CHAPTER 2

PERFORMANCE ANALYSIS OF RECTIFIER - INVERTER BASED UNIFIED POWER FLOW CONTROLLED TWO BUS SYSTEM

2.1 INTRODUCTION

In all electric power transmission system, whether overhead lines or underground cables, there will be a drop of voltage along the system when current flows in it. This drop will vary with the current and power factor. This voltage drop should not exceed values in such a way that the automatic voltage regulator which controls generator terminal voltage is operated in the controllable range of voltage. Practically all present day equipments which utilize electric power such as lights, motors, thermal appliances and electronic appliances are designed for use with a certain definite thermal voltage, the rated voltage. If the voltage deviates from this value, the efficiency, life expectancy, and the quality of performance of the equipment will suffer. Some of the electrical equipments are more sensitive to voltage variation than others such as motors. The variations in voltage are permissible, but with favorable zones, for example the rise or drop in voltage should not exceed a prescribed tolerance of ± 10% of the nominal voltage.

The evaluation of stability and voltage-control in power systems become very important especially when the system is subjected to a disturbance. The disturbance may be small or large. The system must be able to operate satisfactory under these conditions and successfully supply the
maximum amount of load. It must also be capable of surviving against numerous disturbances, such as a short circuit on a transmission line, loss of a large generator or load, or loss of a tie between two subsystems. Otherwise these disturbances could cause voltage instability and eventually a voltage collapse.

2.2 UPFC SYSTEM – CONSTRUCTION AND WORKING

A UPFC is an electrical device used for providing fast-acting reactive power compensation on high-voltage transmission networks. It is a versatile controller which facilitates independent control of active and reactive power flows in a transmission line. The concept of UPFC makes it possible to handle practically all power flow control and transmission line compensation problems using solid state controllers, which provide functional flexibility, generally not attainable by conventional thyristor controlled system. Gyugi (1991) proposed the concept of Unified Power Flow Controller. Figures 2.1 and 2.2 depict the schematic and single line diagrams of the UPFC respectively.

Figure 2.1 Schematic diagram
The UPFC consists of two voltage source converters namely series and shunt converter, which are connected to each other with a common DC link. Static Synchronous Series Compensator (SSSC) is used to add controlled voltage magnitude and phase angle in series with the line. Shunt converter or Static Synchronous Compensator (STATCOM) is used to provide reactive power to the AC system. Besides that it will provide the DC power required for both the converters. Each of the branches consists of a transformer and power electronic converter. The two voltage source converters share a common DC capacitor. The energy storing capacity of this DC capacitor is generally low. Therefore, active power drawn by shunt converter should be equal to the active power generated by the series converter. The reactive power in the shunt or series converter can be chosen independently, giving greater flexibility to the power flow control. The coupling transformers are used to connect the converters to the transmission system.
2.2.1 Basic Operation of UPFC

The series converter is controlled to inject asymmetrical three phase voltage $V_{se}$, of controllable magnitude and phase angle in series with the line to control active and reactive power flows in the transmission line. Hence, this converter will exchange active and reactive power with the line. The reactive power is electronically provided by the series converter and the active power is transmitted to the dc terminals. The shunt converter is operated in such a way as to demand this dc terminal power (positive or negative) from the line keeping the voltage across the storage capacitor $V_{dc}$ constant. Owing to this reason, the net real power absorbed from the line by the UPFC is equal only to the losses of the two converters and their transformers. The remaining capacity of the shunt converter can be used to exchange reactive power with the line so as to provide a voltage regulation at the connection point.

