CHAPTER -III

LOAD FLOW ANALYSIS WITH FACTS DEVICES
3.1 INTRODUCTION

In the present day transmission systems, except for a few HVDC links, transmission of power is through ac lines and the power flows in these lines are uncontrolled. AC lines have the following disadvantages:

i) Often the network is not optimally utilized because of power flow in parallel transmission lines

ii) Power flow in ac lines is limited by stability considerations due to lack of proper control

iii) No dynamic reactive power control to maintain satisfactory voltage profile under all conditions

iv) They may induce negative damping torque while providing synchronizing torque for oscillating generator rotors

These drawbacks can be minimized by deregulating and restructuring of the Power system networks. This approach is feasible only if the operation of ac transmission lines is made flexible by introducing fast-acting high power solid-state controllers using thyristors or GTO valves (switches). The concept of using solid state power electronic converters for power flow control at the transmission level is known as Flexible AC Transmission Systems (FACTS) [18-20]. The modeling aspects of the FACTS devices for load flow studies are discussed in this chapter.

3.2 FLEXIBLE AC TRANSMISSION SYSTEM (FACTS) TECHNOLOGY

FACTS devices can control the flow of power as desired and utilize the existing transmission facilities to its maximum thermal limits without sacrificing reliability. The flexible ac transmission system owes its higher transmission control to its ability to manage the interrelated parameters that constraints today's systems including series impedance, shunt impedance, phase angle and the occurrence of oscillations at various frequencies below the system frequency. By adding flexibility in this way, the controllers enable a transmission line to function nearer to its thermal ratings. The insertion of FACTS devices may significantly reduce the losses. However, the insertion of the device results in a physical change in the system.
There are two distinct means of placing FACTS devices in a transmission line for the purpose of increasing the system's ability to transmit power thereby allowing for the use of more economic generating units.

- The first is to place the device in an underutilized transmission line. This allows more power to be transmitted through the line.
- The second way of locating a FACTS device is to place the device in the most heavily loaded line using the device to limit the flow in that line. This allows more power to be sent through the remaining part of the system while protecting the line with the device from being overloaded.

The second method is most effective way to place the devices. This approach is used in this thesis.

Types of FACTS Devices

The types of FACTS devices currently available can be classified based on the control which they exert on certain electrical parameters. They are categorized into four types namely first generation, second generation, third generation and fourth generation types.

The controllers that are designed based on the concept of FACTS technology to improve the Power flow control, stability and reliability are known as FACTS controllers. These controllers were introduced depending on the type of power system problems. Some of these controllers were capable of addressing multiple problems in a power system but some are limited to solve a particular problem. All these controllers are grouped together as a family of FACTS controllers [17-20] categorized as follows:

First Generation of FACTS Controllers

Static Var Compensator (SVC) and Thyristor Controlled Series Compensator (TCSC)
Second Generation of FACTS Controllers

Static Synchronous Series Compensator (SSSC) and Static Synchronous Compensator (STATCOM)

Third Generation of FACTS Controllers

Unified Power Flow Controller (UPFC).

Fourth Generation of FACTS Controllers

Interline Power Flow Controller (IPFC) and Generalized Unified Power Flow Controller (GUPFC)

The above all generations of FACTS controllers are represented in the block diagram as shown in Fig. 3.1.

Fig. 3.1: Block Diagram of FACTS Controllers

Advantages of FACTS controllers

- **Power system stability:** Instabilities in power system are created due to long length of the transmission lines, interconnected grid, changing system loads and line faults in the system. These instabilities result in reduced transmission
line flows or even tripping of the transmission. FACTS devices stabilize transmission systems with increased transfer capability and reduced risk of transmission line trips.

- **Power Quality and Reliability:** Modern power industries demand for the high quality of electricity in a reliable manner with no interruptions in power supply including constant voltage and frequency. The change in voltage drops, frequency variations or the loss of supply can lead to interruptions with high economic losses. Installation of TCSC at the distribution system without increasing the short circuit current level considerably increases the reliability for the consumer.

- **Environmental Benefits:** The construction of new transmission line has negative impact on the economical and environmental factors. Installation of FACTS devices in the existing transmission lines makes the system more economical by reducing the need for additional transmission lines.

- **Flexibility:** The construction of new transmission lines take several years but the installation of FACTS controllers in a power system requires only 12 to 18 months. It has the flexibility for future upgrades and requires small land area.

- **Reduced maintenance cost:** Maintenance cost of FACTS controllers is less compared to the installation of new transmission lines. As the number of transmission lines increase, probability of fault occurring in a line also increases resulting in system failure. The utilization of FACTS controllers in a transmission network minimizes the number of line faults thus reducing the maintenance cost.

The devices and their functions are summarized in Table 3.1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Main Function</th>
<th>Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVC</td>
<td>Shunt</td>
<td>Voltage Control</td>
<td>Thyristor</td>
</tr>
<tr>
<td>TCSC</td>
<td>Series</td>
<td>Power Flow Control</td>
<td>Thyristor</td>
</tr>
<tr>
<td>TCPAR</td>
<td>Series &amp; Shunt</td>
<td>Power Flow Control</td>
<td>Thyristor</td>
</tr>
<tr>
<td>STATCOM</td>
<td>Shunt</td>
<td>Voltage Control</td>
<td>GTO</td>
</tr>
<tr>
<td>SSSC</td>
<td>Series</td>
<td>Power Flow control</td>
<td>GTO</td>
</tr>
<tr>
<td>UPFC</td>
<td>Series &amp; Shunt</td>
<td>Voltage And Power Flow Control</td>
<td>GTO</td>
</tr>
</tbody>
</table>

In all the above types, device losses are ignored.
3.3 BASIC POWER FLOW CONTROL CONCEPT

Power flow control is an approach to enhance proper utilization of facilities already in existence in the system. The power transfer through a transmission line is determined by the relative magnitude and phase angle of the sending and receiving end voltages and the electrical characteristics of the network. Due to practical considerations, the magnitude of the terminal voltages cannot be varied significantly without a costly voltage up-grade. This leaves modification of the inductive reactance or relative phase angle as viable options. The inductive reactance of transmission line can be reduced by external components having capacitive and inductive reactance characteristics to change the effective reactance.

Let the generalized power flow controller be operated at the middle of the line as shown in Fig.3.2

![Generalized Power Flow Controller](image)

**Fig. 3.2 Generalized Power Flow Controller operated at middle of the line**

The power flow controller consists of two controllable elements Voltage source \( V_{p0} \) and Current source \( I_q \). Voltage \( V_{p0} \) is freely variable whereas only the magnitude of current \( I_q \) can be varied. The following four classical cases of power transmission can be obtained by appropriately specifying \( V_{p0} \) and \( I_q \) in generalized power flow controller power transmission,

- i) Without line compensation
- ii) With series capacitor compensation
- iii) With shunt compensation and
- iv) With phase angle control
Case (i): No Compensation

Dynamically, the power transfer between two interconnected systems are expressed as

\[ P = \frac{V_s V_r}{X} \sin \delta, \quad \delta = \delta_s - \delta_r \]  \hspace{1cm} ... (3.1)

Where:

\( V_s \) = Voltage at the sending end of the transmission line
\( V_r \) = Voltage at the receiving end of the transmission line
\( X \) = Reactance of the transmission line
\( \delta \) = Angular difference between the sending and the receiving end voltages.

