used to reduce capacitor stress during faults. The thyristors are triggered continuously and therefore stay conducting all the time. In this mode the TCSC behaves like a parallel connection of the series capacitor and the inductor. The apparent impedance becomes:

$$X_{TCSC} = \frac{X_L X_C}{X_L + X_C} = \frac{X_C}{(1-\lambda^2)} \qquad 2.17$$

The voltage is inductive and the boost factor is negative. When λ is larger than unity the amplitude of the capacitor voltage (Uc) is much lower in bypass mode than in blocking mode.

Capacitive boost mode

If the trigger pulses are supplied to the thyristors having forward voltage just before the capacitor voltage crosses the zero line a capacitor (dis)charge current pulse will circulate through the parallel inductive branch.

This discharge current is due to the voltage reversal of the capacitor charging during the instant of closing. The discharge current pulse adds to the line current through the capacitor bank. It causes the capacitor voltage that adds to the voltage caused by the line current. The capacitor peak voltage thus will be increased in proportion to the charge that passes through the thyristor branch. The charge depends on the conduction angle β. The waveform for the capacitor voltage rise due to the switching of the TCR is shown in Figure 2.19. The reversal of the capacitor voltage is clearly the key to the control of the TCSC. The time duration of the voltage reversal is dependant primarily on the

X_L / X_C ratio, but also on the magnitude of the line current. If,

$$X_L << X_C \qquad 2.18$$

then the reversal is almost instantaneous.

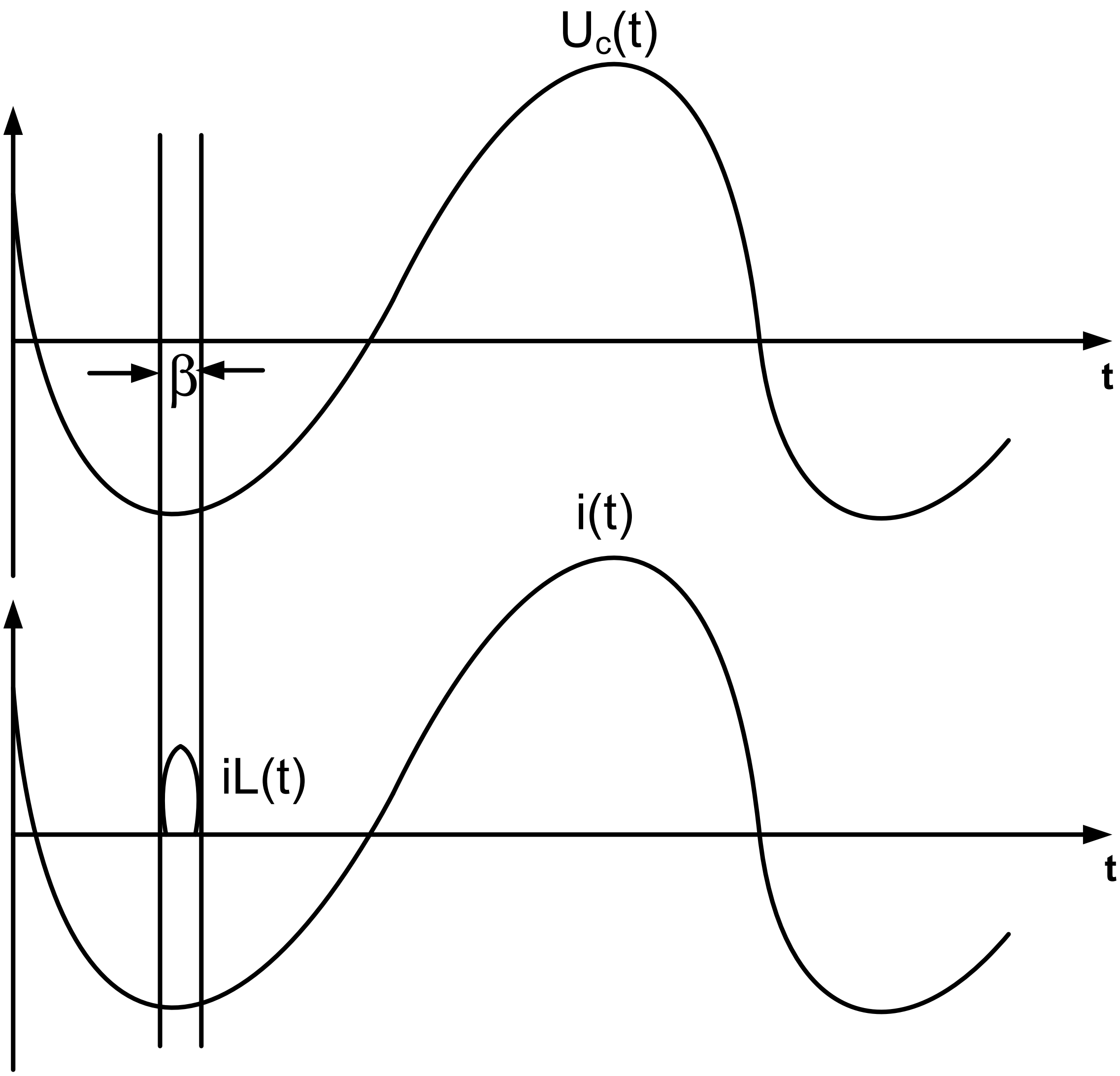


Figure 2.19 Waveform at various boost factors in capacitive boost mode

Inductive Boost mode:

If the conduction angle of the thyristor is increased above β the mode changes from conductive to inductive boost mode. In the inductive boost mode, large thyristor currents may occur. The curves of the currents and the voltage for three different conduction angles are shown in Figure 2.20.

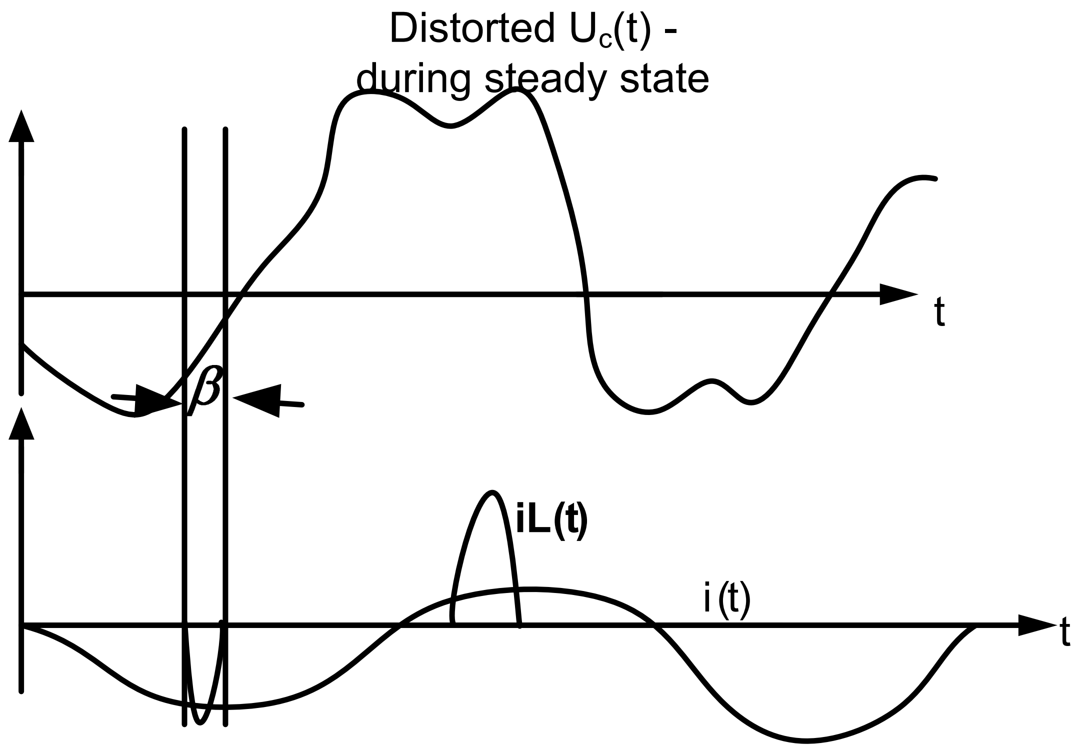


Figure 2.20 Waveforms at various boost factors in inductive boost mode

The capacitor voltage waveform is very much distorted from its desired sinusoidal shape. Because of this waveform and the high valve stress, the inductive boost mode is less attractive for steady state operation.

2.6. CONVERTER BASED FACTS DEVICES

Converter based FACTS devices consist of solid-state voltage source inverters with several Gate Turn off (GTO) thyristors and a DC link capacitor, a magnetic circuit, and a controller. [1], [5].The number of valves and the various configurations of the magnetic circuit depend on the desired quality of AC waveforms generated by the FACTS devices.

2.6.1. Voltage source convertor based Static Synchronous Shunt Compensator (STATCOM)

STATCOM is a converter type FACTS device [1], [5] which generally provides superior performance characteristics compared with conventional compensation methods employing thyristor-switched capacitors and thyristor controlled reactors. It also offers the unique potential to exchange real power directly with the AC system, providing powerful new options for flow control and the counteraction of dynamic disturbances.

The schematic diagram of a STATCOM is shown in Figure 2.21. The charged capacitor C_{dc} provides a DC voltage to the converter, which produces a set of controllable three-phase output voltages synchronous with the AC power system. By varying the amplitude of the output voltage E_1, the reactive power exchange between the converter and the AC system can be controlled. If the amplitude of the output E_1 is increased above the AC system voltage V_T, current flows through the reactance of the converter (coupling transformer) and a leading current is produced, i.e. the STATCOM is seen as a capacitor by the AC system and reactive power is generated. Decreasing the amplitude of the output voltage below that of the AC system, a lagging current results and the STATCOM is seen as an inductor. In this case reactive power is absorbed. If the amplitudes are equal no power exchange takes place.

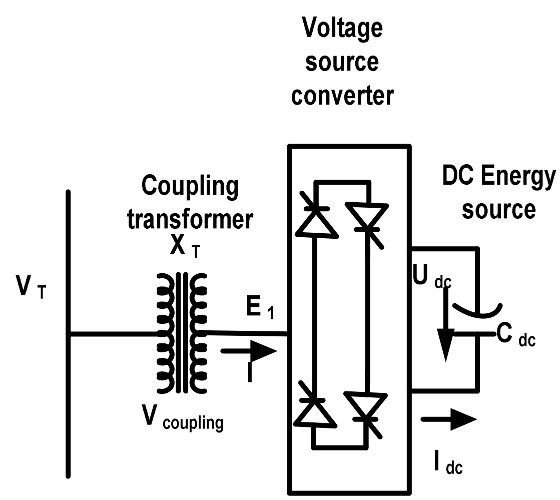


Figure 2.21 Static Synchronous compensator

A practical converter is not lossless. If corrective action is not taken, the energy stored in this capacitor would be consumed by the internal losses of the converter. By making the output voltages of the converter lag the AC system voltages by a small angle, the converter absorbs a small amount of active power from the AC system to balance the losses in the converter. The mechanism of phase angle adjustment can also be used to control the active power generation (Figure 2.22). If the converter is restricted to operate for reactive power exchange only, the AC output voltage is governed by only controlling the magnitude of the DC link voltage. This is possible due to the fact that the magnitude of AC output voltage is directly proportional to DC capacitor voltage.

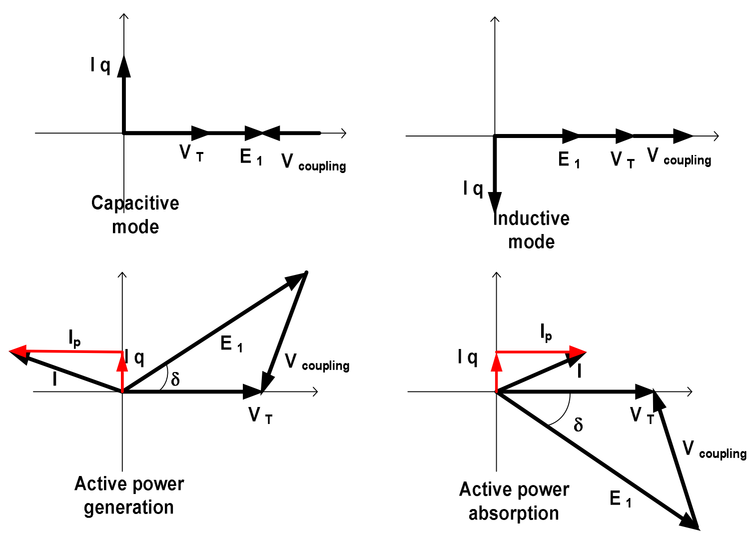


Figure 2.22 STATCOM operating in inductive and capacitive modes

The V-I characteristics of a STATCOM is shown in Figure 2.23. A STATCOM can provide both capacitive(I_C) and inductive (I_L) compensation and is able to control its output current over the rated maximum capacitive (I_{Cmax}) or inductive range (I_{Lmax}) independently of the AC system voltage. This feature is the main advantage of the STATCOM over Static VAR Compensator (SVC); that is STATCOM can provide full capacitive output current at any system voltage, practically down to zero. This is in contrast to the SVC which can supply only diminishing output current with decreasing system voltage as determined by its maximum equivalent admittance. This also means that the maximum capacitive or inductive reactance generated by STATCOM decreases linearly with voltage at constant current.

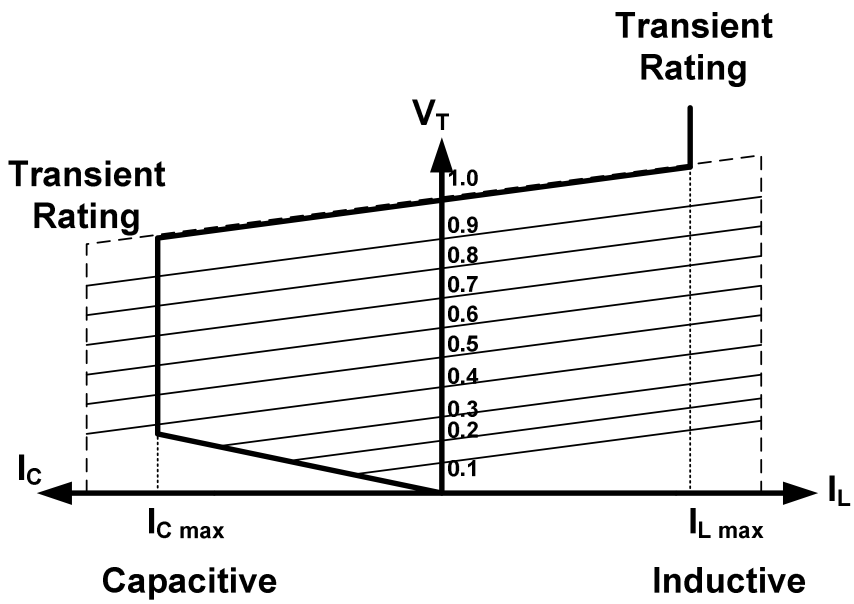


Figure 2.23 V-I Characteristics of STATCOM

2.6.2. Comparison of Shunt Compensators (STATCOM vs SVC Devices)

As discussed in previous sections, although STATCOM and SVC are very similar in their functional capability, the basic operating principles are fundamentally very different. In Table 2.3 the functional comparison between the two types of shunt compensators are covered (thyristor / converter types).

Table 2.3 Comparison between conventional thyristor based shunt compensators and voltage source shunt compensators

STATCOM (Voltage source convertor based shunt compensator)	SVC (Conventional thyristor based shunt compensator)
STATCOM functions as a shunt-connected synchronous voltage source. This difference accounts for the STATCOM's superior functional characteristics, better performance, and greater application flexibility than those attainable with an SVC.	An SVC operates as a shunt-connected, controlled reactive admittance.

In the linear operating range the V-I characteristics and functional compensation capability are similar to an SVC	In the linear operating range the V-I characteristics and functional compensation capability are similar to an SVC
In the non-linear operating range, the STATCOM is able to control its output current over the rated maximum capacitive or inductive range independently of the AC system voltage.	The maximum attainable compensating current of the SVC decreases linearly with the AC voltage.
STATCOM can provide active power compensation in addition to the reactive power compensation.	An SVC does not have the capability to provide the active power compensation.

2.6.3. Voltage source convertor based Static Series Synchronous Compensator (SSSC)

The basic operating principles of the SSSC can be explained with reference to the conventional series capacitive compensation to have a clearer understanding[1],[7]; Figure 2.24 shows the two machine systems with a conventional series capacitor and a simple understanding of its phasor diagram. The respective phasor diagram shows that at a given line current the voltage across the series capacitor forces the opposite polarity voltage across the series line reactance to increase by the magnitude of capacitor voltage. Thus, the series capacitive compensation works by increasing the voltage across the line impedance of the given physical line, which in turn increases the corresponding line current and the transmitted power. In Figure 2.24, V_C is the voltage drop across the capacitor and V_L is the voltage drop across the line, I is the line current, V_S and V_R are the magnitude of the sending and sending end voltage and receiving end voltages respectively as shown in the phasor diagram, X_L and X_C are the reactance of the capacitor and reactance of the line respectively and δ is the angle between the two end source voltages. Thus the power flow in the line is increased by controlling the reactance of the line using series compensation as shown in equation 2.19

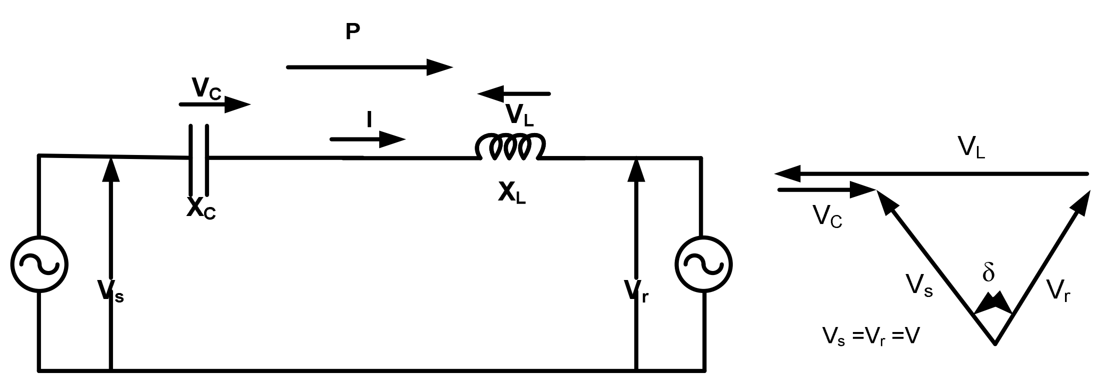


Figure 2.24 A Two machine system with a series capacitor compensated line and associated phasor diagram

$$P = \frac{V^2}{X_L - X_C}\sin\delta \qquad 2.19$$

While it may be convenient to consider series capacitive compensation as a means of reducing the line impedance, in reality it is really a means of increasing the voltage across the given impedance of the physical line. Therefore the same steady state power transmission can be established if the series compensation is provided by a synchronous AC voltage source. This is shown in Figure 2.25, (where $V_q(\xi)$ is the magnitude of the injected compensating voltage ($0 <= V_q(\xi) <= V_{qmax}$) and ξ is the chosen control parameter, I is the line current, and Iref is the settable reactive current setting for control as expressed in equation 2.20)

$$V_q = \pm j V_q(\zeta) \frac{I}{I_{ref}} \qquad 2.20$$

which shows the synchronous voltage source output matches the voltage of the series capacitor; this could be equated as per equation 2.21

$$V_q = V_c = -jX_c I = -jkX_L \qquad 2.21$$

Where $k = X_C / X_L$ is the degree of series compensation and j is the operator which is equal to $\sqrt{-1}$ and V_C is the injected compensating voltage phasor, I is the line current, X_C is the reactance of the series capacitor and X_L is the reactance of the line.

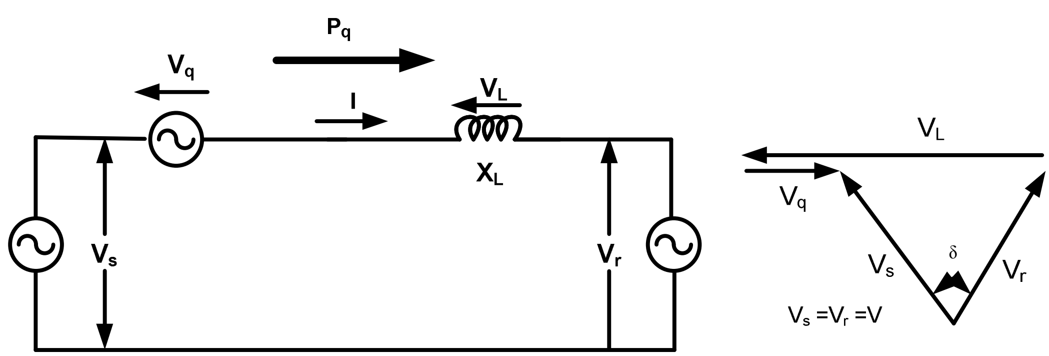


Figure 2.25 A Two machine system with synchronous voltage source (replacing series capacitor) compensated line and associated phasor diagram

Thus the power flow increase in the transmission line by voltage source convertor is given by equation 2.22 which is similar to the power flow increase in the transmission line due to compensation by the series capacitor as shown in equation 2.21.

$$P_q = \frac{V^2}{X_L - \frac{V_q}{I_{ref}}} \sin\delta \qquad 2.22$$

Thus by making the output voltage of the synchronous voltage source a function of the line current as shown in equation, the same compensation as provided by the series capacitor is achieved. However in contrast to the real series capacitor, the synchronous voltage source is able to maintain a constant compensating voltage as the presence of variable line current, or control the amplitude of the injected compensating voltage independent of the amplitude of the line current.

For normal capacitive compensation, the output voltage lags the line current by 90 degrees. For the synchronous voltage source the output voltage can be reversed by simple control action to make it lead or lag the line current by 90 degrees. In this case, the injected voltage decreases or increases the voltage across the inductive line impedance and thus the series compensation has the same effect as if the reactive line impedance was increased or decreased.

Table 2.4 Comparison of functional details between the converter type and thyristor type series compensation devices

SSSC	TCSC	TSSC
SSSC is a voltage source inverter type series compensator	TCSC is a impedance type series compensator	TSSC is a impedance type series compensator
The SSSC is capable of internally generating a controllable compensating voltage over identical Inductive and Capacitive range independently of the magnitude of the line current.	The TCSC can maintain compensating voltage with decreasing line current over a control range determined by the current boosting capability of the thyristor controlled reactor.	The compensating voltage of the TSSC over a given control range is proportional to the line current.
The SSSC has the inherent ability to interface with an external DC power supply to provide compensation for the line resistance by the injection of real power, as well as for the line reactance by the injection of reactive power for the purpose of keeping the effective X/R ratio high, independently of the degree of series compensation.	TCSC cannot exchange real power with the transmission line and can only exchange reactive power	TSSC cannot exchange real power with the transmission line and can only exchange reactive power

SSSC	TCSC	TSSC
The SSSC uses the GTO thyristors. These devices presently have lower voltage and current ratings and considerably lower short-term surge current ratings. They are suitable for short term bypass operation only if the anticipated line fault current is relatively low. Therefore they need external fast protection during severe line faults by an auxiliary conventional thyristor by pass switch.	The TCSC uses conventional thyristors (with no internal turn-off capability). These thyristors are rugged power semiconductors, available with the highest voltage and current ratings, and they also have the highest surge current capability. For short-term use they also provide bypass operation to protect the associated capacitors during the line faults.	The TSSC uses conventional thyristors (with no internal turn-off capability). These thyristors are rugged power semiconductors, available with the highest voltage and current ratings, and they also have the highest surge current capability. For short-term use they also provide bypass operation to protect the associated capacitors during line faults.
The SSSC requires a coupling transformer rated at 0.5 p.u. of the total series compensating range, and a DC storage capacitor. However, it is installed in a building at ground potential and operated at a relatively low voltage. Thus the installation needs low voltage insulation for the cooling system and a control interface.	TCSC are coupled directly to the transmission line and therefore are installed on the high voltage platform. The cooling system and control are located on the ground with high voltage insulation requirements and control interface.	TSSC are coupled directly to the transmission line and therefore are installed on the high voltage platform. The cooling system and control are located on the ground with high voltage insulation requirements and control interface.

SSSC	TCSC	TSSC
At rated line current the loss exhibited by the SSSC would be 0.7 to 0.9% of the rated VAr output.	At rated line current the loss exhibited by the TCSC would be 0.5% of the rated VAr output.	At rated line current the loss exhibited by the TCSC would be 0.5% of the rated VAr output.

2.7. FLEXIBLE AC TRANSMISSION SYSTEM (FACTS) APPLICATIONS AND STATE OF THE ART

Various types of FACTS devices are currently installed throughout the world in a variety of applications. There are no recent state of art information available to be presented, state of art, presented here below are not so recent. Examples are:

1. A 150 MVAr STATCOM is installed at the 115kV Glen brook substation in Stamford, Connecticut. Glenbrook is located with in the Norwalk- Stamford area of South west Connecticut. The purpose of STATCOM is to provide fast acting dynamic reactive compensation for voltage support during contingency events.

2. Tennessee Valley Authority (TVA) installed a FACTS controller, which is providing dynamic and flexible voltage and reactive power support at their Sullivan substation. The controller is a Static Synchronous Compensator (STATCOM). STATCOM has enabled TVA to defer a new 160 kV transmission line and the need to install a 500 kV/160 kV step down transformer at the Sullivan Substation.

3. In 1991 the world's first commercial transmission system STATCOM was installed at the Inuyama substation of the Kansai electric power company in Japan, for the objective of improving power system and voltage stabilization. It has been successfully operating for 9 years. The capacity of the STATCOM is 80 MVA.

4. The STATCOM at Essex was installed for the dynamic reactive compensation needed for fast voltage support during critical contingencies. Rating of STATCOM is 133/41 MVA, 115kV.