Two control modes are possible to operate UPFC viz., VAR control mode and automatic voltage control mode. In the VAR control mode, the reference input is an inductive or capacitive VAR request. The goal of the automatic voltage control mode is to maintain the transmission line voltage at the connection point to a reference value. The real and reactive powers handled by the UPFC are governed by the expressions as follows:

\[
P = \frac{V_1 V_2}{\bar{x}} \sin(\delta_1 - \delta_2) \tag{2.1}
\]

\[
Q = \frac{V_2}{\bar{x}} (V_1 - V_2) \tag{2.2}
\]
Where,

- \( P \) – Real power transmitted in W
- \( Q \) – Reactive power delivered in VAR
- \( V_1 \) – Sending end voltage in Volts
- \( V_2 \) – Receiving end voltage in Volts
- \( \delta_1 \) – Load angle of UPFC’s input voltage in deg
- \( \delta_2 \) – Load angle of UPFC’s output voltage in deg
- \( X \) – Reactance of transmission line in Ohms

The UPFC has many possible operating modes. In particular, the shunt converter is operating in such a way to inject a controllable current \( i_{sh} \) into the transmission line.

This current consists of two components with respect to the line voltage: the real or direct component \( i_{shd} \), which is in phase or in opposite phase with the line voltage, and the reactive or quadrature component \( i_{shq} \), which is in quadrature with the line voltage. The direct component is automatically determined by the requirement to balance the real power of the series inverter. The quadrature component, instead, can be independently set to any desired reference level (inductive or capacitive) within the capability of the inverter, to absorb or generate respectively reactive power from the line.

A simplified scheme of a UPFC utilizes rectifier and inverter circuit connected to an infinite bus via transmission line is shown in Figure 2.3.
Figure 2.3 UPFC installed in transmission line

UPFC consists of a parallel and series branches, each one containing a transformer, power-electronic converter with turn-off capable semiconductor devices and DC circuit. Converter 2 is connected in series with the transmission line by series transformer. The real and reactive power in the transmission can be quickly regulated by changing the magnitude of \( V_2 \) and phase angle \( \delta_2 \) of the injected voltage produced by converter 2. The basic function of the converter 1 is to supply the real power demanded by converter 2 through the common DC link. Gyugyi (1992) and Hingorani & Gyugyi (2000) found that converter 1 can also generate or absorb controllable power. However, they do not deal with the matlab simulation of UPFC using shunt and series sources. An attempt is made in this chapter to model and simulate UPFC using Matlab/Simulink and experimental work is done for this simulation.
2.2.2 Mathematical Modeling of UPFC

A UPFC can be represented by two voltage sources representing fundamental components of output voltage waveforms of the two converters and impedances being leakage reactances of the two coupling transformers. Figure 2.4a depicts two voltage-source model of UPFC. System voltage is taken as reference phasor $V_i = V_i \angle 0^0$ and $V_i' = V_{se} + V_i$, where, $V_i$ is the UPFC’s input voltage and $V_i'$ is the compensated voltage. Voltage sources $V_{se}$ and $V_{sh}$ are controllable in both their magnitudes and phase angles. $r$ and $\gamma$ are respectively the pu magnitude and phase angle of the series voltage source, operating within the following specified limits given by Equation (2.3).

$$0 \leq r \leq r_{max} \quad \text{and} \quad 0 \leq \gamma \leq 2\pi$$

(2.3)

$V_{se}$ is defined as:

$$V_{se} = rV_i e^{j\gamma}$$

(2.4)
The model is developed by replacing voltage $V_{se}$ by a current source $I_{se}$ parallel with the transmission line as shown 2.4b, where $b_{se} = \frac{1}{x_{se}}$.

$$I_{se} = -j b_{se} V_{se} \quad (2.5)$$

The current source $I_{se}$ can be modeled by injecting powers at the two auxiliary buses $i$ and $j$

$$S_{is} = V_i(-I_{se})^* \quad (2.6)$$

$$S_{js} = V_j(-I_{se})^* \quad (2.7)$$

Injected powers $S_{is}$ and $S_{js}$ can be simplified according to the following operations by substituting Equations (2.4) and (2.5) into Equation (2.6)

$$S_{is} = V_i(b_{se}r V_i e^{j\gamma}) \quad (2.8)$$

By using Euler Identity, $(e^{j\gamma} = \cos \gamma + j \sin \gamma)$, Equation (2.8) takes the form of

$$S_{is} = V_i(b_{se}r V_i e^{j\gamma}) \quad (2.9)$$

$$S_{is} = V_i^2 r b_{se} [\cos(-\gamma - 90) + j \sin(-\gamma - 90)] \quad (2.10)$$