Assume that both \( V_s \) and \( I_s \) are zero i.e. power flow controller is off, and \( V_r = V_s = V \). Then the \( P, \delta \) relation is given by

\[ P_i = \frac{V^2}{X} \sin \delta \] \hspace{1cm} ... (3.2)

Case (ii): Series Compensation

When exist the need to transmit large amount of electric power over transmission lines, it is necessary to consider a group of factors that limit the electrical energy transmission capacity. Some of these factors are but not limited to: the voltage drop, the stability problem, the thermal effect on the conductors, etc. The constraints imposed by these factors may be overcome by means the construction of new transmission lines or by a transmission upgrade. These alternatives are commonly very expensive, especially in the case of long transmission lines. A more economic alternative in these cases is the series compensation.

The principal applications of series compensations are:

1. Improves voltage regulation
2. Improves power transfer capability of the transmission line
3. Improves system stability

Therefore, the equivalent system with series compensation as shown in Fig.3.3, which shows the tie line reactance changes from \( X \) to \( X - X_c \) due to series
capacitor compensation, and hence power transferred across the transmission line is increased to

\[ P = \frac{V_V}{X - X_c} \sin \delta \]  

(...3.3)

Assume that \( V_{wL} = V_s = V \), then the above equation becomes

\[ P = \frac{V^2}{X - X_c} \sin \delta \]  

(...3.4)

The degree of series compensation is defined as the relation between the capacitive reactance of the series capacitor and the inductive reactance of the transmission line.

Degree of Compensation = \( \frac{X_c}{X} \times 100\% \)  

(...3.5)

Where:

- \( X_c \): Capacitive reactance of the series capacitor
- \( X \): Inductive reactance of the transmission line.

Therefore, degree of compensation represents as 's or \( k' \), hence. \( X_c = sX \), by substituting this in Equ.3.4 and assume that \( I_s = 0 \) and \( V_{wi} = \frac{1}{j}X \). The voltage source acts at the fundamental frequency precisely as a series compensating capacitor. The degree of Series Compensation is defined by the coefficient, \( s \) \((0 \leq s \leq 1)\). With this, the \( P \) against \( \delta \) relationship becomes

\[ P_s = \frac{V^2}{X(1-s)} \sin \delta \]  

(...3.6)
Theoretically, the degree of compensation could be 100%, however this degree of compensation may produce large currents flows in the presence of small disturbances or faults. The circuit would also series resonant at the fundamental frequency, and it would be difficult to control transient voltages and currents during the disturbance. In the other hand a high level of compensation highlight the problems in protective relays and in the voltage profile during fault conditions.

A practical limitation of compensation is 80%, but common values in current installations are in the order of 50%.

Case (iii): Shunt Compensation

Assume that both \( V_{ph} = 0 \) and \( I_q = -j (4V/X) \) \([1- \cos (\delta/2)]\). The reactive current source acts like an ideal shunt compensator with an impedance of \( X/2 \). For this case of ideal mid point compensation, the \( P \) against \( \delta \) relationship can be written as

\[
P_t = \frac{V^2}{X} \sin \left( \frac{\delta}{2} \right)
\]

... (3.7)

Case (iv): Phase Angle Control

Assume that both \( V_{ph} = \pm j V_M \tan \alpha \) and \( I_q = 0 \). The basic idea behind the phase shifter is to keep the transmitted power at a desired level independent of angle \( \delta \) in a predetermined operating range. In this way, the actual transmitted power may be increased significantly even though the phase shifter does not increase the steady-state power transmission limit for this case of ideal midpoint compensation, the \( P \) against \( \delta \) relationship can be written as

\[
P_t = \frac{V^2}{X} \sin(\delta - \alpha)
\]

... (3.8)

The equations 3.1 to 3.4, define the relationship between the transmitted power and the transmission angle with series and shunt compensation and phase shifting. The idea behind the flexible AC transmission concept is to control these parameters according to prevailing system conditions. Except for UPFC, most of the FACTS controllers use only single control variable which can not control total performance of the transmission line. Due to these facts, the UPFC device is used in
this work to control Voltage profile, Power profile and Security/ Stability of the Electrical transmission system.

3.4 UPFC STRUCTURE AND OPERATING PRINCIPLE

The UPFC is an advanced power system device capable of providing simultaneous control of voltage magnitude, active and reactive power flows in an adaptive fashion. It has

- Instantaneous speed of response
- Extended functionality
- Capability to control voltage, line impedance and phase angle in the power system network
- Enhanced power transfer capability
- Ability to decrease generation cost
- Ability to improve security and stability

3.4.1 Circuit Description and Implementation of UPFC

The circuit diagram of UPFC is shown in Fig. 3.4. It consists of two converters – one connected in series with the transmission line through a series inserted transformer and the other connected in shunt with the transmission line through a shunt transformer. The DC terminals of the two converters are connected together with a DC capacitor. The series converter control the injected voltage magnitude and phase angle in series with the line to control the active and reactive power flows on the transmission line. Hence, the series converter will exchange active and reactive powers with the line.

![Fig. 3.4 Circuit Diagram of Unified Power Flow Controller (UPFC)](image-url)
**Characteristic of UPFC**

The concept of UPFC makes it possible to handle practically all the power flow control and transmission lines compensation problems using solid-state controllers that provide functional flexibility [40] which are generally not obtained by thyristor-controlled controllers.

**Convertible Static Compensator (CSC)**

It is the latest generation device which has the ability to increase the power transfer capability and maximize the use of existing transmission line.

The parameters of the controller in Fig. 3.4 include the control system guides together with the time constants and UPFC voltage/current operating limits. These parameters are predetermined and set the controller prior to its operation. The switching of individual GTO Thyristors or IGBTs in the converters in Fig. 3.5 are generated by the controller. The switching signals are determined to achieve minimum errors between the control variables obtained from measurements and their references.

![Diagram of UPFC implementation](image-url)

*Fig. 3.5 Implementation of the UPFC by two back-to-back Voltage-Sourced Converters (VSC) [10]*

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3.4.2 Power Losses in UPFC Operating Condition

Neglecting UPFC losses, during steady-state operation, it neither absorbs, nor injects real power with respect to the system. Physical interpretation of this statement is that the voltage of the DC link capacitor remains constant at the pre-specified value $V_{\text{DC}}$. This constraint must be satisfied by the UPFC steady-state equation. Under steady-state condition the constraint $P_{\text{sc}} + P_{\text{sh}} = 0$ implies that, no real power is exchanged between the UPFC and system, thus DC link voltage remain constant and the two sources are mutually independent. Therefore, the operation of UPFC is based on

- Reactive shunt compensation
- Series compensation
- Phase shifting

By adding the injected voltage $V_{\text{pi}}$ with appropriate amplitude and phase angle to the terminal voltage, UPFC can fulfill all the above functions thereby meet multiple control.