5. A major addition to the 500 kV transmission system between Arizona and California is being installed to increase power transfer opportunities. Along with the new-series compensated 500 kV lines, two Static VAr Compensators (SVC) with parallel thyristor switched capacitors and thyristor controlled reactors are being installed at the Marketplace and Adelanto switching stations

6. In Canada, in Maine Province a Static VAr Compensator (SVC) was recently installed at the Chester station. This station is located in the 150-mile, 345 kV inter-tie between the Keswick station in New Brunswick and the Orrington station in Maine. The SVC is rated -125 (inductive), +425 (capacitive) MVAr, and is of the thyristor –controlled reactor (TCR) and thyristor-switched capacitor (TSC) design.

7. The world's first multi-module thyristor-controlled series capacitor (TCSC) system has been installed at Bonneville Power Administration's transmission system. The TCSC is part EPRI's Flexible AC Transmission System FACTS program, and was funded by EPRI, BPA and GE.

8. A collaborative project between AEP (Westinghouse Electric corporation) and Electric Power Research Institute (EPRI) in the installation of the world's first Unified power flow controllers (UPFC) comprising 2 x 160 MVA voltage sourced GTO thyristor based converters STATCOM and SSSC both connected at their DC terminals. [9]

9. The New York Power Authority (NYPA) is installing a FACTS Controller to relieve a bottleneck at their Marcy Substation and to provide power flow control on two transmission lines. The controller is a Convertible Static Compensator (CSC). The CSC will increase the total Central-East power transfer capability by 240 MW without adding transmission lines.

10. Central & South West (CSW, now AEP) installed a FACTS controller to interconnect the asynchronous U.S. and Mexico grids at their Eagle Pass substation. The controller is a Voltage Source Converter-based Back-to-Back (VSC-BtB). The BtB has allowed AEP to avoid building a long 138 kV transmission line. Also the BtB has provided a reliable electric bridge between the US and Mexico.

Figure 2.26 [2] shows FACTS device installations sponsored by the Electric Power Research Institute (EPRI) in the US and Canada and Figure 2.27 presents the world wide installations of FACTS devices from the EPRI Journal.

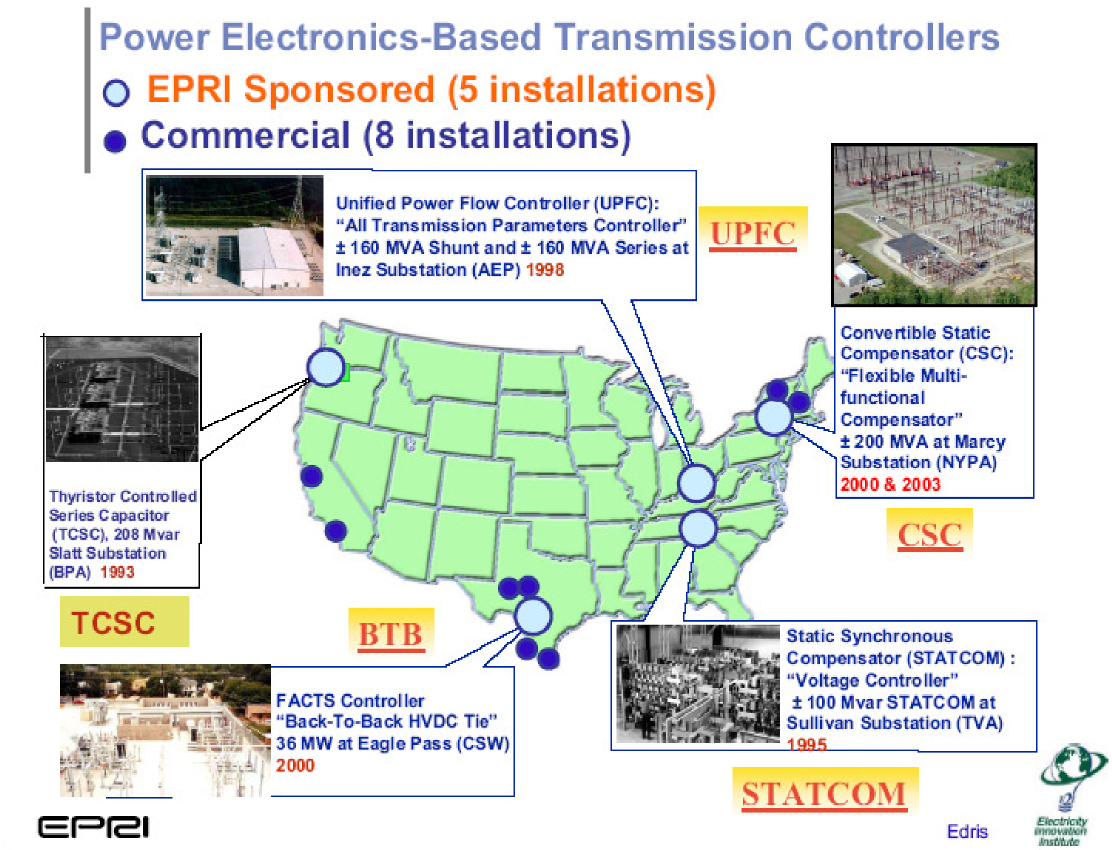


Figure 2.26 EPRI-Sponsored FACTS Installations [2]

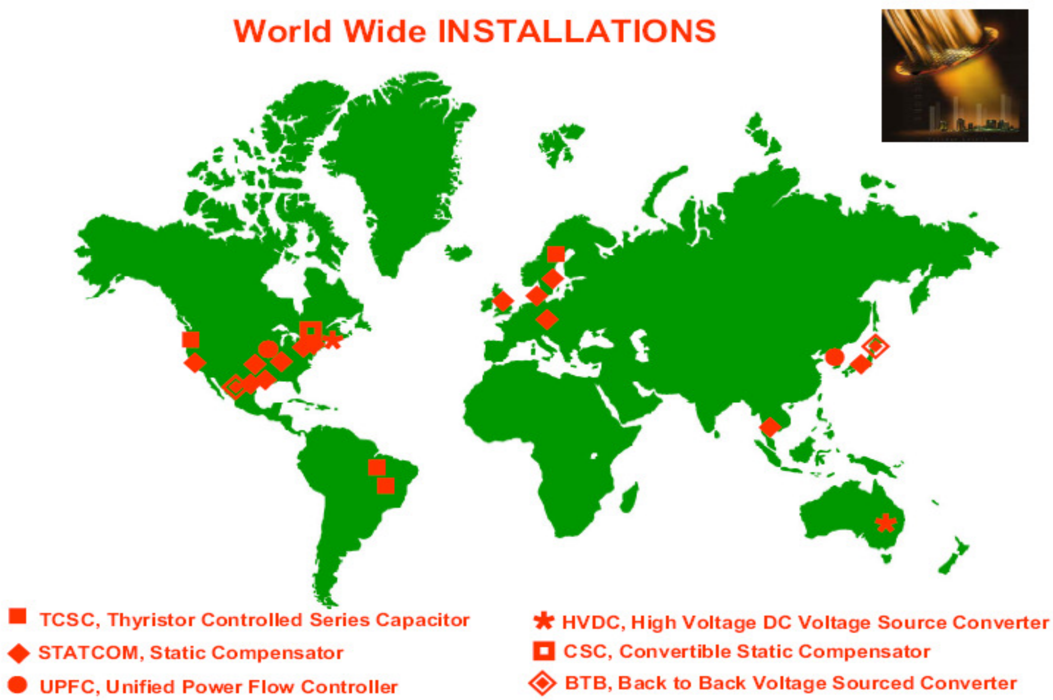


Figure 2.27 [9] World wide installations of FACTS (Information as of 2003)

2.8. CONCLUSION

Various application needs of FACTS devices in power systems are discussed in this chapter. Also an appreciation of FACTS based devices performance for various power systems conditions are covered in this chapter. The chapter also outlines the distinct advantages of the voltage source based convertor FACTS devices over the conventional thyristor type of FACTS devices.

3. EFFECTS OF FLEXIBLE AC TRANSMISSION SYSTEM ON PROTECTION

3.1. INTRODUCTION

With the rapid development of power systems and the large amount of interconnection involved to ensure continuity of supply and good voltage regulation, the problems of combining fast fault clearance with system co-ordination have become very important. To meet these requirements, high speed protective systems, suitable for use with the automatic reclosure of circuit breakers are under continuous development and are already very widely used for the protection of medium and high voltage lines.

Distance protection is a non-unit system of protection offering considerable economic and technical advantages. This form of protection is comparatively simple to apply, is of the high speed class and can provide both primary and back-up facilities in a single protection relay scheme.

3.2. DISTANCE PROTECTION PRINCIPLES

The impedance of a transmission line is proportional to its length, for distance measurement it is appropriate to use a relay capable of measuring the impedance of a line up to a predetermined point (the reach point or setting). Such a relay is described as a distance relay and is designed to operate only for faults occurring between the relay location and the selected reach point or setting, thus discrimination for faults that may occur in different line sections. Figure 3.1 shows the single line diagram of a transmission system shown with the distance relay location. The figure can be used to represent a three phase system using a single line diagram convention, where a single conductor is a representation of a three conductor system, which can be mutually coupled. Thus I_A,I_B,I_C will represent the currents of the 3 phase conductors. As per IEEE C37.2 the acronym for a distance relay is 21. In the Figure 3.1 Z_S is the source impedance behind the relaying point, Z_T is transformer impedance, and

Z_L is the line impedance. I_R and V_R are respectively relay's three phase current and three phase voltage measurement inputs.

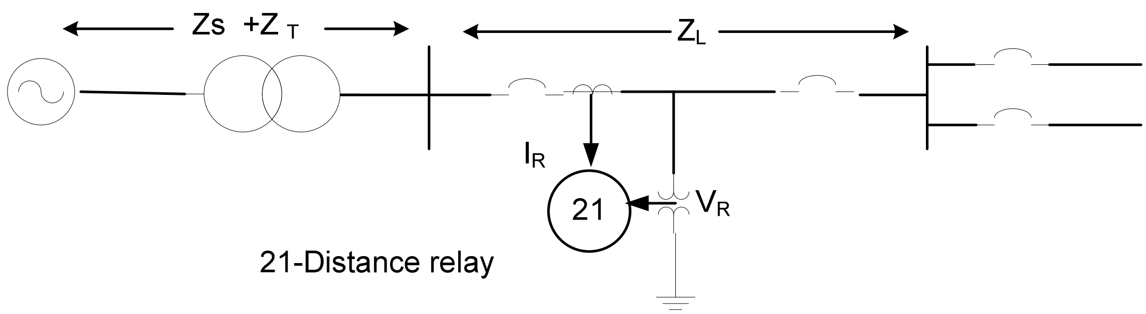


Figure 3.1 Distance relay employed on a transmission line

The basic principle of a distance protection involves the division of measured voltage at the relaying point by the measured current to calculate the impedance seen by the relay. Figure 3.3 and Figure 3.4 show the impedance measured by a distance relay during normal system conditions and during system fault conditions respectively. Figure 3.2 represents the impedance model of transmission system where Z_S is source impedance behind the relaying point, V_S is the source voltage, Z_L is the line impedance of the total line length that is protected by the distance relay, Z_{LOAD} is the impedance of the connected load. I_R is current measured by the relay's current transformer (CT) and V_R is the voltage measured by the relay's voltage transformer (VT).

The apparent impedance so calculated is compared against the pre-determined factor which is called the reach-point. This is given in Equation 3.1 where Z_R is the relay's calculated impedance.

$$Z_R = \frac{V_R}{I_R} = Z_L + Z_{LOAD} \qquad 3.1$$

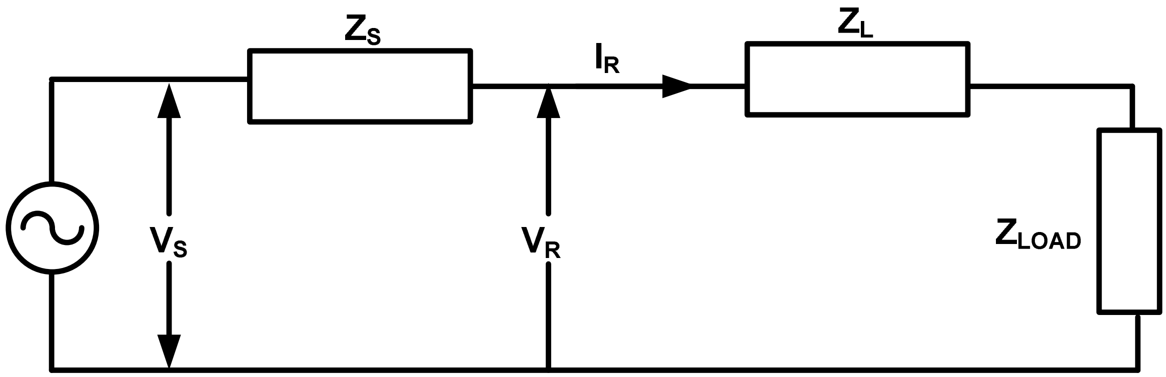


Figure 3.2 Impedance measured under Normal Load

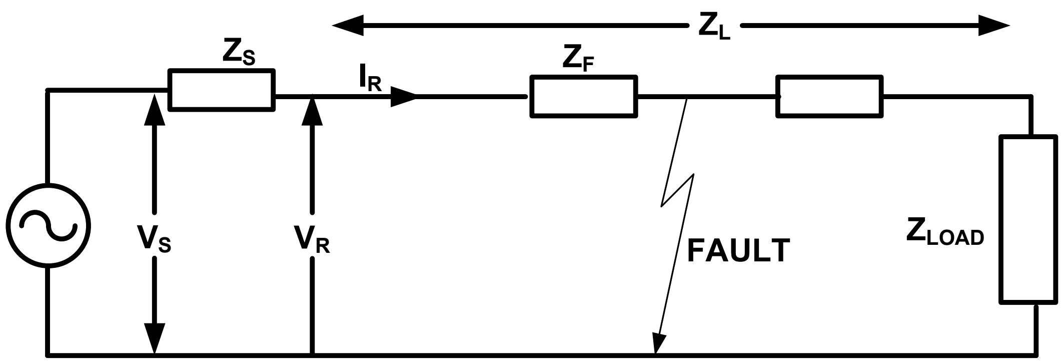


Figure 3.3 Impedance measured under Fault

The impedance calculated at the relay for the situation shown in Figure 3.3 is given by

$$Z_R = \frac{V_R}{I_R} = Z_F \qquad 3.2$$

Where Z_F is the fault impedance

Relay operates if $Z_F < Z$

Where Z is the relay's setting impedance or reach point. If the calculated impedance (Z_R) is less than the reach-point or setting impedance, then the fault exists on the line in between the relay and the reach point.

Increasing V_R has a restraining effect hence V_R is called restraining voltage, and increasing I_R has an operating effect.

The impedance measurement characteristics of a distance relay can be plotted on a polar diagram together with the line fault impedance locus as a means of judging the performance of the reach of a distance relay along the transmission line.

The earliest form of distance relay characteristics was the "impedance characteristics" which was non-directional since it responds to faults on the protected line and also to faults on the system behind the line. Distance relays are required to discriminate between the faults in different line sections and so they are required to be directional. This is how the MHO impedance characteristics for distance relaying were evolved.

3.2.1. **MHO Characteristics:**

The Mho characteristic, as seen on the impedance polar diagram is a circle where the diameter is the relay impedance setting (or reach point), such that the characteristic passes through the origin of the impedance diagram. The Mho impedance relay is therefore a directional relay.

As shown in Figure 3.4 for a fault located at F1 the measured impedance falls inside the Mho characteristics of the distance relay, hence the Mho distance relay "operates". For a fault at F2 which is outside the Mho characteristics, the distance relay restrains from operation. Mho characteristic relays are very popular due to their simplicity.

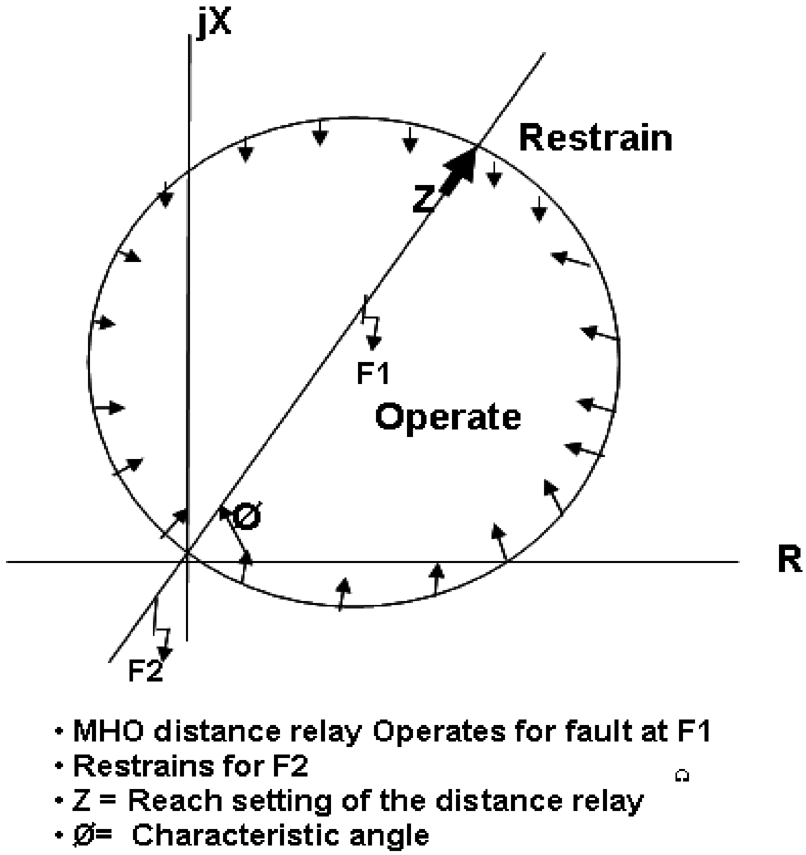


Figure 3.4 Mho Distance relay characteristics

Distance relay performance is defined in terms of the reach point accuracy and the operating time. Reach accuracy is a comparison of the actual Impedance reach of the relay under practical conditions with the relay setting value in ohms. Reach accuracy particularly depends on the level of voltage presented to the relay under fault conditions.

Operating times can vary with fault current, with the fault position relative to the relay setting and with the point on the voltage wave at which the fault occurs.

3.3. FLEXIBLE AC TRANSMISSION SYSTEM (FACTS) DEVICES AND DISTANCE PROTECTION

The impacts of the Flexible AC Transmission Systems (FACTS) Devices (which includes all types of FACTS devices including the fixed series capacitors, thyristor controlled (series / shunt) capacitors and reactors such as

TCSC / SVC, Converter type devices such as STATCOM / SSSC) influencing the operational features of the distance protection relay have been discussed in the following references 10,11 ,12 ,13 ,14 ,15 ,16 ,17 ,18 ,19 ,20 ,21,22,23

The effect of different types of FACT devices on distance relays has been studied in the literature and is summarised below:

1. Fixed series capacitors [10], [19], [20] and [22]

2. STATCOM [10], [11], [12], [13] and [17]

3. SSSC [14]

4. Conventional thyristor controlled FACTS devices type TCSC [15], [18] and [19]

The focus of this research is on converter-based FACTS devices influencing the performance of the distance relay under various system conditions. The following two criteria were considered for the research towards Converter based FACTS devices based on the discussions covered in chapter-1

1) The growing number of installations of Converter based devices for varied applications, in particular number of installations of STATCOM.

2) Converter type FACTS devices represents a new generation of transmission controllers, employing voltage sourced converters to realize rapidly controllable, static synchronous AC voltage sources. This approach provides reactive compensating shunt current that is independent of system voltage, as well as series reactive compensating voltage that is independent of the line current.

The two unique operating features of converter-based FACTS devices in addition to their capability to internally generate reactive power, have so far been established are:

1) The capability to maintain maximum compensating current / voltage in the face of decreasing line voltage / current, which results in superior characteristics for shunt / series compensation.

2) The ability to exchange real as well as reactive power with AC system and thereby provide independent control of real and reactive power flow in the transmission system.

Hence the research work focussed on effects of STATCOM on distance protection.

STATCOM by design can feed inductive or capacitive current even at very low line voltages, rather independently of the line voltages. This enables the STATCOM to emulate a capacitive reactance or inductive reactance at the point of connection. This is a most important point from the distance relay point of view under different system conditions.

3.3.1. Effect of STATCOM on Distance Protection

During a system fault condition the STATCOM compensates for the voltage dip in the system by injecting currents in quadrature to the line voltage thereby maintaining line voltage or bus voltage, depending on the STATCOM point of connection.

Thus rapid changes will happen in the power system most of them occurring in less than a cycle after the occurrence of the fault [12], [13]. Along with introducing system transients it will also affect the measurement of power system parameters such as transmission line impedance, line angle and line currents, and these effects vary with the point of connection of the STATCOM device.

For a STATCOM positioned in the middle of the Transmission line and for a fault occurring beyond the section of line between the relay location and the STATCOM location, the fault impedance seen by the relay will include the impedance of the STATCOM in addition to the line impedance and fault resistance.

Distance protection relay reach setting Z given in the equation 3.3 is set to cover the zone impedance and the effect due to fault resistance. A distance relay is always set in terms of positive sequence impedance of the line, with the earth impedance and mutual impedance being compensated for in the settings. This is how a distance relay operates correctly for all the earth faults and if there are mutual coupling effects from a parallel line.

$$Z = Z_1 + \left[\left(\frac{I_{res}}{I_p} \right) * Z_{res} \right] + \left[\left(\frac{I_{mut}}{I_p} \right) * Z_{mut} \right] \qquad 3.3$$

Where,

Z_1 is the positive sequence impedance reach setting

I_p is the current in the faulted phase

$I_{res} = (I_a + I_b + I_c)$ is the residual current

I_{mut} is the residual current in the parallel line

$Z_{res} = (Z_0 - Z_1)/3$ is the residual impedance, which includes the earth impedance.

Z_{mut} is the mutual compensating impedance

Referring to the above scenario where the fault involves a STATCOM device, because it will inject current in quadrature with the line voltage, depending upon how the injected current leads or lags, the compensating impedance will either be capacitive or inductive.

This impedance has an effect on the total impedance measured by the relay during a fault, causing the relay to either under reach or over reach, depending on the phase of the injected current. Results of test simulations have shown this to be the case [10] [11] [12] [13].

Another potential problem resulting from STATCOM operation in this above scenario is incorrect faulted phase selection by the relay [10] [11]. Again here no solutions have been developed to overcome this problem for distance relays.

The operating time for zone-1 could also be delayed for faults involving STATCOM in the fault loop. This is an important problem for EHV and UHV `networks where the time from fault inception to Zone 1 operation needs to be less than a cycle. No solution has been proposed to this problem so far.

The entire problem may need to involve solutions in both the distance relaying schemes (Appendix 4) and distance relaying algorithms.

3.4. REVIEW OF PREVIOUS WORK

3.4.1. STUDY OF PAPER [10]

Paper [10] provides brief description of the FACTS devices and their characteristics. The paper presents an analytical discussion of the effects of shunt compensation device type STATCOM on distance relaying. In line with the findings the paper lists the results of tests that were performed on a commercially available distance relay which was fed from the modelled power system compensated by STATCOM. It is considered that the STATCOM is placed in the mid-point of the Transmission line and the authors have considered 3-phase fault is considered for the sake of simplicity.

Analytical expression is derived for the measure of the impedance measured by the distance relay, for a 3-phase fault beyond the FACTS device location.

Using the positive sequence reactance of the FACTS device and the positive sequence reactance of the transmission line an expression is arrived for the impedance measured by the distance relay when a fault occurs;

Where,

$$Z_R = Zla1 + \frac{(Zlb1') \times X_{SC}}{(Zlb1') + X_{SC}} \qquad 3.4$$

$$Z_R = Zla1 \times \left[1 + \frac{(2m\text{-}1) \times X_{SC}}{(2m\text{-}1) \times Zla1 + X_{SC}} \right] \qquad 3.5$$

Where,

$$m = \left(\frac{Zla1 + Z1b1'}{Zline} \right) = \left(\frac{Zla1 + Z1b1'}{2Zla1} \right) \qquad 3.6$$

Since the FACTS device is at the mid-point of the transmission line

Z_R = Impedance measured by the relay

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

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

$Zline$ = Total line impedance

Xsc = positive sequence impedance of the FACTS device

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

When there is no FACTS device or when the FACTS device is operating in the floating mode, the term Xsc tends to infinity and equation 3.4 becomes;

$$Z_R = Zla1 + Zlb1' = m \times Zline = Z'_R \qquad 3.7$$

However, when a transmission line is shunt compensated with STATCOM the value of Xsc depends on the amount of compensation. During faults, to improve the voltage collapse, STATCOM provides reactive power to improve the voltage collapse, the reactance of the shunt device is always capacitive; the higher the reactive power support, the lower the value of Xsc. From equation 3.4 as the value of Xsc reduces compared to Zlb1', it has a higher impact on the measured impedance. Another important consideration in this paper is, since the shunt reactance is capacitive (during faults) and series reactance of the line is inductive, the resultant impedance measured has a non-linear relationship with the fault location, this has been explained with the graph plotted with a factor k (Xsc / Zline) to Z_R /Z'_R. The value of k is got from dividing (3.5) by (3.7) and re-arranging the equation

$$\frac{Z_R}{Z'_R} = \left(\frac{1}{2m}\right) \times \left(1 + \frac{(2m - 1 \times 2 \times k)}{(2m - 1 + 2 + k)}\right) \qquad 3.8$$

Equation 3.8 has been used in analysing the effect of FACTS devices on the impedance measurement and is only valid for m>0.5 (faults beyond the compensation point).

