A Project Report on

DIFFERENT SETTINGS OF UPFC AND ITS EFFECT ON DISTANCE PROTECTION

Department of Electrical Engineering
University Institute of Technology
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A Project Report on

DIFFERENT SETTINGS OF UPFC AND ITS EFFECT ON DISTANCE PROTECTION

Submitted in partial fulfilment of the requirement for the award of Bachelor of Engineering in Electrical Engineering

By

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CERTIFICATE

This is to certify that the project entitled "**Different settings of UPFC and its effect on Distance Protection**", submitted by **Abhijeet Anand (Roll No. 20146035, Reg. No. A2619 of 2014-15)** in partial fulfillment of the requirements for the award of Bachelor of Engineering in Electrical Engineering at University Institute of Technology, The University Of Burdwan, Burdwan is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any degree.

In my opinion, the thesis is of standard required for the award of a Bachelor of Engineering degree in Electrical Engineering.

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CERTIFICATE of APPROVAL

The project entitled "**Different settings of UPFC and its effect on Distance Protection**", submitted by **Abhijeet Anand (Roll No. 20146035, Reg. No. A2619 of 2014-15)** in partial fulfillment of the requirements for the award of Bachelor of Engineering in Electrical Engineering at University Institute of Technology, The University Of Burdwan, Burdwan is hereby approved as a credible study of an electrical engineering subject, carried out and presented in a manner satisfactory to warrant its acceptance as a prerequisite to the degree. It is understood that by this approval, the undersigned does not necessarily endorse or approve any statement made, opinion expressed, or conclusion drawn between therein, but approve the project for only the purpose for which it is submitted.

Board of Examiners,

1. 11/06/18
2. 11/06/18
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Date:

Place: Burdwan

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ABSTRACT

In this paper, we have presented the analytical and simulation results of the effects of the incorporation of shunt and series connected FACTS devices (STATCOM and SSSC) over distance protection of a 138 kV, 200 km, double-circuit transmission line. Besides a detailed discussion over principles of distance protection scheme, with and without FACTS devices, we have also proposed a detailed model of STATCOM and SSSC along with their respective control strategies for accurately simulating the transients of a fault. In the subsequent chapters we have formulated an apparent impedance calculation procedure for distance relays under the installation of both STATCOM and SSSC. The results thus obtained significantly show that the performance and characteristics of a distance relay under fault or normal conditions significantly depend upon the presence of FACTS devices, their type, location and control parameters setting. Hence, study of the impact of FACTS devices laid upon the performance of distance relays is of paramount importance for ensuring satisfactory and reliable operation of the syste

Chapter - 1
Introduction

In conventional AC transmission system, the ability to transfer AC power is limited by several factors like thermal limits, transient stability limit, voltage limit, short circuit current limit etc. These limits define the maximum electric power which can be efficiently transmitted through the transmission line without causing any damage to the electrical equipments and the transmission lines. This is normally achieved by bringing changes in the power system layout.

Flexible AC transmission systems (FACTS) controllers have been mainly used for solving various power system steady state control problems. Flexible AC transmission systems or FACTS are devices which allow the flexible and dynamic control of power systems. Enhancement of system stability using FACTS controllers have been investigated.

Types of FACTS Controllers

- **Series Controllers:** Series Controllers consists of capacitors or reactors which introduce voltage in series with the line. They are basically variable impedance devices. Their major task is to reduce the inductivity of the transmission line. They supply or consume variable reactive power. Examples of series controllers are SSSC, TCSC, TSSC etc.
- **Shunt Controllers:** Shunt controllers consist of variable impedance devices like capacitors or reactors which introduce current in series with the line. Their major task is to reduce the capacitance of the transmission line. The injected current is in phase with the line voltage. Examples of shunt controllers are STATCOM, TSR, TSC, SVC.
- **Shunt-Series Controllers:** These controllers introduce current in series using the series controllers and voltage in shunt using the shunt controllers. Example is UPFC.
- **Series-Series Controllers**: These controllers consist of a combination of series controllers with each controller providing series compensation and also the transfer real power along the line. Example is IPFC.

Benefits of utilizing FACTS devices.
The benefits of utilizing FACTS devices in electrical transmission systems can be summarized as follows:

• Better utilization of existing transmission system assets

- Increased transmission system reliability and availability
- Increased dynamic and transient grid stability and reduction of loop flows.
- Increased quality of supply for sensitive industries
- Environmental benefits Better utilization of existing transmission system assets.

For a flexible transmission of AC power, solid state devices are often incorporated in the circuits which are used for power factor improvement and to raise the limits of the AC transmission system. However a major disadvantage is that these devices are nonlinear devices and induce harmonics in the output signal of the system.

To remove the harmonics created due to the inclusion of power electronic devices in the AC transmission system, active filters are used which can be current source power filter or a voltage source power filter. The former involves making the AC current sinusoidal. The technique is to either directly control current or control the output voltage of the filter capacitor. This is the Voltage regulation or Indirect Current control method. Basically the active power filters inject a current which is equal in magnitude but opposite in phase to the harmonic current which is drawn by the load, such that these two currents cancel out each other and the source current is completely sinusoidal. The Active power filters incorporate power electronic devices to produce harmonic current components which cancel out the harmonic current components of the output signal due to the nonlinear loads. Generally the Active power filters consist of a combination of an Insulated gate bipolar transistor and a diode powered by a DC bus capacitor. The active filter is controlled using an indirect current control method. IGBT or Insulated Gate Bipolar Transistor is a voltage controlled bipolar active device which incorporates the features of both BJT and MOSFET. For the AC transmission system a shunt active filter eliminates the harmonics, improve the power factor and balance the loads.

Chapter – 2
Distance Protection

Distance protection which is used by distance relay is basically an induction type relay similar to the non-directional over current relay. In induction type distance relay one additional magnet system, operated by voltage is provided such that under normal operating conditions torque exerted by the voltage operated magnet system is greater than that exerted by the current operated magnet system and trip circuit remains open.

2.1 Principle of operation

Distance protections involves the divisions of voltage at the relaying points by the measured current. The apparent impedance and reach point impedance was compared by means of its magnitude. If measured impedance is less than the reach point, it is assumed that fault exists on the line between relay and reach point. The basic principle of operation of distance relay involves measurement and comparison of the fault current seen by the relay with the voltage at relaying point. By comparing these quantities it is possible to measure the impedance of line up to the occurrence of fault [12].

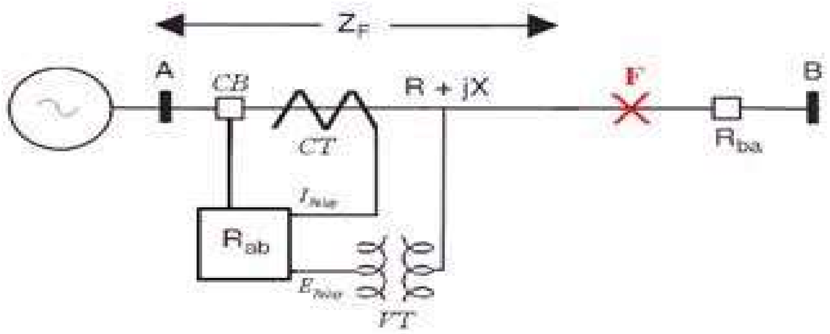


Figure-2.1-Schematic Diagram of Distance Relay

Here- operating torque $\propto (current)^2$

Operating torque $\propto I^2$

Operating torque$= k_1 I^2$

Restoring torque $\propto (voltage)^2$

Restoring torque $\propto V^2$

Restoring torque=k_2V^2

The relay operates if operating torque becomes greater than restoring torque i.e.- operating torque>restoring torque

$$k_1I^2 > k_2V^2$$

$$\frac{k_1}{k_2} > (V/I)^2$$

$$\sqrt{\frac{k_1}{k_2}} > V/I = Z$$

$$Z < \sqrt{\frac{k_1}{k_2}}$$

Three-Zone of Protection of Transmission Line

Reach - Distance of the line protected by distance relay is called Reach.

Under-Reach-If the distance relay fails to operate for the faults within its zone or reach then it is called Under-reach.

Over-Reach- If the distance relay operates for faults outside its reach it is called Over-reach.

In distance protection scheme, there are various operating zones. In most of the distance protection, there is one starting zone which initiates the operation of the distance scheme and it forms the fault zone. Besides these there are three zones described as follows-

Zone-1-80% of the principle line section is covered by Zone-1, due to errors in CTs, errors in PTs and measuring errors it is not possible to cover 100% of protected lines in zone1. The fault in zone-1 is cleared by relay with high speed without adjustment of time delay i.e. it provides high speed protection for line under consideration. Here $Z_1 = 0.8Z_{l_1}$

Zone-2-Remaining 20% of line is covered by Zone-2 which is left by zone1 unprotected. In addition to this, some portion of the line section at the adjacent bus-B is also protected. Theoretically the maximum setting of zone2 can be extended to 80% of the next line but due to some limitations as explained in zone1 case it only covers 64%.

Hence for Zone-2 we have

$$(Z_2)_{min} = 1.$$

$$(Z_2)_{max} = 0.8(Z_{l_1} + 0.8Z_{l_2})$$

<u>Zone-3</u>-Remote back-up protection is provided by Zone-3 for the adjacent line section and therefore, longest adjacent line section should be protected in zone3.Hence for zone-3 we have

$$(Z_3)_{min} = 1.2(Z_{l_1} + Z_{l_2})$$

Thus it covers remaining section left in zone-2 and further reach into the system.

<u>Starting Zone or Zone-4</u>-The setting of starting zone should be 125% of the setting of zone-3 so that starting zone relay may safely operates for fault within zone-3 reach.

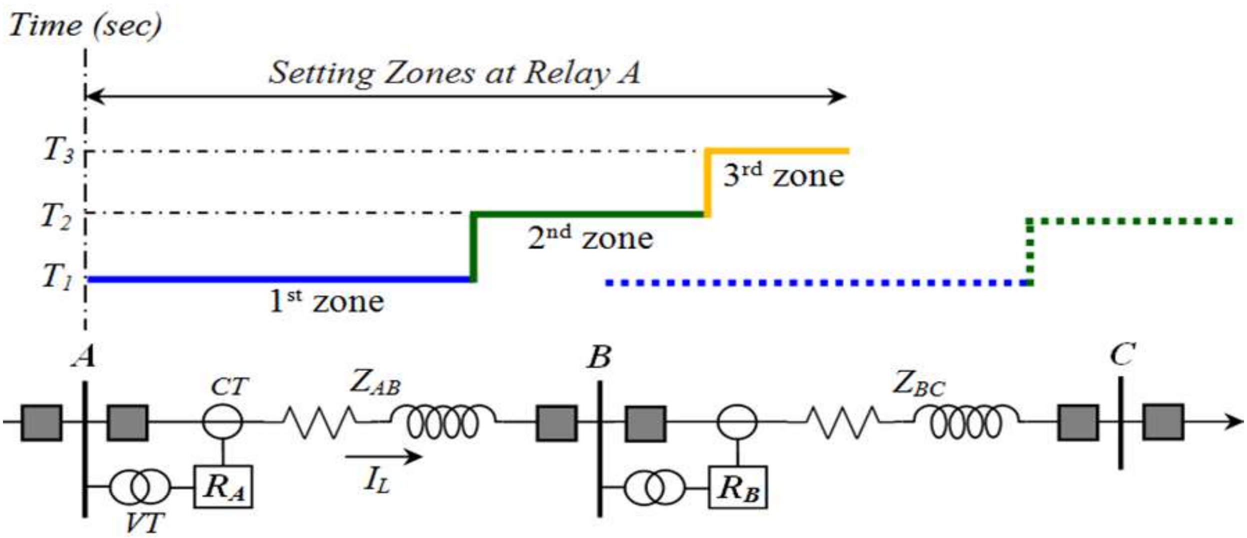


Figure-2.2-Zone setting schematic

Zone-1, zone-2 and zone-3 are connected in parallel to each other.

Operating time of Z_1 is 0.02-0.04seconds.

Operating time of Z_2 is 0.2-0.5seconds.

Operating time of Z_3 is 0.4-1seconds.

From three-zone of protection of transmission line, we saw that distance protection scheme can't be set to over 100% of line section in zone-1 and 20% of the line remains to be protected in zone-2 time which is undesirable. This problem is overcome by carrier aided distance protection scheme. In this scheme, if the fault occurs between the 20% end portions of the line one circuit breaker is tripped in zone-1 time which immediately sends a trip signal command to the other end circuit breaker through communications and thus makes simultaneously opening of both circuit breakers.

2.2 Types of Distance Protection

Impedance Relay- In this, the torque produced by current element is balanced by torque produced by voltage element. The current element produces a deflecting torque, whereas the voltage element produces restraining torque [12].

Torque Equation-T=$k_1|I|^2 - k_2|V|^2 - k_4$

Neglecting the effect of control spring k_4 we have

$$T = k_1|I|^2 - k_2|V|^2$$

When the relay is on the verge of operation, net torque is zero

$$k_1|I|^2 - k_2|V|^2 = 0$$

$$\sqrt{\frac{k_1}{k_2}} = \frac{|V|}{|I|} = Z_{set}$$

If $|Z| < |Z_{set}|, relay\ trips\ CB$

If $|Z| > |Z_{set}|, relay\ block\ CB\ from\ tripping$

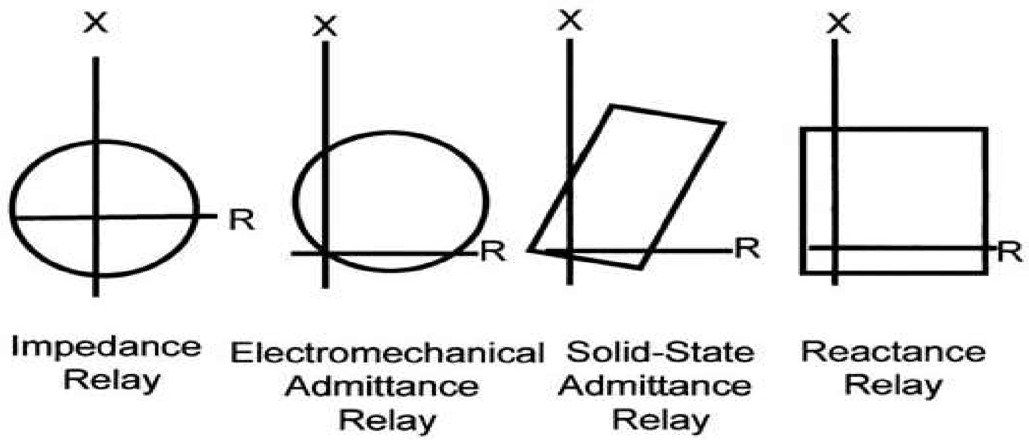


Figure-2.3-Characteristics of Different Distance Relay

Reactance Relay-It is an over-current relay with directional restraint. The directional element is arranged to yield maximum torque when its current lags its voltage by 90°(i.e $\tau = 90°$).Here the over-current relay element develops a deflecting torque and current voltage directional element either aids or opposes the over current element, depending upon the phase angle between current and voltage.

The torque equation is –T=$k_1|I|^2 - k_3|V||I|\sin\theta - k_4$

Neglecting $k_4, the\ relay\ operates\ as$

$$k_1|I|^2 - k_3|V||I|\sin\theta > 0$$

$$\frac{|V|}{|I|}\sin\theta < \frac{k_1}{k_3} \text{ or } |Z|\sin\theta < \frac{k_1}{k_3}$$

Mho Relay-Modified impedance relay called Mho relay results if directional relay is restrained by voltage. The torque equation is given as

$$T = k_3|V||I|\cos(\theta - \tau) - k_2|V|^2 - k_4$$

Neglecting $k_4, the\ relay\ operates$

$$k_3|V||I|\cos(\theta - \tau) - K_2|V|^2 > 0$$

$$\frac{k_3}{k_2}\cos(\theta - \tau) > \frac{|V|}{|I|} = |Z|$$

The right hand side of the above equation is a circle with center located on the line determined by parameter τ and passing through the origin.

If $|Z - Z_{set}| < |Z_{set}|, relay\ trips\ the\ CB$

If $|Z - Z_{set}| > |Z_{set}|, relay\ blocks\ the\ CB$

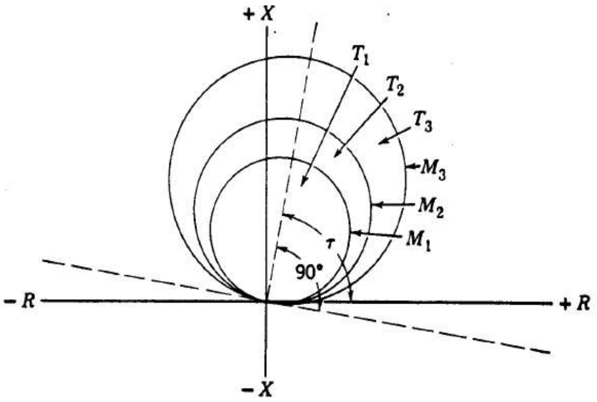


Figure-2.4-Operating characteristics of mho relay

Chapter – 3
Basics of FACTS

In the last decade, commercial availability of Gate Turn –Off (GTO) thyristor switching devices with high-power handling capability and the advancement of the other types of power –semiconductor devices such as IGBTs have led to the development of fast controllable reactive power sources utilizing new electronic switching and converter technology. These switching technologies additionally offer considerable advantages over existing methods in terms of space reductions and fast effective damping.

The GTO thyristors enable the design of the solid-state shunt reactive compensation and active filtering equipment based upon switching convertor technology. These power quality devices (PQ Devices) are power electronic converters connected in parallel or in series with transmission lines, and the operation is controlled by digital controllers. The interaction between these compensating devices and the grid network is preferably studied by digital simulation.