By using trigonometric identities, Eq. (2.10) reduces to

$$S_{is} = -r b_{se} V_i^2 \sin \gamma - j r b_{se} V_i^2 \cos \gamma \quad (2.11)$$

Equation (2.11) can be decomposed into its real and imaginary components,

$$S_{is} = P_{is} + j Q_{is}, \text{ where}$$
\[ P_{ls} = -r b_{se} V_i^2 \sin \gamma \] (2.12)

\[ Q_{ls} = -r b_{se} V_i^2 \cos \gamma \] (2.13)

Similar modifications can be applied to Equation (2.7), final equation takes the form of,

\[ S_{js} = V_i V_j b_{se} \sin(\theta_i - \theta_j + \gamma) + j V_i V_j b_{se} \cos(\theta_i - \theta_j + \gamma) \] (2.14)

Equation (2.14) can also be decomposed into its real and imaginary parts,

\[ S_{js} = P_{js} + j Q_{js} \]

where

\[ P_{js} = V_i V_j b_{se} \sin(\theta_i - \theta_j + \gamma) \] (2.15)

\[ Q_{js} = V_i V_j b_{se} \cos(\theta_i - \theta_j + \gamma) \] (2.16)

Figure 2.4b Replacement of series voltage source by a current source
Based on the Equations (2.12), (2.13), (2.15) and (2.16), power injection model of the series-connected voltage source can be seen as two dependent power injections at auxiliary buses $i$ and $j$ as shown in Figure. 2.4c. In UPFC, shunt branch is used mainly to provide both the real power, $P_{\text{series}}$ which is injected to the system through the series branch, and the total losses incurred by the UPFC. The total switching losses of the two converters are estimated to be about 2% of the power transferred for MOSFET or thyristor based PWM converters (Ned Mohan 1992). If the losses are to be included in the real power injection of the shunt-connected voltage source at bus $i$, $P_{\text{shunt}}$ is equal to 1.02 times the injected series real power $P_{\text{series}}$ through the series-connected voltage source to the system.

$$P_{\text{shunt}} = -1.02 P_{\text{series}}$$  \hspace{1cm} (2.17)

The apparent power supplied by the series converter is calculated as

$$S_{\text{series}} = V_{\text{se}} I_{ij} = re^{j\gamma} V_i \left( \frac{V_i - V_j}{j X_{se}} \right)^*$$ \hspace{1cm} (2.18)

Active and reactive power supplied by the series converter can be calculated from Equation (2.18).

$$S_{\text{series}} = re^{j\gamma} V_i \left( \frac{\left( V_i e^{j(\theta_i + \gamma)} + V_i - V_j \right)}{j X_{se}} \right)^*$$ \hspace{1cm} (2.19)

$$S_{\text{series}} = r V_i e^{j(\theta_i + \gamma)} \left( \frac{\left( V_i e^{-j(\theta_i + \gamma)} + V_i - V_j \right)}{j X_{se}} \right)^*$$ \hspace{1cm} (2.20)

$$S_{\text{series}} = j b_{se} r^2 + j b_{se} r V_i e^{j\gamma} - j b_{se} V_i V_j e^{j(\theta_i - \theta_j + \gamma)}$$ \hspace{1cm} (2.21)
\[ S_{\text{series}} = j b_{se} \rho_i r^2 V_i^2 + j b_{se} \rho_j V_i^2 (\cos \gamma + j \sin \gamma) - j b_{se} V_i V_j \left( \cos (\theta_i - \theta_j + \gamma) + j \sin (\theta_i - \theta_j + \gamma) \right) \]  

(2.22)