Apart from those incurred in the converter coupling transformers, the losses in UPFC arise from the semiconductor switching devices together with the DC link. The power loss in the DC link in the UPFC depends on the DC side current determined by the required operating current levels on the ac side. Although, the operating current levels can be high, the power loss here is not a major one, for a short length of the DC link in the UPFC. However, the power losses associated with the semiconductor device operation can represent a concern in relation to UPFC operational limits. These UPFC power losses are mainly due to forward biased voltage (i.e., on-state voltage) and finite times required in turning on and turning off the practical switching devices.

If $I_0$ is the operating current level in the switching device, then the power losses are classified into three types: on-state power loss, turn-off transition loss, and turn-on transition loss as described in the following equations:

$$P_{\text{loss}}(\text{on-state}) = V_{\text{on}} I_0 (T_{\text{on}}/T_s)$$  \hspace{1cm} (3.9)

$$P_{\text{loss}}(\text{Turn-off}) = 1/2 V_{\text{d}} I_0 f_{T_{\text{on}}}(\text{off})$$  \hspace{1cm} (3.10)

$$P_{\text{loss}}(\text{Turn-on}) = 1/2 V_{\text{d}} I_0 f_{T_{\text{on}}}(\text{on})$$  \hspace{1cm} (3.11)
$P_{\text{Loss}}$ (on-state), $P_{\text{Loss}}$ (Turn-off) and $P_{\text{Loss}}$ (Turn-on) are average power losses during on-state, turn-off transition and turn-on transition respectively for the semiconductor device.

$V_d$ is the semiconductor device off-state voltage  
$V_{\text{on}}$ is the semiconductor device on-state voltage 
$I_o$ is the semiconductor device on-state current  
$f_s$ is the switching frequency

$t_{\text{(on)}}$ is the turn-on transition time interval which is measured from the time instant when the current starts rising (from zero) to the time instant when the voltage achieve a small on-state voltage of $V_{\text{on}}$. 

$t_{\text{(off)}}$ is the turn-off transition time interval which is measured from the time instant when the voltage starts increasing (from the small on-state value) to the time instant when the current reaches to zero. 

$T_s$ is the switching time period.

The sum of the power losses in Equations (3.10) and (3.11) is referred to as the switching power loss which is directly proportional to switching frequency. Eq. (3.10) and (3.11) indicate that the switching losses can be reduced by decreasing the switching frequency.

In UPFC operation, it is desirable to have a switching frequency as high as possible so that the lower order harmonics will be minimal, and the waveform distortions are confined mainly in the high frequency band. When this is the case, the harmonic filtering requirements on the ac side of the UPFC will be substantially reduced as the ac side impedance themselves provide very effectively the filtering functions in the high frequency band.

The finite turn-off and turn-on times of the switching device which lead to higher power loss at high switching frequency, ultimately impose an upper feasible limit on the switching frequency. A principal aim in the UPFC design is to achieve a low overall loss, taking into account the maximum UPFC operating currents. On this basis, it is essential to represent the UPFC loss is, in general, nonlinear function of
the UPFC operating current, given that there will be some dependence on the current level of switching device, turn-on and turn-off times.

However, if the main focus is on the study and the control of power system of which UPFCs are a part, the UPFC power losses will have only secondary effect on the overall power system response which are often discounted without having any impact on the engineering decision.

3.5 UPFC CONTROL MODES

This section describes the steady-state control mode of UPFC of Voltage Sourced Convertor mode (VSC) interfaced with the transmission line which is used in this work [38]. The UPFC is capable of providing the compensation for the transmission line. Subject to the UPFC operating units, a wide range of power system quantities and parameters can be controlled to specified values to achieve system operating requirements or benefits.

3.5.1 Series Converter

The series converter together its controller will generate a variable voltage in series with the line in achieving a wide range of system operating requirements. The individual requirements are in general, expressed in terms of specified control modes and are implemented by the UPFC series converter controller [25] - [29] in Fig. 3.5. The corresponding phasor representations of series converter of UPFC are shown in Fig. 3.6

![Phasor diagrams illustrating the conventional transmission control capabilities of the UPFC](image)

Fig. 3.6 Phasor diagrams illustrating the conventional transmission control capabilities of the UPFC

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a. Direct Voltage Injection Mode

The series converter generates a voltage phasor with magnitude and phase angle specified by the reference inputs [40]. A special case of this controlling mode is that of compensation for the transmission line series reactance in which the injected voltage is kept in quadrature i.e. 90° with the line current as shown in Fig. 3.6. In this case, the level of series compensation depends on the value of the reference for series voltage magnitude.

b. Line Impedance Emulation Mode

The series voltage injector is controlled to the value proportional to the line current so that the series converter transformer together with the series converter is equivalent to impedance, the value of which is specified by the reference input. In order to avoid the resonance or instability caused by a negative resistance or capacitive reactance, the reference value of the impedance has to be chosen carefully. In this mode of control the total resistance and reactance of the interconnection between bus bars i and j in Fig. 3.4, can both be reduced which provides a more effective series compensation in the case of lines with high resistance.

c. Phase Angle Shifter Emulation Mode

The series converter injects an appropriate voltage so that the voltage at bus bar j is phase shifted relative to the voltage at bus bar 'i' in Fig. 3.4, by an angle specified by the reference input. This control mode is used to control mainly the active power flow in the transmission lines.

d. Power Flow Control Mode

In this mode, the series converter can control both active and reactive power flows independently in a transmission line by regulating the series injected voltage in both magnitude and phase angle. The injected voltage is determined automatically and continuously to maintain the desired active and reactive power despite system changes. Among many FACTS devices available at present, only the UPFC has this versatile mode of control [39-40] which provides the optimal operation of the line in terms of both active and reactive power flows.
3.5.2 Shunt Converter

As discussed in section 3.5 there are active and reactive power components associated with the shunt voltage source raised from the shunt converter operation. The active power component is exchanged with that required by the series converter to contribute to the active power flow control in the transmission line. However, it is the reactive power component i.e., the principal one relevant to voltage or reactive power control at bus bar “i” in Fig. 3.4. There are two control modes for the shunt converter- reactive power control mode and voltage control mode [25] - [29].

a. Reactive Power Control Mode

In reactive power control mode, the reference input is a signal representing the required reactive power injection at the bus bar to which the shunt converter is connected and identified by “i” in Fig. 3.4. In practice, it is preferable to control the shunt converter current instead of directly controlling the reactive power, as the shunt converter operating limits are expressed in terms of current [38]. Therefore, the reactive power reference is first transformed into equivalent reactive current component and is then fed into the shunt current controller.

b. Voltage Control Mode

Similar to the reactive power controller, voltage control modes is based on the control of the shunt converter reactive current component. However, the equivalent reactive current required is determined by the outer voltage control loop with the objective of achieving the required steady-state voltage / current characteristic defined by the reference for the voltage at bus bar i in Fig. 3.4 and slope reactance. The output of this voltage control loop is interpreted as the required reactive current for use in the inner shunt converter current control loop.

