POWER SYSTEM PERFORMANCE ENHANCEMENT USING UNIFIED POWER FLOW CONTROLLER

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POWER SYSTEM PERFORMANCE ENHANCEMENT USING UNIFIED POWER FLOW CONTROLLER

by

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A thesis submitted to the School of Graduate

Studies in partial fulfillment of the

Requirements of the degree of

Master of Engineering

Faculty of Engineering and Applied Science

Memorial University of Newfoundland

September 2002

St. John's Newfoundland Canada

Abstract

Electric power utilities in many countries around the world face deregulation and privatization. The utilities are often separated into generation, transmission and distribution companies in order to encourage competition and provide customers with the choice of selecting their electrical energy provider. Environmental concerns, right-of-way and cost have delayed the construction of new transmission lines. The demand for electric power has continued to grow and this must be met by increased transfer of power through available transmission lines.

The overall aim of the research presented in this thesis is to examine the application of Unified Power Flow Controller (UPFC) in power system operation. For this device a general model is derived and used in power system analysis. This model is referred to as the injection model which is valid for load flow analysis. The model has been very helpful for understanding the impact of UPFC on power system operation. As a part of UPFC application, Available Transfer Capability (ATC) has been studied with different methods of calculating ATC. The impact of the UPFC in increasing the available transfer capability of the power system has been studied. Test results using different power system models are presented throughout the thesis to illustrate the effectiveness of Unified Power Flow Controller.

Acknowledgements

Many thanks to my father and mother for their prayers, love, and support. Without them this work would never have come in to existence. Also thanks to my brother Ravinder and my two sisters Parminder and Harpreet for their constant encouragement during my study in Canada.

I would like to thank and express my indebtedness and heartiest gratitude to my supervisor Dr. B. Jeyasurya for his constant advice, encouragement and guidance during all stages of this research.

Thanks are due to the staff at CCAE and faculty for all the useful discussions and suggestions.

Advice and support provided by Mr. Harjeet Singh Gill of ABB Inc., Santa Clara, CA, U.S.A in various ways is highly acknowledged.

Finally, I would like to express my thanks to Memorial University of Newfoundland for the financial support, which made this research possible.

Dedicated To

My Parents

Smt. Balwant Kaur Sethi **S. Prithi Pal Singh Sawhney**

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List of Abbreviations and Symbols

FACTS	:	Flexible A.C Transmission System
TCR	:	Thyristor Controlled Reactor
TSC	:	Thyristor Switched Capacitor
SVC	:	Static Var Compensator
STATCOM	:	Static Synchronous Compensator
TCSC	:	Thyristor Controlled Series Capacitor
SSSC	:	Static Synchronous Series Compensator
PAR	:	Phase Angle Regulator
UPFC	:	Unified Power Flow Controller

Chapter 1

Introduction to Flexible A.C Transmission System

1.1 Introduction

Electric utility planners are currently faced with a major challenge in meeting the increased load demand with high reliability and minimum investment in new transmission facilities. Laying of additional parallel lines and acquiring necessary right of ways or raising system operating voltages may all be prohibitive from economical and other considerations.

Optimal utilization of transmission lines has thus become a strict requirement on energy systems in view of limited availability of transmission corridors. With the growing requirement of transmission of bulk power to expanding load centers over restricted right of ways, the need to use transmission facilities in an optimum and efficient manner is being increasingly felt [1].

Demand of electrical energy continues to grow steadily. Electricity grid upgrade, and especially the construction of new transmission lines, cannot keep pace with the growing power plant capacity and energy demand. Finding suitable right of ways is particularly difficult in the industrialized countries, and gaining the necessary approval is time consuming particularly due to environmental considerations.

Due to these constraints it has become a great challenge to utilize the existing power lines more efficiently. This challenge can be considered from two aspects. In the first place there is a need to improve the transient and steady state stability of long distance high voltage transmission lines. The power transfer capability of long transmission lines is limited from both steady state and transient stability point of view. The other aspect is the flexibility a deregulation energy market requires. Power system operation to ensure that the electricity supply contracts can be fulfilled in a deregulated market needs innovative features. This chapter discusses the limits for power transfer over an interconnected power system. The principle of shunt and series compensation is presented next. Overview of different Flexible A.C Transmission System (FACTS) Controllers and their potential to overcome some of the limits in existing power system are also illustrated in this chapter.