It is mentioned that the highest impact of the shunt compensation occurs around the point at which the shunt compensation value is equal to reactance of the line between the FACTS device and the fault location. Also as the ratio of Xsc to Zline increases, the influence of the shunt compensation decrease.

The analytical analysis is completed by arriving at a critical value of Xsc, showing when the change of the impedance measurement happens from under reaching to over-reaching (this happens when Xsc reduces from higher value than the critical value to a lower value).

For the dynamic study purposes the authors have modelled the power systems in PSCAD/EMTDC software and have considered both SVC and STATCOM. The following were also considered:

- Both STATCOM and SVC is 12 pulse generation models.
- A three phase balanced firing schemes are adopted to model the FACTS device in the transmission system due to voltage control application. This implies all the 3-phases are fired at the same angle but 120 degrees apart.

Summary from the study of Paper 10 are as follows:

1) For an unsymmetrical faults, (since the STATCOM control system acts on a DC voltage equivalent to 3phase voltage) the FACTS device provides equal compensation for all the 3 phases. This would mean increased healthy phase voltage. This result in unequal compensation of all the 3phases, in addition this would in turn results in reduced compensation as the equivalent voltage will not be a true representation of the faulted phase.

2) Thus for unsymmetrical faults the value of STATCOM compensation would depend on factors like pre fault load (load angle), phases involved in the fault, system strength and fault location. This effect can result in incorrect impedance measurements- this is proved by simulation results.

3) The overcompensation on the healthy phase during un-symmetrical fault condition shall result in increased reactive current in healthy phases. This increases the possibility of wrong phase selection particularly for the relays

using the current based phase selection. This point was confirmed during a testing a commercial relay in RTDS.

4) Another inference that has come out in this paper is for a 3 phase fault for a particular location, the measured impedance tends to infinity, and this normally happens when the compensating impedance is equal to the line impedance between the shunt FACTS device and the fault. This can lead to other relays in the system seeing this condition as power swing.

5) The operating time of the distance relays for such faults between the FACTS device and the fault location is also significant delayed and is tabulated after testing of a commercial distance relay in RTDS.

6) It is concluded that the strength of the system also plays an important role – while weak system conditions, relay will tend to over reach ; for strong systems distance relays will tend to under reach for fault position after the STATCOM location up to 100% of the line lengths.

3.4.2. STUDY OF PAPER [12]

In paper [12] the author has considered the study of STATCOM installed at mid-point of transmission line. STATCOM is modelled as a controlled current source that responds instantaneously to changing system conditions. In this study STATCOM is rated to compensate 50% of the reactive power of the transmission line.

In paper [12] STATCOM is modelled to inject current on a per phase basis and value of STATCOM current is automatically adjusted to the changes in load angle, such as to keep the mid-point voltage constant. For the study purpose STATCOM is modelled from a three-phase, two level 12 pulse GTO based voltage source inverter, 300 MVA rated power, 11 kV rated bus voltage, PWM switching frequency method. The Coupling power transformer is a Y-Y transformer, three-single phase transformers connected as Y-Y and each transformer rated as 50MVA ,63.5 / 6.36kV and X=0.1pu; Y-D transformer- 3 single phase transformers connected as Y-D and each transformer rated as 50MVA, 63.5/11 kV and X=0.1 pu. The study was carried out to ascertain the apparent impedance seen by the distance relay under single-phase and three-phase faults as a function of load angle variation with STATCOM connected and with STATCOM disconnected.

In cases where STATCOM is connected for both single and three phase fault conditions, the results indicated that the distance protection under-reached for a fault at the reach point as the line loading increases – it is inferred that this is due to STATCOM trying to maintain the voltage at the mid point to its nominal voltage, in other words the voltage at the midpoint dips from its nominal voltage and this requires the STATCOM to produce more reactive current to boost the voltage at the mid point and thus increases the apparent impedance seen by the distance relay. This observation is in agreement with the studies of paper [10] and [11].

Following further remarks were made:

- Under all the operating conditions, the STATCOM operation increases the R/X ratio of the transmission line as seen from sending end bus- this happens at even at small ratings.
- Under no fault condition as well as single phase to ground fault, it is observed both the analytical and the simulation results are very close.
- It is inferred that with STATCOM connected the operation of the zone-1 is delayed.

3.4.3. CRITICAL REVIEW AND FURTHER STUDY OF THE PROBLEM

In studies carried out so far most previous works are done by applying a three phase fault in the transmission line to understand the effects on distance relay, except in papers [11] and [12].

In order to observe the effects of STATCOM on distance relaying during single phase faults it is important to consider the distribution of currents using symmetrical sequence components, as only for unsymmetrical faults (such as single phase faults) all the three components of positive negative and zero sequence components are involved in the analysis of the fault.

For the transmission system shown in Figure 3.5 transmission line between end A and end B; distance relay located at end A fed from current transformer

(CT) and voltage transformer (VT). STATCOM together with the coupling transformer (coup.tr.fr) is located at mid point of the transmission line. A single phase to ground fault F occurs after the location of STATCOM.

The distribution of fault currents can be analysed using sequence component network as in Figure 3.6. Where,

Z_S1, Z_S2, and Z_S0 = positive, negative and zero sequence components of source impedance behind the relaying point.

Z_L1, Z_L2, and Z_L0 = positive, negative and zero sequence components of part of the line impedance before the location of STATCOM (up to 50% of the line impedance)

Z_L1', Z_L2', and Z_L0' = positive, negative and zero sequence components of part of the line impedance after the location of STATCOM (remaining 50% of the line impedance)

Z_T1, Z_T2 and Z_T0 = positive, negative and zero sequence impedance of coupling star grounded HV transformer connected to STATCOM

As it is difficult to find out exact contribution of fault current due to STATCOM before hand from the sequence network analysis, an estimate using the ratio between the current measured by the relay (I_{relay}) and the STATCOM current (I_{sh}) will able to provide the impact of current contribution due to STATCOM on the apparent impedance of the relay. In the transmission line network the positive sequence impedance is same as the actual line impedance, and negative and positive sequence impedances are the same too. For the single phase to ground faults, it is the zero sequence currents that contribute varyingly depending upon the ratio of the zero sequence impedances. This ratio will affect result the apparent impedance calculated by the relay. It is not sure at this stage whether phase –phase fault after the location of STACOM will have any effect on the performance of distance relaying.

This is shown in equations 3.9 and 3.10 respectively,

$$Z_{relay} = nZ_{line} + \left(\frac{Ish}{Irelay}\right)(n-0.5)Z_{line} + \frac{I_F}{I_{relay}} \times R_F \qquad 3.9$$

Where Z_{relay} is the impedance calculated by the relay, n is the per unit distance of the fault from the relay location, Z_{line} is the impedance of the line, Ish is the shunt current injected by STATCOM, I_{relay} is the relay current, I_F is the fault current and R_F is the fault resistance.

Considering a solid fault we have,

$$Z_{relay} = nZ_{line} + \left(\frac{Ish}{Irelay}\right)(n-0.5)Z_{line} \qquad 3.10$$

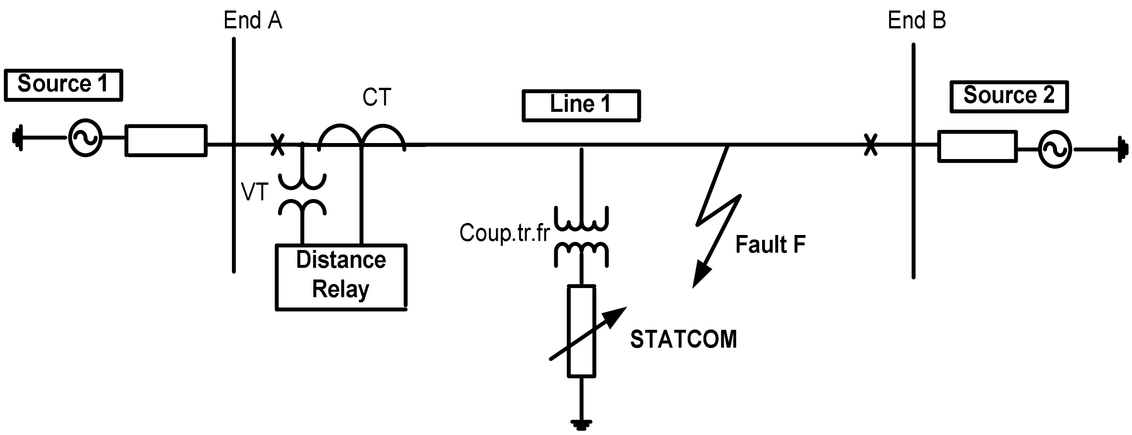


Figure 3.5 Transmission line system with STATCOM at mid-point and fault occurrence after the location of STATCOM

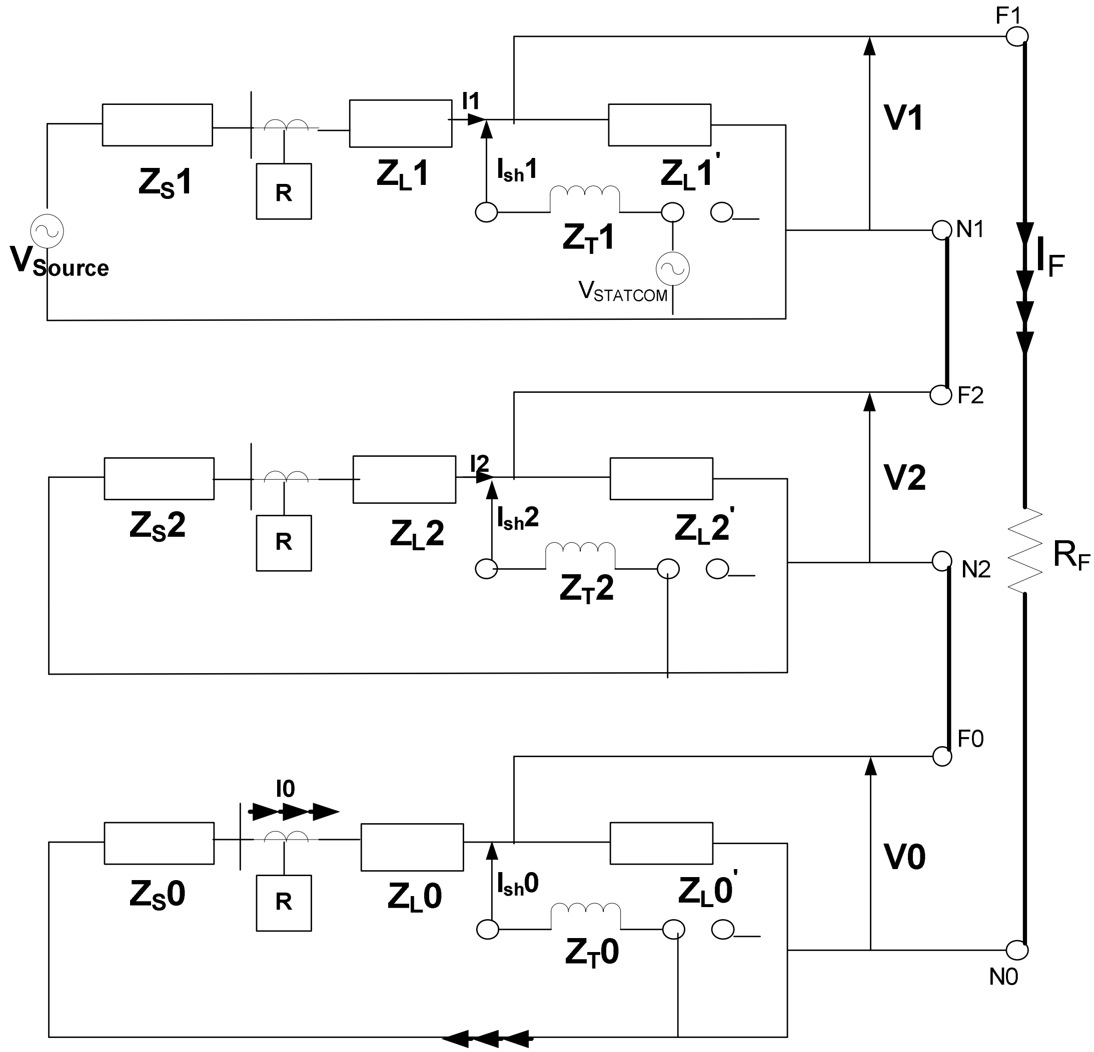


Figure 3.6 Symmetrical components diagram for the system shown in figure 3.5

3.5. AREA OF RESEARCH

One of the main applications of STATCOM devices is to stabilize bus voltages during system disturbances to increase transient stability of the network and most recent installations of STATCOM devices indicate that they are being increasingly connected to bus bars. However a survey of the published literature has revealed that all the work so far has focused on STATCOM's positioned at the mid-point of transmission lines and there is no published work on the effects of STATCOM devices when connected to bus bars. Therefore research focussed on the investigation of problems created for numerical distance protection when STATCOM device are connected at mid-point of the transmission system.

The research work was divided into following sections:

a) Mathematical / theoretical analysis for the various configurations
b) Modelling of STATCOM in PSCAD
c) Modelling of power system and distance relay in PSCAD.
d) Extensive simulation by connecting the modelled STATCOM in the mid-point of power system and studied the behaviour of modelled distance relay.
e) Compilation of the results and analysis of the results.

3.6. CONCLUSIONS

It was shown by mathematical analysis, that the STATCOM located at the midpoint of a transmission line alters the impedance measured by the distance relay at the sending end of the line. Further studies to validate the analytical findings are necessary and one of the ways to validate the effect is model the power system with STATCOM and distance relay in a power system software tool, and this work is covered in the following chapters.

4. DEVELOPMENT OF STATCOM MODEL FOR USE WITH PSCAD/EMTDC FOR PROTECTION STUDIES

4.1. INTRODUCTION

Static Synchronous Compensators (STATCOM) are installed in power systems to increase system stability and for reactive power compensation However, the operation of STATCOM devices can lead to mal-operation of distance protection relays during dynamic system conditions. Hence, it is important to characterise the behaviour of the STATCOM in a power system where the reactive power compensation is provided during steady state and dynamic conditions following load variations and during various system fault scenarios. One way to study the behaviour of STATCOM is by using a power system simulator. In order to be able to simulate systems, which contain a STATCOM, an appropriate STATCOM model is required.

This chapter concerns the development of a STATCOM model using the power system simulator PSCAD/EMTDC. As the simulations are aimed at determining the effects on the protection equipment it is envisaged that, a fundamental frequency average voltage source model is more suitable in terms of less complexity and fast computation.

4.2. PURPOSE

The purpose of the averaged voltage source model is to study the behaviour of STATCOM when connected at the mid-point of a transmission line.

4.3. MODEL DATA

The model shown in Figure 4.1 is a representation of STATCOM connected to an AC power source. The AC source voltage (V_{Source}) is connected to and impedance (Z_s) onto the power system bus. A coupling transformer of impedance X_T is connected to power system bus through the transformer primary voltage terminals. The transformer secondary voltage terminals are connected to terminals of average voltage source.

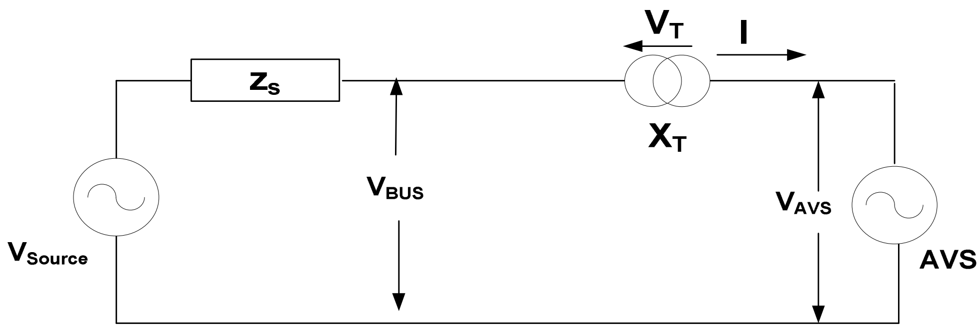


Figure 4.1 Equivalent circuit of Power system with averaged source model

In order to observe the expected behaviour of STATCOM a weak source was modelled.

Source data given in Table 4.1

Table 4.1 Source data

Parameter	Value
Positive sequence source resistance	16800 ohms
Positive sequence inductance	1.68H
Source voltage	230 kV
Externally controlled phase angle	0 degree
Primary short circuit current level	251.723 A
Power system frequency	50HZ

Coupling transformer data is given in Table 4.2:

Table 4.2 Coupling Transformer Data

Parameter	Value
Winding # 1 rms voltage	230kV
Winding # 2 rms voltage	20kV
Three-phase transformer MVA	100MVA
Transformer impedance	18%

4.4. AVERAGE VOLTAGE SOURCE CONSTRUCTION

The construction and connection of Average voltage source, model of STATCOM is as shown in Figure 4.2

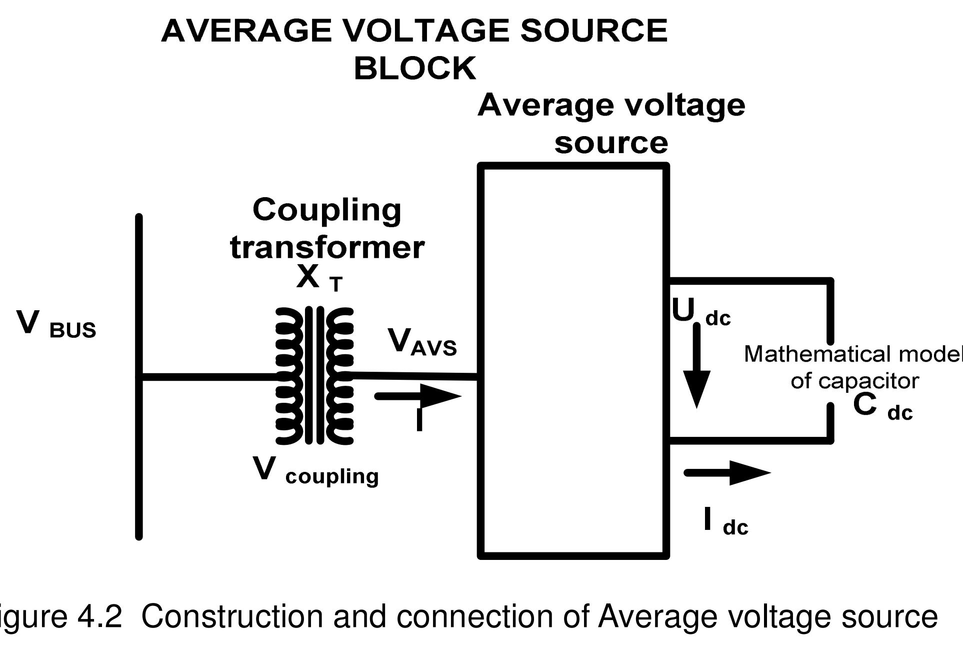


Figure 4.2 Construction and connection of Average voltage source

The mathematically modelled capacitor C provides a DC voltage to the average voltage source, which produces a set of controllable three-phase output voltages synchronous with the AC power system. The production of AC three-phase output voltages is discussed in section 4.5. The mathematical model of capacitor producing the DC voltage source is now discussed.

Work done in a capacitor is expressed as:

$$W = E = \frac{Cv^2}{2}$$

Power required doing the work

$$p = \frac{dW}{dt} = Cv \times \frac{dv}{dt}$$

$$\frac{dv}{dt} = \frac{1}{C} \times \frac{p}{v}$$

Integrating with respect to time

$$\int_0^t \frac{dv}{dt} \times dt = \frac{1}{C} \int_0^t \frac{p}{v} dt$$

$$v(t) - v(0) = \frac{1}{C} \int_0^t \frac{p}{v} dt$$

$$v(t) = v(0) + \frac{1}{C} \int_0^t \frac{p}{v} dt \qquad 4.1$$

Equation 4.1 is the expression for voltage at any time instant across a capacitor. Taking Laplace transforms of equation (4.1) we get,

$$\mathrm{v(s)} = \mathrm{v(0)} + \frac{1}{C(s)} \frac{p(s)}{v(s)} \qquad 4.2$$

Equation 4.2 is modelled in PSCAD as shown in

Figure 4.3 below.

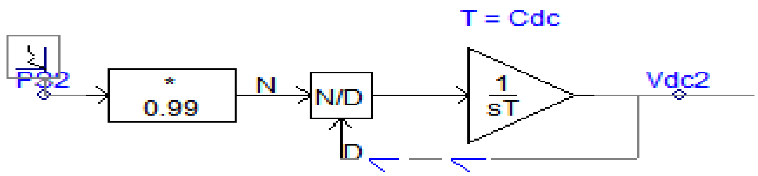


Figure 4.3 PSCAD representation of the mathematical model of capacitor

The right hand side in expression in equation 4.1, is expressed using the following blocks in PSCAD

Integrator

Feedback loop

Divider

This form is expressed in PSCAD as block Integrator.

Value of C is adopted from the capacitor value used in 12-pulse STATCOM model.

Initial output value of Integrator at time t=0, is adopted from capacitor voltage rating used in 12-pulse STATCOM model.

Table 4.3 Capacitor Model

Capacitance value	4167 micro farads
Capacitor voltage rating	40kV

Since instantaneous power measured at any time instant divided by instantaneous voltage at any time instant is directly proportional to reactive current measured at any time instant, the second expression in equation 1 can be re-written as,

$$v(t) = v(0) + \frac{1}{C}\int_0^t i\,dt \qquad 4.3$$

In the average voltage source model, built in PSCAD the mathematically produced DC voltage is V_{dc}, is multiplied by a factor of 0.5 to get the peak voltage magnitude; this is represented in PSCAD as shown in Figure 4.4.

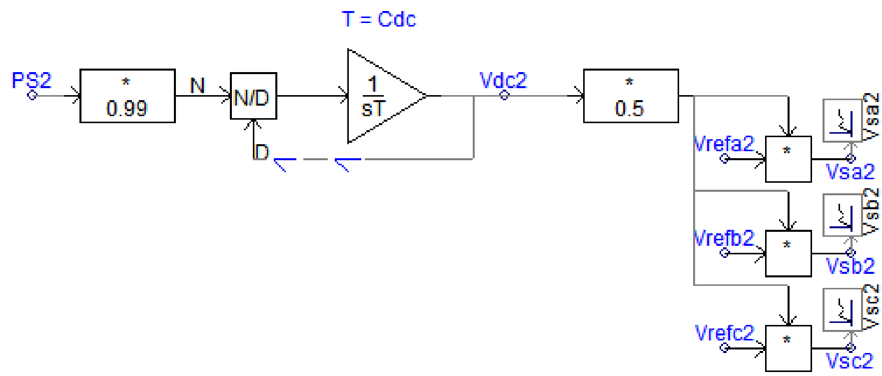


Figure 4.4 PSCAD representation of the mathematical model of capacitor

Where VSa2, VSb2, VSc2 are a set of AC voltage output produced from the average voltage source (AVS).Vrefa2, Vrefb2, Vrefc2 are internal voltage references, which are derived from the control system. This is explained under section AVS model control system.

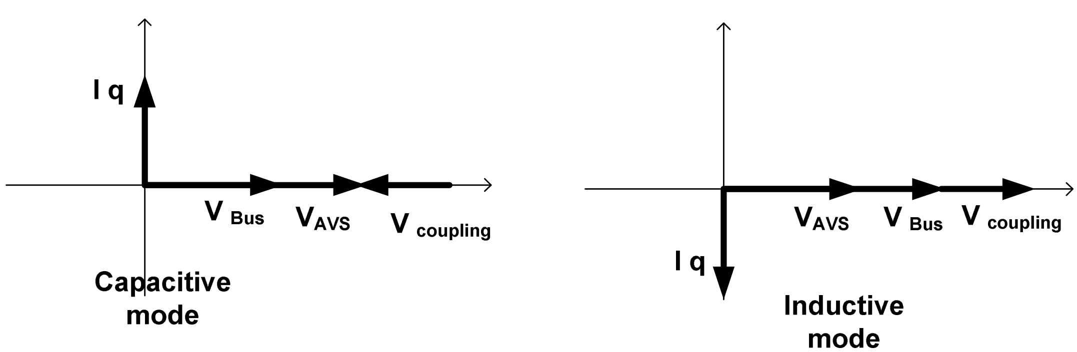


Figure 4.5 Different modes of operation of Average voltage source

4.5. PRINCIPLE OF AVS MODEL CONTROL SYSTEM

The mathematically modelled capacitor (C) provides a DC voltage to the averaged voltage source, whose output is a set of controllable three-phase output AC voltage synchronous with AC power system. By varying the amplitude of VSa2, VSb2, VSc2 measured at AVS terminals, the reactive power exchange between the average voltage source and AC system is controlled. If the amplitude of average voltage source, V_{AVS} is increased above the AC system voltage bus, V_{BUS} then current flows through the reactance of coupling transformer and a leading current is produced. That is the AVS is seen as capacitive VAr generator by the system and reactive power is generated. Decreasing the amplitude V_{AVS} below that of V_{BUS} results in a lagging current, and the AVS is seen as inductive VAr generator. In this, case reactive power is absorbed. Figure 4.5 above shows the different modes of operation of AVS.

The average voltage source different modes of operation explaining the above principles are discussed in section 4.6.

The characteristics of average voltage source of STATCOM characteristics are shown in Figure 4.6. The average voltage source, model draws reactive current from AC system according to an external reference setting, which varies in a range between the same capacitive and inductive maxima setting independent of AC system voltage.