3.6 STAND-ALONE SHUNT AND SERIES COMPENSATION

The UPFC circuit structure offers the possibility of operation in which the two converters operate independently by disconnecting the DC link and splitting the dc capacitor bank [25-29]. In this case, the shunt converter operates as a STATCOM and series converter as a SSSC. This kind of operation is applied to handle the
contingencies in which failure of either of converters occurs or adapt to the future change of the system requirement in which either shunt or series compensation is required of both converters. Because of the disconnection of the dc link in this operation mode neither converter is capable of exchanging the active power with the system. This limits the flexibility of the separate shunt and series compensators in power system control. In the stand alone operation, the series converter controller needs to be modified to provide the dc voltage control.

3.6.1 Operating Limits of UPFC

The operating modes presented are subjected to the operating limits of the shunt and series converters including their transformers, the dc link together with the transmission line voltage limits as shown in Table 3.2 [25], [29-31].

- **Limit on the series injected voltage magnitude**

  The magnitude of the series injected voltage is limited by the maximum voltage rating of the series converter. The series converter and its associated transformer are designed to a specified maximum voltage level. Operation beyond this level is not allowed.

- **Limit on the series converter current**

  Depending on the rating of the series converter and the coupling transformer the series converter current has an allowable maximum value.

- **Limit on the shunt converter current**

  The shunt converter current has two components i.e., active and reactive. The active current component is controlled by the shunt converter controller to achieve a constant dc link voltage in steady-state operation which at the same time leads to the net interchange of the active power between the two converters is zero if the UPFC losses are discounted. The reactive component relates to reactive power supplied to or absorbed from the transmission system that supports the voltage of the bus bars on the high voltage side of the shunt converter transformer. In relation to the operating unit on the shunt converter current the active component is assigned to have in general
UPFC application, a higher priority than the reactive one so that the dc link voltage control together with the active power requirement takes the precedence over reactive power/voltage control at bus bar 'i' in Fig. 3.4, when the shunt converter current reaches its limit.

- Limit on the active power exchanged between the series and shunt converters

Because of the size and rating of the dc link and dc capacitor the active power exchanged between the two converters has the upper limit.

- Lower and upper limits on the line side voltage of the UPFC

The UPFC has the intrinsic ability to raise or lower the voltage magnitude at bus bar j in Fig. 3.4 by a large fraction. Therefore, it will be necessary to impose lower and upper available magnitudes of the voltage at bus bar j to satisfy the line voltage operating limits.

<table>
<thead>
<tr>
<th>UPFC parameters</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series converter Voltage magnitude (p. u.)</td>
<td>0.20</td>
</tr>
<tr>
<td>Active power exchange between shunt and series converters (MW)</td>
<td>100</td>
</tr>
<tr>
<td>Shunt converter current (p. u.)</td>
<td>3</td>
</tr>
<tr>
<td>Series converter current (p. u.)</td>
<td>3</td>
</tr>
<tr>
<td>Minimum line-side voltage magnitude (p. u.)</td>
<td>0.90</td>
</tr>
<tr>
<td>Maximum line-side voltage magnitude (p. u.)</td>
<td>1.10</td>
</tr>
</tbody>
</table>

Currents are in p.u. on 100 MVA bases [33]

3.7 MODELING OF UNIFIED POWER FLOW CONTROLLER

In order to effectively investigate the impact of FACTS devices on power systems their modeling [32-33] and implementation in power system software is essential. There are three types of methods for modeling:

- Electro- magnetic models for detailed equipment level investigation
- Steady- state models for system steady- state operation valuation
- Dynamic models for stability studies
In this research work, steady-state modeling is considered. The UPFC model itself is very flexible. It allows the control of active and reactive powers and voltage magnitude simultaneously. It can also be set to control one or more of these parameters in any combination or to control none of them. Considerable progress has been achieved in UPFC modeling intended for conventional load flow studies.

Performance analysis and control synthesis of UPFC requires its steady-state and dynamic models. Several models have been suggested for modeling of UPFC. Out of those Power flow model has been considered here for the studies. Based on the power flow model a set of load flow equations have been developed after modifying the UPFC connected branch.

There are two aspects in handling the UPFC in steady-state analysis.

- When the UPFC parameters are given, a power flow program is used to evaluate the impact of the given UPFC on the system under various conditions. In this case UPFC is operated in open loop form.
- As UPFC can be used to control the line flow and bus voltage, control techniques are needed to drive the UPFC control parameters to achieve the required objective. In this case UPFC is operated in closed loop form.

The steady-state model is based on the power flow between two buses [53]-[55]. These models are discussed in the following sections.

![Fig. 3.7 UPFC in a Transmission line](image-url)
Let us consider the UPFC as shown in the Fig.3.7, which is used to maintain a pre-specified power flow from 'i' bus to 'j' bus and to regulate the j bus at a specified value. Using power flow terminology 'j' bus is a PV bus and 'i' bus is a PQ bus.

Neglecting UPFC losses $P_{ij} = P_{it}$, a pre-specified value, $\delta_j$ and $V_j$ determine $P_{jt}$ and $V_{jt}$ respectively. To calculate the UPFC control variables for the given power flow condition, a power flow analysis is performed where the UPFC is modeled as shown in Fig.3.7. Then the power flow analysis results are used to solve the UPFC steady-state equations to determine $\delta_j, V_j, \delta_i$, and $V_i$.

The main purpose of adding the UPFC is to keep the complex power flow through the line to specified value of $S_{ij} = (P_{ij} + jQ_{ij})$ and $S_i$ or to regulate the voltage magnitude of bus $i$. The converter voltages and the associated transformer impedances of the UPFC are shown in Fig3.7 (b). Subscripts ‘se’ and ‘sh’ are used to represent the quantities of the series and shunt converters, respectively. Note that in Fig 3.7 (b) a new bus’ k’ is added to represent the receiving-end or second terminal of the UPFC. It may be mentioned here that, for given voltages at buses i and j, the complex power flow through the line can be regulated by controlling the complex voltage $V_{se}$ or $V_{sh}$ that is injected voltage of the series converter.