1.2 Limits to Power Flow in a Transmission System

It is desired to utilize the transmission capacity to its best use taking into account loading capability and contingency conditions, but there is a limit to the loading capability of transmission lines.

The limits to power flow over transmission lines are classified as [2]

- Thermal
- Voltage drop Limits
- Stability

- Loop Flow

Thermal Limits: Thermal limit of a transmission line is a function of the temperature, environmental conditions, physical structure of the conductor, and ground clearance. Line losses convert electrical energy to heat and heat weakens the power lines conductor. This "lost" electrical power heats the power lines and causes the conductor to expand and the line to sag. At some temperature the conductor becomes soft enough to be permanently damaged by the line's weight. At a higher temperature the conductor will melt and break. Hence thermal limit imposes a limit on the power flow through the transmission line.

Voltage drop limits: As load increases, voltage at receiving substation decreases. For the equipments to operate properly, the voltage should not be allowed to fall below a specified value. This limits the power transfer.

Stability Limits: These are a number of stability concerns that limit the transmission capability. These include:

- Transient Stability
- Steady State stability
- Voltage collapse
- Loop Flow

Transient Stability: During fault on a transmission line, at a generator station, or at a substation there is a possibility of rotor angle increasing very rapidly. This leads to reduction in transfer of power from generating end to the sending end. However, mechanical power produced by the turbine remains constant during the fault, and there is consequently an imbalance between mechanical power input to the generator and electrical power output, with mechanical power being in excess. This excess mechanical power is converted to accelerating power and the generator increases its rotational velocity. This may cause the generator to lose synchronism if the fault is not cleared quickly. The resulting system response involves large excursions of generator angles and is influenced by the nonlinear power-angle relationship. The transient stability of generator depends upon the generator loading, fault clearing time and generator reactance etc. [3].

Steady State Stability: It is defined as the ability of the power system to maintain synchronism under small disturbances. Such disturbances occur continually on the system because of small variations in loads and generation. The disturbances are considered sufficiently small for linearization of system equations to be permissible for purpose of analysis [3].

Voltage Collapse: A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable drop in voltage. Voltage collapse is the process by which the sequence of events accompanying voltage instability leads to low unacceptable voltage profile in a significant part of the power system [3].

Loop Flow: In an interconnected power system, power flowing between a generator and a customer moves through all lines connecting the two points. Power follows the path of the least resistance according to the laws of physics. Power flow is inversely proportional to transmission line impedance rather than current capacity of transmission lines. Neighboring transmission systems are usually connected together in a large network. This results in an exchange of power between different areas, and is termed as loop power flow. Loop flows are difficult to control and can damage the transmission equipments. This phenomenon is explained below with a simple example of a two bus system.

Consider a simple case of power flow through two parallel lines as shown in Figure 1.1 below. Power flow is proportional to the inverse of the transmission line impedance. This law governing the power flow suggests that the line with lower impedance may be overloaded and the line with higher impedance might not be fully loaded to its transmission capacity. In Figure 1.1, generators at two different sites are sending power to the load through two parallel lines. Line carrying power P1 and P2 have ratings of 75 MW and 250 MW respectively.

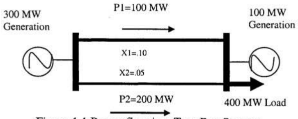


Figure 1.1 Power flow in a Two Bus System

One of the generators is generating 300 MW and other 100 MW to meet the load demand of 400 MW. For the situation shown in Figure 1.1 the line carrying power P1 is overloaded. Assuming there are no control devices to reroute power between the lines, flow is primarily controlled by changing the pattern of generation output or frequently by reducing the load as shown in Figure 1.2.

An alternative to such a case of operation is altering the pattern of generation, or one of the line carrying power P2 could be installed with a load sharing device (Controller). The available generation sources supply a given load for each control area in the most economic manner in real-time generation. The objective is to minimize the total generation cost. The disadvantages of altering the generation is that it would be no longer economical for the customer as the cost of generation may be high. By controlling the impedance or phase angle, or through series injection of appropriate voltage in the line, power flow can be controlled as desired.