From Equation (2.22) takes the form of

\[ S_{\text{series}} = P_{\text{series}} + j Q_{\text{series}} \]

where

\[ P_{\text{series}} = r b_{se} V_i V_j \sin (\theta_i - \theta_j + \gamma) - r b_{se} V_i^2 \sin \gamma \]  

(2.23)

\[ Q_{\text{series}} = -r b_{se} V_i V_j \cos (\theta_i - \theta_j + \gamma) - r b_{se} V_i^2 \cos \gamma + r^2 b_{se} V_i^2 \]  

(2.24)

The reactive power delivered or absorbed by converter 1 is not considered in this model, but its effect can be modeled as a separate controllable shunt reactive source. In this case main function of reactive power is to maintain the voltage level at bus \( i \) within acceptable limits. In view of the above explanations, \( Q_{\text{shunt}} \) can be assumed to be 0. Consequently, UPFC mathematical model is constructed from the series-connected voltage source model with the addition of a power injection equivalent to \( P_{\text{shunt}} + j 0 \) to bus \( i \), as depicted in Figure 2.4d.

![Figure 2.4c Equivalent power injection of series branch](image)
Finally, UPFC mathematical model can be constructed by combining the series and shunt power injections at both bus $i$ and $j$ as shown in Figure 2.4e. The element of equivalent power injections in Figure 2.4e are,

$$P_{i,UPFC} = 0.02r_{se}V_i^2 \sin \gamma - 1.02r_{se}V_iV_j \sin(\theta_i - \theta_j + \gamma)$$ (2.24)  

$$P_{j,UPFC} = r_{se}V_iV_j \sin(\theta_i - \theta_j + \gamma)$$ (2.25)  

$$Q_{i,UPFC} = -r_{se}V_i^2 \cos \gamma$$ (2.26)  

$$Q_{j,UPFC} = r_{se}V_iV_j \cos(\theta_i - \theta_j + \gamma)$$ (2.27)
With the model shown in Figure 2.4e, the digital simulation of power system using UPFC can be carried out and its performance can be studied on the aspects of power quality and transient stability.

### 2.3 SIMULINK MODEL OF UPFC

The main function of the UPFC is to control the flow of real and reactive power by injection of a voltage in series with the transmission line. Both the magnitude and phase angle of the voltage can be varied independently. The real and reactive power flow in the line can be controlled using series injected voltage (Gyugyi & Schauder 1995). To achieve real and reactive power flow control it is required to inject series voltage of appropriate magnitude and angle. The injected voltage can be split into two components which are in phase (“real voltage”) and in quadrature (“reactive voltage”) with the line current. The UPFC primarily injects voltage in series with the line whose phase angle can vary between 0 to 2\(\pi\) with respect to the terminal voltage and whose magnitude can be varied from 0 to defined maximum value (depending on the rating of the device). Hence, the device must be capable of generating and absorbing both real and reactive power.

The control variable is the phase angle of the injected voltages, which is varied physically with respect to the terminal voltage, as it is an open loop system. A simulink model of the UPFC has been developed using shunt and series voltage sources. Converter 1 is represented as a shunt current source and converter 2 is represented as a series voltage source as shown in Figure 2.5. Load voltage and load current waveforms are shown in Figure 2.6. Real and reactive powers are shown in Figure 2.7. Variation of powers with the variation in the angles is given Table 2.1.
Figure 2.5 Simulink Model of UPFC using Shunt and Series Sources
Figure 2.6 Load Voltage and Current Wave Form at $\alpha = 0^0$

Figure 2.7 Real and Reactive power at $\alpha = 0^0$
### Table 2.1 Variation of Power with angle of injection

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Angle of injected V&lt;sub&gt;2&lt;/sub&gt;voltage (deg)</th>
<th>Real power (kW)</th>
<th>Reactive power (kVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0°</td>
<td>96.82</td>
<td>65.34</td>
</tr>
<tr>
<td>2</td>
<td>30°</td>
<td>122.2</td>
<td>78.36</td>
</tr>
<tr>
<td>3</td>
<td>60°</td>
<td>176.1</td>
<td>111.5</td>
</tr>
<tr>
<td>4</td>
<td>90°</td>
<td>245.4</td>
<td>155.6</td>
</tr>
<tr>
<td>5</td>
<td>120°</td>
<td>310.6</td>
<td>199.9</td>
</tr>
<tr>
<td>6</td>
<td>180°</td>
<td>354.1</td>
<td>240.6</td>
</tr>
</tbody>
</table>