On the other hand, the voltage magnitudes of bus $i$ can be regulated by controlling the reactive power injection of the shunt converter. Another important function of the converter is to supply the active power injection required by the series converter. The injected active and reactive power of the shunt converter can be controlled by adjusting the complex voltage $V_{sh}$ or $V_{rab}$ that is the injected voltage of the converter. The ultimate objective is to find the values of $V_{se}$ and $V_{sh}$, through standard load flow simulations, so that the desired complex power flow through the line and voltage magnitude of bus $i$ can be maintained. This requires a careful modeling of the UPFC so that it can be easily incorporated into any standard load flow program.
3.7.1. Model of the Series Converter

![Diagram of Series Converter](image)

The series injected voltage sources $V_{se}$ of the UPFC can be easily transformed into a current source, $I_{sc}$, as shown in Fig 3.8(a). The value of $I_{sc}$ given by

$$I_{sc} = \frac{V_{se}}{Z_{se}}$$

The series current source between buses i and k can be replaced between two shunt current sources (at buses i and k) as shown in Fig 3.8(b). Without loss of generality, the shunt current sources can further be replaced by two complex loads, as shown in Fig 3.8 (c). The complex loads are given by

$$S_{1se} = \frac{S_{se}}{Z_{se}}$$

$$S_{kse} = \frac{S_{se}}{Z_{se}}$$

Fig. 3.8 Representation of Series Converter of UPFC
The complex power balance equation at bus k in Fig 3.8 (c) can be written as

\[
S_{k} = S_{ske} + S_{sh}
\]

Or

\[
V_i \left( \frac{V_i - V_k}{Z_{se}} \right) = -V_i I_{ske}^* + S_{sh}
\]

Or

\[
I_{ske} = \left( \frac{S_{ske}}{V_i} \right) - \left( \frac{V_i - V_k}{Z_{se}} \right)
\]

By equation (3.13) and (3.15), the complex series injected voltage \( V_{ske} \) can be expressed as

\[
V_{ske} = V_i - V_i + Z_{se} \left( \frac{S_{ske}}{V_i} \right)
\]

Thus for given voltages at buses i and k, the series injected voltage that forces the system to maintain the specified line power flow can be obtained from Eq. (3.16.). The active power injection (\( P_{aw} \)) into the system by the series converter can readily be written from Fig 3.8 (b). As

\[
P_{aw} = R_e \left[ V_{aw} \left( \frac{V_i + V_{aw} - V_k}{Z_{aw}} \right) \right]
\]

The above active power of the series converter must be supplied by the shunt converter through the dc link.
3.7.2 Model of the Shunt Converter

Fig. 3.9 Representation of Shunt Converter of UPFC

The shunt converter voltage $V_{sh}$ and the associated transformer impedance $Z_{sh}$ of the UPFC are separately shown in Fig 3.9 (a). The converter injects a complex
power $S_{sh} (=P_{sh} + jQ_{sh})$ into the network at bus i. The power injection model of the converter is shown in Fig 3.9(b). For a given $S_{sh}$ the shunt converter voltage $V_{sh}$ can readily be written Fig 3.9 (a) as

$$V_{sh} = V_i + Z_{sh} \left( \frac{S_{sh}}{V_i} \right)$$  \hspace{1cm} (3.18)

Note that the reactive power $Q_{sh}$ of the converter is used to maintain the desired voltage magnitude at bus i. However the active power $P_{sh}$ of the converter needs to satisfy the active power balance of the UPFC ($P_{se} + P_{sh} = 0$). With this in mind the shunt converter can be represented by a synchronous condenser (with $P = 0$) and an active load of $-P_{sh} (-P_{se})$. As shown in Fig 3.9 (c).

The reactive power limit of the synchronous condenser can be considered as

$$Q_{lim} = \pm \sqrt{\left( S_{sh}^{max} \right)^2 - P_{sh}^2}$$  \hspace{1cm} (3.19)

Here $S_{sh}^{max}$ is the maximum MVA rating of the shunt converter.

The overall model of the UPFC can be now obtained by combining the equivalent circuits of the series converter Fig 3.8(c) and shunt converter Fig 3.9(c).

![Fig. 3.10 Proposed UPFC model for Load flow studies.](image)

Fig 3.10 represents the proposed UPFC model for load flow studies. It consists of a synchronous condenser (with $P = 0$) to fictitious loads ($S_i$ and $S_k$), and an impedance ($Z_{se}$) all of these elements can easily be incorporated into any standard load flow program that is NRLF method. Note that the fictitious loads in Fig 3.10 are
not constant and need to be updated regularly during the iteration process using the computed values of \( V_i \) and \( V_k \).

The performance analysis and control synthesis of UPFC requires its steady-state and dynamic models. Several models have been suggested for modeling of UPFC. Out of those models one known as Power flow model has been considered here for the studies. Based on the Power flow models a set of Load flow equations have been developed after modifying the UPFC connected branch.

Fig.3.11 will give the complete behavior of the electrical transmission system with Voltage Source Converter (VSC) model of UPFC and phase shift position (injected voltage magnitude and its angular position), it is discussed in the next section. This device creates a tremendous quality impact on electrical transmission system security / stability.

\[
P_e = \frac{1}{X} \sin(\delta_1 - \delta_2)
\]

**Fig. 3.11 Power flow (equation) model of UPFC**

### 3.7.3 Voltage-Sourced Converters (VSC) Interfacing To Transmission Line

One of the most commonly used power electronic-based building blocks is a Voltage-Sourced Converter (VSC). A basic building block of any Voltage-Sourced Converter (VSC) is the three-phase converter bridge. One commonly known configuration for a three-phase bridge is shown in Fig.3.12. The bridge has two DC terminals (indicated by "+" and "-" ) and three AC terminals ("~") in the mid points of the converter legs. By controlling the states of switches in the legs it can produce arbitrary voltage waveforms at the AC terminals.
When a VSC is interfaced to a transmission system it has to: (i) operate at the line frequency, and (ii) produce a balanced set of sinusoidal voltages. Therefore, a VSC coupled to the transmission system has only two control degrees of freedom – it can vary the magnitude and the phase angle of its output voltage relative to the system voltage. These two control degrees of freedom can be mapped into freedom to exchange active and reactive power with the transmission system. The amount of exchanged reactive power is limited only by the current capacity of the converter switches, while the active power coupled to (from) the line has to be supplied from (delivered to) the DC terminals, as shown symbolically in Fig. 3.13.

![Fig. 3.12 A three-phase converter bridge – the basic building block of a VSC](image)

![Fig. 3.13 A VSC interfaced to a transmission line: P, Q exchange](image)
3.8 POWER INJECTION MODEL (PIM) OF UPFC

The VSC model of UPFC is converted into two power injections in polar form for power flow studies with approximate impedances as shown in Fig 3.14. This model has two ideal Voltage Sources, one connected in series and other in shunt, between the two buses. The output of series voltage magnitude $V_{sc}$ controlled between the limits $V_{sc\, min} \leq V_{sc} \leq V_{sc\, max}$ and the angle $\theta_{sc}$ between the limits $0 \leq \theta_{sc} \leq 2\pi$ respectively. The shunt voltage magnitude $V_{sh}$ controlled between the limits $V_{sh\, min} \leq V_{sh} \leq V_{sh\, max}$ and the angle between $0 \leq \theta_{sh} \leq 2\pi$ respectively. $Z_{sc}$ and $Z_{sh}$ are considered as the impedances of the two transformers, one connected in series and other in shunt, between the transmission lines [55]. The advantage of power injection representation is that it does not destroy the symmetric characteristics of admittance matrix.

The voltage source can be represented by the relationship between the voltages and amplitude modulation ratios and phase shift of the UPFC. In this model, the shunt transformer impedance, the transmission line impedance and the series transformer impedance are assumed to be constants and no power loss is considered with the UPFC.