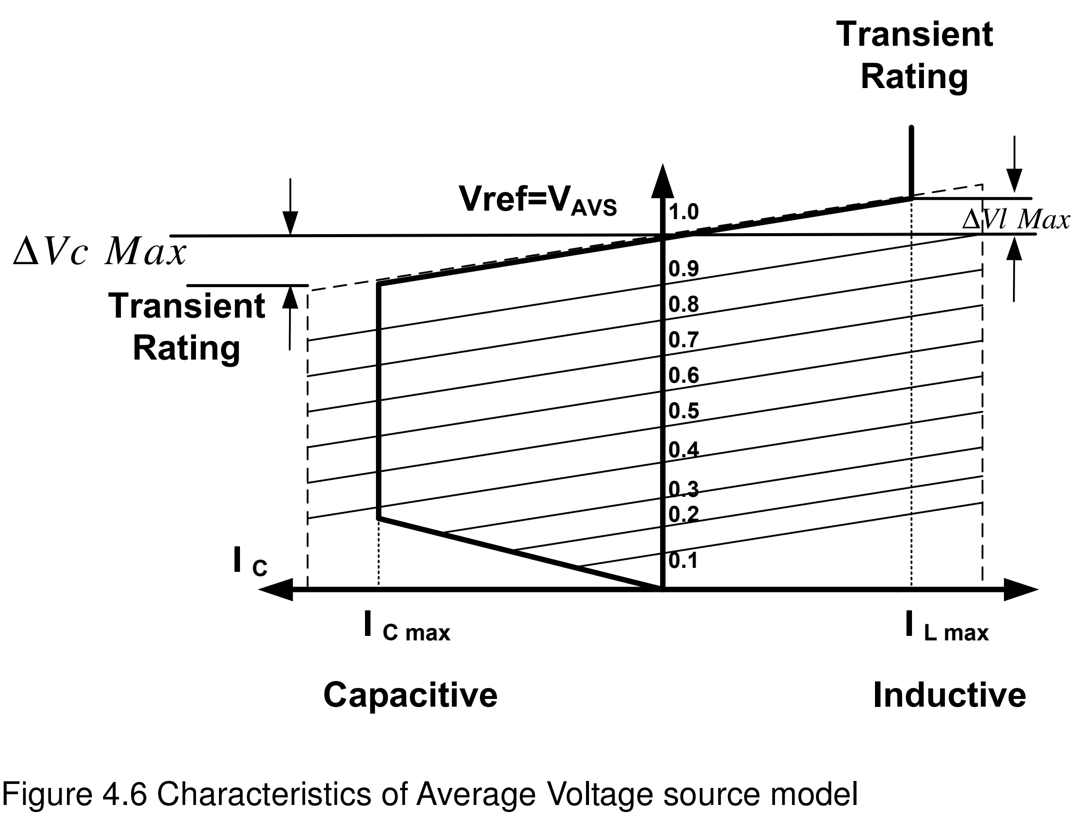


Figure 4.6 Characteristics of Average Voltage source model

The maximum compensation current is maintained independent of the system voltage. The regulation slope setting is also provided in the model. This means the terminal voltage V_{AVS} (VSa2, VSb2, VSc2) is allowed to be smaller than nominal no load value at full inductive compensation. This is achieved through the internal control system where settings for reference voltage are set.

$$Vref^{*} = Vreference + K \times I_{Q} \qquad 4.4$$

$$\mathrm{K} = \Delta V_{\mathrm{cmax}} / \mathrm{I}_{\mathrm{cmax}} = \Delta \mathrm{V}_{\mathrm{lmax}} / \mathrm{I}_{\mathrm{lmax}} \qquad 4.5$$

In the model K is set as 0.1, where K is the regulation slope setting Vreference is the fixed setting and ΔV_{cMax} is the deviation (decrease) of the terminal voltage from its nominal value at maximum capacitive output current, Δ_{VlMax} is the deviation (increase) of the terminal voltage and I_{cmax} and I_{lmax} are maximum compensating capacitive and maximum Inductive currents respectively.

Hence, based on the settings of reference and K (slope) the Vref* is derived in the model.

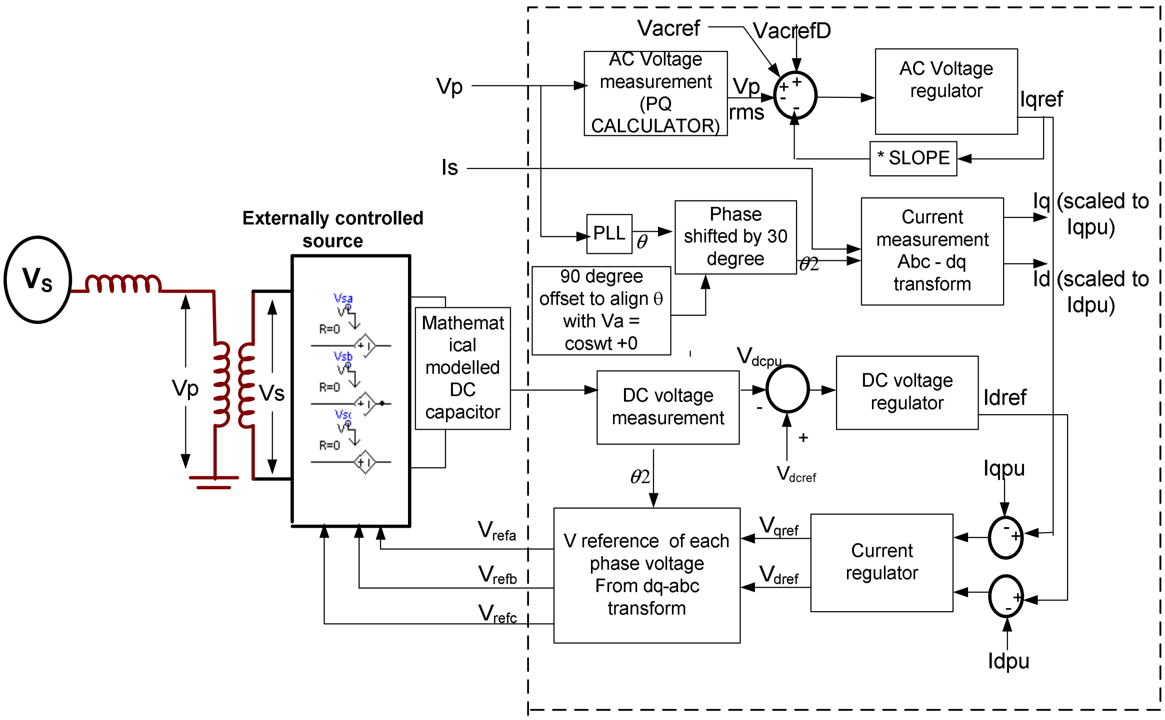
4.6. WORKING OF AVS MODEL CONTROL SYSTEM

4.6.1. Control system of averaged voltage source model

The control system for the averaged voltage source model consists of the following component blocks:

1. Phase locked loop
2. ABC-DQ transform block
3. PI controlled AC Voltage regulator
4. PI controlled DC voltage regulator
5. PI controlled Current regulator
6. PQ calculator (discrete block)
7. DQ-ABC transform block

The block diagram of the control systems part of the averaged voltage source model is shown in Figure 4.7



Single Phase view of a three phase power system coupled through a transformer, whose secondary terminal is connected is to the average voltage source model

Figure 4.7 Control system block diagram of Average voltage source model

4.6.2. Phase locked loop

A Phase locked loop is a device, which causes one signal to track another signal. It keeps an output signal synchronizing with a reference input signal in phase and in frequency. A Phase locked loop controls the phase of its output signal in such a way that the phase error between output phase and reference phase is reduced to a minimum. In this application, the software model of Phase locked loop is used to recover the phase information of the power system.

The Phase locked loop used in the averaged model application has the following functional blocks.

1. Phase detector

2. Loop filter

3. Voltage-controlled oscillator (VCO)

A brief description of functioning of the Phase locked loop used in the averaged voltage source model is explained below

The Phase detector is a signal multiplier; initially, if the loop is unlocked and the Phase detector has sinusoidal characteristics, the output signal at the Phase detector consists of a dc error signal that has the phase information of the input signal and an ac signal.

The dc error signal corresponds to the phase error between the input signal to phase detector and output signal from VCO.

Loop filter

Loop filter is a low pass filter.

The low pass filter eliminates the higher frequency signal component (ac signal) fed into it from the phase detector output.

The dc error signal from the Loop filter is fed to the input of the VCO. The VCO responds in case of non-zero error signal by adjusting its operating frequency and thus producing an estimated angle, until a phase lock achieved which is fed back to the phase detector. If the error signal is zero the VCO produces the reference frequency resulting in estimated angle and grid phase angle being the same.

The reference angle theta obtained, is passed through adder circuit, where

30 degrees is added to compensate for star- delta transformer winding phase correction.

90 degrees is added to align reference Va vector to cosine frame.

The reference angle shifted by (30 + 90) degrees will be utilised through out the control system wherever a three phase vectors are derived from its 2-plane vector or vice versa.

The three phase currents measured at the secondary side of the transformer, Isa2, Isb2 ,Isc2 are passed through dq transform and their phase locked to power system frequency, to derive the real current (I_d) (otherwise called direct current) and reactive current (I_q) (otherwise called quadrature current) frames.

4.6.3. ABC- DQ transforms

The dq-abc transformation block used in the averaged source model is based on Park transformation. Using Park's transform a three-phase system of phasors can be transformed into an equivalent two-phase system of Phasors in quadrature. The two phasor are referred to as the direct axis (d-axis) phasor and a quadrature axis phasor (q-axis) respectively. The inverse of the Park's transform, transforms dq phasors equivalent three-phase phasors. The phase angle reference extracted from the phase locked loop is used as reference angle in extracting the three-phase voltages from the two-phase system.

The derivation of dq-abc is explained in. Appendix 1

The extracted real and reactive currents compared with their reference settings, which are I_d reference and I_q reference respectively.

I_d reference and I_q reference currents are achieved as per below:

I_q reference is derived from the proportional–integral (PI) controlled AC voltage regulator.

4.6.4. PI controlled AC voltage regulator

The three-phase instantaneous system voltage measured at primary side of power transformer is converted to rms voltage using the pq calculator and scaled to per unit voltage. This value is passed as input to summing/ differential block in ac voltage regulator of the model, whose other input is

Vref*, the difference between the two inputs is passed through PI controlled error generator. (Explanation of pq calculator and per unit conversion used in average voltage source model, discussed in Appendix 2).

The output from PI controlled error generator of AC voltage regulator is the reactive current (I_q reference). The transfer functions for the control systems part of AC voltage regulator is explained in Appendix 3.

4.6.5. PI controlled DC voltage regulator

The DC voltage measured at any time instant V (t) is scaled to V_{dc} PU, passed as input to summing block in the DC voltage regulator of the model; DC voltage reference, which is settable, is passed as other input to the summing block.

The difference between the two inputs is passed through the PI controlled error generator block. The output from the PI controlled error generator of DC voltage regulator is the real current I_d reference. The transfer functions for the control systems part of DC voltage regulator is explained in Appendix 3.

4.6.6. PI controlled current regulator

Reactive current reference (I_q reference) processed from AC voltage regulator discussed in 4.6.3 passed as an input, to the summing / difference block of the PI controlled current regulator. The measured reactive currents (I_q) extracted from the abc-dq transform, is passed as another input to the summing block. The difference between the two inputs is then, passed through the PI controlled error generator block. The output from the current regulator is the derived (V_q) quadrature axis voltage.

The real current reference (I_d reference) processed from DC voltage regulator discussed as in section 4.6.5, is passed as an input, to the summing / difference block of the PI controlled current regulator. The measured real current (I_d) extracted from the abc-dq transform, is passed as other input to the summing block. The difference between the two inputs is then, passed through the PI controlled error generator block. The output from the current regulator is the derived (V_d) direct axis voltage. The transfer functions for the control systems part of current regulator is explained in Appendix 3.

4.6.7. PQ calculator (discrete block)

The PQ calculator block used in the averaged voltage source model is a customised block used to extract the instantaneous values of active and reactive power from the input three-phase power system side current and voltage.

The PQ calculator also extracts the rms values for the current and voltage of the input side of the three-phase power system.

4.6.8. DQ-ABC transform (discrete block)

Thus the derived two-phase quantities V_d, V_q are passed to the next stage of dq-abc transform block, whose phase is locked to the power system frequency to derive the three phase voltages tracked to the power system voltages. The derived three phase voltage of Vrefa2, Vrefb2, and Vrefc2 are multiplied by the amplitude of DC voltage, provided to average voltage source (provided by the mathematically modelled Capacitor, explained in section 4.4). An output voltage which is three phase, is generated at the output of average voltage source which is controllable and is directly proportional to the product of the magnitude of DC voltage and the three phase reference voltages generated internally.

4.7. MODEL IMPLEMENTATION IN PSCAD / EMTDC

The averaged model, used for this research work is an existing model constructed by the ex-colleagues in Power electronics division (PES) of ALSTOM GRID. In order to carry out the simulation studies first an understanding of the model is required. This chapter initially focuses on the model details and then focuses on the simulation studies to understand the behaviour of Averaged voltage source.

The AVS model control system detailed as block functions described in section 4.6, has an inner current control loop which is current regulator and outer AC and DC voltage control loops which are AC voltage regulator and DC voltage regulators respectively.

The function of the averaged model control system is to control the reactive (quadrature) current output and hence the quadrature voltage output there by controlling the voltage at the connected power system bus-terminal to maintain desired voltage under possible system disturbances and contingencies.

4.7.1. AC voltage regulator

The outer AC voltage control loop generates an error signal based on AC voltage reference, which is, then PI regulated to get reactive (quadrature) current and passed through the inner current regulator where reactive (quadrature) current compared with the reference reactive (quadrature) current value to generate error signal. The control system for AC voltage regulator is shown in Figure 4.8 below.

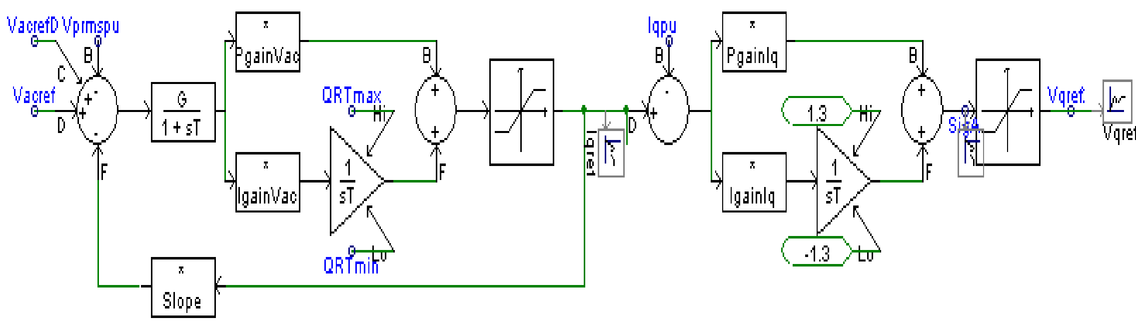


Figure 4.8 Control system for AC voltage regulator

4.7.2. DC voltage regulator

Similarly, the outer DC voltage control loop generates an error signal based on DC voltage reference, which is then PI regulated to get direct current and passed through the inner current regulator, where the direct current is compared with the reference direct current setting to generate error signal. The control system for DC voltage regulator is shown in Figure 4.9 below,

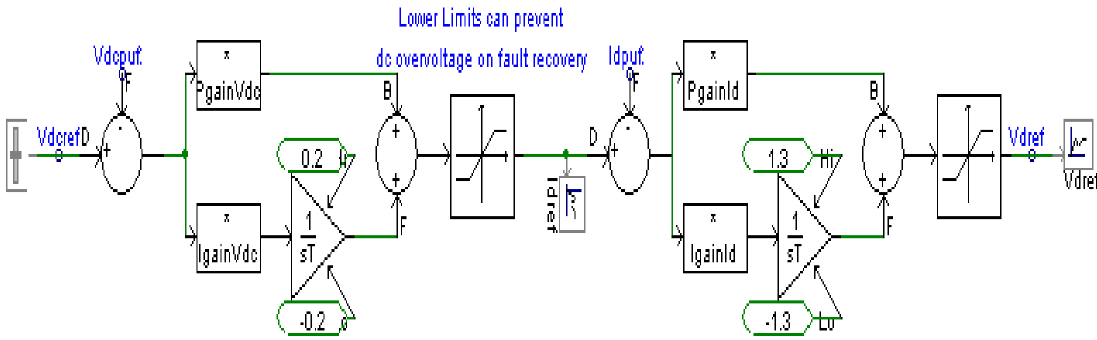


Figure 4.9 Control system for DC voltage regulator

The regulators and their control system used in averaged model are briefly discussed below. The transfer functions for each of the regulators discussed under Appendix 3.

4.8. MODEL VALIDATION

Average voltage source model is analysed and validated in the following ways:

1. Analytical validation
2. Simulation validation

The validation exercise is carried out, to observe the performance of averaged voltage source model connected to power system during voltage variations due to sudden change in the connected load and during transient period during fault conditions.

Average voltage source model is validated against the following scenarios

1. Reactive load variation (Inductive) in the power system
2. Reactive load variation (Capacitive) in the power system

4.8.1. Inductive reactive load variation in the power system to which average voltage source model is connected

In the power system bus shown in Figure 4.10, Inductive reactive loads connected through two breakers. In the start up of the simulation the first breaker is closed on resuming of "START SEQUENCE" of the simulation, during which 10MVAr Inductive load is switched' ON", after 1sec, second breaker is closed which switches 110MVAr Inductive load to the power system at 230kV 3phase voltage.

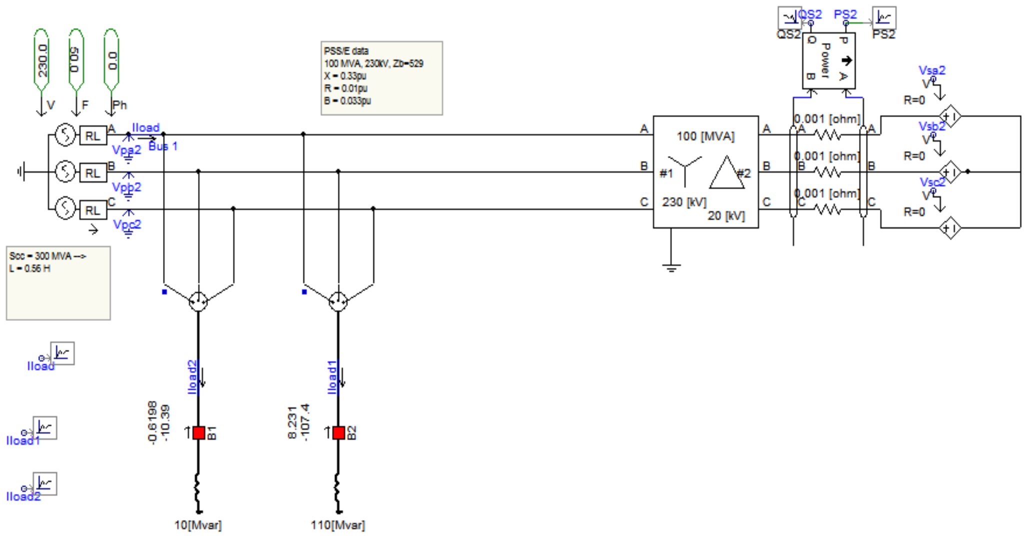


Figure 4.10 Power system representation with different Inductive load

4.8.1.1. Load change under steady state condition, without averaged source model connected to power system

a) Analytical study

Under the above condition with the STATCOM disconnected to power system, with two parallel inductive loads of 10MVAr and 110MVAr connected, the calculated load phase to neutral voltage at power system bus is 60.45kV.

The load current when both loads are connected is 0.137 kA. An exercise in MathCAD is used to calculate the bus voltage and the load current as per below,

Source Impedance:

$$Z_{S1\_P} = (16.565 + 527.267\,j)\Omega$$

$\left|Z_{S1\_P}\right| = 527.527\Omega$ arg(Z_{S1_P}) = 88.201deg

Load impedance due to 10MVAr is

Load1MVAr=10MVA

$$X_{L1} = \frac{\left(\frac{V_{LL}}{\sqrt{3}}\right)^2}{\frac{Load\,1MVar}{3}}$$

$V_{LL=}$ 230 kV; Load 1MVArs =10MVA

$$X_{L1} = 5290 \quad \Omega$$

Where V_{LL} is phase-phase voltage, $V\varphi n$ is phase to neutral voltage

The calculated load current is,

$$I_{L1} = \frac{V\varphi n}{[ZS1\_P + j(X_{L1})]}$$

$$I_{L1} = (0.068 - 22.827j)A$$

$\left|I_{L1}\right|$ =0.023kA arg(I_{L1})=-89.837deg

Load current =0.023kA

Load impedance due to 110MVAr inductive load is

Load 2MVAr=110MVA

$$X_{L2} = \frac{\left(\frac{V_{LL}}{\sqrt{3}}\right)^2}{\frac{Load\ 2MVar}{3}}$$

$$X_{L2} = 480.909\Omega$$

Parallel impedance due to 10MVAr and 110MVAr Inductive loads are

Load1MVAr=10MVA

$$I_{L2} = \frac{V\varphi n}{\left[ZS1\_P + j\left(\frac{1}{X_{L1}} + \frac{1}{X_{L2}}\right)^{-1}\right]}$$

$I_{L2} = (2.346 - 137.126j)A$

$|I_{L2}| = 0.137KA$ $\arg(I_{L2})$=-89.02deg

Calculated load current at power system bus 0.137 KAmps

Calculate voltage at power system Bus is,

$V_{Bus} = I_{L2} \times X_{Le}$

$V_{Bus} = (1034.318 - 60449.687j)V$

$|\mathrm{VBus}|$ = 60.459kV

b) Simulation study

Simulation results agree with the analytical analysis.

Both 10MVAr load and 110MVAr loads are connected in a period of 1 second. Figure 4.11 is plotted. The steady state voltage measured at the power system bus V_{Bus} is 61kV. Both the analytical and simulation results agree for the case study.

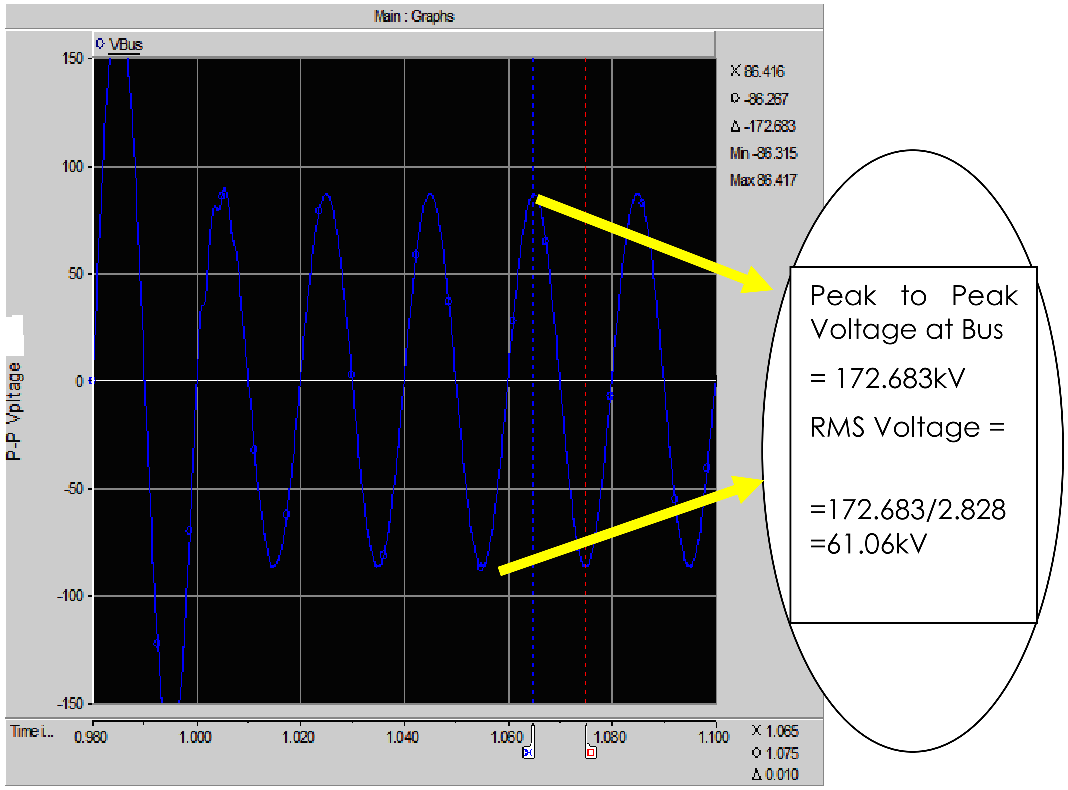


Figure 4.11 Bus Voltage waveform from simulation in PSCAD without STATCOM average voltage source connection

4.8.1.2. Load change under steady state condition, when averaged source model is connected to power system:

a) Analytical study

Under the above condition with STATCOM connected to power system, with two parallel loads of 10MVAr and 110MVAr inductive loads connected, the calculated load voltage at power system bus can be calculated using the mesh equation after arranging the equivalent circuit of the power system with the averaged voltage source model as per the following diagram as shown in Figure 4.12,

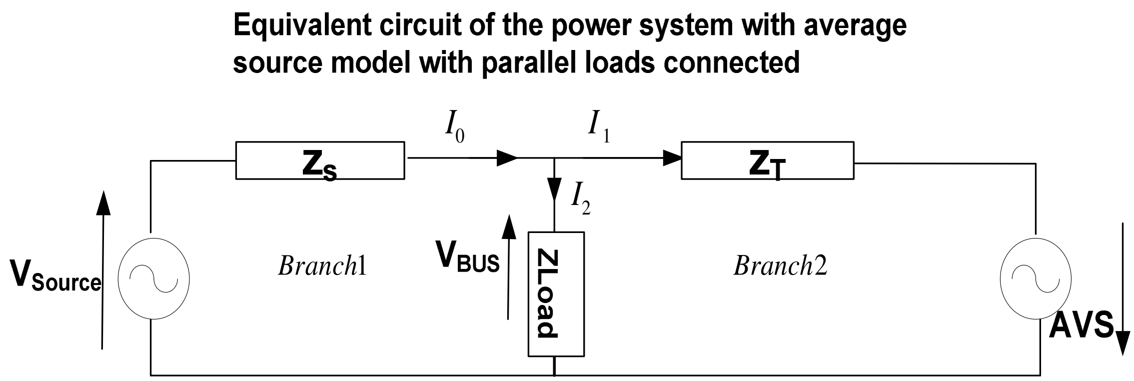


Figure 4.12 Equivalent circuit representation for calculation of steady voltage and current using Mesh Equation (for different Inductive loads)

The following equations can be used for calculating the bus voltage under steady state condition when the average voltage source model is connected to the power system bus.

$$V_{Source} = I_0 Z_S + I_0 Z_{Load} - I_1 Z_{Load}$$

$$V_{AVS} = I_1 Z_T + I_1 Z_{Load} - I_0 Z_{Load}$$

$$I_2 = I_0 - I_1$$

$$I_2 \times Z_{Load} = V_{Bus}$$

Following MathCAD exercise using Matrix equation solving is carried out, to calculate currents during the steady state condition (when Average voltage source is connected) in both the branches using the Mesh equation.