Flexible alternating current transmission systems (FACTS) devices are usually used for fast dynamic control of voltage, impedance, and phase angle of high-voltage ac lines. FACTS devices provided strategic benefits for improved transmission system power flow management through better utilization of existing transmission assets, increased transmission system security and reliability as well as availability, increased dynamic and transient grid stability, and increased power quality for sensitive industries (e.g., computer chip manufacture).

This paper deals with a novel cascade multilevel converter model, which is a 48- pulse (three levels) source converter. The voltage source converter described in this paper is a harmonic neutralized, 48- pulse GTO converter. It consists of four three phases, three-level inverters and four phases –shifting transformers. In the 48- pulse voltage source converter, the dc bus V_{dc} is connected to the four three-phase inverters. The four-voltage generated by the inverters are applied to secondary windings of four zig-zag phase-shifting transformers connected in Y or Δ. The four transformer primary windings are connected in series, and the converter pulse patterns are phase shifted so that the four voltage fundamental components sum in Phase on the primary side.

3.1 48-Pulse Voltage Source GTO based Converter

Two 24-pulse GTO-converters, phase-shifted by 7.5 º from each other, can provide the full 48-pulse converter operation. Using a symmetrical shift criterion, the 7.5 º are provided in the following way: phase-shift winding with ---3.75º on the two coupling transformers of one 24-pulse converter and +3.75º on the other two transformers of the second 24-pulse converter. The firing pulses need a phase-shift of +3.75º, respectively. The 48-pulse converter model comprises four identical 12-pulse GTO converters interlinked by four 12-pulse transformers with phase-shifted windings [1].

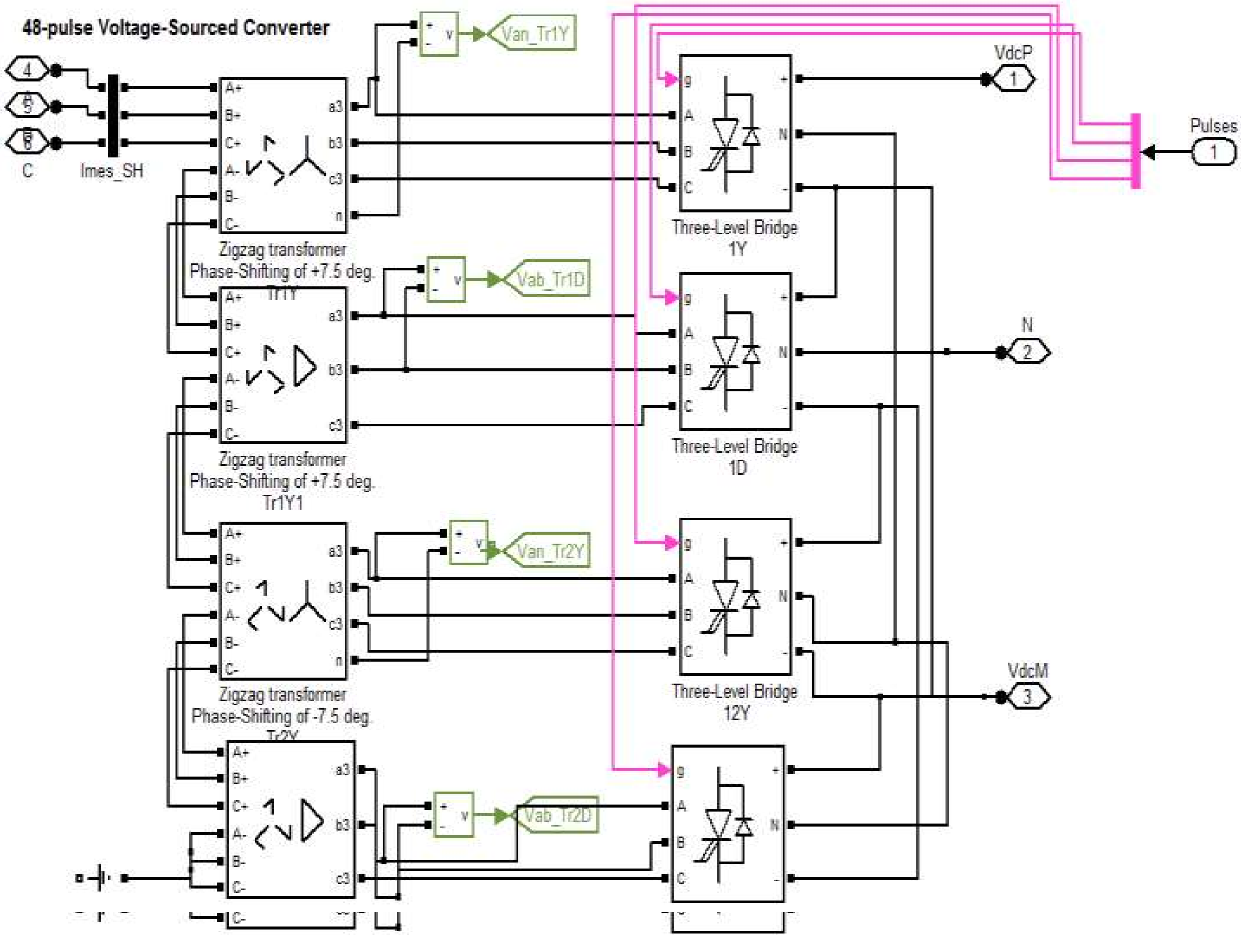


Fig.2.1. Forty-eight-pulse GTO's voltage source converter.

The transformer connections and the necessary firing-pulse logics to get this final 48-pulse operation are modelled.

The 48-pulse converter can be used in high-voltage high-power applications without the need for any ac filters due to its very low harmonic distortion content on the ac side. The output voltage has normal harmonics n=48r± 1, where r=0,1,2…, i.e., 47th ,49th,95th ,97th …., with typical magnitudes (1/47th ,1/49th, 1/95th ,1/97th ….), respectively, with respect to the fundamental; on the dc side, the lower circulating dc current harmonic content is the 48th.

The phase-shift pattern on each four 12-pulse converters are cascaded.

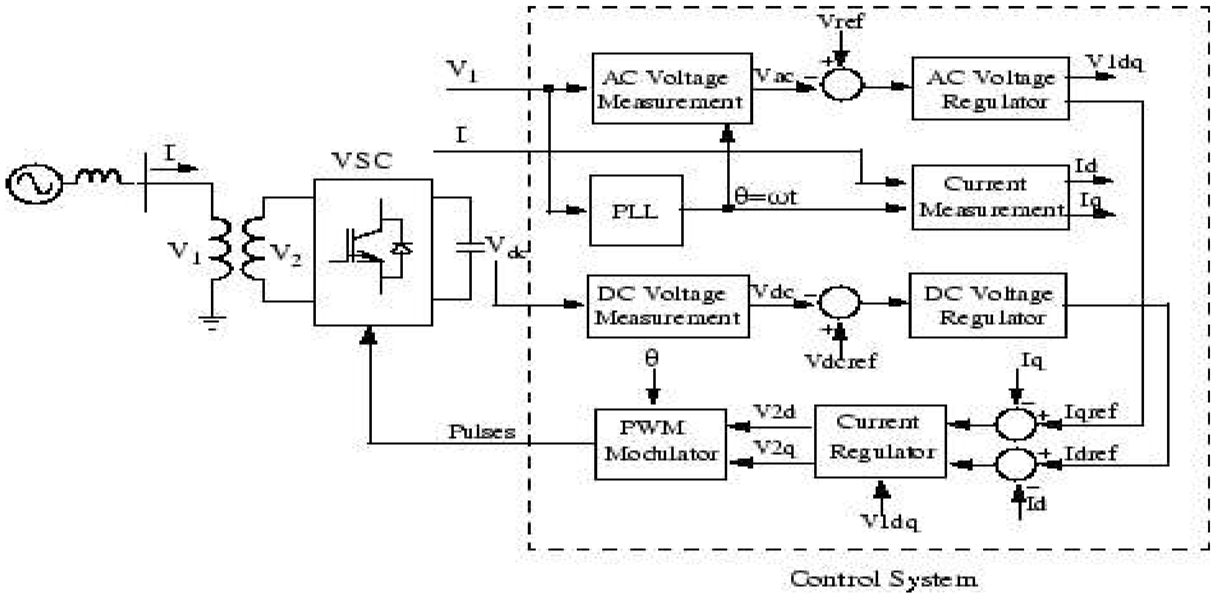
Chapter - 4

The Static Synchronous Compensator (STATCOM)

It is a shunt device of the Flexible AC Transmission Systems (FACTS) family using power electronics to control power flow and improve transient stability on power grids [1]. The STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the STATCOM generates reactive power (STATCOM capacitive). When system voltage is high, it absorbs reactive power (STATCOM inductive).

The variation of reactive power is performed by means of a Voltage-Sourced Converter (VSC) connected on the secondary side of a coupling transformer. The VSC uses forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to synthesize a voltage V2 from a DC voltage source. The principle of operation of the STATCOM is explained on the figure below showing the active and reactive power transfer between a source V1 and a source V2. In this figure, V1 represents the system voltage to be controlled and V2 is the voltage generated by the VSC.

4.1 Single-line Diagram of a STATCOM and Its Control System Block Diagram



4.2 STATCOM Control Model

Components

A 48-pulse STATCOM comprises a large number of gate-controlled semiconductor power switches (GTO, IGBT). The main function of the control model is to operate the converter power switches so as to generate a fundamental output voltage waveform with the demanded magnitude and phase angle in synchronism with the AC system. The amplitude and phase angle of voltage is controlled by the external (STATCOM system) control via appropriate reference signal(s) that forces the reactive (and real) power exchange for required compensation.

Its task is to increase or decrease the capacitor DC voltage so that the generated AC voltage has the correct amplitude for the required reactive power. The control system must also keep the AC generated voltage in phase with the system voltage at the STATCOM connection bus to compensate transformer and inverter losses. The control system uses the following modules

1. PLL: The firing pulses for the GTO Thyristor switches have to be synchronized to the bus voltage such that, in steady state, the fundamental component of the voltage injected by the converter leads the supply (sinusoidal) voltage by the control angle (α). This synchronization is achieved by a Phase Locked Loop (PLL) which produces the phase angle of the bus voltage as an output. Actually, the output is (θt) which is defined as,

$$\theta_t = \omega_0 t + \theta$$

Where ωo is the operating frequency (in radians/sec) and θ is the relative phase of the bus voltage with respect to a synchronously rotating reference. The PLL consists of a P-I controller, a saw tooth generator (whose output is θt which is restricted in the range of $(0 \le \theta t \le 2\pi)$ and an oscillator that produces the output, sinθt and cosθt, which are used to compute the quantities Vd and Vq according to the relationship given by,

$$V_d = V_\alpha sin\theta_t + V_\beta cos\theta_t$$

Where,

$$V_\alpha = \sqrt{\frac{2}{3}}(v_a - 0.5v_b - 0.5v_c)$$

$$V_\beta = \frac{1}{\sqrt{2}}(v_c - v_b)$$

The three phase voltages at the connecting point are sent to PLL to calculate the reference angle which is synchronized to the phase A voltage

2. Measurement System: It computes the positive-sequence components of the STATCOM voltage and current, using phase-to-dq transformation and a running window averaging. The three phase currents of STATCOM are decomposed into its real part Id and reactive part Iq by abc-dq0 transform (Kronn's transformation) using the phase-lock-loop angle as a reference.

3. *Voltage regulation*: It is performed by two PI regulators- from the measured voltage Vrms and the reference voltage Vref, the Voltage Regulator block (outer loop) computes the reactive current reference Iq refused by the current regulator block (inner loop). The output of the current regulator is the α angle which is the phase shift of the inverter voltage with respect to the system voltage. This angle stays very close to zero except during short periods of time, as explained below.

A voltage drop is incorporated in the voltage regulation to obtain V-I characteristics with a droop (0.03 pu/100 MVA in this case). The phase angle together with the phase-lock-loop signal is fed to the STATCOM firing pulse generator (as shown in fig. 3.5) to generate the desired pulse for the voltage source inverter (the dead angle of STATCOM is kept fixed at $\gamma = \pi/48$).

4. Firing Pulse Generator: It generates pulses for the four inverters from the PLL output (ω, t) and the current regulator output (α angle).

To explain the regulation principle, let us suppose that the system voltage Vmag becomes lower than the reference voltage Vref. The voltage regulator will then ask for a higher reactive current output (positive Iq= capacitive current). To generate more capacitive reactive power, the current regulator will then increase α phase lag of inverter voltage with respect to the system voltage, so that an active power will temporarily flow from AC system to capacitors, thus increasing DC voltage and consequently generating a higher AC voltage.

As the conduction angle σ of the 3-level inverters has been fixed to 172.5°, the 23rd and 25th harmonics can be minimized. The first significant harmonics generated by the inverter will then be 47th and 49th. Using a bipolar DC voltage, the STATCOM thus generates a 48-step voltage approximating a sine wave. So, this conduction angle minimizes 23rd and 25th harmonics of a voltage generated by the square-wave inverters. Also, to reduce non-characteristic harmonics, the positive and negative voltages of the DC bus are forced to stay equal by the DC Balance Regulator module. This is performed by applying a slight offset on the conduction angles σ for the positive and negative half-cycles. There are mainly two approaches to achieve the proposed control model, *Indirect approach*– It is done by controlling the DC capacitor voltage which in turn is controlled by the angle of the output voltage.

Direct approach– It is done by the internal voltage control mechanism (e.g., PWM) of the converter in which case the DC voltage is kept constant (by the control of the angle). Note that if the converter is equipped with an energy storage device, then the internal control can accept an additional real current reference, which would control the angle of the output voltage so as to establish a real component of current in the output as demanded by this reference.

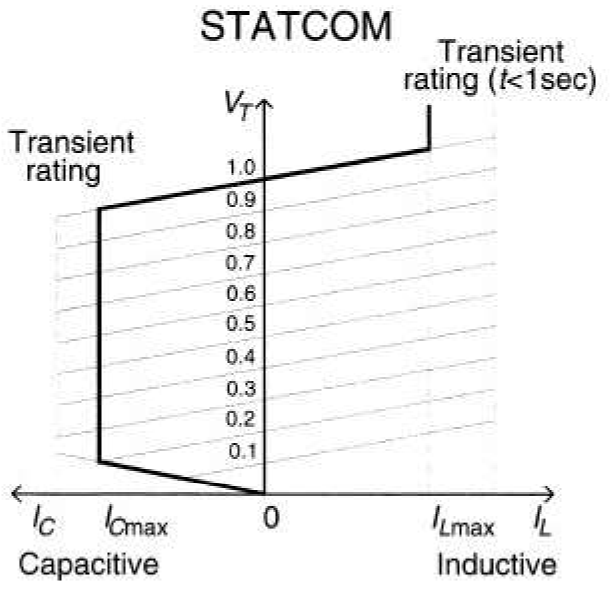
4.3 STATCOM V-I Characteristic

The STATCOM can be operated in two different modes:

- In voltage regulation mode (the voltage is regulated within limits as explained below)
- In var control mode (the STATCOM reactive power output is kept constant)

When the STATCOM is operated in voltage regulation mode, it implements the following V-I characteristic.

STATCOM V-I characteristic



As long as the reactive current stays within the minimum and minimum current values (-Imax, Imax) imposed by the converter rating, the voltage is regulated at the reference voltage Vref. However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and the V-I characteristic has the slope indicated in the figure. In the voltage regulation mode, the V-I characteristic is described by the following equation:

$$V = V_{\mathrm{ref}} + Xs\, I$$

Where,

v = Positive sequence voltage (pu)

I = Reactive current (pu/Pnom) (I > 0 indicates an inductive current)

Xs = Slope or droop reactance (pu/Pnom)

Pnom = Three-phase nominal power of the converter specified in the block dialog box

Chapter - 5

STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)

STATIC SYNCHRONOUS SERIES COMPENSATOR is a solid-state voltage source inverter, which is an essential series FACTS device. SSSC is used for enhancement of active power transfer capability by reduction of equivalent line impedance. The main component of SSSC is a VSI (Voltage Source Inverter) which is supplied by a DC storage capacitor. A static synchronous series compensator operated without an external energy source as reactive power with output voltage.

SSSC control the electric power flow by increasing or decreasing the overall the reactive voltage drop across the transmission line. It can provide either capacitive or inductive injected voltage compensation. For steady state operation, SSSC performs a similar function to the static phase shifter, which is injecting voltage in quadrature with one of the line end voltages for regulation of active power flow.

If SSSC ac injected voltage (vs), lag the line current by 90', a capacitive series voltage compensation is obtained in the transmission-line. If lead line current by 90', an inductive series compensation is achieved.

5.1 Operation of SSSC

A SSSC can work like a controllable serial condenser and a serial reactance.it can be used with excellent result with low loads as well as with high load. The main function of the SSSC device is to regulate the feeder power flow. This can be accomplished by either direct or indirect control by compensating the impedance Xs via (buck/boost) compensating injected voltage vs.

The SSSC has a controllable output voltage which is in quadrature with the line current. It models a series capacitive or a series inductive reactance in the transmission line to increase or decrease the overall reactive voltage drop across the line. It is made to operate capacitor by inducing a voltage 90 deg, lagging to that of the line current. It is also operated as an inductor by making the induced voltage lead the line current by 90, deg.