![Fig. 3.14: Equivalent circuit of UPFC](image)

The ideal series and shunt voltage source equations from the Figs. 3.4, 3.5 and 3.6 which were presented in this Chapter, section 3.4, can be written as

$$V_{sc} = V_{se}(\cos \theta_{sc} + j \sin \theta_{sc})$$  \hspace{1cm} \hspace{1cm} (3.20)

$$V_{sh} = V_{sh}(\cos \theta_{sh} + j \sin \theta_{sh})$$  \hspace{1cm} \hspace{1cm} (3.21)
The magnitude and the angle of the converter output voltage used to control the power flow mode and voltage at the nodes as follows [34-35-36]

1. The bus voltage magnitude can be controlled by injecting a series voltage $V_v$ in phase or anti-phase

2. Power flow as a series reactive compensation controlled by injecting a series voltage $V_v'$ in quadrature to the line current

3. Power flow as phase shifter controlled by injecting a series voltage of magnitude $V_v''$ in quadrature to node voltage $\theta_v$

Based on the equivalent circuit shown in Fig3.14, the active and reactive power equations can be written as follows:

At node i:

$$P_i = V_i^2 G_i + V_i V_v \left( G_i \cos(\theta_i - \theta_v) + B_i \sin(\theta_i - \theta_v) \right) + V_v V_v'$$

$$Q_i = -V_i^2 B_i + V_i V_v \left( G_i \sin(\theta_i - \theta_v) - B_i \cos(\theta_i - \theta_v) \right) + V_v V_v' \left( G_i \sin(\theta_i - \theta_v) - B_i \cos(\theta_i - \theta_v) \right)$$  \hspace{1cm} (3.22)

At node k:

$$P_k = V_k^2 G_k + V_k V_v \left( G_k \cos(\theta_k - \theta_v) + B_k \sin(\theta_k - \theta_v) \right) + V_v V_v' \left( G_k \cos(\theta_k - \theta_v) + B_k \sin(\theta_k - \theta_v) \right)$$  \hspace{1cm} (3.24)

$$Q_k = -V_k^2 B_k + V_k V_v \left( G_k \sin(\theta_k - \theta_v) - B_k \cos(\theta_k - \theta_v) \right) + V_v V_v' \left( G_k \sin(\theta_k - \theta_v) - B_k \cos(\theta_k - \theta_v) \right)$$  \hspace{1cm} (3.25)
Series converter branch:

\[ P_{sr} = V_{sr}^2 G_{sr} + V_{sr} V_{s}' (G_{sr} \cos(\theta_{sr} - \theta_s) + B_{sr} \sin(\theta_{sr} - \theta_s)) + \]

\[ V_{sr} V_{s}' (G_{sr} \cos(\theta_{sr} - \theta_s) + B_{sr} \sin(\theta_{sr} - \theta_s)) \]  \hspace{1cm} (3.26)

\[ Q_{sr} = -V_{sr}^2 B_{sr} + V_{sr} V_{s}' (G_{sr} \sin(\theta_{sr} - \theta_s) - B_{sr} \cos(\theta_{sr} - \theta_s)) + \]

\[ V_{sr} V_{s}' (G_{sr} \sin(\theta_{sr} - \theta_s) - B_{sr} \cos(\theta_{sr} - \theta_s)) \]  \hspace{1cm} (3.27)

Shunt converter branch:

\[ P_{sh} = -V_{sh}^2 G_{sh} + V_{sh} V_{s}' (G_{sh} \cos(\theta_{sh} - \theta_s) + B_{sh} \sin(\theta_{sh} - \theta_s)) \]  \hspace{1cm} (3.28)

\[ Q_{sh} = V_{sh}^2 B_{sh} + V_{sh} V_{s}' (G_{sh} \sin(\theta_{sh} - \theta_s) - B_{sh} \cos(\theta_{sh} - \theta_s)) \]  \hspace{1cm} (3.29)

Where

\[ Y_{ii} = G_{ii} + jB_{ii} = Y_{i}' + Y_{sh} \]  \hspace{1cm} (3.30)

\[ Y_{is} = G_{is} + jB_{is} = Y_{s}' \]  \hspace{1cm} (3.31)

\[ Y_{si} = Y_{si}' = G_{si} + jB_{si} = -Y_{i}' \]  \hspace{1cm} (3.32)

\[ Y_{sh} = G_{sh} + jB_{sh} = -Y_{sh}' \]  \hspace{1cm} (3.33)

Detailed derivation of the equations 3.22-3.33 is given in Appendix-D.

Assuming a free converter loss operation of UPFC, the active power supplied to the shunt converter \( P_{sh} \) equals to the active power demanded by the series converter \( P_{sr} \).

\[ P_{sr} + P_{sh} = 0 \]  \hspace{1cm} (3.34)

Furthermore if the coupling transformers are assumed to contain no resistance then, the active power at bus i matches the active power at bus k; that is,

\[ P_{sr} + P_{sh} = P_i + P_k = 0 \]  \hspace{1cm} (3.35)

The UPFC power equations are linearised and combined with the equations of the AC transmission network. For the cases when the UPFC controls the following parameters:
1) Voltage magnitude at the shunt converter terminal (bus i)
2) Active power flow from bus i to bus k and
3) Reactive power injected at bus k, and taking bus k to be PQ bus.

N-R method has been adopted to solve the power flow problem [59-60] where each UPFC is represented by a set of nodal power injections, the values which are tentatively determined from the solution of optimization. Iterations in the optimization power flow loop are required until convergence is achieved. As many of the UPFC operation limits are in practice expressed in terms of voltages and currents, the power injection models which are based on the transformation into nodal powers have a difficulty in representing all the practical limits encountered in UPFC operation.

Based on power injection model for representing the UPFC, power flow solution method has also been developed where constrained optimization is not required. The solution obtained in sections 3.4 - 3.8 is used for checking against UPFC operating limits mentioned in Table 3.2. Depending on the outcome of the checking, UPFC parameters which include series and shunt voltage magnitudes, shunt and series converter currents and active power exchange between the two converters are adjusted for complying with the specified limits.

Following the adjustments, a revised power flow problem is formulated when the UPFC injected power flows are modified, and a new power flow solution is obtained. Further checking against UPFC operating limits will then be carried out, and the iterative process of the power flow limits checking loop continue until all the UPFC parameters are within their specified limits.

More recently, a new model for the UPFC based on ideal transformer with a complex turns ratio and variable shunt admittance has been proposed in [57-60]. The model is an approximate one. The principal use of which is for identifying possible optimal locations for installing UPFC. While simulating the program in Matlab, the operating limits as given in Table 3.2 are imposed on UPFC operation.