Figure 1.3 shows that with the help of a controller the line overload can be relieved, more power can be pushed through the line resulting in the line being used to its transmission capacity. The overall cost of generation is also reduced.

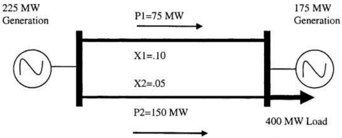


Figure 1.2 Power flow after altering generation

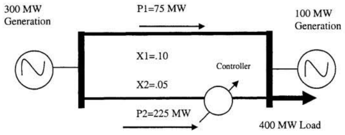


Figure 1.3 Power System with a controller

1.2.1 Basics of AC Power Transmission

The main components of an ac power transmission system are generators, transmission lines, distribution lines and loads, with their related auxiliaries and protection equipment. The generators are rotating synchronous machines. The transmission systems are designed to operate at high, medium, and low, alternating voltages. The loads may be synchronous, non-synchronous and passive, consuming generally both real and reactive power. The modern power system is a complex network of transmission lines interconnecting all the generator stations and all the major loading points in the power system. These lines carry large block of power to meet the demands at various parts of the power system.

Alternating current transmission lines are characterized by their distributed circuit parameters: the series resistance and inductance and the shunt conductance and capacitance. The characteristic behavior of the transmission line is primarily determined by the series inductance and shunt capacitance. A representation of the transmission line, together with the sending-end and receiving-end generators, is shown in Figure 1.4 [2].

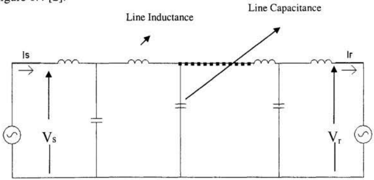


Figure 1.4 Lumped element representation of a lossless transmission line [2]

The power transmitted through the transmission line is given by

$$P=\frac{V_s V_r Sin\delta}{Z_o Sin\theta} \quad 1.1$$

Where

V_s is the magnitude of the sending-end voltage

V_r is the magnitude of the receiving-end voltage

δ is the phase angle between V_s and V_r (transmission or load angle),

Z_o is the surge or characteristic impedance of the transmission given by

$$Z_o=\sqrt{\frac{l}{c}} \quad 1.2$$

l and c are the series inductance per unit length and shunt capacitance per unit length respectively. θ is the electrical length of the line expressed in radians by

$\theta = \frac{2\pi}{\lambda} a = \beta a$, λ is the wavelength, β is the number of complete waves per unit line length and a is the length of the line.

$$\beta = \frac{2\pi}{\lambda} = \omega\sqrt{lc} = 2\pi f\sqrt{lc} \qquad 1.3$$

It is well known that the voltage along the transmission line remains constant only at surge impedance or natural loading when the transmitted power is $P_o = V_o^2/Z_o$ where V_o is the nominal or rated voltage of the line. However, transmission lines rarely have surge impedance loading. At lighter loads the receiving end voltage increases and for heavier loads it decreases [2].

Consider a simple two machine system, which has an inductive transmission line with zero shunt capacitance, as shown in Figure 1.5 with the corresponding power transmission vs. angle characteristic as shown in Figure 1.6.

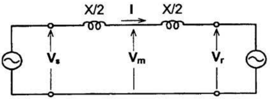


Figure 1.5 Two machine power system with inductive line [2]

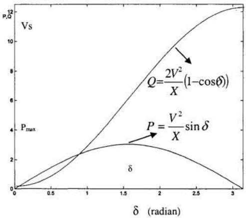


Figure 1.6 Power transmission vs. angle characteristic

The relationships between real power P, reactive power Q and angle δ are shown in Figure 1.6. At a constant voltage (V_s=V_r=V) and fixed transmission system (X=constant) the transmitted power is a function of angle δ. The real power, P, cannot be controlled without changing the reactive power demand on the sending and receiving ends [2].