V_{AVS} =160.08kV $\quad$ V_{AVS} is average voltage source Ph neutral voltage

$V\varphi n$ =132.791kV $\quad$ $V\varphi n$ is source Ph-neutral voltage of power system

Z_{TX} =95.22Ω $\quad$ Z_{TX} is transformer impedance

Solving the variables of Mesh equation using the matrix form

$$E = \begin{pmatrix} V_{\varphi n} \\ V_{AVS} \end{pmatrix} \qquad Z = \begin{bmatrix} Z_{S1\_P} + X_{Le} & -X_{Le} \\ -X_{Le} & Z_{TX} + X_{Le} \end{bmatrix}$$

$$I = Z^{-1} \times E$$

$$I = \begin{pmatrix} 87.408 & -485.793j \\ 370.509 & -399.501j \end{pmatrix} A$$

$I_0 = (87.408 - 485.793j)A$ $\quad |I_0| = 493.594A$ $\quad \arg(I_0) = -1.393$

$I_0 = (370.509 - 399.501j)A$ $\quad |I_1| = 544865A$ $\quad \arg(I_1) = -0.823$

$$I_2 = I_0 - I_1$$

$$I_2 = (-283.101 - 86.292j)A$$

$$|I_2| = 295.96A$$

$$V_{Bus1} = |I_2| \times |X_{Le}|$$

$$|V_{Bus1}| = 130468.996V$$

Thus the calculates bus voltage at V_{Bus1}=130.5kV

b) Simulation study

Simulation results agree with the analytical analysis.

Both 10MVAr load and 110MVAr loads are connected in a period of 1 second. In Figure 4.13, V_{BUS}, is plotted. The steady state voltage (Phase to neutral) measured at the power system bus V_{BUS} =130.5kV. Both the analytical and simulation results agree for the case study.

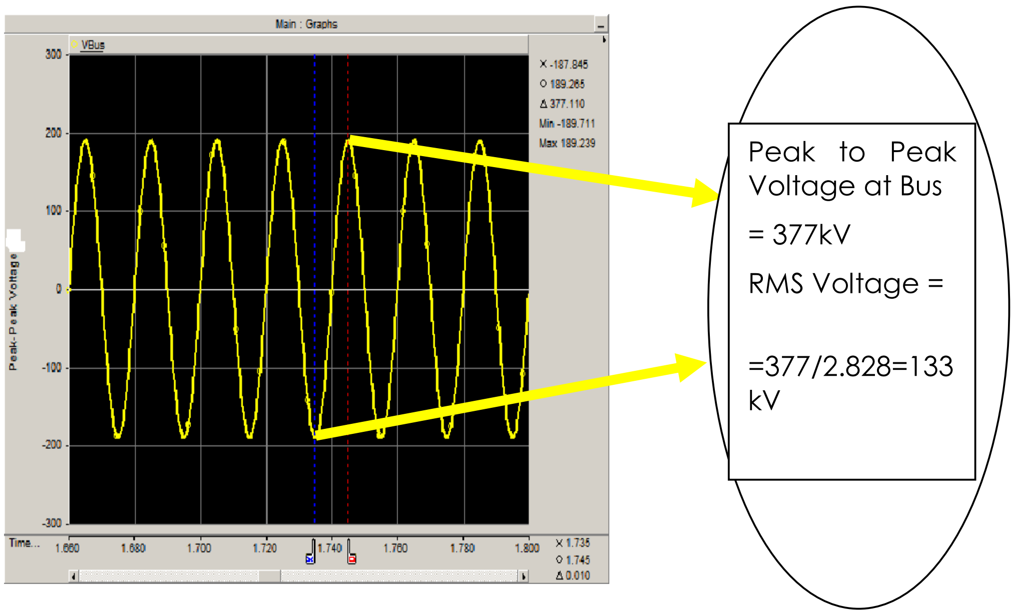


Figure 4.13 Voltage waveform with average voltage source connected to the Bus

The characteristics of STATCOM has also been confirmed during the operation as capacitive mode, as shown in Figure 4.14, the voltage of the average source is higher than that of the power system bus voltage and hence STATCOM is seen as capacitive source by the power system. The characteristics of average voltage source model of STATCOM during a capacitive mode operation is shown in the below Figure 4.14. Finally the results for the inductive load variations are tabulated in Table 4.4.

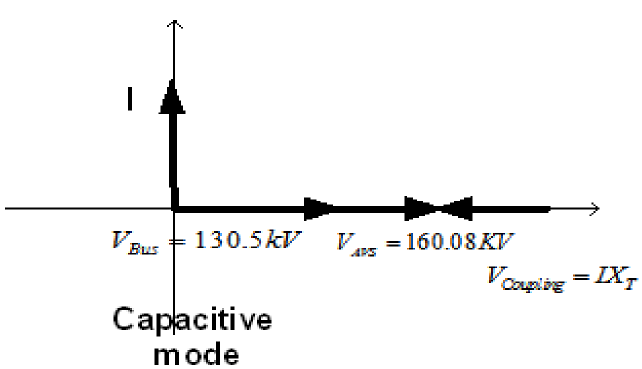


Figure 4.14 Current and voltage vectors when AVS in capacitive mode of operation

Table 4.4 Results for Inductive load variation

System condition	Expected result		Actual result	Reference diagram
	without averaged voltage source	with averaged voltage source	with averaged voltage source	
Inductive load followed by increase in Inductive reactive load.	Voltage decreases in the connected bus	Voltage at the connected bus is maintained at nominal voltage	Agrees with expected result	Figure 4.14

4.8.2. Inductive reactive load connected to power system, followed by sudden increase in capacitive load condition in the power system to which average voltage source model is connected

In the power system bus, of Figure 4.15 Inductive reactive and capacitive reactive loads connected through two breakers. In the start up of the simulation the first breaker is closed on resuming of "START SEQUENCE" of the simulation, during which 10MVAr of Inductive load is switched' ON", after 1sec the second breaker is closed which switches 25MVAr of capacitive load to the power system bus.

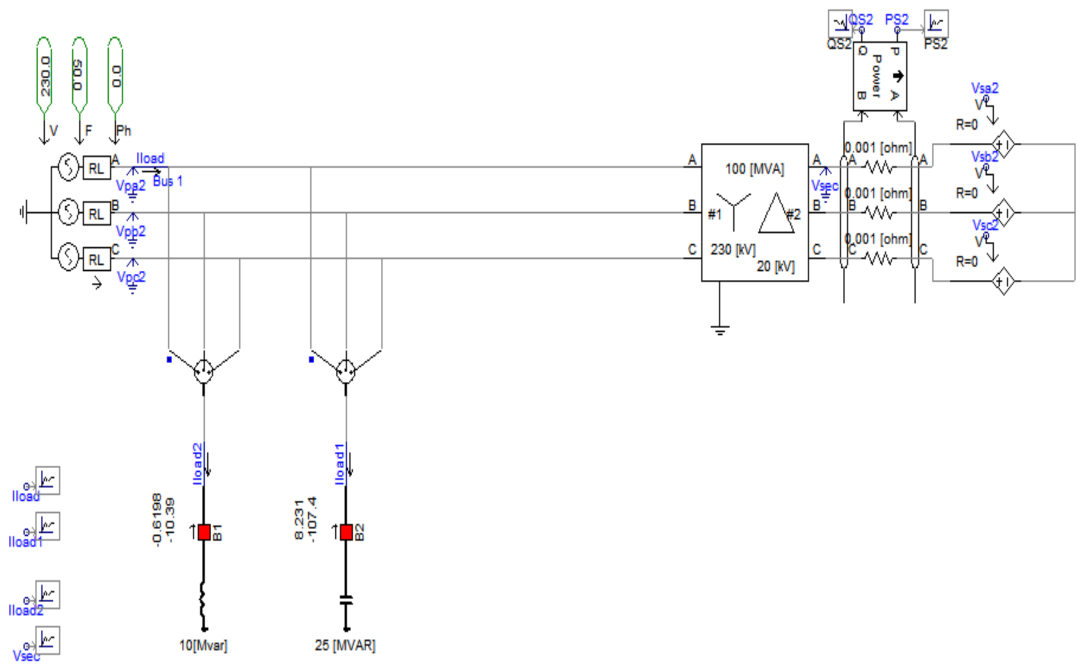


Figure 4.15 PSCAD Power system model for Inductive and capacitive loads connected

4.8.2.1. Load change under steady state condition, without averaged source model connected to power system

a) Analytical study

Under the above condition with out STATCOM connected to power system, with two parallel loads of 10MVAr Inductive and 25MVAr capacitive loads are connected, the calculated load voltage and load current (rms) when both loads are connected at power system bus are 156kV and 0.044 kA angle 89.7 degrees respectively. An exercise in MathCAD is used to calculate the bus voltage and the load current as per below.

10MVAr Inductive load followed by 25 MVAr Capacitive loads.

Parallel impedance due to 10 MVAr Inductive and 25 MVAr capacitive loads are

$$X_{L21} = 5290\Omega$$

$$X_{L22} = 2116\Omega$$

Load current due to parallel loads connected is,

$$I_{L21} = \frac{V\varphi n}{\left[ZS1\_P + j\left(\frac{1}{X_{L21}} + \frac{1}{X_{L22}} \right)^{-1} \right]}$$

$$I_{L21} = (0.244 + 44.271j)A$$

$|I_{L21}| = 0.044KA$ arg(I_{L21})=-89.684deg

Calculated load current at power system bus 0.044 k.Amps

Calculate voltage at power system Bus is,

V_{Bus2}= $I_{L21} \times X_{Le1}$

V_{Bus2}=$(-862.244 - 156129.174j)V$

$|V_{Bus2}|$ = 156.132kV

b) Simulation study

Simulation results agree with the analytical analysis.

Both 10MVAr load and 25MVAr loads are connected in a period of 1 second. In the graph below (Figure 4.16) Load current and V_{Bus} are plotted; the steady state voltage (phase to neutral) measured at the power system bus V_{Bus} is 155.635 kV. Both the analytical and simulation results agree for the case study.

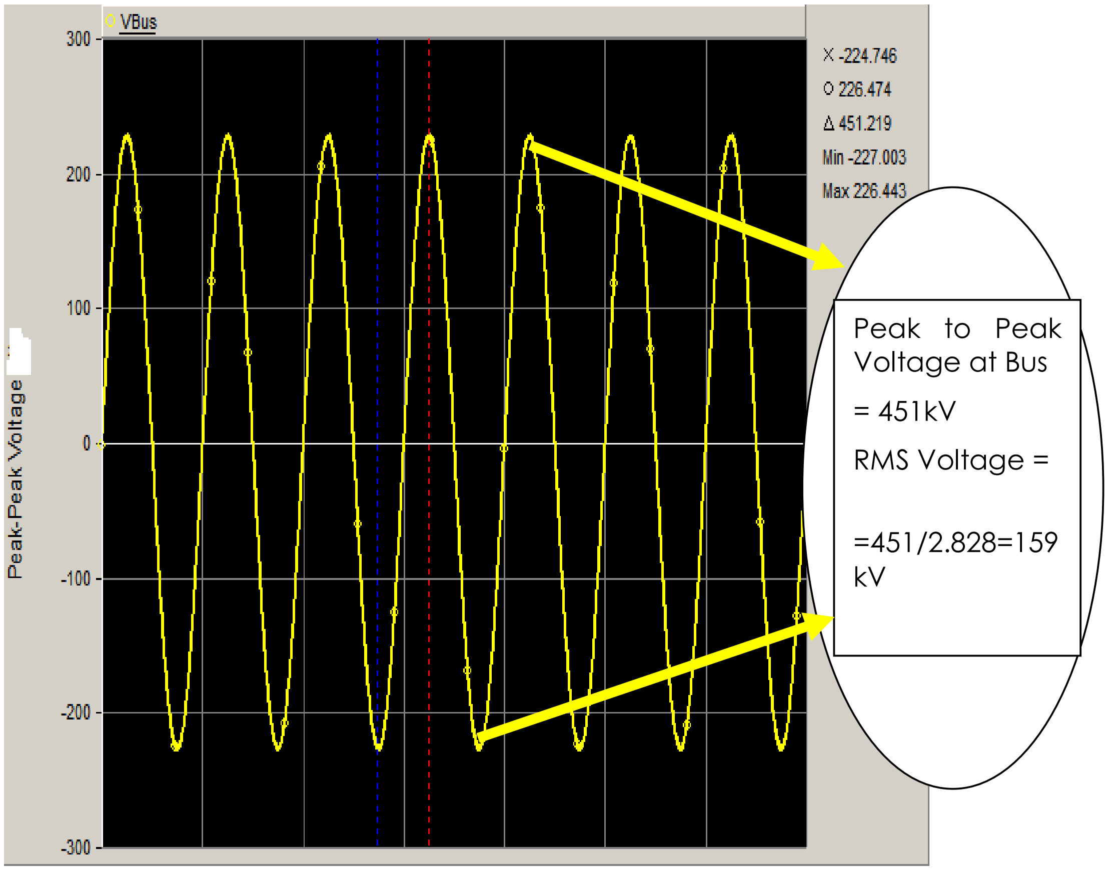


Figure 4.16 Voltage at Bus when Inductive and capacitive reactive loads connected at bus without Average voltage source connection

4.8.2.2. Load change under steady state condition, with averaged source model connected to power system

a) Analytical study

Under the above condition with STATCOM connected to power system, with two parallel loads of 10MVAr and 25MVAr inductive and capacitive loads connected, the calculated load voltage at power system bus can be calculated using the mesh equation after arranging the equivalent circuit of the power system with the averaged voltage source model as per the following diagram,

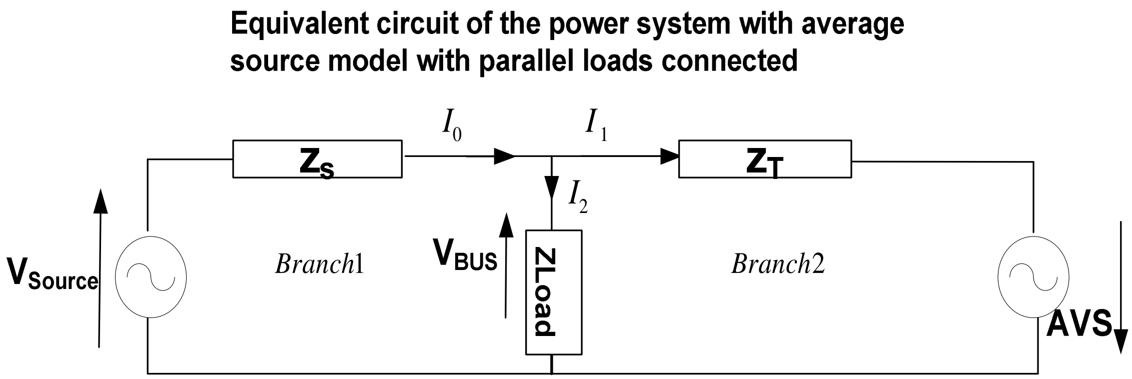


Figure 4.17 Equivalent circuit power system for Inductive and capacitive loads connected

The following equations can be used for calculation of the bus voltage under steady state condition when Average voltage source model is connected to the power system bus.

$$V_{Source} = I_0 Z_S + I_0 Z_{Load} - I_1 Z_{Load}$$

$$V_{AVS} = I_1 Z_T + I_1 Z_{Load} - I_0 Z_{Load}$$

$$I_2 = I_0 - I_1$$

$$I_2 \times Z_{Load} = V_{Bus}$$

Using Mesh equation, the currents in the branches during steady state condition (when Average voltage source is connected) in both the branches is calculated.

V_{AVS} =144.516kV V_{AVS} is average voltage source Ph neutral voltage

$V\varphi n$ =132.791kV Vφn is source Ph-neutral voltage of power system

Z_{TX} =95.22Ω Z_{TX} is transformer impedance

Solving the variables of Mesh equation using the matrix form

$$E1 = \begin{pmatrix} V_{\varphi n} \\ V_{AVS3} \end{pmatrix} \qquad Z_1 = \begin{bmatrix} Z_{S1\_P} + X_{Le1} & -X_{Le1} \\ -X_{Le1} & Z_{TX} + X_{Le1} \end{bmatrix}$$

$I3 = Z^{-1} \times E$

$$I = \begin{pmatrix} 110.58 & -509.54j \\ -71.533 & -523.679j \end{pmatrix} A$$

$I3_0 = (110.58 - 509.54j)A$ $\quad |I3_0| = 521.4A$ $\quad \arg(I3_0) = -1.357$

$I3_1 = (-71.533 - 523.679j)A$ $\quad |I3_1| = 528.542A$ $\quad \arg(I_1) = -1.435$

$I4 = I3_0 - I3_1$

$I4 = (39.047 + 14.139j)A$

$|I4| = 41.528A$

$V_{Bus3} = |I4| \times |X_{Le1}|$

$|V_{Bus3}| = 146454.956V$

Thus the calculates bus voltage at V_{Bus3}=146.5kV

b) Simulation study

Simulation results agree with the analytical analysis.

Both 10MVAr load and 25MVAr loads are connected in a period of 1 second. Figure 4.18 is a record taken from simulation results from PSCAD. In the attached Graph (Figure 4.18) steady state voltage (phase to neutral) measured at the power system bus $V_{BUS=}$ 146kV. Both the analytical and simulation results agree for the case study.

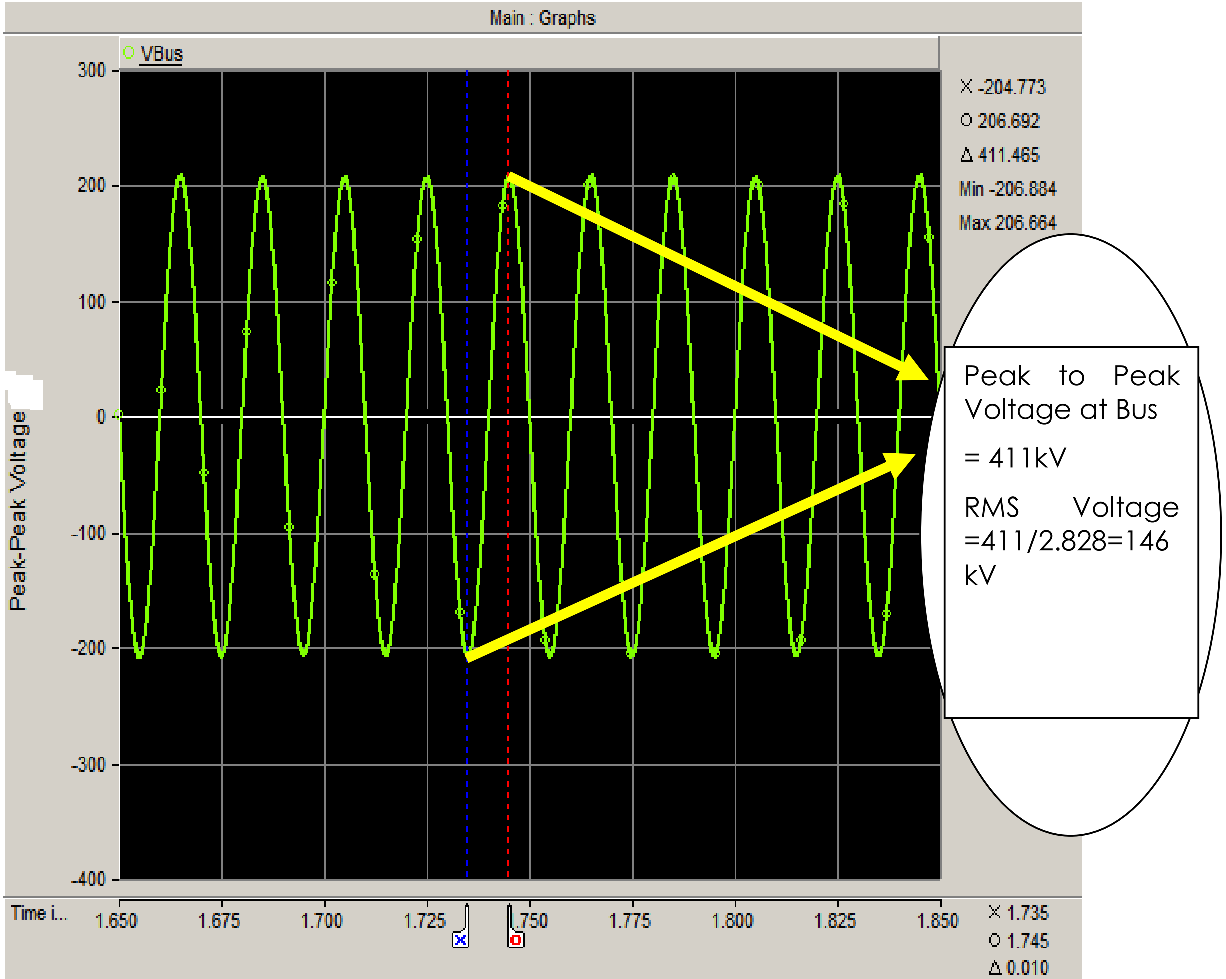


Figure 4.18 Waveform of the voltage at the connected busbar, when Average Voltage Source is connected with varying Inductive and capacitive reactive loads connected

The characteristics of STATCOM has also been confirmed during the operation as Inductive mode, voltage of the average source is lesser than that of the power system bus voltage and hence power system is seen as capacitive source. The characteristics of average voltage source model of STATCOM during an inductive mode operation is shown Figure 4.19

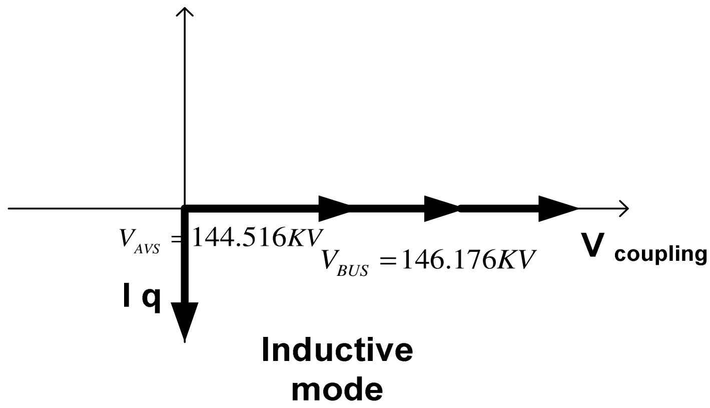


Figure 4.19 Current and voltage vectors when AVS in Inductive mode of operation

Results tabulated in Table 4.5

Table 4.5 Results for Capacitive load variation

System condition	Expected result		Actual result	Reference diagram
	Without averaged voltage source	with averaged voltage source	With averaged voltage source	
Inductive load followed by increase in capacitive reactive load.	Voltage increases in the connected bus	Voltage at the connected bus is maintained at nominal voltage	Agrees with expected result	Fig4-19

4.9. DISCUSSION

The STATCOM simulation modelled using an averaged voltage source model has been tested with several different scenarios of load change. According to the modelled STACOM its response time to system disturbances is in the order of microseconds ensuring voltage stability of the connected power system.

The voltage source model has its internal protections like the under voltage block, reactive power minimum and maximum limits to be set, and over current protection. The model can be used for power system voltage stability study purpose. The control system settings are set in per unit values, so there are not much foreseeable problems to use the model with any power system for system study purposes.

In case the DC voltage rating requires a change, then the time constant setting in the mathematical model has also to be changed to meet the modelling requirement of charging of capacitance value.

When the Voltage source model is applied on a similar system to which it is connected to, it is anticipated less or no tuning of PI control in the control system of the model is required.

5. SIMULATION STUDIES TO DETERMINE EFFECTS OF STATCOM ON DISTANCE PROTECTION RELAYING

5.1. INTRODUCTION

The STATCOM model developed previously was validated on a power system, which was weak enough for effects of any type of load variations of capacitive reactive load or inductive reactive loads to have an effect on the power system voltage. The compensation of the power system voltage is achieved by the operation of the STATCOM model.

In this chapter, simulation studies are carried out to evaluate the behaviour of a distance protection relay when protecting a long transmission line, when the designed STATCOM is employed to maintain voltage stability of the transmission system during power system disturbances.

5.2. TEST SYSTEM

5.2.1. Power system model

The power system and FACTS models discussed in the earlier section were built using the PSCAD/EMTDC software.

The test power system for the study is taken from [10] and is shown in Figure 5.1. The power system model has four infeeds, and they are interconnected by transmission lines. Voltage stability is normally an issue associated with long transmission lines and in the model each of the transmission lines is of 300 km in length. The power system has been modelled so that several parameters can be changed. These include the system strength, fault location, type of fault, load flow and direction of load so that all the possible conditions can be simulated and studied. A FACTS device is installed at the mid-point of one of the transmission lines. The power system data is shown in Table 5.1and Table 5.2 below.