3.9 POWER EQUATIONS OF THE UPFC CONNECTED BRANCH

Consider a UPFC with its booster transformer connected in series with a transmission line. Assume that the exciting transformer is connected to the bus ‘i’
and the two terminals of the transmission line are denoted as bus 's' and 'k' respectively. By using the UPFC model illustrated in Fig. 3.14 and 'P1' equivalent circuit of the transmission line, the branch with the UPFC connected between bus 'i' and 'k' can be modeled. \( Z_{lk} = R_a + jX_a \) and \( jB_a \) denote the parameters of the transmission line. \( Y_i \) and \( Y_k \) represent the system shunt admittance at bus 'i' and 'k' respectively.

\[
S_{ki} = P_i + jQ_i = P_i + jQ_i + \Delta S_e \quad \ldots \quad (3.36)
\]

\[
P_i + jQ_i = \left( \frac{V_i - V_k}{R_a + jX_a} + jB_a V_k \right) V_k \quad \ldots \quad (3.37)
\]

\[
\Delta S_e = P_i + jQ_i = \left( \frac{V_i}{R_a + jX_a} \right) V_k \quad \ldots \quad (3.38)
\]

\[
S_{ak} = P_a + jQ_a \quad \ldots \quad (3.39)
\]

\[
P_a = R_a \left( \frac{P_i^2 + Q_i^2 + B_a^2 V_i^2 + 2B_a Q_i}{V_i^2} \right) - P_i \quad \ldots \quad (3.40)
\]

\[
Q_a = -I_a V_e = \left[ (E_i V_i + F_i V_k) \sin \delta_a - (E_i V_i + F_i V_k) \cos \delta_a \right] V_i \quad \ldots \quad (3.41)
\]

Where

\[
E_i = C_x P_c + C_y Q_c
\]

\[
E_2 = C_y P_c - C_x Q_c
\]

\[
F_i = B_a C_y
\]

\[
F_2 = -B_a (1 + C_x)
\]

\[
C_x = 1 - B_a (1 + C_y)
\]

\[
C_y = B_a R_a
\]

\[
\delta_a = \delta_i - \delta_k \cdot \delta_a \quad \text{is the phase angle difference between bus 'i' and 'k'}
\]

Detailed derivation of the above equations 3.36-3.41 is given in APPENDIX- C.

Based on the above analysis, the subsequent sections of this chapter present a study on steady-state model of UPFC applied to 22kV and 33kV transmission line system.
3.10 STUDY ON EFFECT OF UPFC DEVICE FOR 22kV AND 33kV TRANSMISSION LINE SYSTEM

In section 2.8, of second chapter MATLAB program is run to evaluate the Voltage profile, Power profile and Transmission losses on IEEE-14 bus system with conventional load flow method.

In the beginning of this work a sample MATLAB Simulink model [37-46] is used to evaluate the performance of 22kV and 33kV single line transmission system [Appendix-B]. The system is simulated with and without UPFC device. This section adopts the approach for developing a new steady-state UPFC model in which the UPFC controller dynamics are simulated during the power flow solution process. This is feasible as the power network variables are updated at each iteration can be interpreted as dynamic ones.

The UPFC offers an alternative means to mitigate the transmission system oscillations. The crucial part of development of UPFC is the selection of the input signals and the adopted control strategy for this device in order to damp power oscillations in an effective and robust manner [46]. The UPFC parameters can be controlled in order to achieve the maximal desired effect in solving first swing stability problem. This problem appears bulky for power transmission systems with long transmission lines.

In the simulation study, the UPFC facilitates the real-time control and dynamic compensation of AC transmission system [41-44]. It provides the necessary functional flexibility required for solving the problems faced by the utility industry. The corresponding simulation models with and without UPFC are implemented in Matlab / Simulink [46 - 47] environment for the following cases.

3.11 TESTING OF ELECTRICAL TRANSMISSION SYSTEM WITHOUT UPFC DEVICE

The basic function of the electrical power system is to supply electrical energy to consumers as economically as possible with an acceptable level of reliability. An efficient transmission system is expected to have the optimum capability to provide the transfer of electrical energy between the point of supply and the point of delivery.
Transmission line performance assessment depends on data collection capabilities and performance metrics to ensure continued grid adequacy and security. The following section discusses the testing of transmission line without UPFC device in Matlab / Simulink model.

A standard 22kV European power system is considered for evaluation of a non-Indian power system and a 33kV system is taken into account to test the performance of UPFC in Indian conditions. This provides a comprehensive testing of UPFC.

3.11.1 Simulink Model of 22kV Transmission Line

The Simulink model of single line of electrical transmission system of 22kV Line is shown in Fig 3.15. The system is considered with the following parameters are given in Appendix-B. The load parameters are selected in such a way that it realizes more practical operating conditions [37-46]. The model is simulated and corresponding results of voltage magnitude of peak value, real and reactive power flows are shown in Figs. 3.16 and 3.17 respectively.

Fig. 3.15 Simulink model of 22kV Transmission Line
Fig. 3.16 Voltage magnitude of 22 kV Transmission Line ($V_p = 20.04$ kV)

Fig. 3.17 Real and Reactive power flows of 22 kV Transmission Line for
(a) 93.69 MW and (b) 57.53 MVar
By observing the above waveforms, at steady-state time $t = 0.02\,\text{sec}$, the real power is $93.69\,\text{MW}$ and the reactive power is $57.53\,\text{MVAr}$ and corresponding the voltage magnitude of peak value is $20.4\,\text{kV}$.

3.11.2 Simulink Model of 33kV Transmission Line

The Simulink model of single line of electrical transmission system of 33kV Line is shown in Fig. 3.18. The system is considered with the following parameters are given in Appendix-B. The load parameters are selected in such a way that it realizes more practical operating conditions [37-46]. The model is simulated and corresponding results of voltage magnitude of peak value, real and reactive power flows in line are shown in Figs 3.19 and 3.20 respectively.

![Simulink model of 33kV Transmission Line](image)

Fig.3.18 Simulink model of 33kV Transmission Line
Fig. 3.19 Voltage magnitude of 33 kV Transmission Line ($V_p = 31.08$ kV)

Fig. 3.20 Real and Reactive power flows of 33 kV Transmission Line
for (a) 140MW and (b) 88.50 MVAR
By observing the above waveforms, at steady-state time $t = 0.02\text{sec}$, the real power is $140\text{MW}$ and the reactive power is $88.501\text{MVAr}$ and the corresponding voltage magnitude of peak value is $31.08\text{kV}$.

3.12 TESTING OF ELECTRICAL TRANSMISSION SYSTEM WITH UPFC DEVICE

With the development of power systems, especially, the opening of electric energy markets, it becomes more and more important to control the power flow along the transmission line, thus to meet the need of power transfer. On the other hand, the fast development of power electronic technology has made UPFC a promising part for future power system needs. This device is an advanced power system device capable of providing simultaneous control of voltage magnitude, active and reactive power flows in an adaptive fashion. The following section discusses the testing of transmission line with UPFC device in Matlab / Simulink model.

3.12.1 Simulink Model of 22kV Transmission Line

The Simulink model of UPFC, a single line transmission system of 22 kV Line is shown in Fig 3.21. The system is considered with the following parameters with UPFC device parameters are given in Appendix-B. The load parameters are selected in such a way that it realizes more practical operating conditions [37-46]. The model is simulated and corresponding results of voltage magnitude of peak value, real and reactive power flows are shown in Figs.3.23 and 3.24 respectively.