The power transmitted is a parametric function of the injected voltage (Vq), which is given as

$P_q = \frac{V^2}{(X_L - X_q)} sin\delta, X_q = \frac{V_q}{I}$., as shown in fig

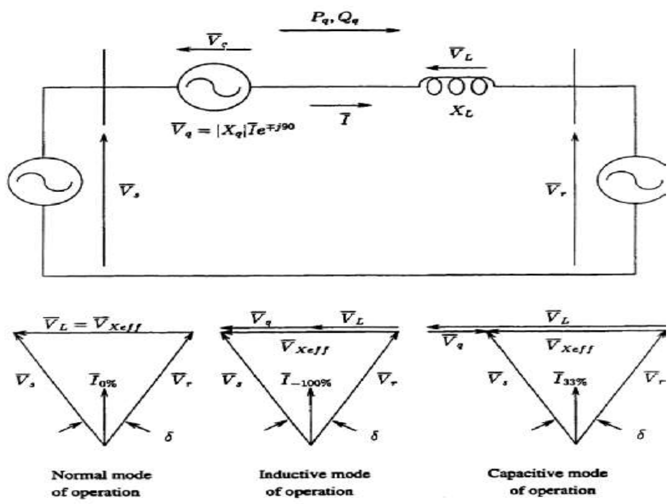


Fig 5.1 Different modes of of SSSC

When SSSC operates in an inductive mode, the compensating reactance (XQ) is negative and it has positive value during the operation of SSSC in a capacitive mode, as shown in figure 5.1

The main difference is that the voltage infected through a SSSC is not related to the line intensity and can be controlled independently. The simulation result of both inductive and capacitive region are obtained.

5.2 Rating of SSSC

The SSSC can provide capacitive or inductive compensating voltage independent of the line current. The VA rating of the SSSC (solid- state inverter and coupling transformer)is simply the product of the maximum line current (at which compensation is still desire)and the maximum series compensation voltage: VA=Imax*Vmax. . The SSSC can maintain the rated inductive or capacitive compensating voltage in the face of changing line current theoretically in the total operating range while operating in voltage compensation mode.

A control range corresponding to 2 p.u. compensating VARs is covered by an SSSC of 1 p.u. VA rating, so the control range is continuous from -1 p.u. (inductive) VARs to +1 p.u. (capacitive) VARs.

5.3 Series capacitive compensation

The reduction of total effective series impedance between the two ends of a transmission line is the reason behind series capacitive compensation. The effective reactance is reduced when a portion of the actual line inductive reactance is cancelled by the reactance of the series compensating capacitor, improving the transmittable power transfer of the line.

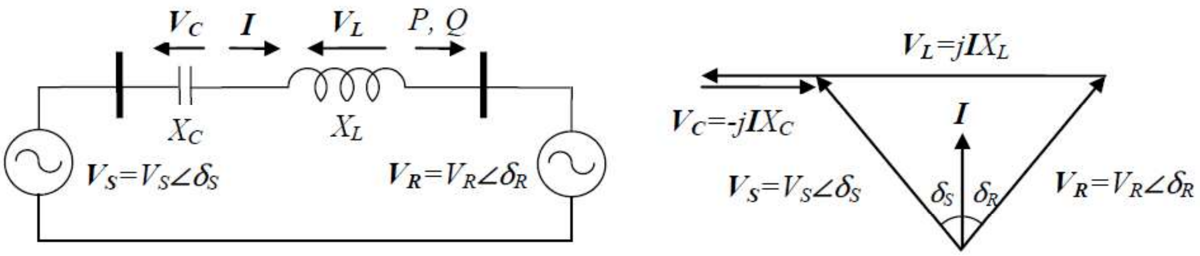


Fig 5.2 A schematic diagram of a simple two-machine power system and its vector diagrams with series capacitor compensation

$$P = \frac{V^2}{X_{eff}} \sin\delta = \frac{V^2}{(X_L - X_C)} \sin\delta = \frac{V^2}{X_L(1-\frac{X_C}{X_L})} \sin\delta = \frac{V^2}{X_L(1-k)} \sin\delta$$

Where X_C is the capacitor reactance, $X_{eff} = (X_L - X_C)$ is the effective reactance, and $k = X_C/X_L$ is the degree of series compensation ($0 \le k < 1$).

The normalized active power versus the load angle of the series capacitor compensated system as a parametric function of the degree of series capacitive compensation is shown in the figure below. The transmitted power is increased by series capacitor compensation by a fixed percentage of the power transmitted by the uncompensated line at a given δ and it is obtained by increment of the degree of the compensation,

Where,

V_1 = The voltage magnitude of machine 1.

V_2 = The voltage magnitude of machine 2.

δ = The phase difference between V_1, V_2.

I = The current flowing from machine 1 to machine 2.

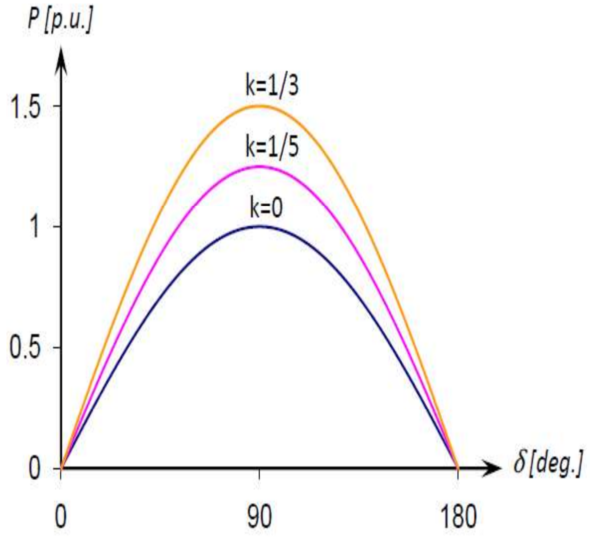


Fig 5.3: Transmitted power versus the load angle as a parametric function of the degree of series capacitive compensation

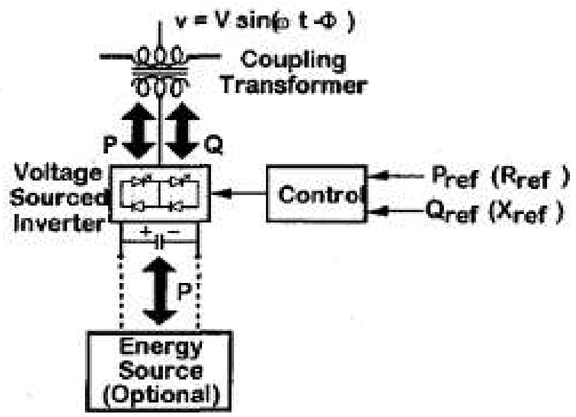


Fig. 5.4: Block diagram of SSSC

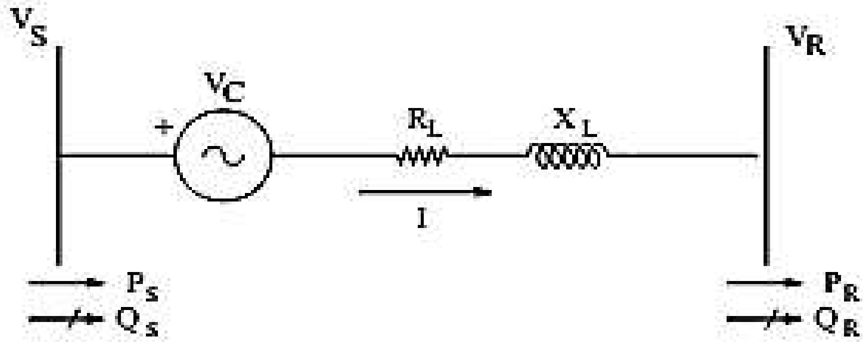


Fig. 5.5: A SSSC in lousy transmission line

V_L = Voltage drop across the line impedance.

P_q = The active power flowing through the line.

V_q = The injected voltage by SSSC.

The compensating voltage, in series with the line, is injected by the SSSC, is irrespective of line current. As a parametric function of the injected voltage (VQ), the relationship between the transmitted powers (PQ) versus the transmission angle δ, for a two-machine system can be given as:

$$P_q = \frac{V^2 sin\delta}{X_L} + \frac{V}{X_L} cos\left(\frac{\delta}{2}\right)$$

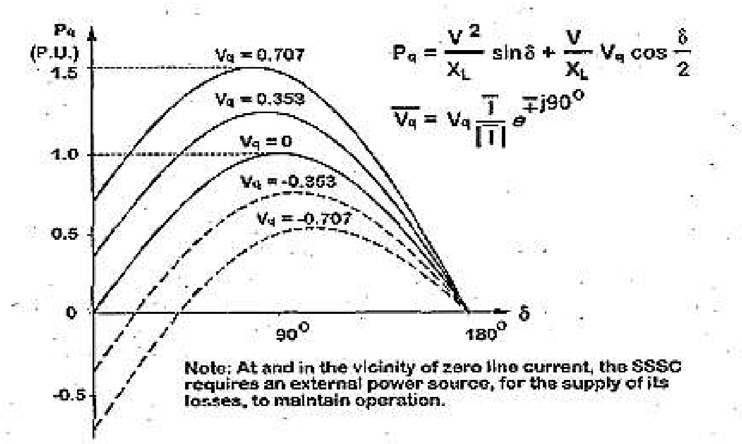


Fig. 5.6: Transmitted power P_q vs. Transmission angle δ as a parametric function of series compensating voltage V_q provided by SSSC

The increase of the power to be transmitted is achieved by the SSSC and by reversing the injected AC voltage polarity, it can be decreased. The reactive line impedance is increased when the reversed (180°phase-shifted) voltage is added directly to the reactive voltage drop of the line. The power flow reverses if the voltage injected is made larger than the impressed voltage across the uncompensated line by the sending and receiving end systems which is $|VQ|>|V1-V2|$. The SSSC has a very good (sub-cycle) response time, apart from the stable operation of the system where both positive and negative power flows.

5.4 Advantages

- These devices (SSC, DVR, UVC) correct the voltage when there is a fault in the network but also have a lot of advantage in normal use, when there are no disturbance like.
- Due to the continuous voltage injection and in combination with a properly structure controller, it is possible to control the power factor of connected loads.
- It can also help to cover the capacitive reactive power demand if cable network, which is higher than in aerial lines mainly during low loads period that cause inadmissible load elevations.
- It reduce the harmonic caused because of the use of distributed electrical generation plants at a distribution network level, by active filtering by injecting voltage, with the converter at the load side.
- It balance loads in interconnected distribution network, providing a balance system.

5.5 Effect of SSSC on Distance protection

Fig. 5.7 shows the block diagram of the control model of SSSC compensator. As seen from the diagram, the fault current (I2) formed as a result of the fault in transmission line splits up into in-phase (ip) and quadrature (ir) components of current. Similarly the reference quantities of active power (P*) and reactive power (Q*) splits up into its in-phase (ip*) and quadrature (ir*) components of the reference value of current. Now the in-phase component of current is compared with its reference value resulting in an error signal. Similarly, the quadrature component of current is compared with its respective reference value resulting in another error signal. These two error signals are then passed through the PI controller respectively resulting in the formation of the direct (Vp) and quadrature (Vr) component of voltage. These two components are passed through Magnitude and Angle Calculator to obtain Magnitude |Vc| and Conduction angle (Alpha).The magnitude so obtained |Vc| is converted into Sigma.

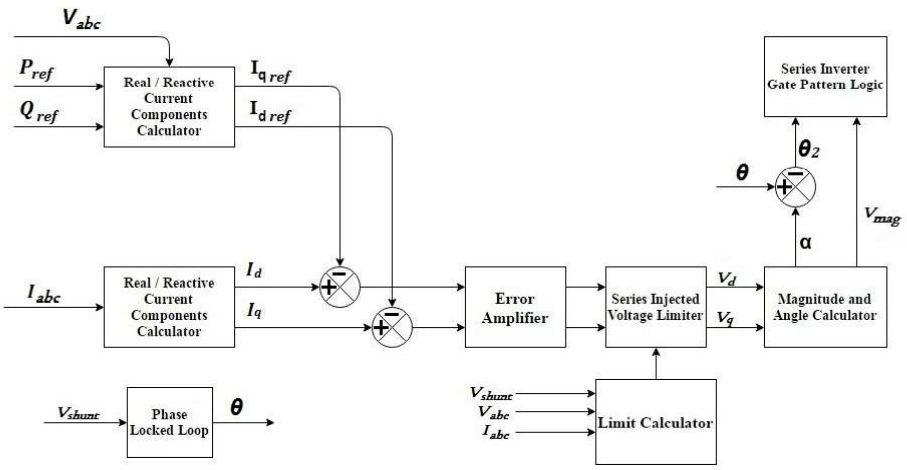


Fig 5.7

5.6 Applications

- For injection of a controllable voltage in quadrature with the line current of a power network, a voltage source inverter is used by the SSSC.
- The damping of the low-frequency power oscillations in a power network can be improved by the SSSC with a suitably designed external damping controller.
- Power factor correction trough continuous voltage injection and in combination with a properly structure controller.
- A SSSC is inserted in the middle of this combination and thus acting as shunt connected static compensator, there not affecting active power significantly but improving reactive power profile directly.

Chapter - 6

UPFC and its Effect on Distance Protection

6.1 UPFC – A Brief Discussion

The concept of UPFC(Unified Power Flow Controller) was introduced by L. Gyugi in 1995.Its operation is extremely efficient , its used to control active and reactive power flows in a transmission line . In terms of components used, its just a combination of two voltage source converter (VSC) coupled via a common DC voltage link. A systematic diagram of UPFC is shown in figure 6.1 . If initially the switches 1 and 2 are open, the VSC acts as a STATCOM controlling the reactive current injected in the shunt and the other one acts as a SSSC controlling the reactive voltage injected in series with the line. When the switches 1 and 2 both are closed simultaneously, active power is exchanged between the two converters. The real power (active power) can be either absorbed or supplied by converter [2].

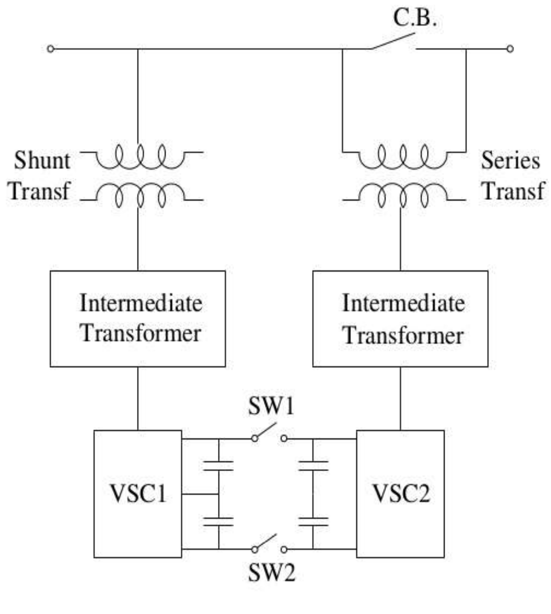


Fig 6.1 – A systematic UPFC representation

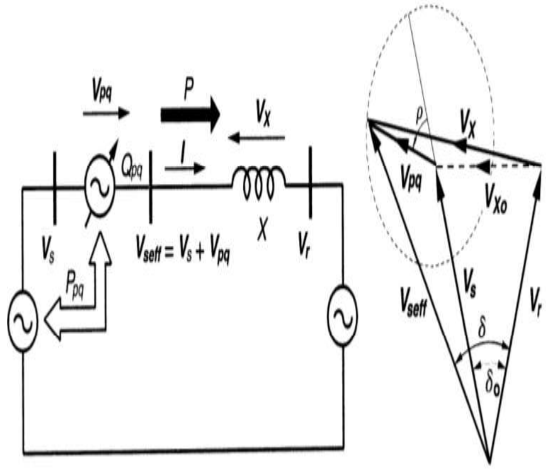


Fig 6.2-Coneptual Representation Of UPFC

6.2 Operating Principle

We can consider the UPFC as a generalized synchronous voltage source(SVS). Representing it by a voltage phasor Vpq with controllable magnitude Vpq (0≤c≤Vpq max) and angle ρ(0≤ρ≤2π) at the power frequency in series with the transmission line, as seen in the basic two machine system in Fig 6.2. In this operation that clearly includes the voltage and angle regulation, the SVC generally exchanges both active and reactive power with the transmission system [1,2].

A SVS is capable of exchanging only reactive power, the real or active power must be supplied from it or absorbed from it from a suitable power supply or sink. This is the reason in an UPFC operation, the real power exchange is provided by one of the end buses like sending the end bus as shown in fig 6.2.

VSC 2 provides the main function of the UPFC by injecting a voltage Vpq with controllable magnitude Vpq and phase angle ρ in series with the line via an insertion transformer. This injected voltage here acts as a synchronous AC voltage source. Reactive and real power exchanged between the transmission line and this AC voltage source when line current flows through this voltage source. The reactive power exchanged at the terminal of the series insertion transformer is generated internally by the converter. The real power exchanged at the AC terminal is converted into DC power which appears at the DC link as a positive or negative real power demand.

The fundamental function of VSC 1 is to supply or absorb the real power demanded by VSC 2 at the common DC link to supply the real power required for the series voltage injection. This DC link power demand of VSC 2 is converted back to AC by VSC 1 and coupled to the transmission line bus via a shunt connected transformer. Here the VSC 1 can also generate or absorb controllable reactive power if it is desired. Thus independent shunt reactive compensation is done.

The representation of UPFC, as a generalized Synchronous Voltage Source (SVS) at the fundamental (power system) frequency by voltage Phasor V_{pq} with controllable magnitude $V_{pq}(0 \leq V_{pq} \leq V_{pq_{max}})$ and angle $\rho(0 \leq \rho \leq 2\pi)$, in series with the transmission line, as shown in Figure 6.2

Under normal operation, involving voltage and angle regulation the SVS exchanges both real power and reactive power with the transmission system. As stated earlier, an SVS has the ability to produce only the reactive power to be exchanged; the real power must be absorbed from it, or supplied to it, by a suitable power supply or sink. The UPFC arrangement shows that one of the end buses (e.g., the sending-end bus) provides the exchange of real power, as given in Figure 6.2

The two voltage source converter in UPFC are operated from a common dc link provided by a dc storage capacitor. In this arrangement the UPFC acts as an ideal ac to ac power converter in which the real power can freely flow in either direction between the ac terminals of the two converters, its main function is provided by converter 2 by injecting a voltage Vpq with controllable magnitude Vpq and phase angle ρ in series with the line after passing through an insertion transformer. This voltage acts as a synchronous ac voltage source. The transmission line current flows through this voltage source resulting in reactive and real power flow between the ac system. The reactive power exchanged at the ac terminal is generated internally by the converter. Whereas the real power exchanged at the ac terminal is converted into dc power which appears at the dc link as a positive or negative real power demand.