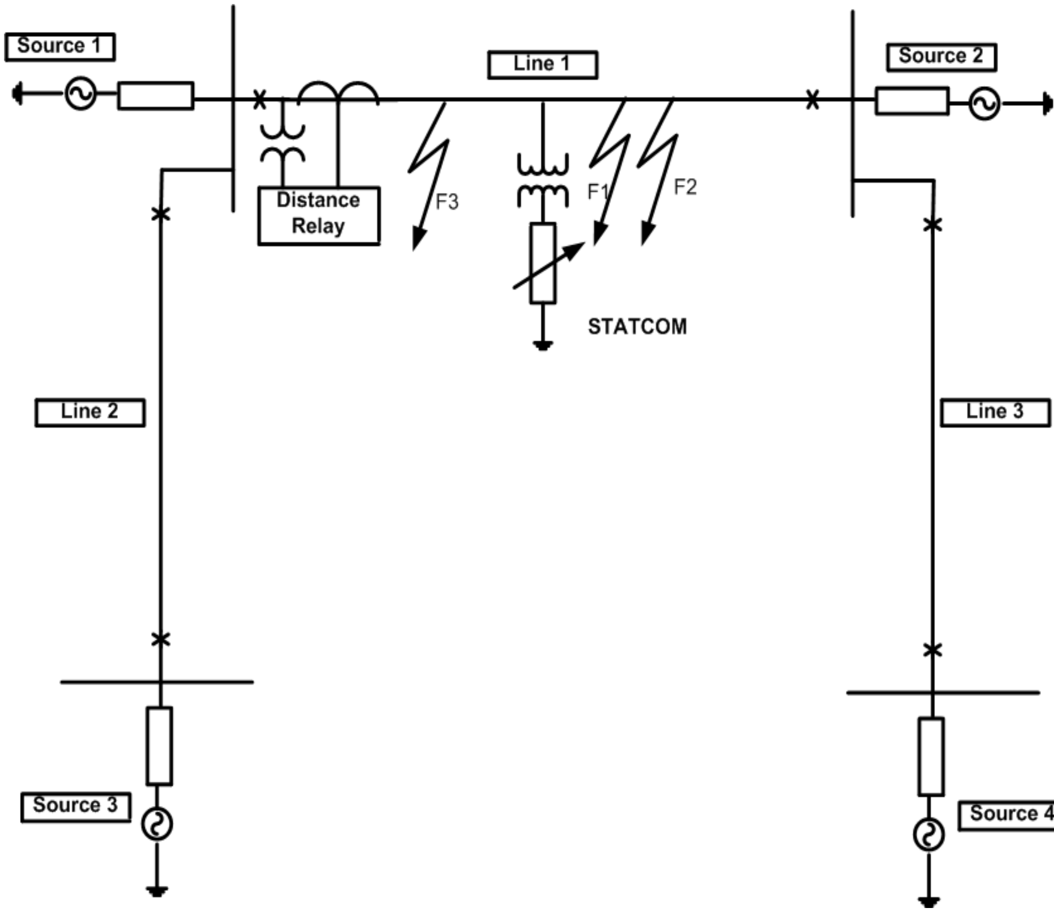


Figure 5.1 Transmission system with STATCOM installed at mid-point of the transmission line

Table 5.1Transmission lines (I, II &III)

Parameter	Value
Line length	$300\,km$
Positive seq.impedance	$0.51\angle 85.92°\Omega\ /km$
Zero seq.impedance	$25.9\angle 80.0°\Omega\ /km$

Table 5.2 Equivalent sources (1, 2, 3 &4)

Parameter	Value
Power rating	$100MVA$
System voltage	$230kV$
System Frequency	$60Hz$
Positive seq.impedance	$25.9\angle 80.0°\Omega\ /km$
Zero seq.impedance	$25.9\angle 80.0°\Omega\ /km$

5.2.2. STATCOM

The test power system consists of STATCOM installed at the mid-point of the transmission line connecting Source 1 and Source 2. The aim of the STATCOM installation is to provide voltage stability during disturbance in the transmission line. The STATCOM model used in the study has been modelled using the average voltage source studied previously. For the purpose of simulation studies, the position of STATCOM in addition to the mid-point position was moved to a distance of 100 km from Source 1 to observe how a different location affects the simulation results.

5.3. DISTANCE RELAY

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

Zones of protection: Distance relays are normally set for protection in terms of the zones of protection. Distance relays have Zone 1, Zone 2, Zone 3, and

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

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

Zcalc = Vmeas/Imeas

where Vmeas is the measured voltage at the relaying point and Imeas is the measured current at the relaying point. The calculated impedance Zcalc is then compared against a set value, Zset. The relay will trip if:

Zcalc < Zset

Impedance Diagram

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

By using a complex R-X plane, it is easy to understand how the relay operates and the operation of the relay with the presence of system faults can be analyzed. An example of an Impedance diagram is shown in Figure 5.2.

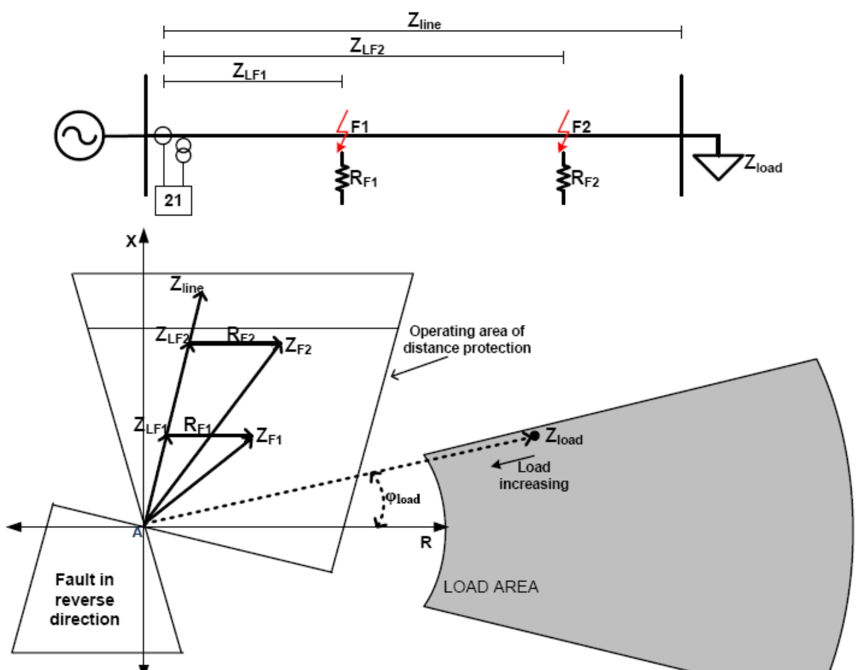


Figure 5.2: Impedance measurements drawn on R-X Plane

The power system one-line diagram shows:

The distance relay location (21 is the IEEE C37.2 acronym for distance relay)

The impedance of the protected line (Zline)

Two possible fault locations at F1 and F2:

ZLF1- Impedance of the line from the relaying point to the fault point F1

ZLF2- Impedance of the line from the relaying point to the fault point F2

RF1 – Resistance of the fault at fault point F1

RF2 – Resistance of the fault at fault point F2

ZF1 = ZLF1 + RF1 – Impedance of the fault at Fault point F1

ZF2 = ZLF2 + RF2 – Impedance of the fault at Fault point F2

The quantities can then be plotted in the R-X plane as shown in the lower figure of Figure 5.2 where the relay location is located at the origin of the R-X plane.

Distance Protection Characteristic

The measured impedance at a certain fault position must not depend on the fault type. The correct voltages and currents must be measured for each fault loop and evaluation of the loop impedance and phase impedance to the fault must be done. The distance relay settings are practically based on the phase impedance of the fault. In section 3.2 of this thesis, the Mho characteristics are briefly explained.

For phase to phase and three phase faults, the measured phase voltage and the difference between the measured phase currents are used. With this principle, the calculated impedance seen by the relay is equal to the positive sequence impedance to the fault location. Figure 5.3 shows an example of the Mho characteristic, which when plotted on an impedance polar diagram is a circle where the diameter is the relay impedance setting (or reach point) such that the characteristic passes through the origin of the impedance diagram. In the diagram Figure 5.3, Z1A is Z1 characteristics for A phase to ground faults,

Z2A is the characteristics for Zone2 A phase to ground faults

Z3A is the characteristics for Zone3 A phase to ground faults

A and B – are the distance relay location at local and remote end respectively of the protected section; C and D – are the distance relay location of the adjacent line sections,

The Mho impedance relay is therefore a directional relay. The ground fault impedance calculation is more complicated because account has to be taken of the earth return impedance. The calculated impedance from the measured phase currents and phase voltages will include a contribution from the positive sequence impedance and the zero sequence impedance of the fault loop. In the figure the phase to ground fault characteristics are shown, for the phase to phase fault the characteristics will remain the same expect for the zone settings. For this reason a distance protection relay reach setting (Z) is calculated according to equation [5.1] and is set to cover the Zone impedance and the effect due to fault resistance.

The first part on the right hand side of equation 5.1 is positive sequence impedance of the line; a distance relay is always set in terms of the positive sequence impedance of the line. So for the positive sequence impedance a setting is available to be set in the relay.

The second part of the equation is to compensate for the earth impedance which includes the zero sequence impedance of the line as setting in the relay. This setting is to account for the zero sequence currents during phase to ground a fault (which is 3 times the residual current).

The third part of the equation is to account for the mutual impedance when the distance relay is protecting one of the parallel lines in a transmission system being compensated in the settings. This is how a distance relay operates correctly for all the earth faults and if there are mutual coupling effects from a parallel line.

$$Z = Z_1 + \left[\left(\frac{I_{res}}{I_p}\right) * Z_{res}\right] + \left[\left(\frac{I_{mut}}{I_p}\right) * Z_{mut}\right] \quad [5.1]$$

Where,

Z1 is the positive sequence impedance reach setting

Ip is the measured current in the faulted phase

Ires = (Ia +Ib +Ic) is the residual current; Ires=3I0, where I0 is the zero sequence current

Imut is the residual current in the parallel line

Zres = (Z0 –Z1)/3 is the residual impedance, which includes the earth impedance, where Z0 is the zero sequence impedance of the transmission line and is a setting in the distance relay.

Zmut is the mutual compensating impedance

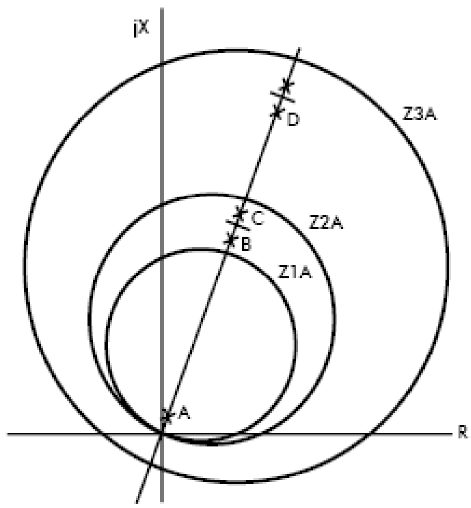


Figure 5.3 Mho Characteristic of a distance relay

5.4. DESCRIPTION OF THE MODELLED DISTANCE RELAY

In the power system model illustrated by Figure 5.1 the relay Voltage Transformer (VT) and Current Transformer (CT) are located as shown in the diagram at the left-hand end of Line 1. For the purposes of this study a simplistic model of a distance relay has been modelled. The test power system has a modelled distance relay location at end-A (there is no End-A in the diagram) of the transmission line system. The distance relay model constructed in PSCAD is as shown in Figure 5.4 and Figure 5.5. The outputs of the VTs and CTs are passed through a Fourier filter, which extracts the magnitude and phase of the input signals as a function of time. The input signals are first sampled before they are decomposed into harmonic constituents. The extracted sampled values of magnitude and phase of the voltage and current signals are then passed through the sequence component block.

The sampling rate of the Fourier filter is 32 samples per cycle of the base frequency. The sequence component block calculates the positive, negative and zero sequence components from the output voltage and current magnitudes and phases from the Fourier filter. The calculated sequence components are then passed through the simple distance algorithm, which calculates the phase to phase and phase to ground impedance seen by the relay. The calculated impedance is then compared at every time step to check whether the impedance falls within the mho characteristics.

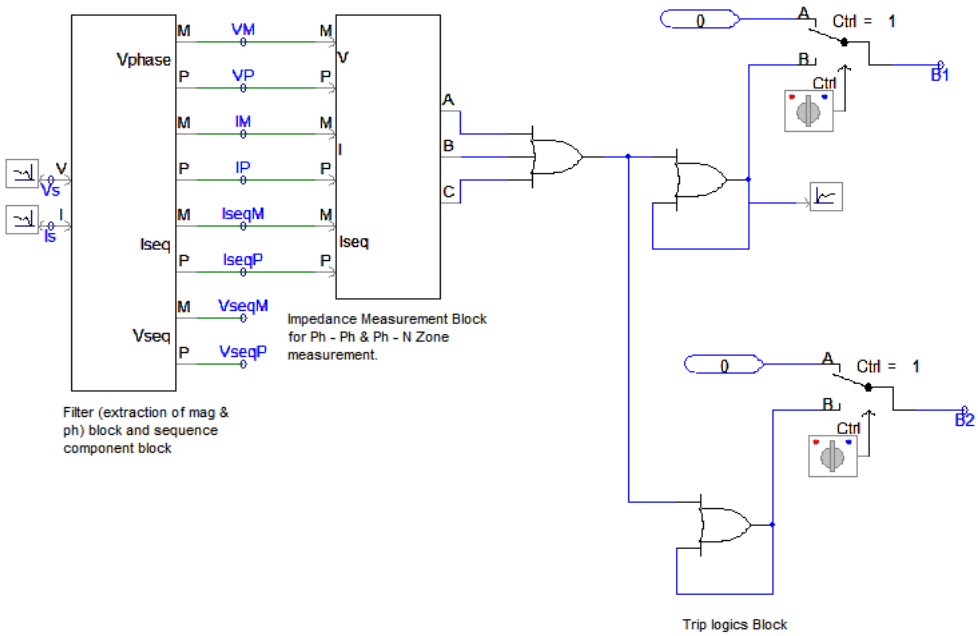


Figure 5.4 Block diagram of Modelled Distance relay

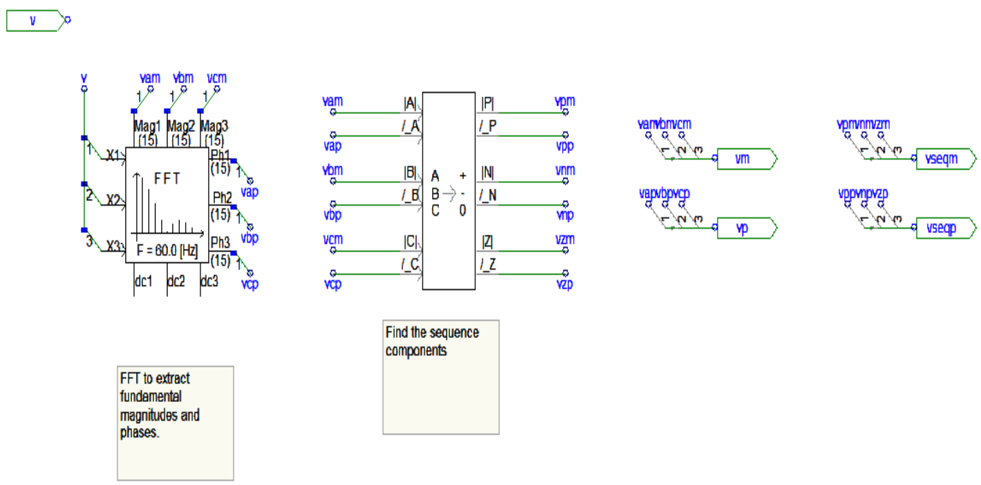


Figure 5.5 Fast Fourier Transform block (to extract Magnitude and Phase) & Sequence component block (to extract the positive, negative and zero sequence components)

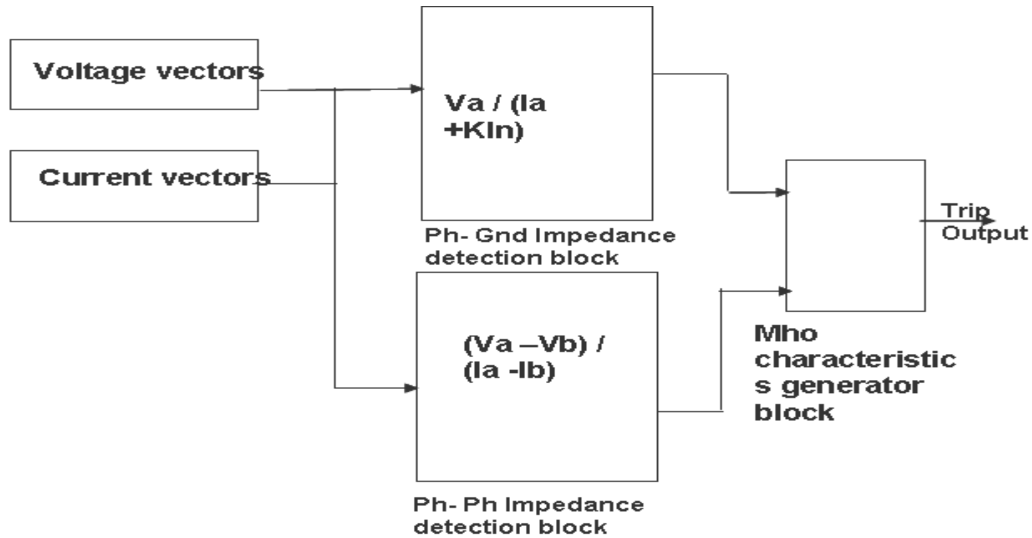


Figure 5.6 Simplified functional Block Diagram Impedance calculation and Mho generation blocks

To simplify the understanding of diagrams shown in Figure 5.7 and Figure 5.8 a functional diagram is included in Figure 5.6. This block diagram shows the voltage and current vectors are passed through the impedance detection blocks. The impedance detection blocks are independent for each phase (AN, BN, CN impedance measurements) and also for phase to phase impedance detection blocks (to calculate AB impedance, BC impedance, and CA impedance).The mho impedance circle generator block generates the characteristics as per the line parameters. If the calculated impedance enters into the fixed mho impedance circle then a trip output is generated by the distance relay (i.e. at the output from mho characteristics generator block).

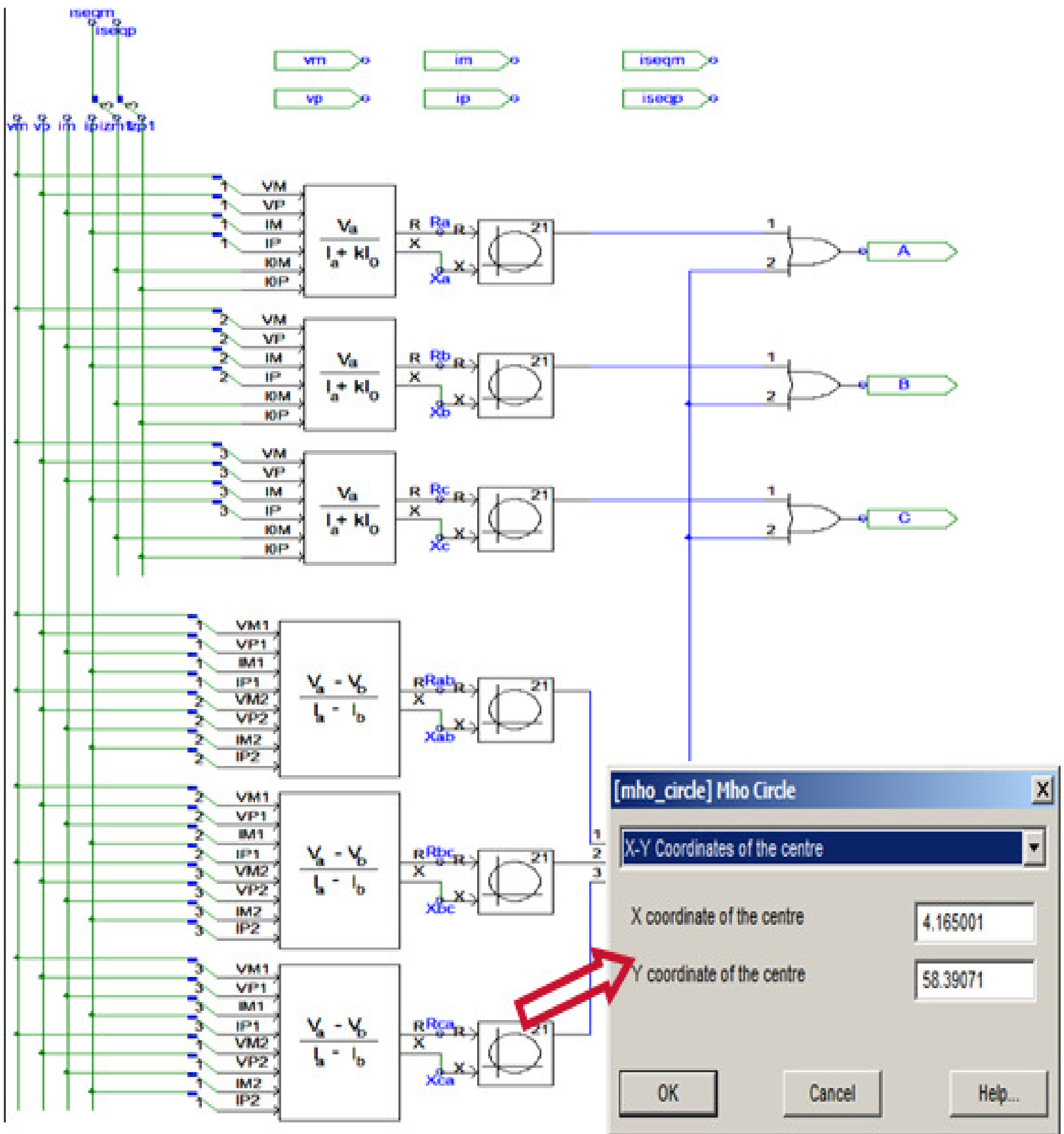


Figure 5.7 Impedance detection block

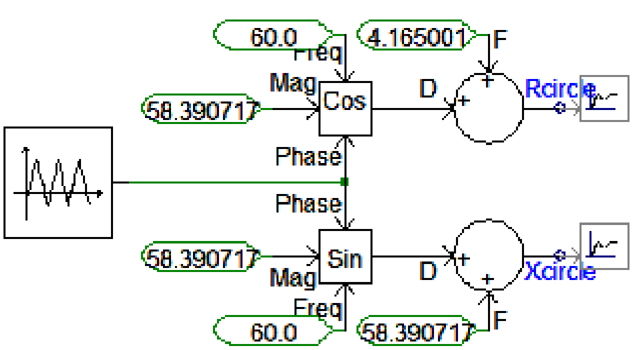


Figure 5.8 Generation of Mho characteristics (that determine the boundary of operation)

Figure 5.7 the distance relay impedance calculation blocks are shown. The blocks shown are for phase to phase impedance and phase to ground impedance. Both the blocks receive the current and voltage inputs from all three phases. The output from the phase to ground and phase to phase blocks are provided as resistance and reactance values for all the 6 measurement loops of Phase A, Phase B, Phase C, Phase AB, Phase BC, and Phase CA. Setting is available for the R and X values in the block. Mho characteristics generator generates the characteristics for the measurement loops. This block is shown in Figure 5.8.

5.4.1. Parameterisation of the distance relay

In the modelled distance relay, only the first zone is used. The reasoning behind using only the first zone element is to understand the effects of STATCOM on the behaviour of the protected line only. As zone-1 is employed to protect the transmission line under discussion, the study is limited with the distance relay having zone-1.

As the length of the line is 300 km, zone1 normally applied to cover 80% of the line length the modelled distance relay is set to cover 80% of the line length in terms of the total line impedance.

The calculations for the zone 1 measuring element applied in the modelled distance relay carried out in the following section. The phase-to-phase impedance element for zone-1 independently calculated from the phase-to-ground zone-1 element. When the calculated impedance enters into the mho impedance characteristic of the distance relay, the relay immediately issues a trip command to “open” the circuit breaker. The mho impedance characteristics are generated based on the zone 1 value for the total length.

5.4.2. Calculations for the Impedance measurement element (Zone-1) for the distance relay protecting the transmission system under study

Line length =300Km

Positive sequence Impedance/Km $= (0.036286 + 0.508707j)\,\Omega$

Zero sequence Impedance/Km $= (0.36593 + 1.335784j)\,\Omega$

Power system frequency = 60Hz

Current transformer ratio = 2000/1

Voltage transformer ratio =230kV/110V

Positive sequence line Impedance of the line ZL=$10.412504 + 145.97679 j)\Omega$

$|ZL| = 397.4346\Omega$ arg(ZL)=74.68deg

Zone1=$0.8 \times ZL$

Zone1 =$(8.330003 + 116.781 j)\Omega$

$|Zone1|$=117.078Ω

5.5. SIMULATION STUDIES

Simulation studies carried out to understand the behaviour of distance relay in the transmission system when STATCOM is in service. At each fault location, the fault resistance increased in steps of one ohm until there was a difference in operation between STATCOM being "in service" and "out of service". The purpose was to determine the limiting resistance value up to which the distance relay was normally sensitive enough irrespective of the operation of STATCOM. The reason for varying the fault resistances is that such types of high resistance faults are common at transmission voltage levels. The study extended to determine the operating time of distance relay for faults with and without STATCOM. Different types of faults applied at all the different locations. Fault locations chosen along 300 km of line length:

1) Fault location F1: FAULT applied at 140 km, STATCOM placed AT 100 km; (Fault beyond STATCOM location)

2) Fault location F2: FAULT applied AT 165 km, STATCOM placed AT 150 km; (Fault beyond STATCOM location)

3) Fault location F3: FAULT applied AT 50 km, STATCOM placed AT 150 km; (Fault before STATCOM location, i.e. faults applied between the relaying point and STATCOM location.) as shown in Figure 5.1.