![Simulink model of 22kV Transmission Line](image-url)

**Fig. 3.21 Simulink model of 22kV Transmission Line**
3.12.2 UPFC Sub-System

The sub-system of the UPFC model that is interconnected to the electrical transmission line model with parameters as given in Appendix-B, is shown Fig.3.22. The range of variations of delay angle for different IGBTs in bridges is given in below:

<table>
<thead>
<tr>
<th>Rectifier</th>
<th>Delay period</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGBT-1, IGBT-2</td>
<td>0 – 5 msec</td>
</tr>
<tr>
<td>IGBT-3, IGBT-4</td>
<td>10 msec - 15 msec</td>
</tr>
<tr>
<td>Inverter</td>
<td></td>
</tr>
<tr>
<td>IGBT-5, IGBT-6</td>
<td>0 - 10 msec</td>
</tr>
<tr>
<td>IGBT-7, IGBT-8</td>
<td>10 msec - 20 msec</td>
</tr>
</tbody>
</table>

The corresponding voltage waveform of 22kV line with compensation is shown Fig.3.23 and the real and reactive power waveforms are shown in Fig.3.24 respectively.

Fig3.22 UPFC Sub-System model for 22kV Transmission Line
Fig. 3.23 Voltage magnitude of 22 kV Transmission Line ($V_p = 21.23$ kV)

Fig. 3.24 Real and Reactive power flows of 22 kV Transmission Line

for (a) 98.15MW and (b) 61.64 MVAr
By observing the above waveforms, at steady-state time $t = 0.02$ sec, the real power is 98.15 MW and the reactive power is 61.64 MVAr and the corresponding voltage magnitude of peak value is 21.23 kV.

### 3.12.3 Simulink Model of 33kV Transmission Line with UPFC

The simulink model of Single line Transmission system of 33kV, line is shown in Fig. 3.25. The model is simulated and corresponding results of voltage magnitude of peak value, real and reactive power flows in line are shown in Fig’s 3.27 and 3.28 respectively.

![Simulink model of 33kV Transmission Line](image)

**Fig.3.25 Simulink model of 33kV Transmission Line**

### 3.12.4 UPFC Sub-System

The sub-system of the UPFC model that is interconnected in the electrical transmission line model with parameters as given in Appendix-B, is shown Fig. 3.26. The range of variations of delay angle for different IGBTs in bridges is given below:

<table>
<thead>
<tr>
<th>Rectifier</th>
<th>Delay period</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGBT-1, IGBT-2</td>
<td>0 - 5 msec</td>
</tr>
<tr>
<td>IGBT-3, IGBT-4</td>
<td>10 msec - 15 msec</td>
</tr>
<tr>
<td>Inverter</td>
<td>Conduction Period</td>
</tr>
<tr>
<td>IGBT-5, IGBT-6</td>
<td>0 - 10 msec</td>
</tr>
<tr>
<td>IGBT-7, IGBT-8</td>
<td>10 msec - 20 msec</td>
</tr>
</tbody>
</table>
The corresponding voltage waveform with compensation is shown in Fig. 3.27 and the real and reactive power waveforms are shown in Fig. 3.28 respectively.

**Fig. 3.26** UPFC Sub-System model for 33kV Transmission Line

**Fig. 3.27** Voltage magnitude of 33 kV Transmission Line ($V_p = 32.50$ kV)
Fig. 3.28 Real and Reactive power flows of 33 kV Transmission Line
for (a) 177 MW and (b) 109.5 MVAr

By observing the above waveforms, at steady-state time $t=0.02$ sec the real power is 177 MW and the reactive power is 109.50 MVAr respectively and the corresponding voltage magnitude of peak value is 32.5 kV.

The comparison of Figs. 3.17 and 3.24 indicates that at, the steady-state time $t=0.02$ sec the magnitude of real power is improved from 93.69MW to 98.15MW and the reactive power is improved from 57.53MVAr to 61.64MVAr, the corresponding voltage magnitude of peak value, by comparing Fig 3.16 and 3.23, is improved from 20.04 kV to 21.23 kV for 22kV transmission line.

Similarly the comparison of Figs. 3.20 and 3.28 indicates that at, the steady-state time $t=0.02$, the magnitude of real power is improved from 140MW to 176MW and the reactive power is improved from 88.50MVAr to 109.50MVAr, the corresponding voltage magnitude of peak value, by comparing Fig 3.19 and 3.27 is improved from 31.08 kV to 32.50kV for 33kV line.
The voltage levels without UPFC in 22kV and 33kV system are 0.91 p.u. and 0.94 p.u. in terms of per-unit values. These are less than minimum specified by the normal range (0.95 p.u. to 1.06 p.u.). These levels are improved to 0.96 p.u. to 0.97 p.u. with UPFC in respective systems (22kV and 33kV). The Voltages, real and reactive powers with compensation have showed improvement when compared to normal circuit. The UPFC scheme provides a way to transfer real power between sensitive loads in individual line through the common DC link.

The summary of the 22 kV and 33 kV transmission lines results are tabulated in Table.3.3. For both 22 kV and 33 kV transmission line, there is an increase in reactive power when UPFC is inserted into lines. As this is Converter-Inverter combination to improve the voltage profile only, an increase in both real and reactive power is noted. The objective is to inject the voltage into line, and it is indicated.

Table.3.3: Summary of 22kV and 33kV Transmission lines with and without UPFC Device

<table>
<thead>
<tr>
<th>Parameters</th>
<th>22kV Line</th>
<th>33kV Line</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without UPFC</td>
<td>With UPFC</td>
</tr>
<tr>
<td>Voltage magnitude of peak value (kV)</td>
<td>20.04 (0.91 p.u.)</td>
<td>21.23 (0.96 p.u.)</td>
</tr>
<tr>
<td>Real Power (MW)</td>
<td>93.69</td>
<td>98.15</td>
</tr>
<tr>
<td>Reactive Power (MVAr)</td>
<td>57.53</td>
<td>61.64</td>
</tr>
</tbody>
</table>

In the simulation study, Matlab/Simulink model is used to simulate the model of rectifier and inverter based UPFC connected with transmission lines i.e. 22kV and 33kV. This work gives control and performance of the UPFC used for power quality improvement and to obtain the steady-state time, objectives are achievable by control settings of the UPFC controllers. Simulation results show the effectiveness of UPFC to control the real and reactive powers as well as voltage magnitude. It is found that there is an improvement in the real and reactive powers and voltage magnitude through the transmission line when UPFC is introduced. The UPFC concept provides a powerful tool for the cost-effective utilization of individual transmission lines by
facilitating the independent control of both the real and reactive power flows. There is an improvement in both voltage and power profiles, through the transmission line when UPFC is incorporated in the system. The economical analysis of UPFC device will be discussed in Chapter-IV, section 4.9.

The above process may also be extended to two interconnected systems maintained at different voltage levels. UPFC can be controlled to supply power to a healthy line if one of the lines develops faulty and gap isolated. The same process may be extended for a complex power system.