Operation of Unified Power Flow Controller under normal power transmission based on reactive shunt compensation, series compensation, and phase angle regulation, UPFC fulfils all these functions and meets multiple control objectives by adding the injected voltage Vpq, with the appropriate amplitude and phase angle, to (sending-end) terminal voltage Vs. The basic UPFC power flow control functions are illustrated in Figure 6.2 with help of phasor representation Figure 6.2 shows voltage regulation with continuously variable in-phase/anti-phase voltage injection for voltage increments Vpq= ±ΔV (ρ = 0).

Series reactive compensation depicted in Figure 6.2 where Vpq=Vq is injected in quadrature with the line current **I** similar to series capacitive and inductive line compensation achieved by the SSSC. This injected voltage which is in series can be kept constant by two means, either by keeping it independent of the line current variation, or varying in proportion with the line current to imitate the compensation achieved by series capacitor or reactor.

In case of Phase angle regulation (phase shift) where Vpq= **Vσ** is injected with an angular relationship with respect to Vs achieves the desired **σ** phase shift (advance or retard) with keeping magnitude constant is shown in Figure 6.2(c). Thus UPFC functions as a perfect Phase Angle Regulator which also supplies the reactive power involved with the transmission angle control by internal var generation.

Simultaneous terminal voltage regulation along with series capacitive line compensation, and phase shifting, executes multifunction power flow controls shown in Figure 6.2(d) where **(Vpq= ΔV + Vq + Vσ).** UPFC has this unique functional capability. No single conventional equipment has similar multifunctional capability.

We can express the power flow capability of UPFC by taking conventional control as our reference, representing by the real and reactive power transmission vs transmission angle characteristics by simple two machine systems, so we can express it as

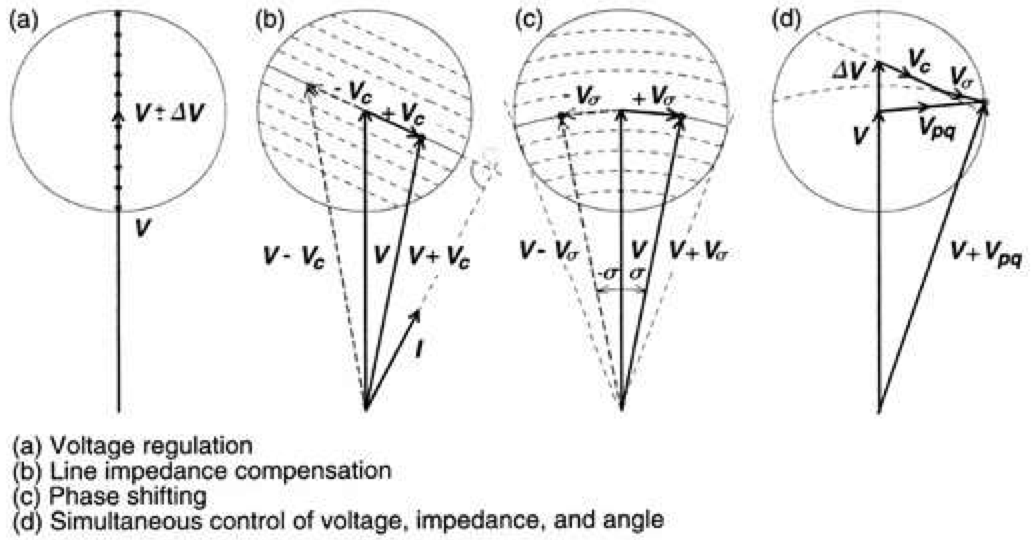


Fig 6.3

The real and reactive power change from their uncompensated values, $P_0(\delta)$ and $Q_{0r}(\delta)$ as functions of magnitude V_{pq} and angle ρ of the injected voltage phasor V_{pq}. Since angle ρ is an unrestricted variable ($0 \leq \rho \leq 2\pi$), the boundary of the attainable control region for $P(\delta,\rho)$ and $Q_r(\delta,\rho)$ is obtained from a complete rotation of phasor V_{pq} with its maximum magnitude V_{pqmax}. The control region is a circle with a centre defined by coordinates $P_0(\delta)$ and $Q_{0r}(\delta)$ and a radius of V_rV_{pq}/X. With $V_s = V_r = V$, the boundary circle can be described by the following equation:

$$\{P(\delta, \rho) - P_0(\delta)\}^2 + \{Q_r(\delta, \rho) - Q_{0r}(\delta)\}^2 = \left\{\frac{VV_{pq\max}}{X}\right\}^2$$

Where, P = Transmitted real power

Q_r = Reactive power demand at receiving end

P_0, Q_{0r} = Values of P and Q_r at origin of $\{Q_r, P\}$ plane

The control regions defined by the above equation are 5.4(a) through (d).

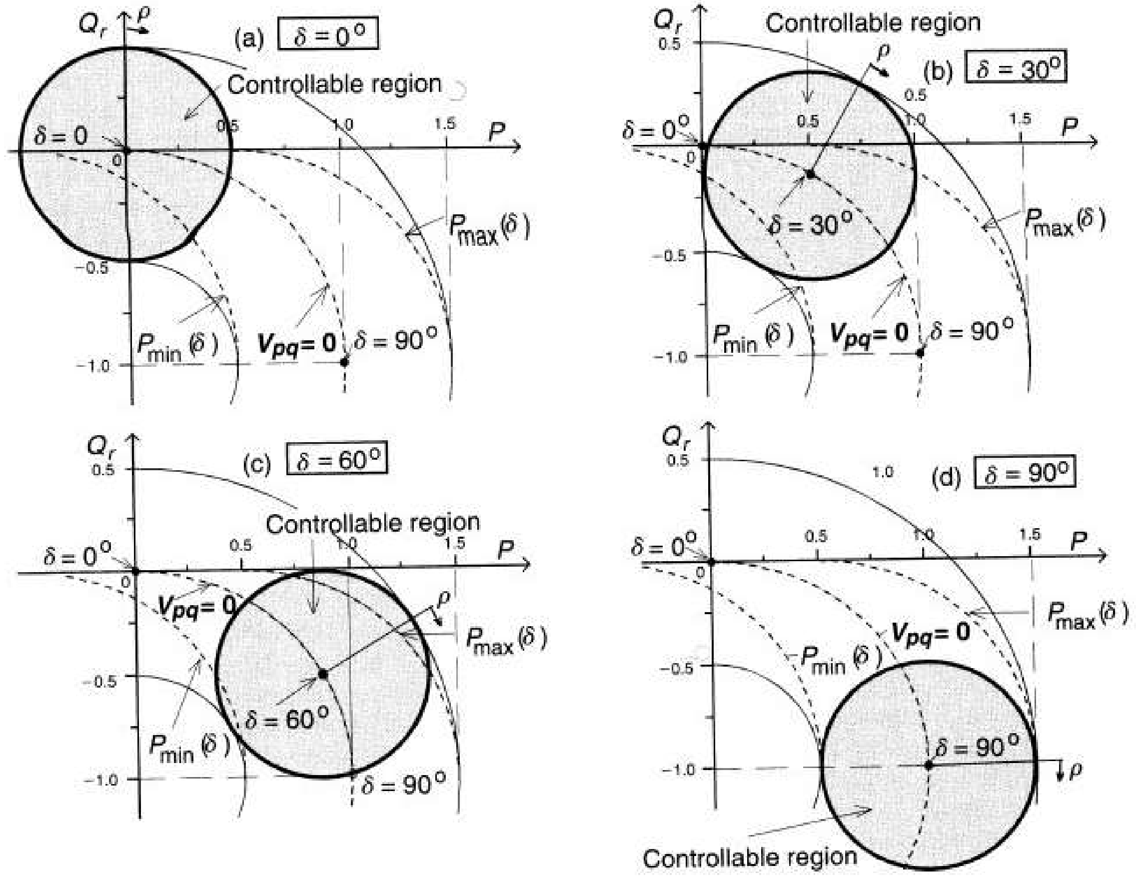
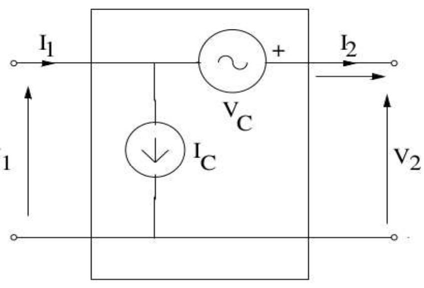


Fig 6.4 - Control region of the attainable real power P and receiving-end reactive power demand Q_r with a UPFC controlled transmission line at (a) δ = 0°;(b) δ = 30°; (c) δ = 60°; (d) δ = 90°

Consider first fig. 6.4(a), which illustrates the case when the transmission angle is zero (δ=0). With Vpq = 0, P, Qr, (& Qs) are all zero, i.e. the system is at standstill at the origin of the Qr, P coordinates. The circle around the origin of the {Qr, P} plane is the loci of the corresponding Qr & P values, obtained as the voltage phasor Vpq is rotated a full revolution ($0 \le \rho \le 360°$) with its maximum magnitude Vpq max. This area within this circle defines all P and Qr values obtainable by controlling the magnitude Vpq and angle ρ of phasor Vpq. In other words the circle in the {Qr, P} plane defines all P and Qr values attainable with the UPFC of a given rating. It can be observed, for example that the UPFC with the stipulated voltage rating of 0.5 pu is able to establish 0.5 pu, in either direction, without imposing any reactive power demand on either the sending-end or the receiving-end generator. Of course, the UPFC, as illustrated, can force the system at one end to supply reactive power for, or absorb that from, the system at the other end. Similar control characteristics for real power P and the reactive power Qr can be observed at angles $\delta = 30°, 60°, \& 90°$ in figs 6.4(b), 6.4(c), & 6.4(d).

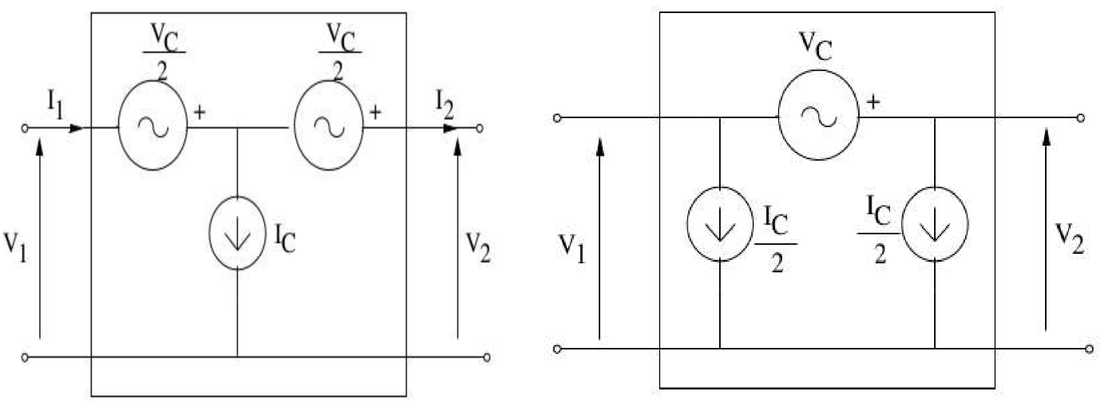
In general we can say that at any given transmission angle δ, the transmitted real power P as well as the reactive power demand at the receiving end Qr can be easily controlled by the UPFC within the boundary circle obtained in [Qr,P] plane by simply rotating the injected voltage phasor Vpq with its maximum magnitude.

Considering that a UPFC is connected at the middle of a symmetrical lossless line. The UPFC is represented by the two-port network shown in fig 6.5. The series converter injects a voltage ($V_c\angle\beta$) and shunt converter draws a current ($I_c\angle\psi$). It can be observed that the two port networks in fig 6.6(a), 6.6(b) are equivalent to the two-port network shown in fig 6.5



$$\mathrm{Re}\,[\,V_1 I_C^* = V_C\, I_2^*\,]$$

Fig 6.5-Two port network representing a UPFC



(a) Equivalent network 1 (b) Equivalent network 2

Fig 6.6- Alternative representation of UPFC

For ease of analysis, the UPFC can be represented by any one of the two equivalent networks shown in fig 6.5. The detailed analysis is shown in appendix c. From the analysis, we get the expression of active power P

$$P = \frac{V^2}{X} sin\delta + \frac{V_C V}{X} cos\frac{\delta}{2} cos\left(\frac{\delta}{2} - \beta + 90^o\right) - \frac{I_C V}{2} sin\frac{\delta}{2} cos\left(\psi - \frac{\delta}{2} + 90^o\right)$$

and maximum power P_{max} is transferred by UPFC when $\beta = \delta/2 + 90^o$, $\psi = \delta/2 + 90^o$ and P_{max} is given by

$$P_{max} = \frac{V^2}{X} sin\delta + \frac{V_C V}{X} cos\frac{\delta}{2} + \frac{I_C V}{2} sin\frac{\delta}{2}$$

Remarks: For the maximum power transfer, we have

$$\hat{V}_m = \left(V cos\frac{\delta}{2} + \frac{X}{4} I_C\right) \measuredangle \frac{\delta}{2}$$

$$\hat{I}_m = \frac{\left(2V sin\frac{\delta}{2} + V_C\right)}{X} \measuredangle \frac{\delta}{2} \quad \text{and} \quad Re\left[V_m I_C^*\right] = 0, Re\left[V_C I_m^*\right] = 0,$$

This indicates that shunt converter draws only reactive current and operates as an STATCOM. The two halves of series converter exchange real power as the power generated by the series converter near port 2 is,

$$P_{DC} = Re\left[\frac{V_C}{2}\left(I_m^* - \frac{I_C^*}{2}\right)\right] = -\frac{V_C I_C^*}{4} = -\frac{V_C I_C}{4}$$

It is observed that for the maximum power flow in the line DC power remain constant. The right half of the series converter absorbs this power from the network and supplies to the left half.

6.3 Control of UPFC

UPFC is consisting of two converters coupled on DC side, so the control of each converter is discussed individually [2].

Control of Shunt Converter

Controlled current is drawn from the system by shunt converter. This current has two component Ip and Ir. Ip is automatically determined by the requirement to balance the real power supplied to the series converter through DC link.

The other component Ir is the reactive current which can be controlled same as STATCOM. The shunt converter has two operating modes. These are,

1) **VAR control mode:** In this mode the reactive current reference is determined by inductive or capacitive VAR command. From the current transformers (CT) located on the bushings of the couple transformer the feedback signals are obtained.
2) **Automatic voltage control mode:** In this mode, the reactive current reference is determined by the output of the feedback voltage controller. From the potential transformers (PT) measuring the voltage V1 at the substation feeding the coupling transformer the voltage feedback signals is obtained.

Control of Series Converter

The main function of a series converter is to inject a series voltage of the required magnitude and angle. It has different control modes described below

Direct Voltage Injected Mode: In this mode of operation, the converter simply generates a voltage phasor in response to the reference input. It is a special case when the desired voltage is a reactive voltage in quadrature with the line current.

Phase Angle Shifter Emulation Mode: In this mode the injected voltage Vc is phase shifted relative to the voltage V1 by an angle specified by the reference input.

Line Impedance Emulation Mode: In this mode, the series injected voltage is controlled in proportional to the line current. The complex impedance seen by the line current is determined by the reference inputs. It is essential to avoid instability and resonance caused by negative values of resistance and a large value of capacitive reactance respectively.

Automatic Power Flow Control Mode: In this mode, the reference inputs determine the required real power (P) and the reactive power (Q) at a specified location in the line. Both P and Q can be controlled independently by the satisfaction of various constraints.

For the above mechanisms the series injected voltage is determined by a vector control system to ensure the desired current to flow.

We implement automatic power flow control by utilizing the vector control scheme that regulates the line current based upon the Synchronous Reference Frame (SRF). The controlled quantities for this are the in-phase and quadrature components relative to the voltage at port 1 of the UPFC. If harmonics are neglected, these components are constants in steady state and depend on the desired reference values of P and Q. To determine the magnitude and angle of the series injected voltage the feedback control of the in-phase and quadrature components of the line current is utilized.

6.4 Operating Constraints

There are mainly six major constraints that must be satisfied for scheduling the control of a UPFC in steady state. These are discussed below.

1) The upper limit on the magnitude of the shunt converter current

$|I_c| < I_{c\,max}$ ... (6.5)

2) The upper limit on the magnitude of the voltage injected by the shunt converter.

3) The upper limit on the magnitude of the voltage injected by the series converter, $|V_c| < V_{c\,max}$ ... (6.6)

4) The upper limit on the magnitude of the line current flowing through the series converter

5) Maximum and minimum limits on the line side voltage, V_L given by,

$V_{L\,min} < |V_L| < V_{L\,max}$ ... (6.7)

6) The upper limits on the magnitude of the power flow (PDC) in the DC link.

The limits on the voltages injected by the shunt and series converter depend on both the voltage ratings of the converters (and the coupling transformers) and the magnitude of the DC bus voltage. This implies that $V_{c\,max}$ (for the series converter) is not constant but varies with the operating conditions. In general, for $V_c \leq V_{c\,max}$, the phase angle (β) of the voltage can vary over 360°.

Fig. 6.5 which shows the boundary of the range for V_L (V_1+V_c). Due to the leakage reactance (X_l) of the coupling transformer, the voltage appearing across the primary winding of the coupling transformer is ($V_c - j\, I_{line}.X_l$) rather than V_c.