5.5.1. Results of simulation

Results of the studies are shown in Table 5.3 and Table 5.4. The values under the fault location columns indicate the value of fault resistance at which the performance of the relay when the STATCOM was in service and when the STATCOM was out of service diverged. The tabulated resistance values are the values, beyond which distance relay model did not operate when STATCOM was "In Service", but did operate when STATCOM was "taken out of service".

Table 5.3 Resistance values for which STATCOM operated

Sl.No	Type of fault	(STATCOM IN & OUT of service)		
		Location F1	Location F2	Location F3
1	AN	18	15	-
2	BN	18	15	-
3	CN	18	15	-
4	ABN	22	16	-
5	AB	-	-	-
6	BC	-	-	-
7	CA	-	-	-
5	ABCN	19	15	-

For all the fault applications, a steady state was maintained for 4 seconds and the fault was applied at 4 seconds. Table 5.4 shows the operating time for different types of fault recorded at different fault locations.

Table 5.4 Operating time values

Sl.No	Type of Fault	Location F1		Location F2		Location F3	
		STATCOM In service	STATCOM Out	STATCOM In	STATCOM Out	STATCOM In	STATCOM Out
1	AN	21 ms	17 ms	22 ms	16 ms	17 ms	17 ms
2	BN	21 ms	17 ms	22 ms	16 ms	17 ms	17 ms
3	CN	21 ms	17 ms	22 ms	16 ms	17 ms	17 ms
4	ABN	30 ms	16 ms	19 ms	17 ms	16 ms	16 ms
5	ABCN	55 ms	16 ms	50 ms	17 ms	17 ms	17 ms

Operating time for the maximum fault resistance value for which the distance relay operated

5.5.2. Discussion of the results

From the analysis of the results so far, the distance relay's performance was affected in the presence of STATCOM concerning:

a) Operating time

b) Sensitivity to High resistance faults

c) When a phase-to-phase fault or 3 phase fault occurs in the presence of STATCOM, as far as the study is carried out, there is no effect on operating time or the sensitivity of the distance element (zone-1) operation. Both a) and b) above were affected when STATCOM was "in service"

5.5.3. Case under study

Fault at F2, AN fault applied with primary fault resistance of 16 ohms, with STATCOM out of service, correct modelled relay operation observed. The measured zero sequence current is 0.196 Amps RMS and its peak to peak current as measured is 0.556 Amps as shown in Figure 5.9. The measured Phase to ground impedance for this case is 93 Ohms as from graph in Figure 5.10. The zone-1 reach value calculated at 117 Ohms, as the actual impedance is less than the threshold set value the modelled distance element operates, with STATCOM out of service.

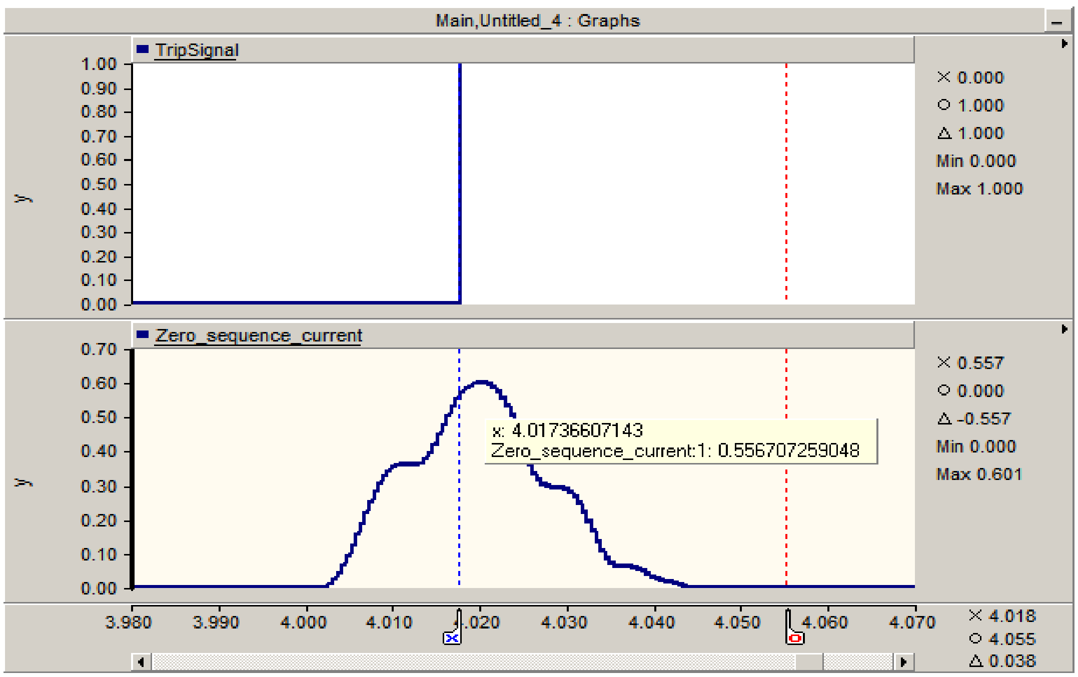


Figure 5.9 Zero sequence current measured at the instant of trip with STATCOM out of service

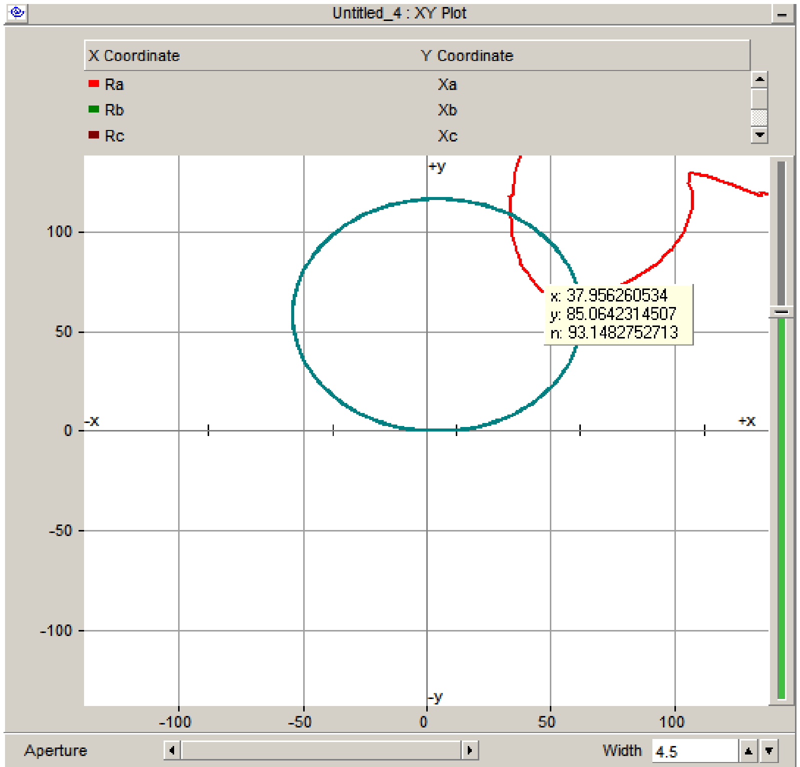


Figure 5.10 Phase to Ground Impedance measurement plot with STATCOM out of service

With STATCOM in service, the relay did not operate for the same fault location and same type of fault as well as the fault resistance. One of the observations is that the zero sequence current measured during this instance is lesser than that of the previous instance when the STATCOM was out of service and during this instance, the measured RMS value of the zero sequence current value was 0.115 Amps and the peak-to-peak current value was 0.323 Amps. The plot for the RMS measurement is as shown in Figure 5.11. The zero sequence current plots while STATCOM is in service are as shown in Figure 5.12. The phase to ground impedance as from the graph is 117.115 Ohms. As the actual impedance during fault is higher than the zone-1 threshold value, the modelled distance relay does not operate with STATCOM out of service.

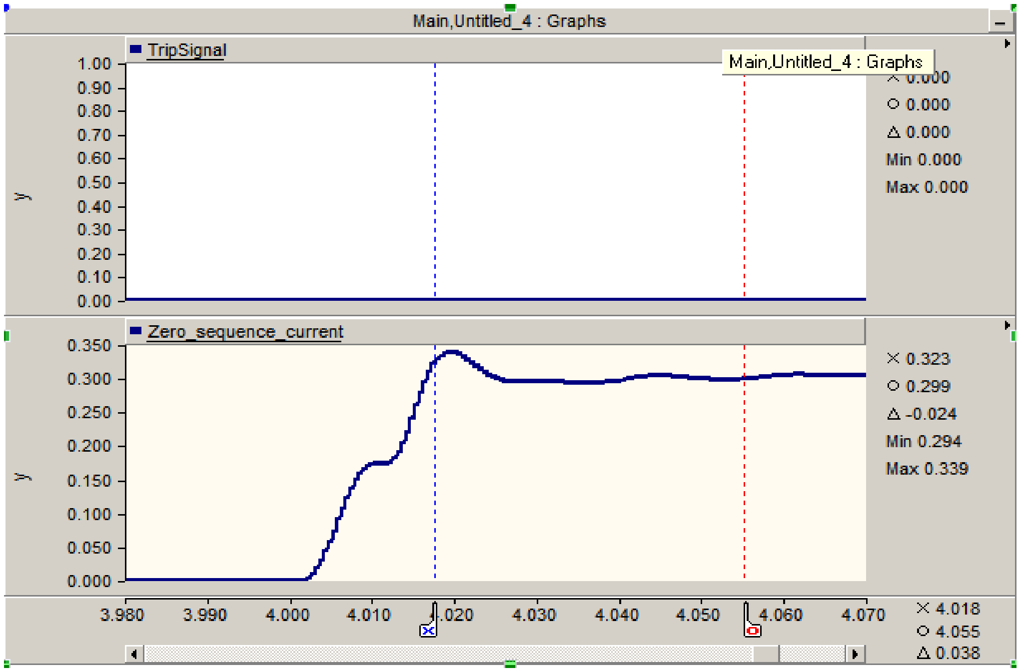


Figure 5.11 Zero sequence current plot at the per previous time instant when no trip occurred with STATCOM in service

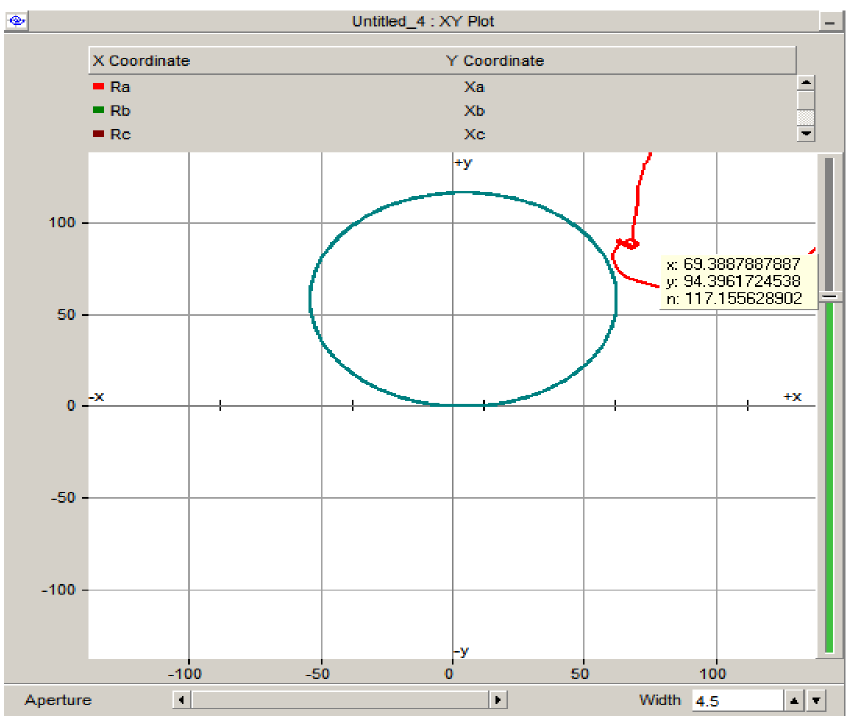


Figure 5.12 Phase to Ground Impedance measurement plot with STATCOM in service

5.6. OBSERVATIONS

It is clear from the above analysis for one specific fault case, when STATCOM is “in-service” during single phase to ground faults or any faults that involve fault with respect to ground the zero sequence impedance of the sequence component network altered by the presence of STATCOM. This is only possible by increasing the zero sequence impedance and hence reducing the zero sequence current distribution when fault-involving phase to ground is active.

In Table 5.5 from the measured values of A phase current and voltages and the zero sequence current, the resulting magnitude of the A phase impedance is tabulated when STATCOM is in service and out of service. From the results it is clearly evident the most varying parameter is the zero sequence current, which changes due to zero sequence impedance involving STATCOM in the fault current path, which alters the zero sequence current.

As from Table 5.5 below the calculated phase to ground impedance of the distance relay based on the measurements from the faulted phase voltage and currents, it can be seen that the calculated impedance when the STATCOM was “in service” the distance relay “under-reached” by 12.5% as against the impedance calculated when STATCOM was “out of service”.

This under-reaching of the distance relay could lead to delayed operation of distance relay. The delayed operation of the distance relay can be overcome by distance relay schemes (Appendix 4).

The level of under-reaching of the distance relay could vary between different voltage levels of the power system and the type of earthing of the power system.

Table 5.5 Measurements from simulation run

	With STATCOM in service	w/o STATCOM in service	
	RMS Values (measured from graph)	RMS Values (measured from graph)	
Zero_Seq_Current	0.114	0.197	AMPS
IA_Current	0.285	0.266	AMPS
Van Voltage	43.153	43.716	VOLTS
Phase-Ground Impedance (calculated)	108.008	94.582	

6. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The effect of a STATCOM applied to the mid-point of transmission system on the performance of a distance relay has been studied using simulation models. It is clear that for the purpose of distance relay studies in the presence of STATCOM an average voltage source model of STATCOM is sufficient as it deals with only fundamental frequency. In order to use the average voltage source model for the study purpose a systematic simulations studies to understand the behaviour of the AVS model of STATCOM was carried out. It is shown in the studies that the characteristics of AVS model during the steady state load changes behaved the same way as a more detailed STATCOM model.

In the present research study the working of the distance relay is affected in the following areas by the presence of STATCOM. They are:

a) Reach performance of the distance relay for resistive faults (the distance relay is under-reaching) b) the operating time of the distance relay in the presence of STATCOM is also affected.

At a similar level or at the same voltage level (230kV) in the transmission system compensated by STATCOM when distance relays are deployed it is concluded that the performance of the distance relay will not operate for fault resistances of 15 Ohms and above and also the operating time for the phase to ground and phase to phase to ground faults will be longer than 50ms. This is due to the fact that STATCOM introduces non-linear impedance in the fault loop measure but not compensated for by the relay, since distance relays at present are only compensated for the system earth impedance and the mutual impedance. So the additional impedance introduced by STATCOM is not compensated for by distance relay. The apparent impedance measured by the distance relay is higher by 12% due to the reduced zero sequence current by 1.7 times. (this could vary depending on the zero sequence impedance of the system. This necessitates zone 1 reach cannot be set to normally as is set for plain transmission system but with reduced zone1 reach value to cope up with the under-reaching scenario.

On a smaller voltage level system (below 230 kV) (up to sub-transmission level voltages that are up to 66 kV) that are compensated by STATCOM for various applications, it is quite possible the performance of the distance relay will be affected, as the zero sequence impedance at those levels are higher than the zero sequence impedance of the system at 230 kV level.

On a solidly grounded 400kV transmission line system compensated by STATCOM it is possible that the performance of distance relay is less likely to be affected as the zero sequence impedance at 400kV system is lesser than the zero sequence impedance at 230kV systems. But if these higher level of systems are resistance earthed or low impedance earthed or isolated systems (such as in countries like Germany at 380kV systems) then it is likely that the performance of distance relay is affected under such conditions.

Further research works has to be carried out to confirm the above findings. Further more, studies involving simulations, has to be carried out to ascertain, whether presence of STATCOM employed at the mid-point of the long transmission line affects distance relay's performance of the following

Distance to Fault location

Phase selection

Directional problems

The above functions of the distance relays are equally important in the overall performance of the distance relay.

Recommendations:

From the present study it is confirmed the distance relay under-reaches by 12% of Zone1 reach, which means the relay zone1 should be set to 68% of line positive sequence impedance. But in practice this may not be the case always, due to the non-linear behaviour of STATCOM under performing under fault conditions. In order to overcome this, permissive under reaching schemes of distance relays may be employed. If the transmission lines are short, then permissive over reach schemes could be employed.

The strength of the distance relay lies in making a reliable decision using local measurements. The methods recommended in this thesis uses local measurements to stabilise and enhance the decision making process but with the technological advancements happening in IEC 61850, it shall be possible to use IEC61850-9-2 / IEC 61850-90-1 (communication used to pass the current and voltage measurements as sample values) paradigm to simplify the more difficult problems faced by this type of protection by taking into account of remote measurements. Conference paper [25] DPSP 2010 has addressed the above points.

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8. APPENDIX 1

Brief Explanation of d-q Transform

A phase signal:

$$V_a = V_a \cos(\omega t + \phi);$$
$$= V_a \cos\omega t.\cos\phi - V_a \sin\omega t.\sin\phi$$

Similarly the remaining 2 phases can be written as,

$$V_b = V_b \cos[(\omega t - 2\pi/3) + \phi]$$
$$= V_b \cos\phi.\cos(\omega t - 2\pi/3) - V_b \sin\phi.\sin(\omega t - 2\pi/3)$$
$$V_c = V_c \cos[(\omega t + 2\pi/3) + \phi]$$
$$= V_c \cos\phi.\cos(\omega t + 2\pi/3) - V_c \sin\phi.\sin(\omega t + 2\pi/3)$$

Now,

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix}_{2\times1} = (2/3)\begin{bmatrix} \cos\omega t & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\ -\sin\omega t & -\sin(\omega t - 2\pi/3) & -\sin(\omega t + 2\pi/3) \end{bmatrix}_{2\times3} \begin{bmatrix} V_a \cos\omega t.\cos\phi - V_a \sin\omega t.\sin\phi \\ V_b \cos\phi.\cos(\omega t - 2\pi/3) - V_b \sin\phi.\sin(\omega t - 2\pi/3) \\ V_c \cos\phi.\cos(\omega t + 2\pi/3) - V_b \sin\phi.\sin(\omega t + 2\pi/3) \end{bmatrix}_{3\times1}$$

This gives,

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix}_{2\times1} = \begin{bmatrix} V_a \cos\phi \\ -V_a \sin\phi \end{bmatrix}_{2\times1} \quad \ldots\ldots\ldots(1)$$

The explanation of above expression is detailed as per below derivations.

Equation (1) gives,

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix}_{2\times1} = (2/3).\begin{bmatrix} \cos\omega t & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\ -\sin\omega t & -\sin(\omega t - 2\pi/3) & -\sin(\omega t + 2\pi/3) \end{bmatrix}_{2\times3} \begin{bmatrix} V_a \cos\omega t.\cos\phi - V_a \sin\omega t.\sin\phi \\ V_b \cos\phi.\cos(\omega t - 2\pi/3) - V_b \sin\phi.\sin(\omega t - 2\pi/3) \\ V_c \cos\phi.\cos(\omega t + 2\pi/3) - V_b \sin\phi.\sin(\omega t + 2\pi/3) \end{bmatrix}_{3\times1}$$

Using the Matrix Multiplication, the first row term in eqn(1),

$$= \cos\omega t.[V_a \cos\omega t.\cos\phi - V_a \sin\omega t.\sin\phi]$$
$$+ \cos(\omega t - 2\pi/3).[V_b \cos\phi.\cos(\omega t - 2\pi/3) - V_b \sin\phi.\sin(\omega t - 2\pi/3)]$$
$$+ \cos(\omega t + 2\pi/3).[V_c \cos\phi.\cos(\omega t + 2\pi/3) - V_b \sin\phi.\sin(\omega t + 2\pi/3)]$$

Assuming $V_a = V_b = V_c$,

$$=(V_a\cos\phi)\left[\cos^2\omega t+\cos^2(\omega t-2\pi/3)+\cos^2(\omega t+2\pi/3)\right]$$

$$-(V_a\sin\phi)\left[\cos\omega t.\sin\omega t+\sin(\omega t-2\pi/3)\times\cos(\omega t-2\pi/3)+\sin(\omega t+2\pi/3)\times\cos(\omega t+2\pi/3)\right]\ldots\ldots\ldots(i)$$

Simplifying the terms in above equation

$$\cos(\omega t-2\pi/3)=\cos\omega t.\cos(2\pi/3)+\sin\omega t.\sin(2\pi/3)$$

$$=\frac{-1}{2}.\cos\omega t+\frac{\sqrt{3}}{2}.\sin\omega t$$

$$\cos^2(\omega t-2\pi/3)=\frac{1}{4}.\cos^2\omega t+\frac{3}{4}.\sin^2\omega t-\frac{\sqrt{3}}{2}\cos\omega t.\sin\omega t$$

$$\cos^2(\omega t+2\pi/3)=[\frac{-1}{2}.\cos\omega t-\frac{\sqrt{3}}{2}.\sin\omega t]^2$$

$$=\frac{1}{4}.\cos^2\omega t+\frac{3}{4}.\sin^2\omega t+\frac{\sqrt{3}}{2}\cos\omega t.\sin\omega t$$

the first term in the eq (i) is,

$$V_a\cos\phi.\underbrace{[\cos^2\omega t+\cos^2(\omega t-2\pi/3)+\cos^2(\omega t+2\pi/3)]}_{=\left(\frac{3}{2}\right)}=\left(\frac{3}{2}\right)V_a\cos\phi$$

Similarly simplifying for second term in eq(i) :

$$\sin(\omega t-2\pi/3)=\sin\omega t.\cos(2\pi/3)+\cos\omega t.\sin(2\pi/3)$$

$$=\frac{-1}{2}.\sin\omega t-\frac{\sqrt{3}}{2}.\cos\omega t$$

$$\sin(\omega t+2\pi/3)=\frac{-1}{2}.\sin\omega t+\frac{\sqrt{3}}{2}.\cos\omega t$$

Now,multiplying $\sin(\omega t-2\pi/3)\times\cos(\omega t-2\pi/3)$

$$=\left[\frac{-1}{2}.\sin\omega t-\frac{\sqrt{3}}{2}.\cos\omega t\right].\left[\frac{-1}{2}.\cos\omega t+\frac{\sqrt{3}}{2}.\sin\omega t\right]$$

$$=\left(\frac{1}{4}\right)\cos\omega t.\sin\omega t+\frac{\sqrt{3}}{4}\cos^2\omega t-\frac{\sqrt{3}}{4}\sin^2\omega t-\left(\frac{3}{4}\right)\cos\omega t.\sin\omega t$$

$$=\left(\frac{\sqrt{3}}{4}\right)\left[\cos^2\omega t-\sin^2\omega t\right]-\left(\frac{1}{2}\right)\cos\omega t.\sin\omega t$$

$$Multiplying\ \ \sin(\omega t+2\pi/3)\times\cos(\omega t+2\pi/3)$$
$$=\left[\frac{-1}{2}.\sin\omega t+\frac{\sqrt{3}}{2}.\cos\omega t\right].\left[\frac{-1}{2}.\cos\omega t-\frac{\sqrt{3}}{2}.\sin\omega t\right]$$
$$=\left(\frac{1}{4}\right)\cos\omega t.\sin\omega t+\frac{\sqrt{3}}{4}\sin^2\omega t-\frac{\sqrt{3}}{4}\cos^2\omega t-\left(\frac{3}{4}\right)\cos\omega t.\sin\omega t$$
$$=-\left(\frac{\sqrt{3}}{4}\right)\left[\cos^2\omega t-\sin^2\omega t\right]-\left(\frac{1}{2}\right)\cos\omega t.\sin\omega t$$

$$\therefore\text{-}\ (V_a\sin\phi)\left[\cos\omega t.\sin\omega t+\sin(\omega t-2\pi/3).\cos(\omega t-2\pi/3)+\sin(\omega t+2\pi/3).\cos(\omega t+2\pi/3)\right]$$
$$=\text{-}\ (V_a\sin\phi)\left[\cos\omega t.\sin\omega t+\frac{\sqrt{3}}{4}\left[\cos^2\omega t-\sin^2\omega t\right]-\frac{1}{2}\cos\omega t.\sin\omega t-\frac{\sqrt{3}}{4}\left[\cos^2\omega t-\sin^2\omega t\right]-\frac{1}{2}\cos\omega t.\sin\omega t\right]$$
$$=0$$

Hence, the first row of eq(1) is equal to $\left(\frac{3}{2}\right)V_a\cos\phi$.