### 2.4 VOLTAGE SAGS

Voltage sag is sudden, momentary decrease in supply voltage. It can last from a cycle to several seconds. Voltage sags are most often caused by faults on the electrical transmission or distribution system. They can be caused by lightning strikes, animal contact, bird menace and starting of large motors or an internal fault within a consumer’s facility. Depending on the proximity to the fault, which can be hundreds of miles away, the voltage during a sag is typically 40 percentage to 90 percentage of nominal utility voltage. The operation of circuit breakers, fuses and reclosers limits most sags to less than 15 cycles.

Voltage sags are experienced 10 to 20 times more frequently than complete outages. However, voltage sags are equally disruptive to sensitive equipment. Voltage sag is not a complete interruption of power; it is a temporary drop below 90 percentage of the nominal voltage level. Most voltage sags do not go below 50 percentage of the nominal voltage, and they normally last from 3 to 10 cycles – or 60 to 200 milliseconds, if the rated
frequency is 50 Hz. Voltage sags are probably the most significant power quality (PQ) problem encountered by large commercial and industrial consumers today. Voltage sag compensation is necessary for secure system operation.

2.4.1 Causes of Voltage Sag in Consumer’s Side

Usually caused by equipment start-up – such as elevator, air conditioners, compressors etc., – or nearby short circuits on the utility systems.

2.4.2 Effects of Voltage Sag

Voltage sag causes a problem depend on the magnitude and duration of the sag and on the sensitivity of equipment. Many types of electronic equipment are sensitive to voltage sags, including variable speed drive controls, motor starter contactors, robotics, programmable logic controllers, controller power supplies and control relays. The voltage sag causes very expensive downtime of these equipments used in applications where they are critical to an overall process.

2.4.3 Total Harmonic Distortion

Total Harmonic Distortion (THD) of a signal is a measurement of the harmonic distortion present in it. It is used to characterize the linearity of audio systems and the power quality of the electric power systems. In power systems, lower THD means reduction in peak currents, heating, emissions and loss in the systems. THD is measured as a percentage. Lower the THD better the power quality.

THD is defined as the square root of sum of the square of RMS values of all the harmonic components of a signal other than the fundamental
divided by the RMS value of its fundamental component. Hence, THD is given by,

\[ \text{Total Harmonic Distortion (THD)} = \frac{l_H}{l_F} \]

Where

\[ l_H = \sqrt{l_2^2 + l_3^2 + \cdots + l_n^2} \]

\( I_n = \) RMS value of current of \( n^{\text{th}} \) harmonic

\( I_F = \) RMS value of current of fundamental harmonic

The value of THD lies between zero and 1. It is null for a pure sinusoidal voltage or current.

In this research chapter, two simulation models of single machine two bus system, i.e., with and without UPFC, have been developed. These simulation models have incorporated into MATLAB based Power System Toolbox (PST) for their transient stability analysis. These models were analyzed with additional load connected with the existing system. Transient stability was studied with the help of curves of additional current, active power and reactive power, sag of load voltage, injected voltage and its angle and measure of Total Harmonic Distortion.

With the addition of UPFC, the sag of load voltage reduces. Series and Shunt parts of UPFC provide series and shunt injected voltage at different angle. The unified power flow controller is put in so as to guard a sensitive load from all disturbances. It consists of 2 voltage supply inverters connected back to back, sharing a standard dc link. One electrical converter is connected parallel with the load. It acts as shunt active power fitter, helps in compensating load harmonic current, reactive current and maintain the dc link
voltage at constant level. The second electrical converter is connected serial
with the road mistreatment series transformers, acts as a controlled voltage
supply maintaining the load voltage curved and at desired constant voltage
level.