So boundary of the achievable range of V_L shifts for a specified line current. Here the feasible region is shown by the shaded portion.

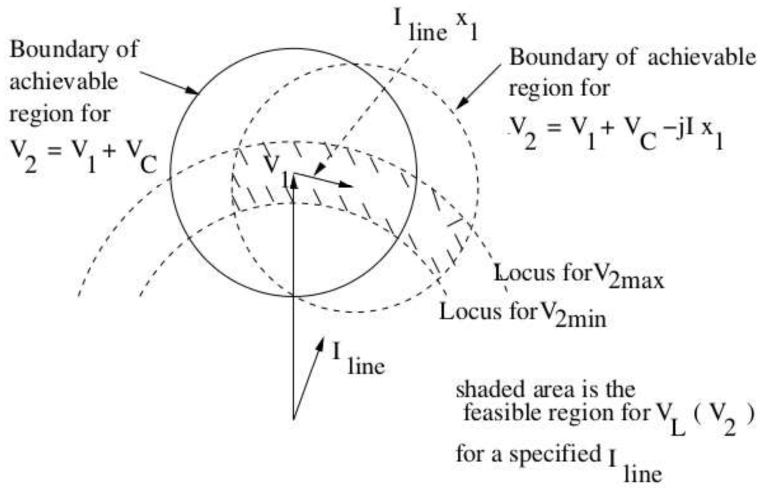


Fig 6.6- Feasible Region for VL and V2

We see that the complete range for Vl cannot be used to the maximum potential as the line side voltages magnitude has to satisfy limits of (eq.6.7)

A new control scheme is also suggested. In this scheme instead of controlling the reactive power flow in the line, the magnitude of the line side voltage (V_L or V_2) is regulated. Here the two specifications ($Q = Q_{spec}$ and $|V_2| = V_{2\,spec}$) are related. However, if $|V_2| = V_{2\,spec}$ is used, this control scheme would eliminate the need to monitor the constraints imposed by eqn. (6.7). It is observed with the regulation of the two port voltage magnitudes and if $|V_1| = |V_2| = V$, then the UPFC behaves like an ideal phase shifter. The automatic voltage control mode of the shunt converter can be used to regulate $|V_1| = V$).

In the automatic power flow control mode for the series converter, in some operating conditions it is possible that the specified P and Q may be outside the feasible region (see fig. 5.6). For these cases, the limits on V_c can be imposed in two ways: (1) both P and Q are reduced while maintaining the requested angle for β (of the injected voltage) or (2) the reactive power is reduced while the active power (P) is maximized. It is required to change in β while the magnitude of the injected voltage maintains maximum magnitude for later strategy.

If the feedback controller for P sets the reference of V_r, and if the injected voltage V_p is used to regulate the line side voltage of the UPFC then the reference voltage V_p* is calculated directly from the equation $V_2^2 = (V_{1r} + V_r)^2 + \left(V_{1p} + V_p\right)^2$

Where V_{1p} and V_{1r} are the components of the voltage V_1, in phase and quadrature with the line current. These components can be computed utilizing the phase angle (φ) of the line current is obtained from PLL. The real power controller also uses feed forward from the phase angle φ for improving the phase margin in the controller design.

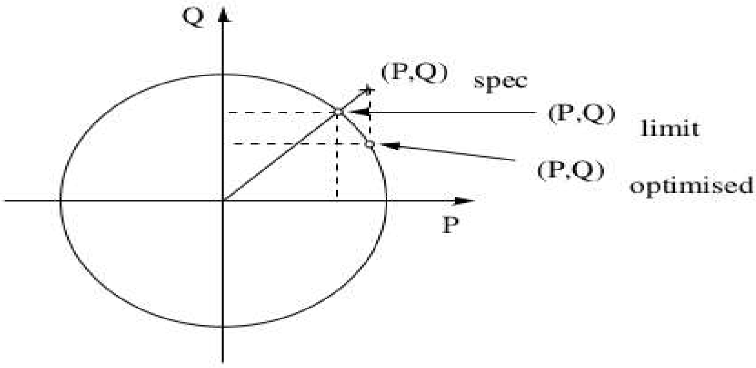


Fig 6.7- P-Q diagram demonstrating handling limits

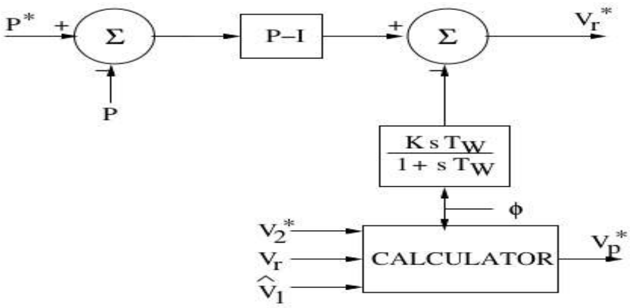


Fig 6.8- Alternative Series VSC controller

6.5 Effect on Distance Protection

We install the relay on the right portion of the bus B5 and the power frequency components of voltage and current signals measured at the relay point are used for calculating the apparent impedance.

6.6 Calculation of Apparent Impedance

When a single phase-to-ground fault occurs on the right side of the UPFC and the distance is $n*L$ from the relay point. The impedance calculations are shown in *Appendix D*. The equation is given by

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

From the above, it can be seen when the conventional distance relay is applied to the transmission system employing UPFC during the phase-to-ground fault, the apparent impedance seen by this relay has three parts: positive sequence impedance from the relay point to fault point, which is what the distance relay is set to measure; the second is due to the impact of UPFC on the apparent impedance, which can be further divided into injected by the two parts; one results from the shunt current STATCOM and another is the impact of the series voltage injected by the SSSC; the last part of the apparent impedance is due to the fault resistance.

Maximum power P_{max} is transferred by UPFC when $\beta = \delta/2 + 90^o$, $\psi = \delta/2 + 90^o$ and

P_{max} is given by

$$P_{max} = \frac{V^2}{X}sin\delta + \frac{V_C V}{X}cos\frac{\delta}{2} + \frac{I_C V}{2}sin\frac{\delta}{2}$$

Remarks: For the maximum power transfer, we have

$$\hat{V}_m = \left(Vcos\frac{\delta}{2} + \frac{X}{4}I_C\right)\measuredangle\frac{\delta}{2}$$

$$\hat{I}_m = \frac{\left(2Vsin\frac{\delta}{2} + V_C\right)}{X}\measuredangle\frac{\delta}{2} \quad \text{and}$$

$$Re\left[V_m I_C^*\right] = 0, Re\left[V_C I_m^*\right] = 0,$$

This indicates that shunt converter draws only reactive current and operates as an STATCOM. The two halves of series converter exchange real power as the power generated by the series converter near port 2 is,

$$P_{DC} = Re\left[\frac{V_C}{2}\left(I_m^* - \frac{I_C^*}{2}\right)\right] = -\frac{V_C I_C^*}{4} = -\frac{V_C I_C}{4}$$

It is observed that for the maximum power flow in the line DC power remain constant. The right half of the series converter absorbs this power from the network and supplies to the left half.

Chapter 7
Result Analysis

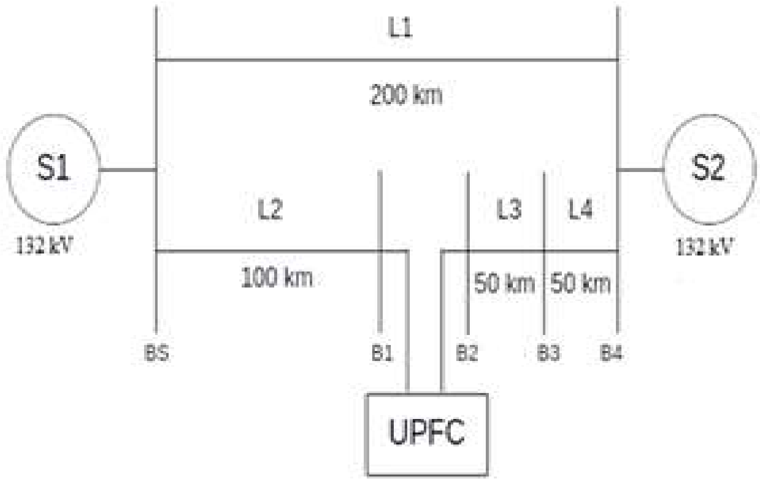


Fig 7.1 Single line Diagram of UPFC

Above figure shows two 132 kv generating stations. Line length is 200 km.

Second line has UPFC installed at a distance of 100 km from line 1. It is installed in the middle of the line to provide optimum compensation to the system.

7.1 SSSC simulation results

Simulation is done by selecting SSSC mode of the control model so described earlier.

In case of single line to ground fault the voltage waveforms are shown below.

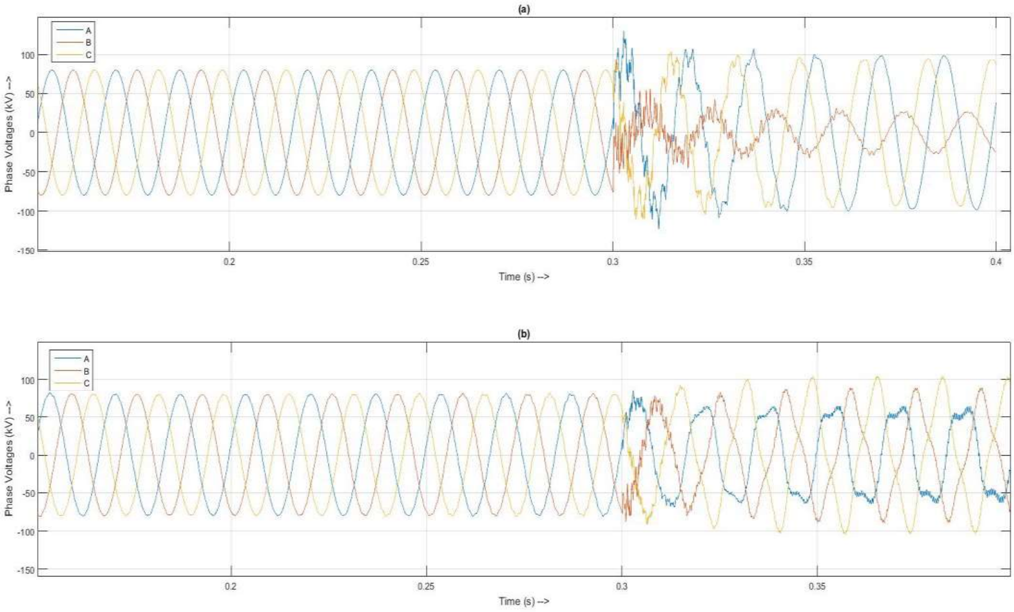


Fig.7.2 (a)Phase voltage with respect to time without SSSC.(b) Phase voltage with respect to time with SSSC

After observing the waveforms, it can be seen that at no fault, the faulty phase voltage (B phase) has been decreased below 50KV and by the introduction of SSSC compensation, a 0.08pu voltage (10% of the system voltage) injected to the faulty phase. (This injected voltage is almost sinusoidal of variable magnitude and angle).

Similarly the current waveform for (line to ground fault) is shown below:-

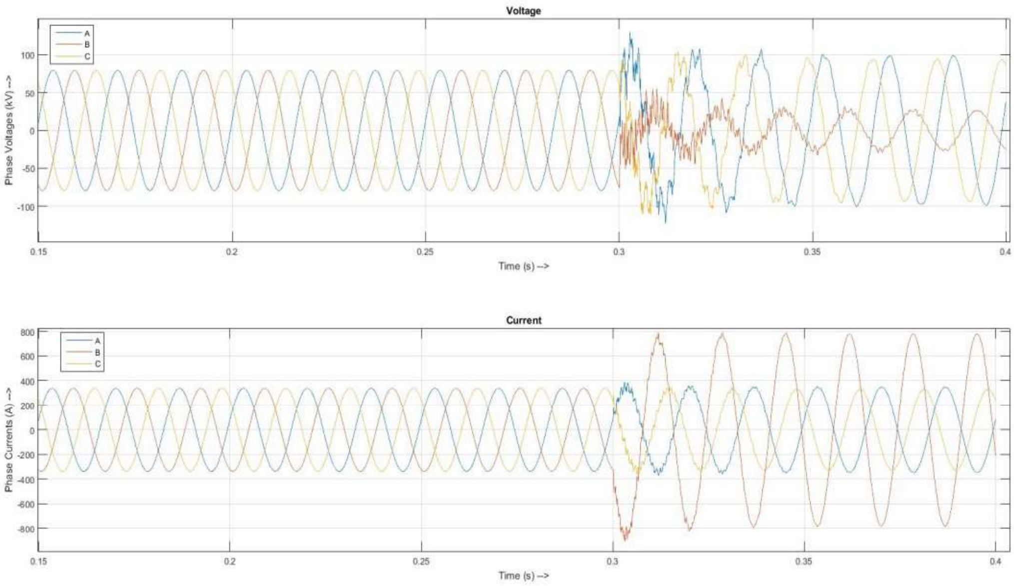


Fig.7.3 (a) Phase current with respect to time without SSSC. (b) Phase current with respect to time with SSSC

There is no change in active power during compensation so it remains constant. Below figure shows the apparent reactance which was 30 ohm initially which increases to 38 ohm approximately, however the system resistance increases from 36ohm to 39ohm and hence there is no change in apparent impedance.

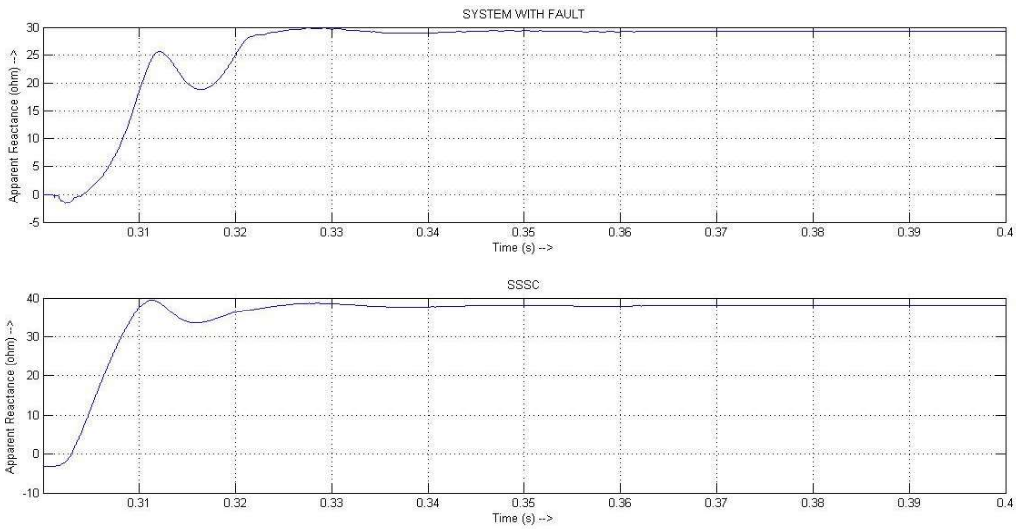


Fig.7.4 (a) Apparent Reactance with respect to time with fault (b)Apparent Reactance with respect to time with SSSC

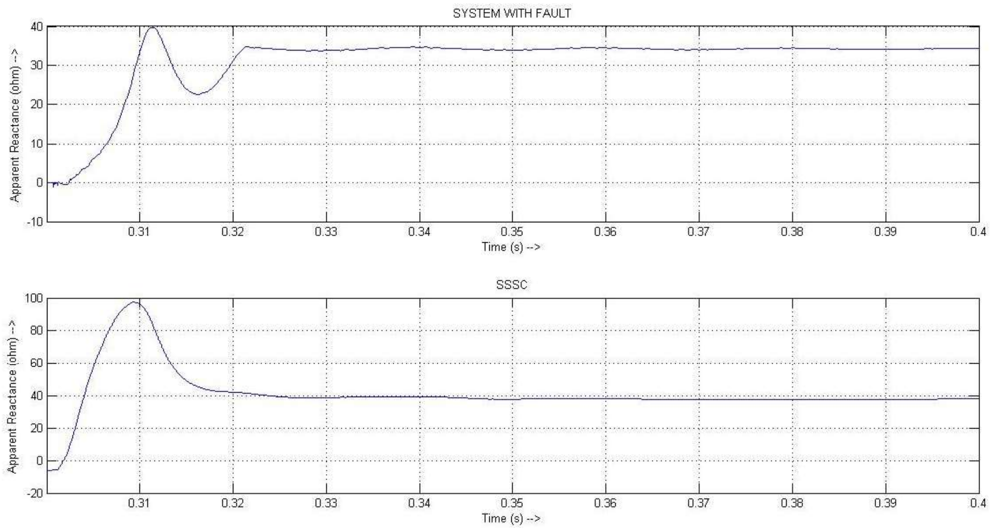


Fig.7.5 (a) Apparent Resistance with respect to time with fault (b)Apparent Resistance with respect to time with SSSC

Below figure shows the apparent impedance trajectory of the fault system and SSSC along with distance relay mho characteristics. Clearly, the relay detects fault in case of uncompensated system but with SSSC the R-X trajectory goes outside the circle (Z-SET), thereby under-reaching the relay and it does not trip. In this case, the change in resistance is less than for STATCOM. With SSSC also relay settings should be adjusted.