1.2.2 Steady State Limit of Power Transmission

The maximum power $P_{max}=\frac{V^2}{X}$, transmittable over a line at a given transmission voltage is determined by the line reactance X and thus sets the limit for steady state power transmission. In real-time, practical limit for an actual transmission line with resistance R may be imposed by the I^2R loss that heats the conductor. At a high temperature, the characteristics of the conductor would irreversibly change (e.g., it could get deformed with permanent sag). This sets the thermal limit for the maximum power that can be transmitted. Basically, for long lines the reactance X and for short lines the resistance R limits the power transfer. As the line length increases, the power flow is limited by steady state stability [4].

1.3 Line Compensation and Power Flow Control

The steady-state power transfer can be increased and the voltage profile along the line can be improved by appropriate reactive compensation. The main purpose of reactive compensation is to change the natural characteristics of the transmission line to make it more compatible with the prevailing load demand. Thus, shunt connected switched reactors are applied to minimize line overvoltage under light load conditions and shunt connected fixed or mechanically switched capacitors are used to maintain voltages under heavy load conditions. In some cases there is need to change the naturally imposed transmission angle of the line. In this case, a phase shifter can be used to control the angle of the line independent of prevailing overall transmission angles.

1.3.1 Shunt Compensation

Consider a simple two machine (two bus) transmission system model in which a static var compensator (SVC) is shunt connected at the midpoint of the transmission line as shown in Figure 1.7. A static var compensator generates or absorbs shunt reactive power at its point of connection in the transmission line. This compensator is represented by a sinusoidal voltage source (of the fundamental frequency), in phase with the midpoint voltage, V_m, with an amplitude identical to that of the sending and receiving end voltages ($V_m=V_s=V_r=V$).

The midpoint compensator in effect divides the transmission line into two independent parts: the first part, with an impedance of X/2, carries power from sending end to the midpoint, and the second segment also with an impedance of X/2, carries power from the midpoint to the second receiving end. There is only an exchange of reactive power with the transmission line in this process.

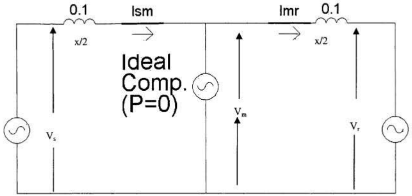


Figure1.7 Two machine power system with an ideal midpoint reactive compensator [2]

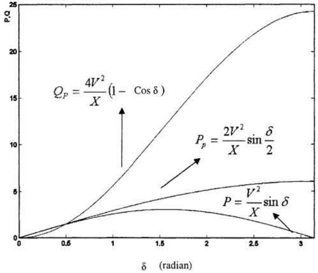


Figure 1.8 Power transmission vs. angle characteristic

The relationship among real power P, reactive power Q, and angle δ for this case of shunt compensation is plotted in Figure 1.8 where as P_p and Q_p are changed real and reactive power. The figure shows that the midpoint shunt compensation can significantly increase the transmittable power. The concept of transmission line segmentation can be extended to the use of multiple compensators located at equal segments of transmission line. Theoretically, the transmittable power would double with each doubling of segments for the same overall line length. As the number of segments are increased the voltage variation along the line would rapidly decrease, approaching the ideal case of constant voltage profile.

Eventually, with a sufficiently large number of line segments, an ideal distributed compensation system could theoretically be established which would have the characteristics of surge impedance loading, but would have no power transmission limitations, and would maintain a flat voltage profile at any load [2].

1.3.2 Series Compensation

Series capacitive compensation decreases the overall effective series transmission impedance of the line from the sending-end to the receiving-end. The impedance of the series connected compensating capacitor cancels a portion of the actual line reactance and thereby the effective transmission impedance is reduced as if the line was physically shortened. The maximum power transfer capability of a transmission line may be significantly increased by the use of series capacitor banks.

Consider the previous simple two-machine model with a series capacitor compensated line, composed of two identical segments shown in Figure 1.9.