2.4.4 Voltage Swell

Voltage swell is defined by IEEE 1159 as the increase in the RMS
voltage level to 110% - 180% of nominal, at the power frequency for
durations of $\frac{1}{2}$ cycle to one minute. Voltage swell is basically the opposite of
voltage sag or dip. Voltage swells are characterized by their RMS magnitude
and duration.

2.4.5 Causes of Voltage Swells

Voltage swells are usually associated with system fault conditions -
just like voltage sags but are much less common. This is particularly true for
ungrounded or floating delta systems, where the sudden change in ground
reference result in a voltage rise on the ungrounded phases. In the case of a
voltage swell due to a single line-to-ground (SLG) fault on the system, the
result is a temporary voltage rise on the healthy phases, which last for the
duration of the fault. Voltage swells can also be caused by the deenergization
of a very large load. The abrupt interruption of current can generate a large
voltage, and it is governed by the expression, $V = L \frac{di}{dt}$, where $L$ is the
inductance of the line and $\frac{di}{dt}$ is the change in current flow. Moreover, the
energization of a large capacitor bank can also cause a voltage swell. The rise
in voltage during a fault condition depends on system impedance, location of
the fault, and the circuit grounding configuration.
2.4.6 Effects of Voltage Swell

Effects of a voltage swell are often more destructive. It may cause breakdown of components used in the power supplies of the equipment, though the effect may be a gradual. It can cause control problems and hardware failure in the equipment due to overheating that could eventually result to shutdown. Also, electronics and other sensitive equipments are prone to damage due to voltage swell.

2.5 LINE MODEL

2.5.1 Uncompensated System
A two bus system without compensation circuit is shown in Figure 2.8. The simulation has been done using matlab/simulink and the results are presented. This line model without compensation consists of transmission line additional load and breaker. An additional load (load-2) is connected in parallel with load-1 by closing the breaker in series with the load at t=0.3 sec. Sag is produced when additional load is added as shown in Figure 2.9 and corresponding real and reactive powers are shown in Figure 2.10.

Similarly the additional load (load-2) is disconnected from the system in series with load-1 by opening the breaker at t=0.3 sec. Voltage across load 1 swells when the load2 is removed as shown in Figure 2.11 and corresponding real and reactive powers are shown in Figure 2.12.

![Voltage across Load 2 and Load 1](image)

**Figure 2.9 Voltage across Load 2 and Load 1**
Figure 2.10 Real Power and Reactive Power (during Sag)

Figure 2.11 Voltage across Load 2 and Load 1
Figure 2.12 Real Power and Reactive Power (during Swell Condition)

2.5.2 Compensated System

Figure 2.3 shows a system configuration of general UPFC, which is installed between the sending end and the receiving end of a transmission line. The series device acts as a controllable voltage source \( V_C \), whereas the shunt device acts as a controllable current source \( I_C \). The main purpose of shunt device is to regulate the DC link voltage by adjusting the amount of active power drawn from the transmission line. In addition, the shunt device has capability of controlling reactive power.

Figure 2.13 shows a single-phase equivalent circuit of the UPFC, where the reactor \( L \) and the resistor \( R \) represent the inductance and resistance in the transmission line, respectively. It is reasonable to remove the line
resistance $R$ because $\omega_0 L \gg R$ in the over head transmission line. Thus the line current phasor vector $I$ is given by

$$\tilde{I} = \frac{V_S - V_R + V_C}{j\omega_0 L} \tag{2.28}$$

For the sake of simplicity, it is assumed as $V_S = V_R$.