The second row in eqn(1),

$$=-[\sin\omega t.\{V_a\cos\omega t.\cos\phi-V_a\sin\omega t.\sin\phi\}$$
$$+\sin(\omega t-2\pi/3).\{V_b\cos\phi.\cos(\omega t-2\pi/3)-V_b\sin\phi.\sin(\omega t-2\pi/3)\}$$
$$+\sin(\omega t+2\pi/3).\{V_c\cos\phi.\cos(\omega t+2\pi/3)-V_b\sin\phi.\sin(\omega t+2\pi/3)\}]$$

Assuming $\mathrm{V_a}=\mathrm{V_b}=\mathrm{V_c}$,

$$=(V_a\sin\phi)\left[\sin^2\omega t+\sin^2(\omega t-2\pi/3)+\sin^2(\omega t+2\pi/3)\right]$$
$$\text{-}\ (V_a\cos\phi)\left[\cos\omega t.\sin\omega t+\sin(\omega t-2\pi/3).\cos(\omega t-2\pi/3)+\sin(\omega t+2\pi/3).\cos(\omega t+2\pi/3)\right]\ldots\ldots\ldots\text{(ii)}$$

The second term in the above eqn is Zero as calculated before,

$$\sin(\omega t-2\pi/3)=\frac{-1}{2}.\sin\omega t-\frac{\sqrt{3}}{2}.\cos\omega t$$

$$\sin(\omega t+2\pi/3)=\frac{-1}{2}.\sin\omega t+\frac{\sqrt{3}}{2}.\cos\omega t$$
$$\sin^2(\omega t-2\pi/3)=\frac{1}{4}.\sin^2\omega t+\frac{3}{4}.\cos^2\omega t+\frac{\sqrt{3}}{2}\cos\omega t.\sin\omega t$$
$$\sin^2(\omega t+2\pi/3)=\frac{1}{4}.\sin^2\omega t+\frac{3}{4}.\cos^2\omega t-\frac{\sqrt{3}}{2}\cos\omega t.\sin\omega t$$

The first term in the eqn (ii) is $\left(\frac{3}{2}\right)V_a\sin\phi$ and hence the second row element in eqn(1)

$$=\left(\frac{3}{2}\right)V_a\sin\phi.$$

Putting the value of the row elements from above derivations in eqn(1),

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = T.\begin{bmatrix} \left(\frac{3}{2}\right) V_a \cos\phi \\ \left(\frac{3}{2}\right) V_a \sin\phi \end{bmatrix} \ldots\ldots\ldots (2)$$

$$T = \left(\frac{2}{3}\right),$$

Therefore we have,

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} V_a \cos\phi \\ V_a \sin\phi \end{bmatrix}$$

9. APPENDIX 2

Measurement conversion of quantities to respective per unit quantities (scaling factors):

1) $V_p\ Scale = \frac{1}{230KV}$

2) $V_p rms \times V_p\ Scale = V_p pu$

3) $V_{dc}\ scale = \frac{1}{2\times 20} = \frac{1}{2}\times\frac{1}{20}$

4) $I\ Scale = \frac{1}{I_{base}}$

5) $I_{base} = \frac{MVAbase}{\sqrt{3}\times Vbase} = \frac{100}{20\times\sqrt{3}}$

6) $\frac{1}{I_{base}} = \frac{20\times\sqrt{3}}{100}$

7) $\left(\frac{1}{I_{base}}\right) peak\ rms = \frac{20}{100}\times\frac{\sqrt{3}}{\sqrt{2}}$

8) $I_d \times I\ Scale = I_d pu$

9) $I_q \times I\ Scale = I_q pu$

10) $Q\ scale = \frac{1}{100}$

11) $Q_p measured \times Q\ scale = Q_p pu$

12) $Q_p measured \times \frac{1}{100} = Q_p pu$

10. APPENDIX 3

1. AC voltage regulator

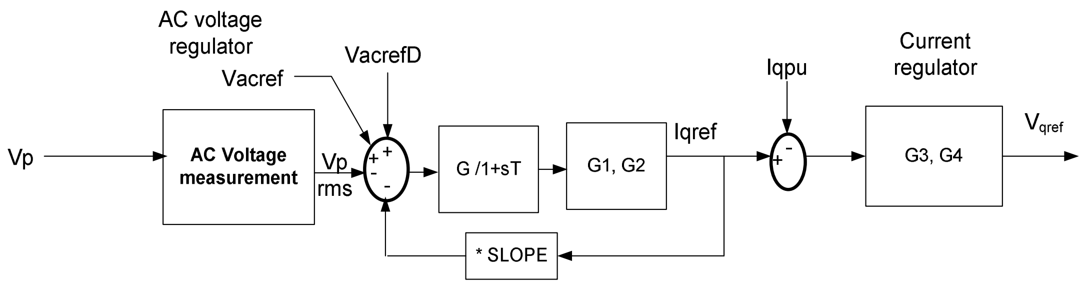

Figure 10.1 Transfer function block diagram for AC voltage regulator and current regulator

Proportional gain –G1 set in terms of (pu of I / pu of Vac)

Integral gain- G2/sT (integration limited to reactive power maximum & minimum values) set in terms of (pu of I / pu of Vac) /s

Where Vac is the AC voltage error and I is the output of voltage regulator.

H is the slope or droop reactance value (normally expressed for voltage droop which is 1% to 4% at maximum reactive power output).

1a Current regulator

Proportional gain –G3 set in terms of (pu of V / pu of I)

Integral gain- G4/sT (integration limited to reactive current maximum and minimum values) set in terms of (pu of V / pu of I)/s; a point of interest here, the limits of reactive current is defining the dynamic behaviour of the compensator as a function of power system impedance. Here the limits are set for maximum power system impedance (otherwise, minimum short circuit capacity) and hence limited to 130% of the rated current flow in the system.

V is the output V_q of the current regulator and I is the Iq current error.

Now the transfer function for V_{qref} can be written as,

$$V_{qref} = \left(G_3 + \frac{G_4}{sT}\right)\left(x - I_q pu\right)$$ 10.1

$$x = \left(G_1 + \frac{G_2}{sT}\right)\left(\frac{G}{1+sT}\right)\left(V_{acref} + V_{acref} D - V_{prmspu} - xH\right)$$ 10.2

Re-arranging equation 11-2 for x we get,

$$x = \frac{\left(G_1 + \frac{G_2}{sT}\right)\left(\frac{G}{1+sT}\right)\left(V_{acref} + V_{acref} D - V_{prmspu}\right)}{\left(1 + H\left(G_1 + \frac{G_2}{sT}\right)\left(\frac{G}{1+sT}\right)\right)}$$ 10.3

Substituting 11-3 in 11-1, we get,

$$V_{qref} = \left(G_3 + \frac{G_4}{sT}\right)\left(\frac{\left(G_1 + \frac{G_2}{sT}\right)\left(\frac{G}{1+sT}\right)\left(V_{acref} + V_{acref} D - V_{prmspu}\right)}{\left(1 + H\left(G_1 + \frac{G_2}{sT}\right)\left(\frac{G}{1+sT}\right)\right)} - I_q pu\right)$$ 10.4

2. DC voltage regulator

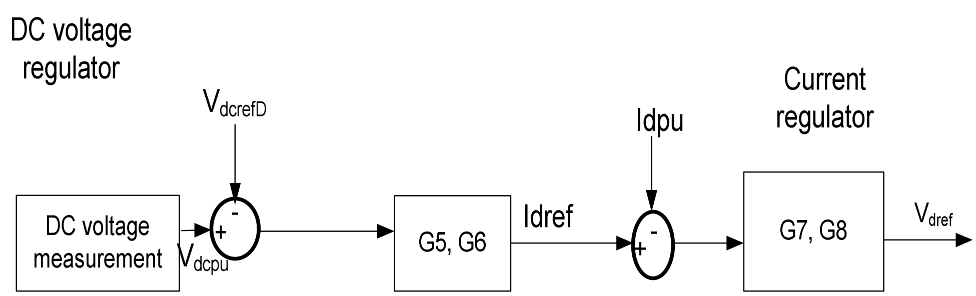

Figure 10.2 Transfer function block diagram for DC voltage regulator and current regulator

Proportional gain –G5 set in terms of (pu of I) / V_{dc}

Integral gain- G6/sT set in terms of (pu of I) / V_{dc}/s

Where V_{dc} is the DC voltage error and I is the output of the voltage regulation.

2a Current regulator

Proportional gain –G7 (pu of V / pu of I)

Integral gain- G8/sT (integration time limited to reactive current maximum and minimum values) set in terms of (pu of V / pu of I)/s; a point of interest here, the limits of reactive current is defining the dynamic behaviour of the compensator as a function of power system impedance. Here the limits are set for maximum power system impedance (otherwise, minimum short circuit capacity) and hence limited to 130% of the rated current flow in the system.

Where V is the output Vd of the current regulator and I is the Id current error.

Now the transfer function for V_{dref} can be written as,

$$V_{dref} = \left(G_7 + \frac{G_8}{sT} \right)\left(x - I_d\, pu \right) \qquad 10.5$$

$$x = \left(G_5 + \frac{G_6}{sT} \right)\left(V_{dcref} - V_{dcpu} \right) \qquad 10.6$$

Substituting 11-5 in 11-6, we get,

$$V_{dref} = \left(G_7 + \frac{G_8}{sT} \right)\left(\left(G_5 + \frac{G_6}{sT} \right)\left(V_{dcref} - V_{dcpu} \right) - I_d\, pu \right) \qquad 10.7$$

11. APPENDIX 4

One of the main disadvantages of conventional time-stepped distance protection, as illustrated in Figure 11.1 is the fact that the instantaneous Zone 1 of the protection at each end of the protected line cannot be set to cover the whole of the feeder length and is usually set to about 80%. This leaves two 'end zones', each being about 20% of the protected feeder length, in which faults are cleared instantaneously (Zone 1 time) by the protection at one end of the feeder but in Zone 2 time (0.3 to 0.4 seconds typically) by the protection at the other end of the feeder.

In some applications this situation cannot be tolerated, for two main reasons.

Faults remaining on the feeder for Zone 2 may cause the system to become unstable.

Where high speed auto-reclosing is used, the non-simultaneous opening of the circuit breakers at both ends of the faulted section results in no 'dead time' during the auto-reclose cycle for the fault to be extinguished and for ionized gases to clear. This results in the possibility that a transient fault will cause permanent lockout of the circuit breakers at each end of the line section.

Unit schemes of protection which compare the conditions at the two ends of the protected feeder simultaneously can positively identify whether the fault is internal or external to the protected section, and are capable of providing high speed protection for the whole feeder length. This advantage is balanced by the fact that the unit scheme does not provide the back-up protection to adjacent feeders given by a distance scheme [24].

The most desirable scheme is obviously one which combines the best features of both arrangements, that is, instantaneous tripping over the whole feeder length plus back-up protection to adjacent feeders. This can be achieved by interconnecting the distance protections at each end of the protected feeder by a signalling channel. The signalling channel may be high frequency (hf) operating over the overhead line conductors, voice frequency (vf) using either pilots or a power line carrier communications channel, a radio link, microwave channel or a fibre optic link.

The purpose of the signalling channel is to transmit information about the system conditions from one end of the protected line to the other; it can also be arranged to initiate or prevent tripping of the remote circuit breaker. The former arrangement is generally referred to as a 'transfer trip scheme' while the latter is known as a 'blocking scheme'.

When carrier or signalling equipment is not available, fast tripping for all line faults can be achieved by extending the Zone 1 reach of distance relays under control of an associated auto-reclose scheme. The resulting distance scheme is referred to as a 'Zone 1 Extension Scheme' and its application is normally limited to distribution systems or to interconnected power systems when a carrier is temporarily taken out of service.

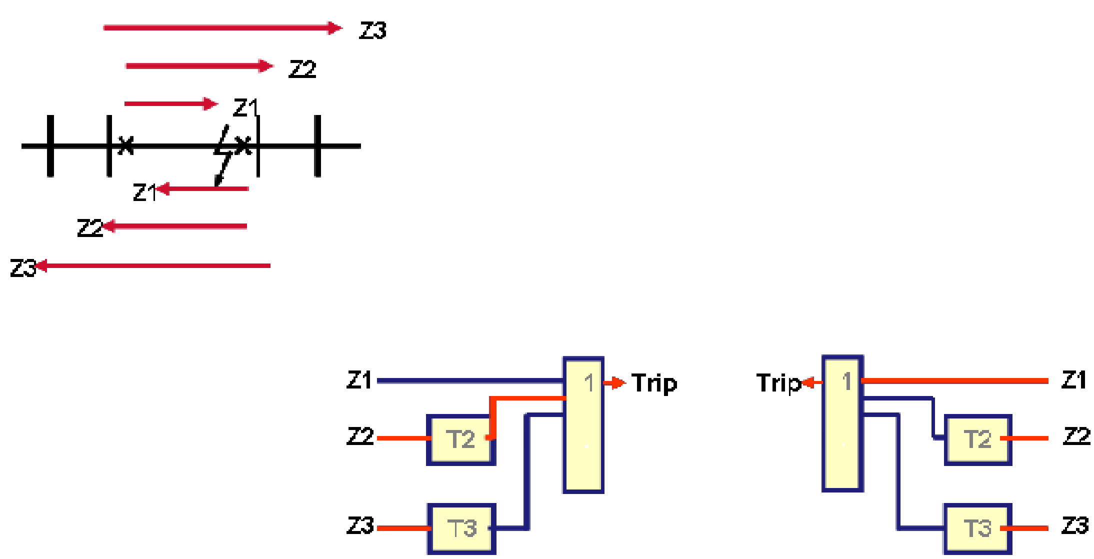

Figure 11.1 Conventional Distance Scheme

ZONE 1 EXTENSION SCHEME

The scheme is intended for use with an auto-reclose relay. The Zone 1 units of the distance relay have two setting controls; one, as in the basic distance scheme, is set to cover 80% of the protected line length and the other, known as 'Extended Zone 1', is set to cover 120% of the protected line. The Zone 1 reach is normally controlled by the extended Zone 1 setting and is reset to the basic value when a command from the auto-reclose relay is received.

On occurrence of a fault at any point within the extended Zone 1 reach, the relay operates in Zone 1 time, trips the circuit breaker and initiates auto-reclosure. A contact from the auto-reclose relay is used to reset the Zone 1 reach of the distance relay to the basic value of 80%. The auto-reclose contact used for this purpose operates before the closing pulse is applied to the breaker and resets only at the end of the reclaim time. The contact should also operate when the auto-reclose facility is out of service.

If the fault is transient, the tripped circuit breakers will reclose successfully but, if permanent, further tripping during the reclaim time is subject to the discrimination obtained with normal Zone 1 and Zone 2 settings. The scheme is shown in Figure 11.2.

The disadvantage of the Zone 1 extension scheme is that external faults, between the far end of the line and the first 20% of the next line, result in the tripping of the circuit breakers external to the faulted section, increasing the amount of breaker maintenance needed.

Since the use of signalling equipment is not necessary, this scheme is often used as a temporary replacement for carrier aided schemes when the signalling equipment is out of service.

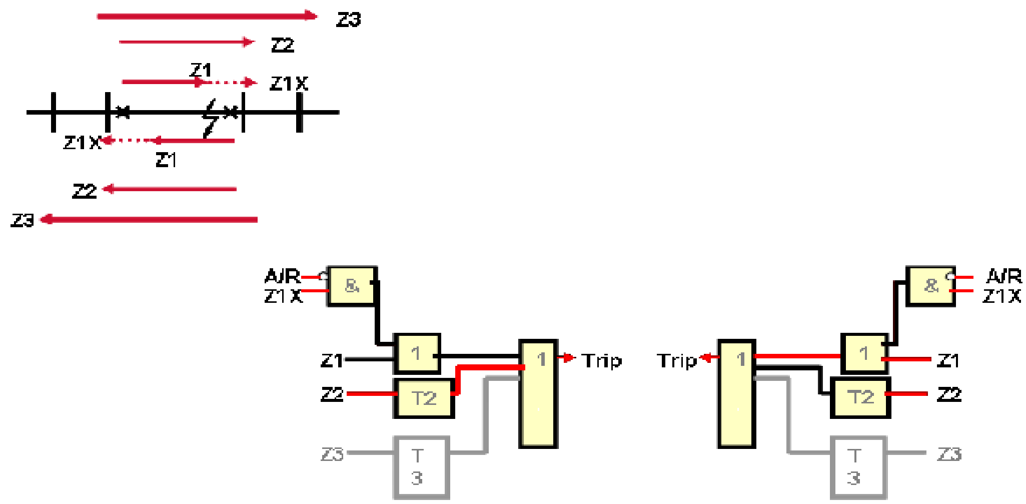

Figure 11.2 Distance relays fitted with Zone 1 extension when used with auto-reclose

Permissive Under-reach Transfer Trip Scheme

The direct transfer trip scheme is made more secure by supervising the received signal with the instantaneous Zone 2 operation before allowing tripping, as shown in Figure 11.3. The scheme is then known as a 'permissive under-reach transfer trip scheme'.

Time delayed resetting of the 'Signal Received' element is required to ensure that the relays at both ends of a single-end fed faulted line of a parallel feeder circuit have time to trip when the fault is close to one end.

This scheme requires only a single signalling channel for two-way signalling between line ends as the channel is keyed by the under-reaching Zone 1 units.

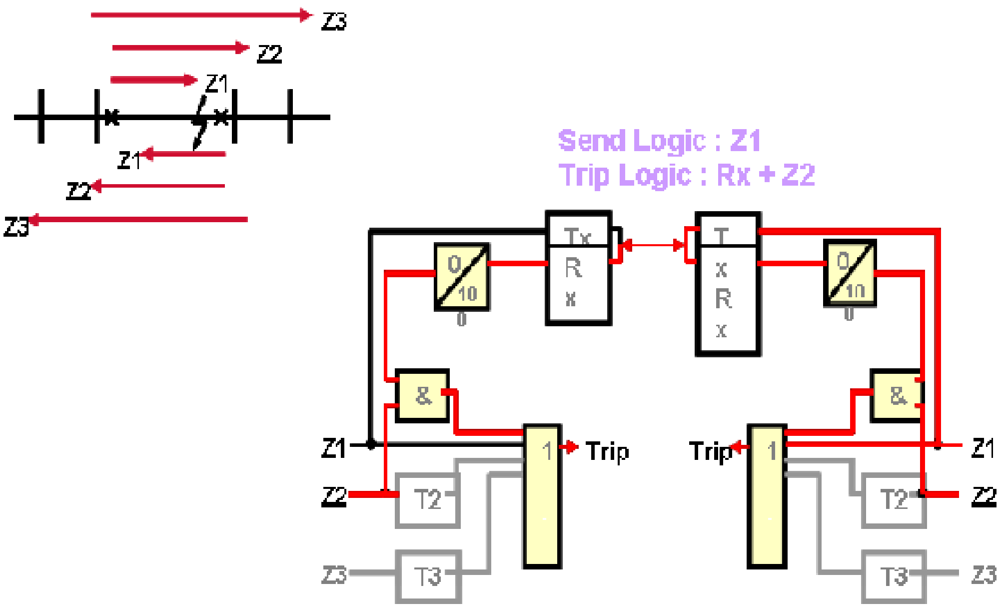

Figure 11.3 Permissive Under-reach Transfer Trip Scheme

Permissive Over-reach Transfer Tripping Scheme

In this scheme (as in Figure 11.4) a relay set to reach beyond the far end of the protected line is used to send an intertripping signal to the remote end. In this case, however, it is essential that the receive relay contact is monitored by a directional relay contact to ensure that tripping does not take place unless the fault is within the protected section; The instantaneous contacts of the Zone 2 unit are arranged to send the signal, and the received signal, supervised by Zone 2 protection, is used to energize the trip circuit. The scheme is then known as a 'permissive over-reach transfer trip scheme' or 'directional comparison scheme'.

Since the signalling channel is keyed by over-reaching Zone 2 units, the scheme requires duplex signalling channels, one frequency for each direction of signalling.

If distance relays with mho characteristics are used, the scheme is better suited than the permissive under-reaching scheme for protecting short lines, because the resistive coverage of the Zone 2 unit is greater than that of Zone 1.

To prevent operation in under current reversal conditions, in a parallel feeder circuit it is necessary to use a time delayed unit in the permissive trip circuit. This current reversal guard is necessary only when the Zone 2 reach is set greater than 150% of the protected line impedance.

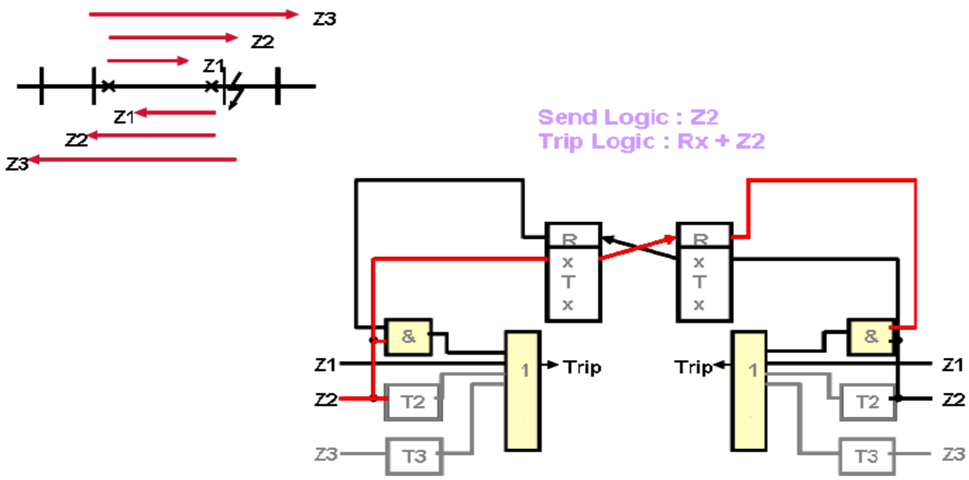

Figure 11.4 Permissive Over-reach Transfer Trip Scheme

Acceleration Scheme

This scheme is similar to the permissive under-reach transfer trip scheme in its principle of operation, but it is applicable only to zone switched distance relays which share the same measuring units for both Zone 1 and Zone 2. In these relays the reach of the measuring units is extended from Zone 1 to Zone 2 by means of a range change relay, after Zone 2 time.

In this scheme, the under-reaching Zone 1 unit is arranged to send a signal to the remote end of the feeder in addition to tripping the local circuit breaker. The receive relay contact is arranged to operate the range change relay which extends the reach of the measuring unit from Zone 1 to Zone 2 immediately instead of at the end of Zone 2 time delay. This accelerates the fault clearance at the remote end. The scheme is shown in Figure 11.5.

The scheme is not quite as fast in operation as the permissive intertrip schemes, since time is required for the distance measuring unit to operate after the reach has been changed from Zone 1 to Zone 2. It may be argued, though, that the slightly slower operation will result in increased security from maloperation.

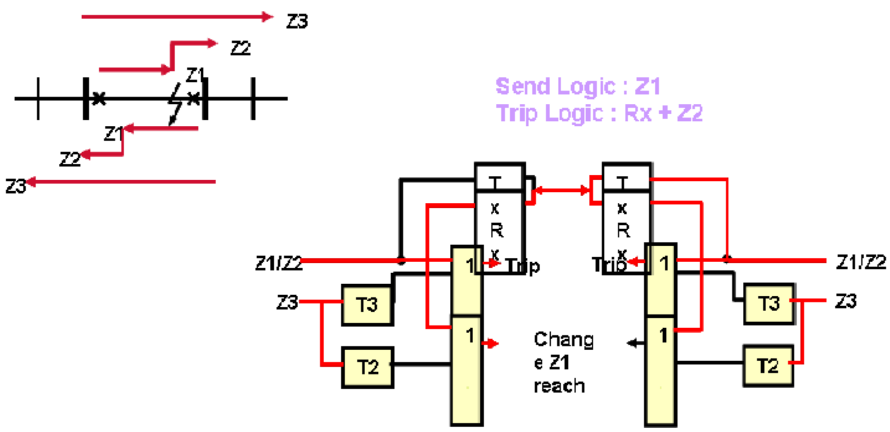

Figure 11.5 Acceleration Scheme

BLOCKING SCHEME

The alternative arrangements so far described have used the signalling channel to transmit a tripping instruction. If the signalling channel fails or there is no infeed from one end, end-of-zone faults will take longer to be cleared.

The blocking scheme uses inverse logic. Signalling is initiated only for external faults and signalling transmission takes place over healthy line sections. Fast fault clearance occurs when no signal is received and the over-reaching distance measuring units (Z2) looking into the line operates. The signalling channel is keyed by reverse looking distance units (Z3). An ideal blocking scheme is shown in Figure 11.6.

The signalling channel used need only be of the single frequency type that operates both local and remote receive relays when a block signal is initiated at any end of the protected section.

A blocking instruction has to be sent by the reverse looking Zone 3 units to prevent instantaneous tripping of the remote relay for Zone 2 faults external to the protected section. To achieve this, the reverse looking Zone 3 units and the signalling channel must operate faster than the forward looking Zone 2 units. In practice this is seldom the case and to ensure discrimination, a short time delay is generally introduced into the blocking mode trip circuit.

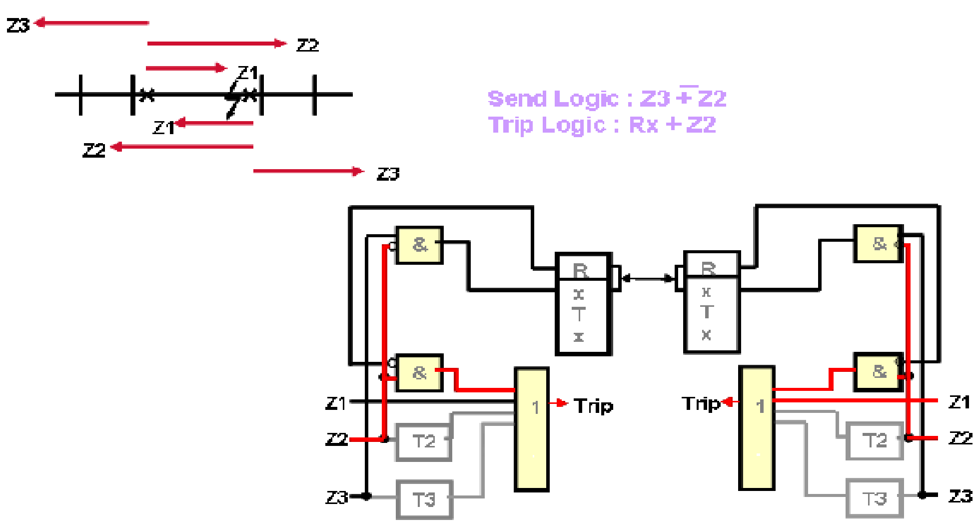

Figure 11.6 Blocking scheme