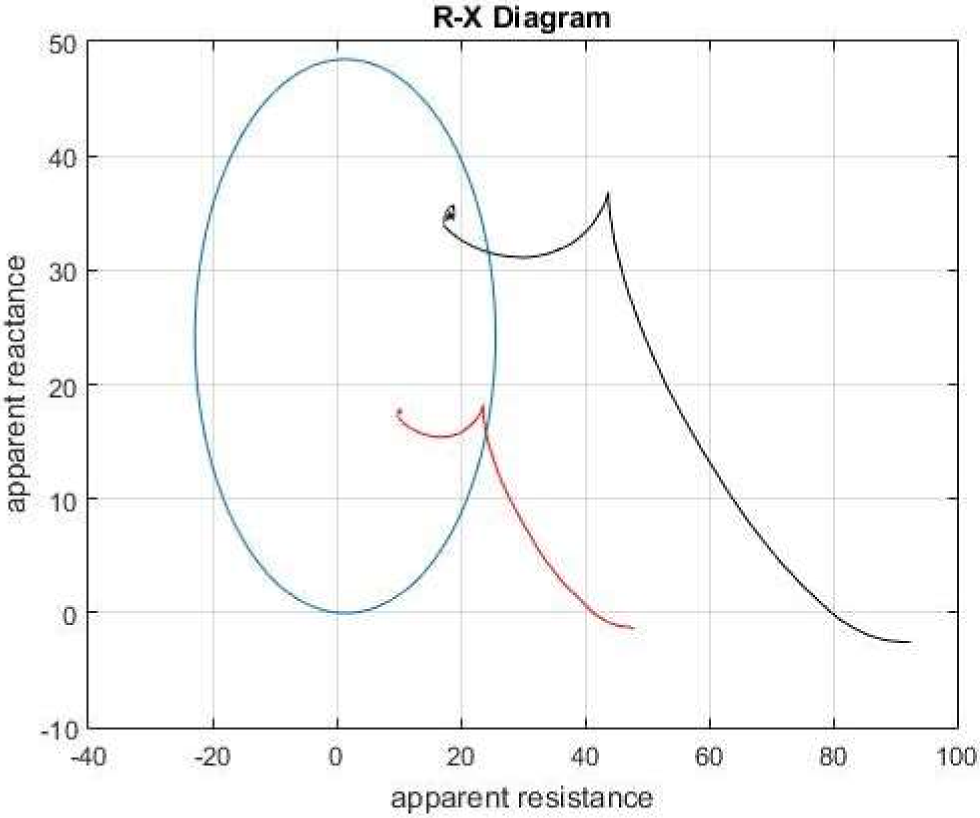


Fig. 7.6 shows apparent impedance trajectories during fault and SSSC compensation.

From above discussion we have seen that by introducing SSSC two things happened. They are,

1. Voltage control- voltage of the power system remains almost constant at 0.96pu and phase displacement between all the buses is reduced.
2. Active power control- There is stabilization in active power transfer capability

7.2 STATCOM simulation result

Setting the UPFC in STATCOM mode (Voltage control with Vref=1 pu) the simulation is run and results are discussed below.

Single line to ground (B TO G):

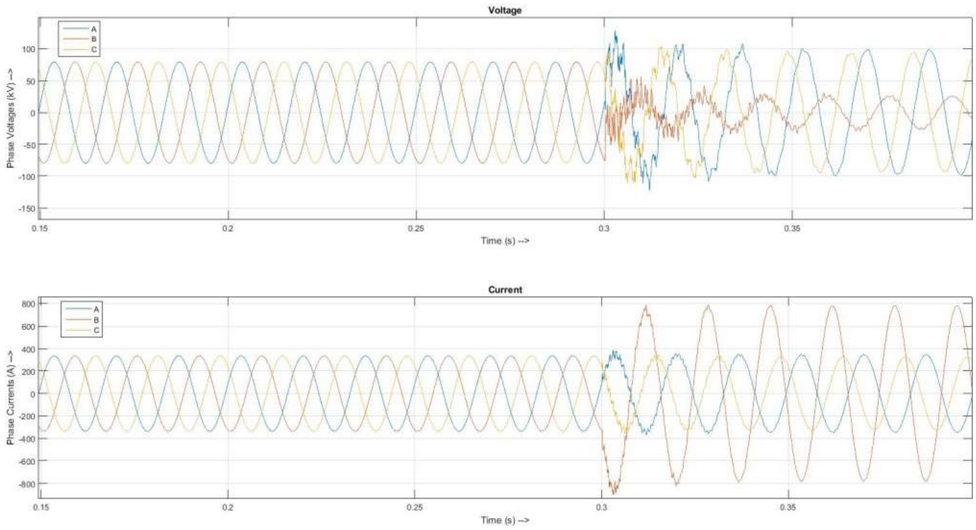


Fig.7.7 shows V-I characteristics of system where fault start after 0.3 second

From above figures we see that during normal condition, the STATCOM has adjusted the three phase voltages and currents in such a way that line voltage remains near about 0.8pu. Also during fault, the line voltages have remained close to V_{ref} due to lagging current injection on healthy phases and leading current injection on faulty phase by the device, thus reducing voltages for higher current of healthy phases and increasing voltage for reduced current of faulty phase. In this manner it controls system voltage.

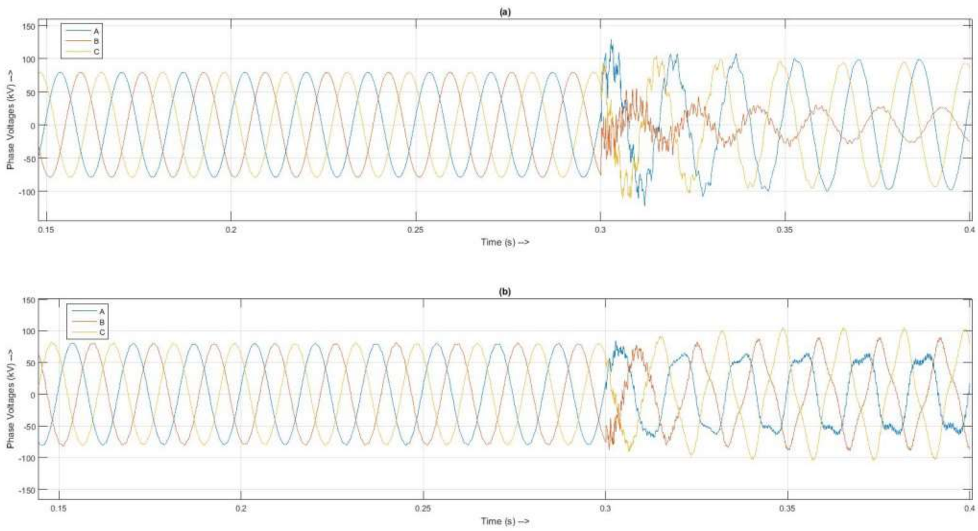


Fig.7.8 (a) Phase voltage during fault (b) Phase voltage after compensation

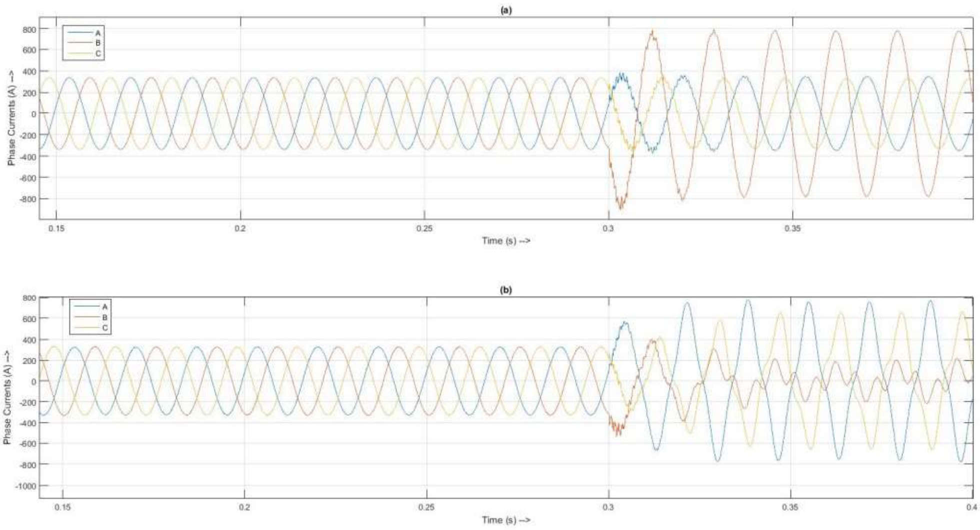


Fig.7.9 (a) Current waveform of system during fault

(b) Current waveform with STATCOM

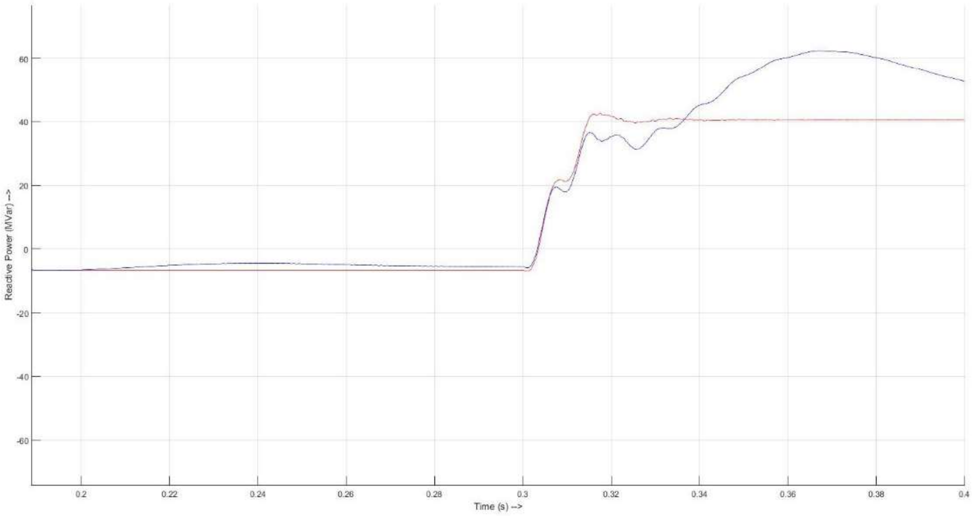


Fig.7.10 Reactive power of system

Blue line shows system without compensation (STATCOM)

Red line shows system with compensation using STATCOM

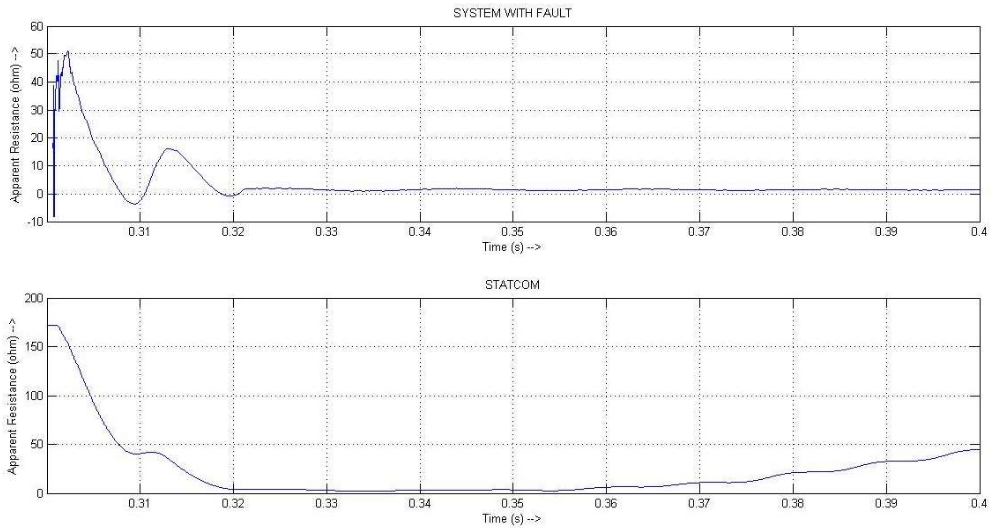


Fig.7.11 Upper one fig. shows that apparent resistance of system during fault and lower one shows apparent resistance after compensation by STATCOM.

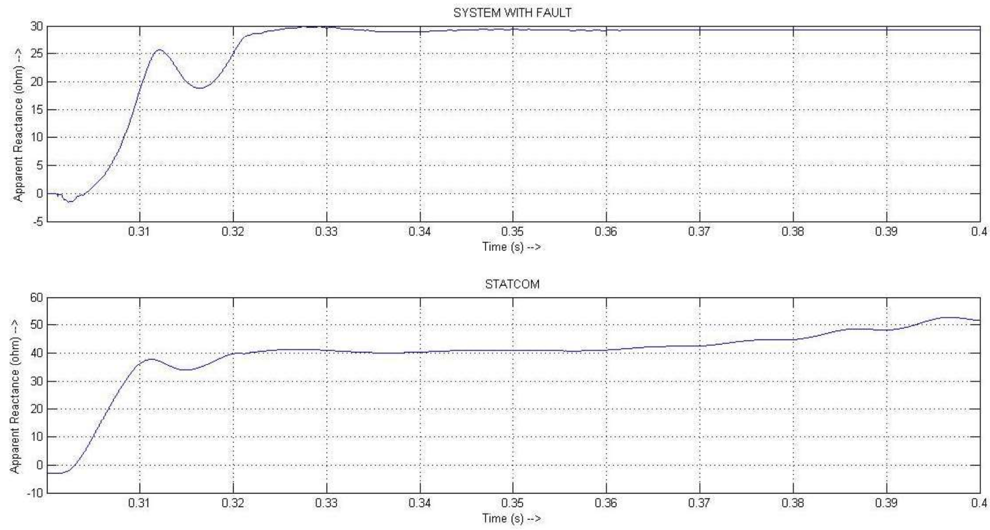


Fig. 7.12 Upper one fig. shows that apparent reactance of system during fault and lower one shows apparent reactance after compensation by STATCOM.

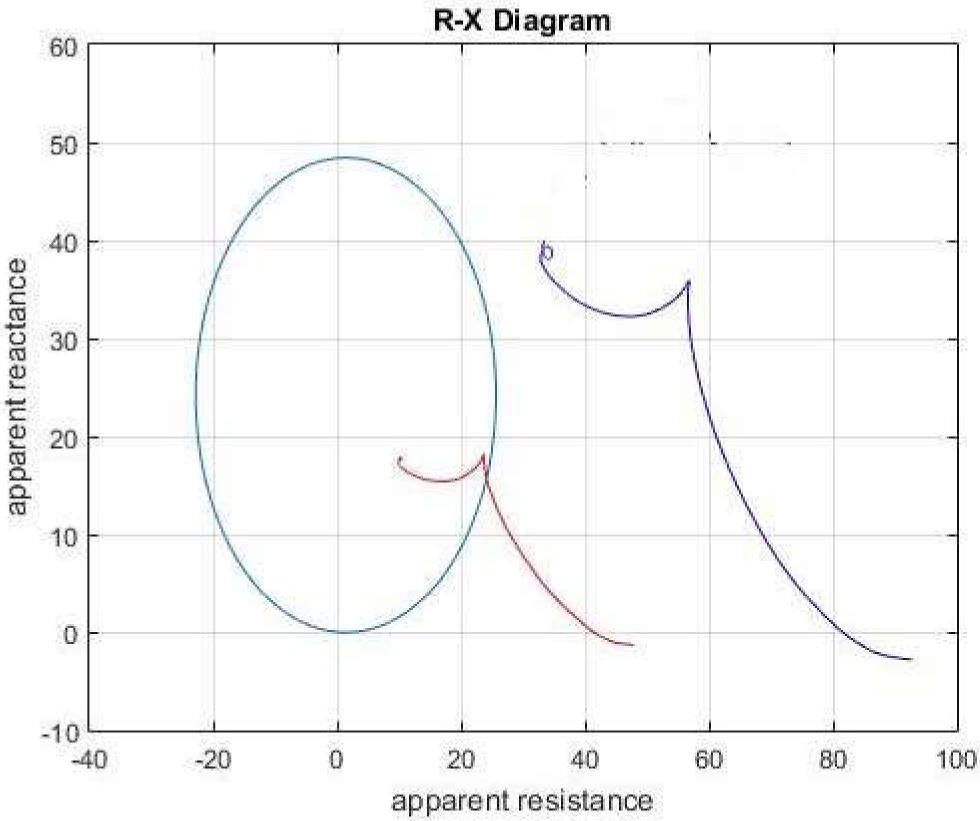


Fig. 7.13 shows R-X diagram with STATCOM

From above discussion we have seen that by introducing STATCOM two things happened. They are,

1. Voltage control-The voltage of the power system remains almost constant at 0.7pu and phase displacement between all the buses is reduced during fault condition.
2. Reactive power control-Due to inclusion of STATCOM, the fault system positive reactive power decreases to desirable value.

7.3 UPFC simulation result

Setting the UPFC (Power flow control) the simulation is run and results are discussed below.