![Single phase equivalent circuit](image)

**Figure 2.13 Single phase equivalent circuit**

The complete Simulink diagram of the compensated system is shown in Figure 2.14. The diagram consists of a rectifier, inverter based UPFC block as a subsystem. It is a two bus system with UPFC. The details of subsystem are shown in Figure 2.14a.
Figure 2.14 Line Model Circuit With UPFC
2.6 SIMULATION RESULTS

2.6.1 Simulation Parameters

The rectifier-inverter based UPFC controlled two bus system has been simulated using Matlab/Simulink tool and the results are presented. The simulation parameters of the system are detailed below:

- Peak amplitude of AC voltage source: 6350V
- Frequency: 50Hz
- Peak Amplitude AC current source: 10A
- Peak amplitude of series voltage source: 2000V
- Phase angle: 0 - 360°

Parameters of Compensation circuit:

- Existing load: 5Ω, 10mH
- Additional load: 25Ω, 50mH
- Transmission line: 30mH

The parameters of the simulation circuit are

- IGBT / Diode
  - Internal resistance of the IGBT: $1*10^{-3}$ Ω
  - Snubber resistance of the IGBT: $1*10^5$ Ω
  - DC link capacitance: 9000e-6 F

The voltage sag is produced by connecting an additional load and it is compensated as depicted in Figure 2.15. The variation of real and reactive power against varying load in the compensated system are illustrated in Figures 2.16 and 2.17.
(a) Voltage across Load 2 and Load 1 at $\alpha = 0^\circ$

(b) Real Power and Reactive Power at $\alpha = 0^\circ$

Figure 2.15 (Continued)
(c) Voltage across Load 2 and Load 1 at $\alpha = 36^0$

(d) Real Power and Reactive Power at $\alpha = 36^0$

Figure 2.15 Compensated Parameters
For performance comparison the readings observed from simulation studies have been tabulated as shown. Comparison of Table 2.2 and 2.3 reveals that the compensated system exhibits significant reduction in THD from 20.34% to 15.65%. In the case of compensation system, increase in firing angle increases load voltage, real and reactive power flow, as shown in Figures 2.18(a), 2.18(b) and 2.18(c) respectively. Switching of UPFC, causes a transient of 20kV peak in the voltage waveform as shown in Figure 2.15 (c). Decrease in THD has been observed with increase in firing angle as depicted in Figure 2.18 (d).
Irrespective of the firing angle of the series converter, sag remains constant. With the compensation system, the period of sag is reduced to a significant extent. The load voltage dips to almost \(1/6\)th of system voltage and it remains constant during the period of sag. At higher degrees of firing angle ranging from \(60^\circ\) to \(90^\circ\), there is a marginal decrease in load voltage has been observed after the period of sag.

### Table 2.2 Comparison of various parameters without and with compensation devices

<table>
<thead>
<tr>
<th></th>
<th>Load Voltage (V)</th>
<th>Real Power (W)</th>
<th>Reactive Power (VAR)</th>
<th>THD (%)</th>
<th>Sag Period (Sec)</th>
<th>Load Voltage (V)</th>
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<tbody>
<tr>
<td></td>
<td>Before sag</td>
<td>During sag</td>
<td>After sag</td>
<td>Before sag</td>
<td>During sag</td>
<td>After sag</td>
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<tr>
<td>Without UPFC</td>
<td>1927</td>
<td>1.918e4</td>
<td>2576</td>
<td>20.34</td>
<td>After connecting additional load (from 0.3 sec)</td>
<td>6000</td>
</tr>
<tr>
<td>With UPFC</td>
<td>3632</td>
<td>2.248e5</td>
<td>9.15e4</td>
<td>15.65</td>
<td>0.3 to 0.4 (0.1)</td>
<td>6000</td>
</tr>
</tbody>
</table>

### Table 2.3 Comparison of various parameters with compensation device

<table>
<thead>
<tr>
<th>Firing Angle (Degree)</th>
<th>Load Voltage (V)</th>
<th>Real Power (W)</th>
<th>Reactive Power (VAR)</th>
<th>THD (%)</th>
<th>Sag Period (Sec)</th>
<th>Load Voltage (V)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Before sag</td>
<td>During sag</td>
<td>After sag</td>
<td>Before sag</td>
<td>During sag</td>
<td>After sag</td>
</tr>
<tr>
<td>0</td>
<td>3632</td>
<td>2.248e5</td>
<td>9.156e4</td>
<td>15.65</td>
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</tr>
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<td>9.065e4</td>
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<td>6000</td>
</tr>
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<td>45</td>
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<td>8.505e4</td>
<td>12.52</td>
<td>0.1</td>
<td>6000</td>
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<tr>
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<td>1.852e5</td>
<td>7.533e4</td>
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<td>0.1</td>
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<td>6.435e4</td>
<td>9.287</td>
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<tr>
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<td>2832</td>
<td>1.368e5</td>
<td>5.558e4</td>
<td>9.005</td>
<td>0.1</td>
<td>6000</td>
</tr>
</tbody>
</table>
(a) Load Voltage Vs Firing Angle

(b) Real Power Vs Firing Angle

Figure 2.18 (Continued)
EXPERIMENTAL STUDY

The laboratory model of rectifier – inverter based UPFC has been physically realized and tested to obtain experimental results. Figure 2.19 shows the block diagram of the laboratory model developed. The eight bit
microcontroller 89C0251 ALP used in the control circuit of this model shown in Figure 2.20 generates triggering pulses for the switching devices employed in the rectifier and inverter. The driver circuits which form part of control circuit has high and low side driver IR2110 which is 3.3V logic compatible with CMOS or LSTTL output. It amplifies pulses from microcontroller upto 10V. The program embedded in the microcontroller to generate trigger pulses for switches is given in appendix 3.

![Block Diagram of Rectifier – Inverter based UPFC](image)

**Figure 2.19 Block Diagram of Rectifier – Inverter based UPFC**

### 2.7.1 Control Circuit

The control circuit of the rectifier-inverter based UPFC is shown in Figure 2.20. The rectifier and inverter are built with MOSFET switches. Each converter constructed with four IRF840 MOSFET switches as shown in Figure 2.21. The ratings and pin details of the MODFET IRF840 employed in this circuit have been given in Appendix 4.

The regulator ICs 7812 and 7805 provide supply voltage of +12 V and +5 V respectively to the microcontroller and driver ICs of the control circuit. It consists of two IR2110 driver ICs. The 3.3 V amplitude of
triggering pulses generated by microcontroller 89C2051 are amplified to 20 V by these driver ICs. It may be noted that for the satisfactory operation of the MOSFET, the minimum Gate to Source voltage ($V_{GS}$) required is ±10 V. Hence the driver ICs IR2110 are used not only for isolation but also for amplification of $V_{GS}$. The driver ICs drive the MOSFET whenever these ICs are triggered by microcontroller.

![Control Circuit of UPFC](image)

**Figure 2.20 Control Circuit of UPFC**

### 2.8 EXPERIMENTAL RESULTS

The experimental setup for the laboratory model UPFC is shown in Figure 2.21. Pulses applied to the gate of MOSFET are shown in Figure 2.22. Figure 2.23 shows the load voltage of a compensated system.
Figure 2.21 Experimental Setup of laboratory model UPFC

Figure 2.22 Driving pulses to the MOSFETs

Figure 2.23 Load voltage of a compensated system


2.9 CONCLUSION

A comparison is made between uncompensated power system and the compensated one in this chapter. The compensation of the power system is done using rectifier – inverter based power systems. The comparison shows that there is voltage compensation in the system during the sag period when sudden connections of load. The value of THD is found to be 15.62% in the case of compensated system which is much below the value of the uncompensated system. It may be noted that the value of THD of the uncompensated system is 20.34%. The sag lasts for 0.3 secs in the case of uncompensated system, whereas in the case of compensated systems it lasts only for 0.1 sec. In addition to the aforesaid advantages, improvement is observed in the case of compensated system as far as real and reactive power flow is concerned. It is found that the maximum real and reactive power flow are 19.18kW and 2.5kVAR respectively, in the uncompensated system whereas it is 22.42kW and 9.15kVAR in the compensated system respectively.