Phase currents(A) vs Time(s)

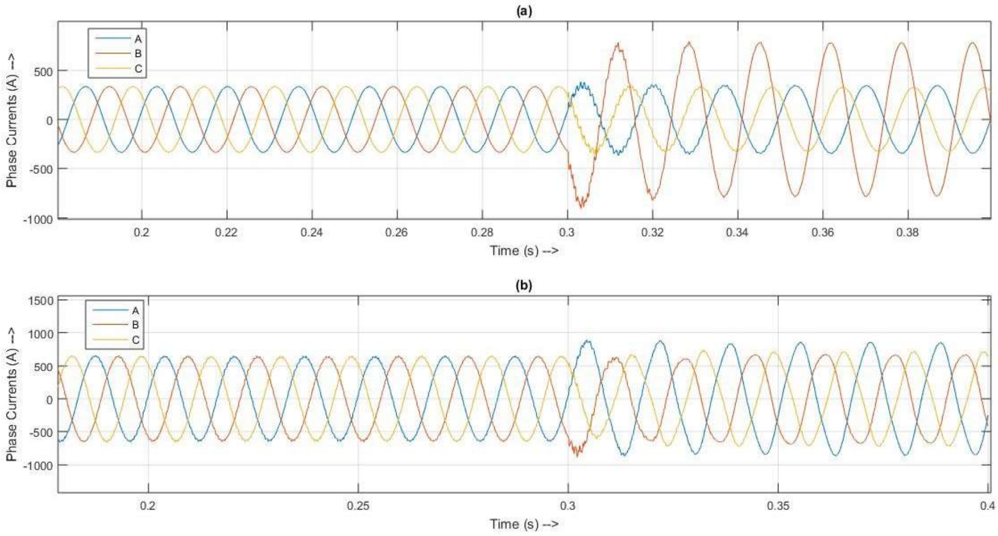


Fig.7.14 (a) Phase current without UPFC (b) Phase current with UPFC

Phase voltages (kv) vs Time(s)

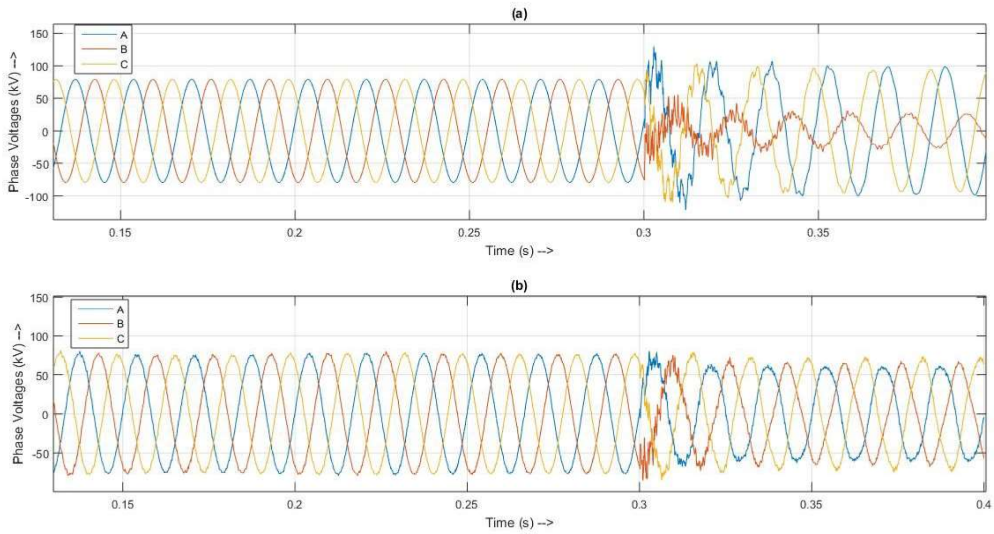


Fig.7.15 (a) Phase voltage without UPFC

(b)Phase voltage with UPFC

From above figures it is observed that during normal condition, the UPFC has adjusted the three phase voltages and currents in such a way that line voltage remains near about 0.8pu.

Active power (MW) vs Time(s)

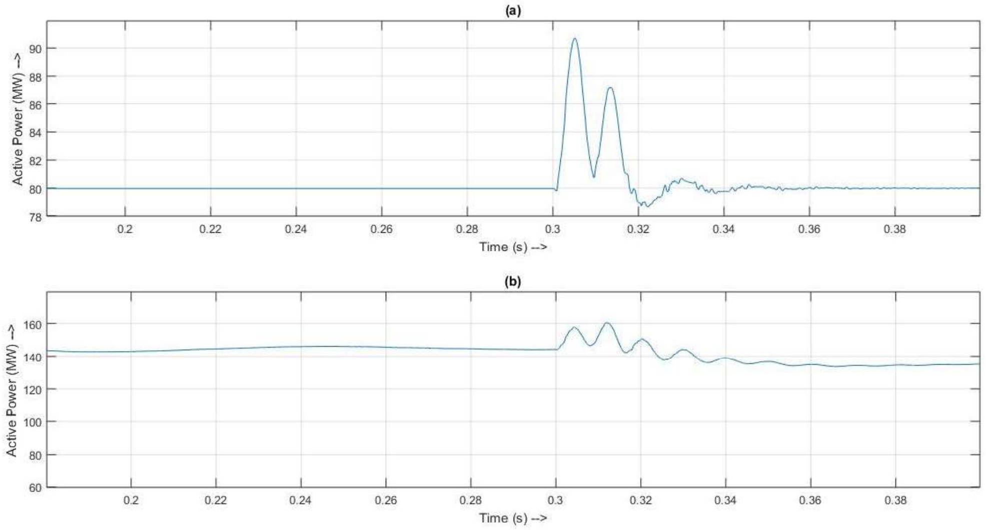


Fig. 7.16 (a)Active power waveform with fault (Fault sustained In between 0.3 to 0.4 sec) (b)Active power waveform during compensation

Reactive power(MVAR) vs Time(s)

From Fig. it is seen that line active power before fault nearly equal to 45 MW.Even during fault, the deviation is very small,indicating no appreciable change real components of voltage, current during fault.

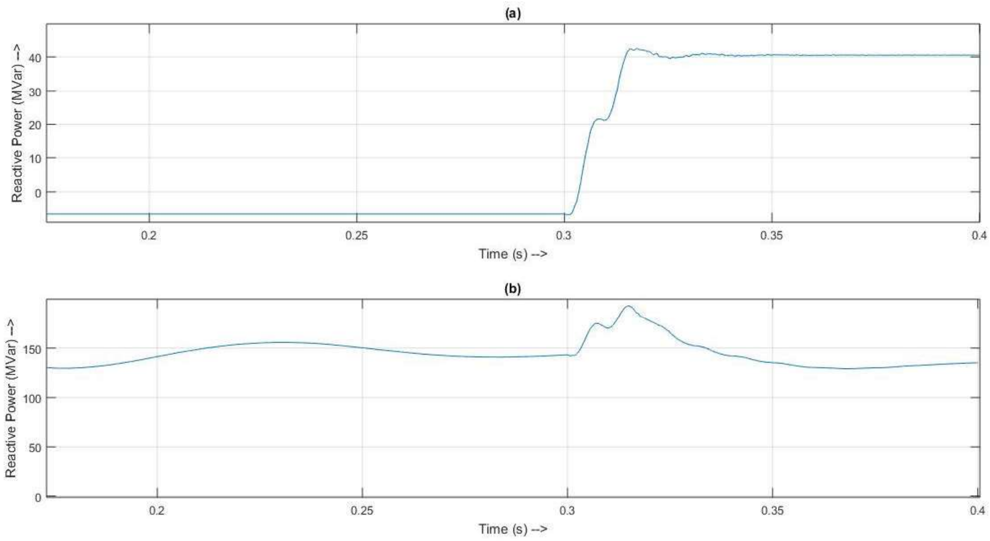


Fig. 7.17 Reactive power wave forms at transmission line

It is observed that before fault, system has a negative reactive power (caused by capacitive load) of 8 MVAR. But during fault, there is a positive reactive power (caused by inductive load or fault) of 57 MVAR indicating occurrence of lagging reactive current in the line. Under the operation of UPFC, this much reactive power reduced to 43 MVAR. So, it is very hard to nullify the effect without making a very fast transition of circuit breaker.

Figs. (a) & (b) show respectively the apparent resistance and reactance waveforms of the faulty system and UPFC along with the distance relay mho characteristics. In case of faulty system, we see that apparent resistance decreases and reactance increases during fault. The apparent resistance starts from same value as for uncompensated line (~ 15 ohms) and becomes nearly to 20 ohms. Apparent reactance steady value is comparatively higher (~ 41 ohms) from uncompensated system (~ 29 ohms) . UPFC has more adverse effect on distance protection relay operation.

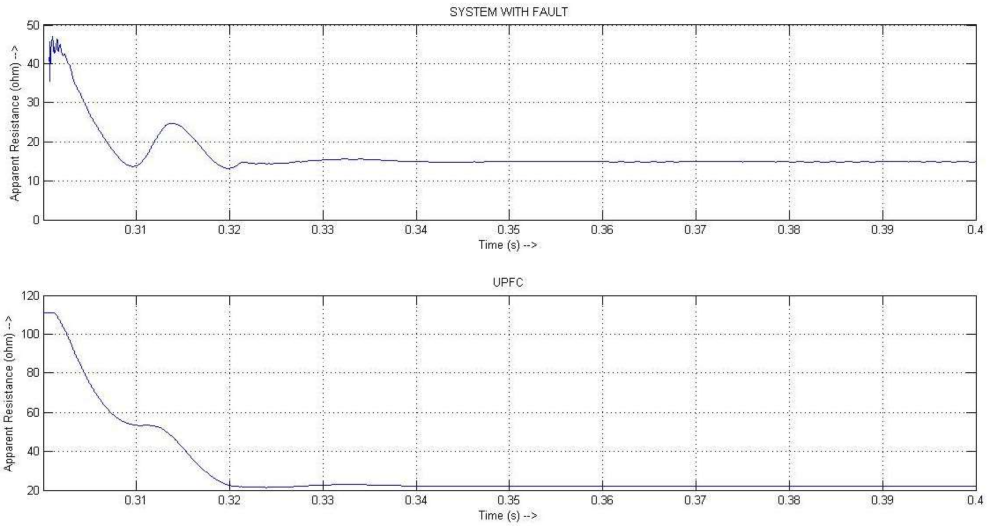


Fig. 7.18 (a) Variation of Apparent Resistance without UPFC

(b) Variation of Apparent Resistance with UPFC

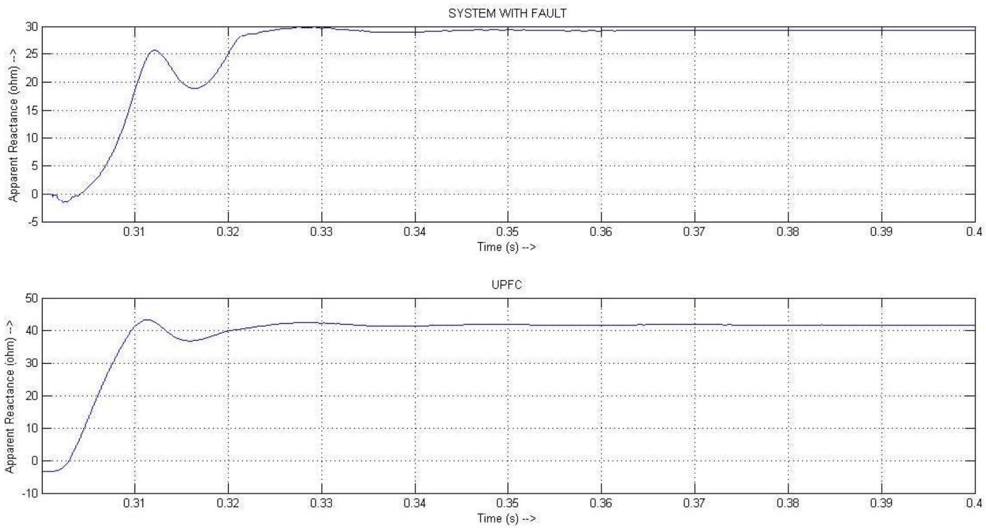


Fig. 7.19 (a) Variation of Apparent Reactance without UPFC

(b) Variation of Apparent Reactance with UPFC

R-X diagram for UPFC

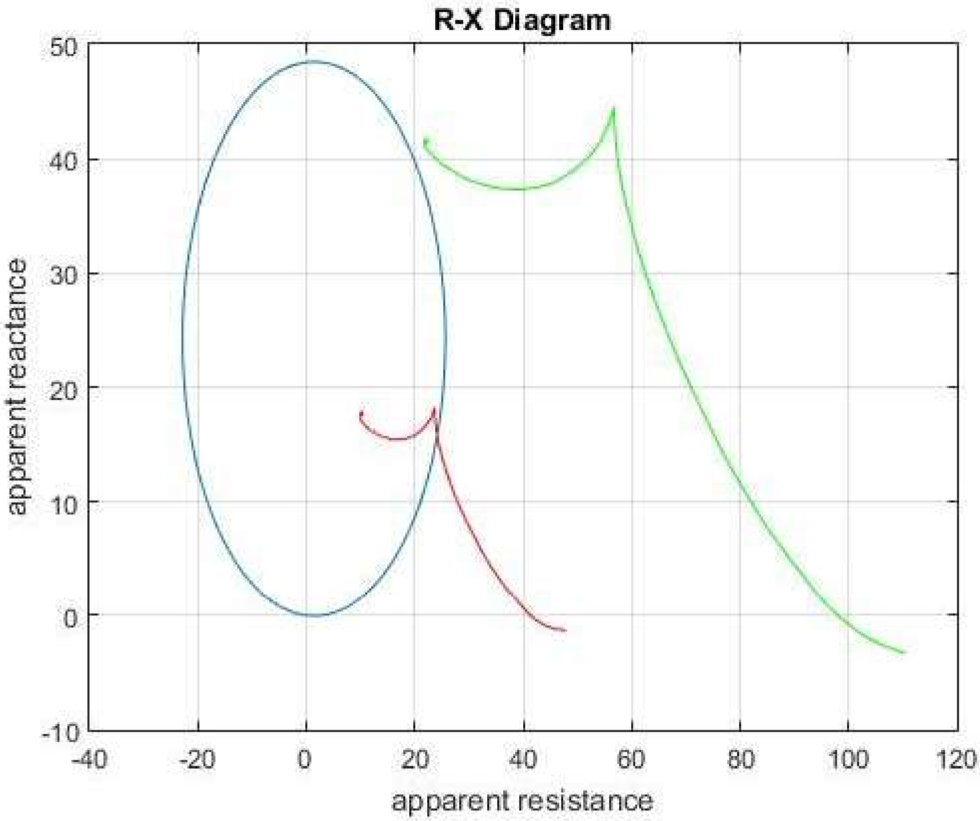


Fig. 7.20 shows apparent impedance trajectories during fault and UPFC compensation.

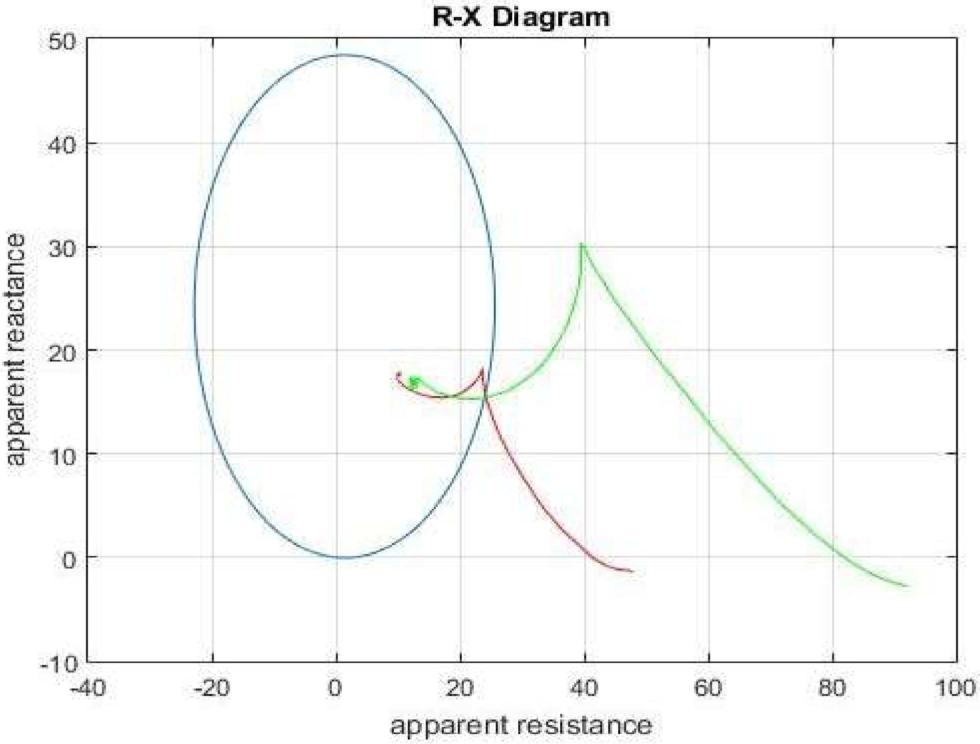


Fig 7.21 R-X Diagram in case of single line to ground fault.

Green line shows the graph with UPFC and Red line shows the system without compensation.

As before, uncompensated system is able to detect fault as apparent impedance trajectory falls within the mho circle. But with UPFC installed, the apparent impedance trajectory goes very much outside of the circle and relay under-reach occurs. So relay settings have to be modified

7.4 Comparative study of different modes of UPFC

Under L-G fault

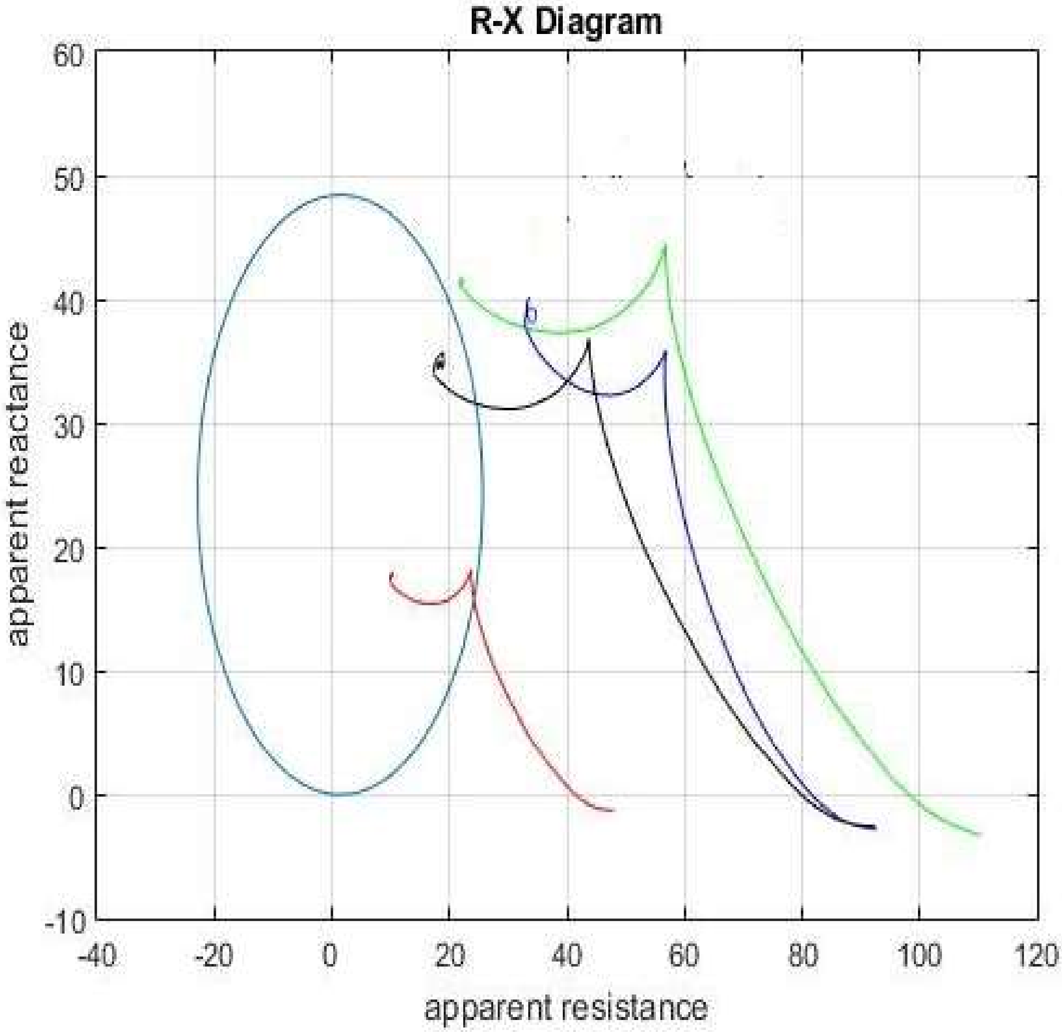
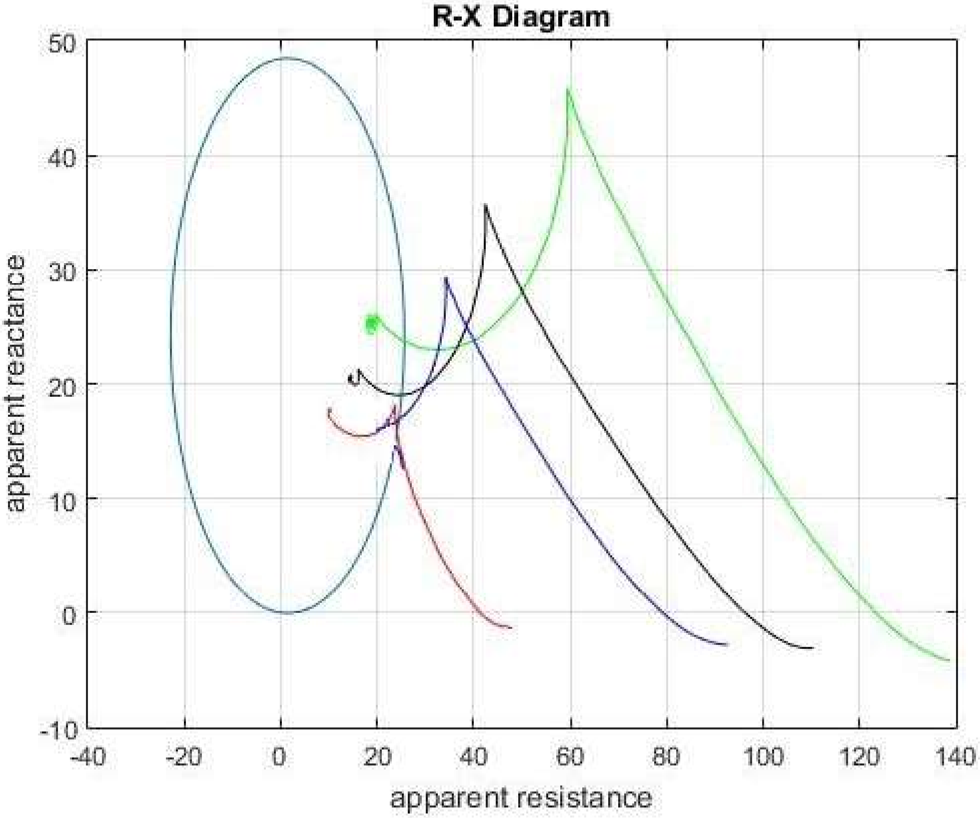


Fig 7.21 R-X Diagram under different modes of settings in UPSC

Under L-L fault



The above Fig 7.20 shows the R-X curve for different settings of UPFC.

Blue line indicates the curve for STATCOM

Green line indicates the curve for UPFC

Black curve indicates the operation under SSSC.

As can be seen, R-X curve, apparent impedance curve (red) is inside the mho circle but with UPFC installed in its different mode viz. STATCOM, SSSC the curve goes out of the circle and hence relay under reaches.

Chapter - 8

Conclusion

From this project, different conditions of faults and there rectification through FACTS devices have been analysed.

We have studied different settings of UPFC and its effect on distance protection.

The results of simulation have been compared taking two conditions, one without using any compensation technique and other with various modes of using FACTS Devices.
We have used three modes of compensation using FACTS:-

(i) In case of STATCOM during single line to ground fault, both the apparent resistance and reactance are increased (STATCOM supplies negative reactive power to the system). So, the overall apparent impedance is increased which will result into the distance relay under-reach.
For a line to line fault, the apparent reactance increases but the apparent resistance remains near to zero for maximum period of time, causing a possible under-reach.

(ii) In case of SSSC, during single line to ground fault, the apparent resistance starts from nearly same value as in uncompensated system but attains slightly higher value in steady state. The apparent reactance starts from nearly same value as in uncompensated system but attains higher steady state value.
For line to line fault SSSC consumes reactive power from the system, it is operated like a series inductance and the apparent impedance increases. So, the distance relay is under-reached.

(iii) In case of UPFC, during single line to ground fault, the apparent resistance starts from nearly same value as in uncompensated system and attains higher value in steady state. The apparent reactance starts from nearly same value as in uncompensated system but attains very high steady state value compared to uncompensated system. So, the overall increase in apparent impedance leads to distance relay under reach.

Various results of simulation have been obtained for two conditions namely:-

1) Line to line fault
2) Line to ground fault.

Results have been obtained for Voltage, current, active power, reactive power, apparent resistance and apparent reactance.

All these results have been compared for various modes.

Chapter - 9

FUTURE SCOPE

In the changing system of power production more storage systems will be needed in the future. The more renewable energy power plants with fluctuating supply of solar radiation or wind are connected with the grid, the more additional compensation technique will be needed to guarantee a balancing of demand and supply of power. FACTS (Flexible AC Transmission Systems) devices which handle both real and reactive power to achieve improved transmission system performance are a better proven power electronic devices now being introduced in the utility industry worldwide.

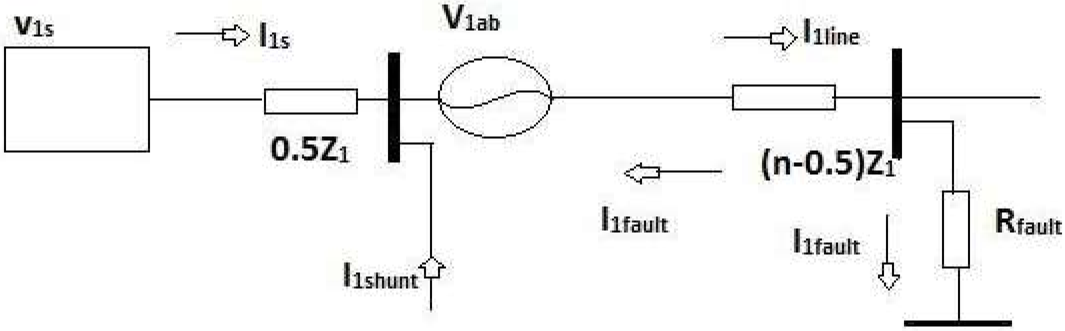
Hopefully in future if we get the opportunity to improve our project we would like to incorporate few things

1) To find precise location of the Fault position.
2) To get an improved R-X diagram for different modes of UPFC.
3) To assimilate adaptive relaying scheme.
4) To make the practical model more cheaper.

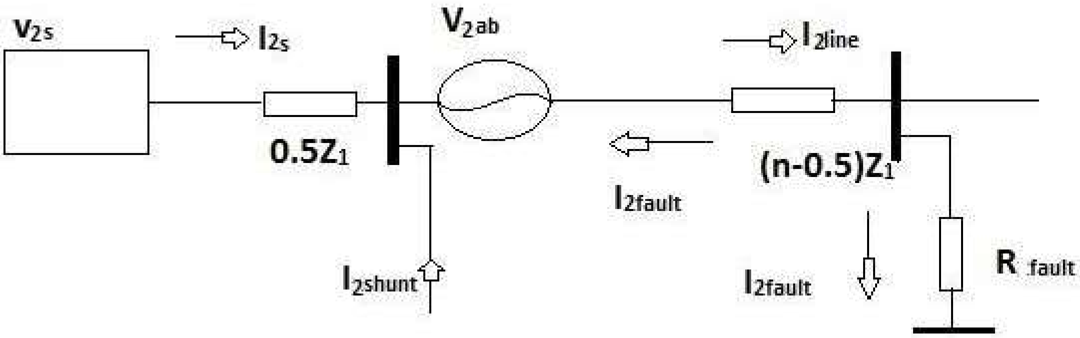
Facts offer the possibility to increase transmission network capacity and flexibility and generally enhance system reliability, security and controllability with limited environmental impact.

Appendix A

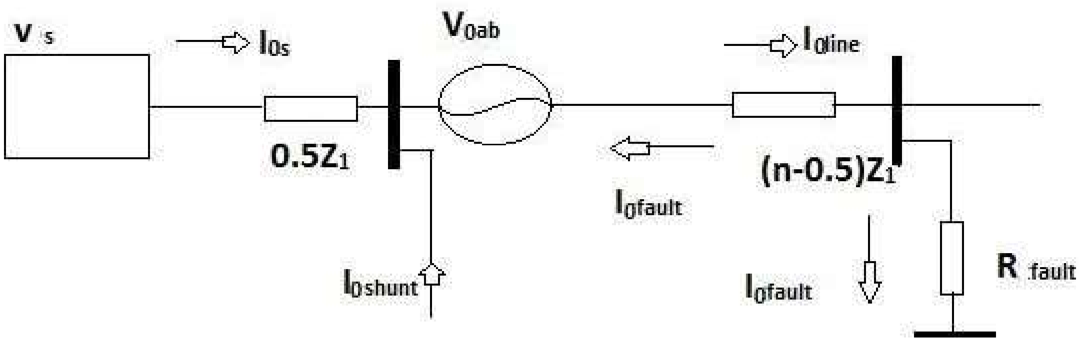
Apparent Impedance Calculation with UPFC for Single line to ground fault:



POSITIVE SEQUENCE NETWORK



NEGETIVE SEQUENCE NETWORK



ZERO SEQUENCE NETWORK

When a single phase to ground fault occurs on the transmission line and the distance between the fault point and the relay point is n × L, then at the time of fault the positive, negative and zero sequence networks of the system are as follows,

$V1_s = I1_s 0.5Z1 + V1_{ab} + I1_{line}(n - 0.5)Z1 + RfaultI1_{fault}$ ….(1)

$V2_s = I2_s 0.5Z1 + V2_{ab} + I2_{line}(n - 0.5)Z1 + RfaultI2_{fault}$ ….(2)

$V0_s = I0_s 0.5Z0 + V0_{ab} + I0_{line}(n - 0.5)Z0 + RfaultI0_{fault}$ ….(3)

$I1_{line} = I1_s + I1_{shunt}$ ….(4)

$I2_{line} = I2_s + I2_{shunt}$ ….(5)

$I0_{line} = I0_s + I0_{shunt}$ ….(6)

Where

$V1_s$, $V2_s$, $V0_s$ sequence phase voltages at the relay location;

$V1_{ab}$, $V2_{ab}$, $V0_{ab}$ series sequence phase voltages injected by UPFC;

$I1_s$,$I2_s$, $I0_s$ sequence phase currents at the relay location;

$I1_{line}$, $I2_{line}$, $I0_{line}$ sequence phase currents in transmission line;

$I1_{fault}$, $I2_{fault}$, $I0_{fault}$ sequence phase currents in the phase;

$I1_{shunt}$, $I2_{shunt}$, $I0_{shunt}$ shunt sequence phase currents injected by UPFC;

Z1 , Z0 sequence impedance of the

transmission line; n per unit distance

of a fault from the relay location

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

$Vs = nIsZ1 + nI0_s(Z0 - Z1) + Ishunt(n - 0.5)Z1 + (n - 0.5)I0_{shunt}(Z0 - Z1) + Vab + RfaultIfault$ …(7)

Where

$$Vs = V1_s + V2_s + V0_s \qquad \text{....(8)}$$

$$Is = I1_s + I2_s + I0_s \qquad \text{....(9)}$$

$$Vshunt = V1_{shunt} + V2_{shunt} + V0_{shunt} \qquad \text{....(10)}$$

$$Vab = V1_{ab} + V2_{ab} + V0_{ab} \qquad \text{....(11)}$$

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

[redacted] ....(12)

Where

VR & IR are phase voltage and current at relay point respectively;

IR0 is zero sequence

phase current; Irelay is

relaying current.

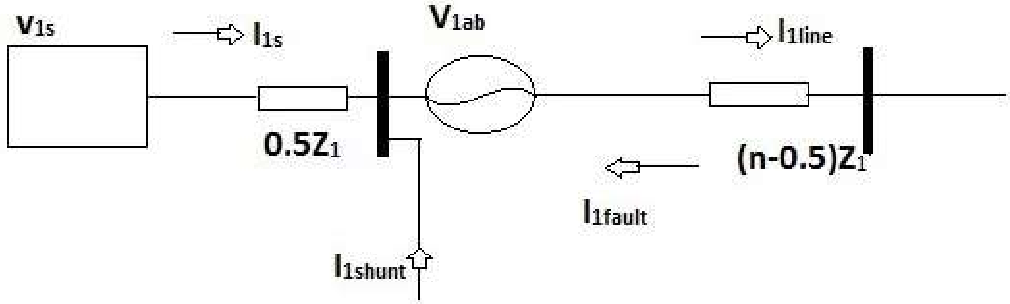
If this traditional distance relay is applied to the transmission system with UPFC, the apparent impedance seen by this relay can be expressed as,

[redacted]

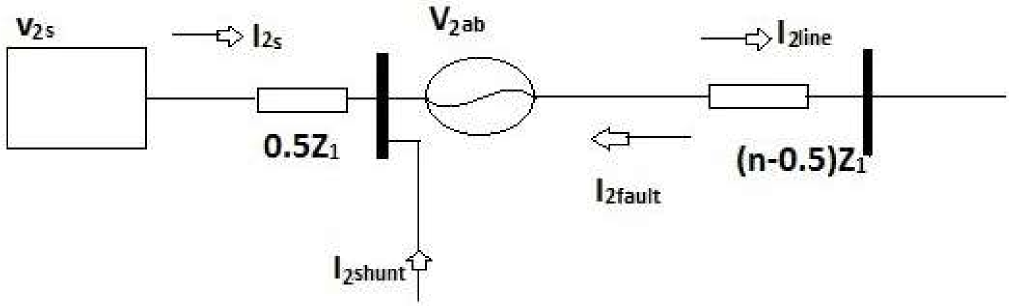
...(13)

Appendix B

Apparent Impedance Calculation with UPFC for Double line fault



POSITIVE SEQUENCE NETWORK



NEGETIVE SEQUENCE NETWORK

When a single phase to ground fault occurs on the transmission line and the distance between the faulty point and the relay point is n × L, then at the time of fault the positive negative and zero sequence networks of the system are as follows,

$V1_s = I1_s 0.5Z1 + V1_{ab} + I1_{line}(n - 0.5)Z1$ ….(14)

$V2_s = I2_s 0.5Z1 + V2_{ab} + I2_{line}(n - 0.5)Z1$ ….(15)

$I1line = I1s + I1shunt$ ….(16)

$I2line = I2s + I2shunt$ ….(17)

Where

$V1_s$, $V2_s$ sequence phase voltages at the relay location;

$V1_{ab}$, $V2_{ab}$ series sequence phase voltages injected by UPFC;

$I1_s$, $I2_s$ sequence phase currents at the relay location;

$I1_{line}$, $I2_{line}$ sequence phase currents in transmission line;

$I1_{fault}$, $I2_{fault}$ sequence phase currents in the phase;

$I1_{shunt}$, $I2_{shunt}$ shunt sequence phase currents injected by UPFC;

Z1, Z2 sequence impedance of the transmission line;

n per unit distance of a fault from the relay

location

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

$Vs = nIsZ1 + nI0_s(Z2 – Z1) + Ishunt(n – 0.5)Z1 + (n – 0.5)I0_{shunt}(Z2 – Z1) + Vab$ ….(18)

Where

$Vs = V1_s + V2_s$ ….(19)

$Is = I1_s + I2_s$ ….(20)

$Vshunt = V1shunt + V2shunt$ ….(21)

$Vab = V1_{ab} + V2_{ab}$ ….(22)

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

$$Z = (V_a - V_b)/(I_a - I_b) = V_r / I_{relay} \quad \ldots 23$$

Where Vr and Ir are phase voltage and phase current at relay point respectively.

Irelay is relaying current.

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

$$Z = (V_a - V_b)/(I_a - I_b) = V_r / I_{relay}$$

$$= nZ_1 + (I_{shunt}/I_{relay})(n-0.5) + (I_{2shunt}/I_{relay})(n-0.5)(Z_2-Z_1) + V_{ab}/I_{relay}$$

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