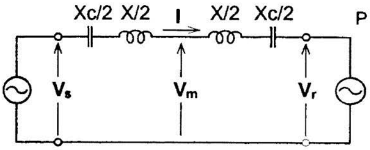


Figure 1.9 Two machine power system with series capacitive compensation [2]

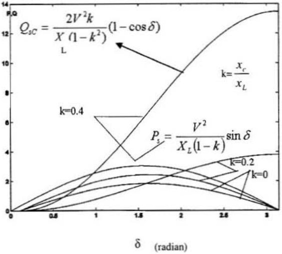


Figure 1.10 Power transmission vs. angle characteristic

The relationship among the real power P, series capacitor reactive power Q_{sc}, and compensation k (degree of series compensation) is shown in Figure 1.10. It can be observed that the transmittable power rapidly increases with the degree of series compensation k. Similarly, the reactive power supplied by the series capacitor also increases sharply with k and varies with angle δ in a similar manner to the line reactive power. Series capacitors have been used to compensate for very long overhead lines. There has been an increasing recognition of the advantages of compensating shorter, but heavily loaded, lines by using series capacitors.

1.3.3 Phase Angle Control

In power system operations, it is possible that power transmission angle required for the optimal use of a transmission line would be incompatible with the proper operation of the overall transmission system. Such cases would occur, for example, when power between two buses is transmitted over parallel lines of different electrical length or when two buses are intertied whose prevailing angle difference is sufficient to establish a power flow. In these cases a phase shifter or phase angle regulator is frequently applied. The concept is explained with the two machine system in which a phase shifter is inserted in between the sending-end generator (bus) and the transmission line, as illustrated in Figure 1.11. The phase shifter can be

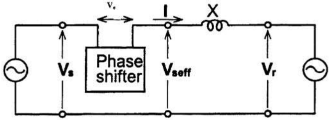


Figure 1.11 Two machine power system with a phase shifter [2]

considered as a sinusoidal ac voltage source with controllable amplitude and phase angle. In other words, the sending end voltage V_s becomes the sum of generator voltage and the voltage $V\sigma$ provided by the phase shifter. The power can be kept at its peak value after angle δ exceeds $\pi/2$ (the peak power angle) by controlling the amplitude of quadrature voltage $V\sigma$ so that the effective phase angle between the sending and receiving end voltages stays at $\pi/2$. This way, the power transmitted through the transmission line may be increased significantly even though the phase shifter does not increase the steady state power transmission limit. The relationship between real power P and angles δ and σ is shown plotted in Figure 1.12. It is seen that, although the phase shifter does not increase the transmittable power of the uncompensated line, yet it makes it possible to keep the power at its maximum value at any angle δ in the range $\pi/2 < \delta < \pi/2 + \sigma$ by, in effect, shifting the P versus δ curve to the right. It should be noted that the P versus δ curve can also be shifted to the left by inserting the voltage of the phase shifter with an opposite polarity [2].

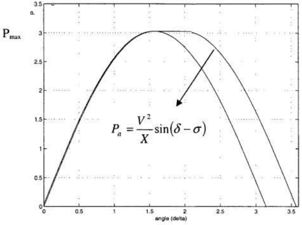


Figure 1.12 Power transmission vs. angle characteristic

1.4 Flexible A.C Transmission Systems

Basic transmission problems that have caused inefficient use of transmission and other assets have motivated power system engineers to consider power electronics based system for traditional compensation techniques.

The Flexible A.C Transmission System (FACTS) technology was developed to overcome the problems in the power systems due to increase in demand and supply of power and restriction on construction of transmission lines because of necessary right of ways. The main objectives of FACTS technology are

- To increase the power transfer capability of transmission systems.
- To keep power flow over designated routes.

The first objective implies that power flow in a given line should be able to be increased up to the thermal limit by forcing the necessary current through the series line impedance. FACTS technology helps in operating the transmission lines at their thermal limits which results in transmitting more power. This motive does not mean to say that the lines would normally be operated at their thermal limit loading (the transmission losses would be unacceptable), but this option would be available, if needed to handle severe system contingencies. However, by providing the necessary rotational and voltage stability using FACTS controllers, instead of large steady-state margins, the normal power transfer over the transmission lines is expected to increase significantly [5].

1.4.1 FACTS Controllers

The generation of FACTS controllers has incorporated two different approaches, both resulting in a comprehensive group of controllers able to address targeted transmission problems. The first group of controllers employs reactive impedances or a tap changing transformer with thyristor switches as controlled elements; the second group uses self-commutated converters as controlled voltage sources. In the next section the two groups of controllers are discussed in detail.

1.4.2 Thyristor Controlled FACTS Controllers

The thyristor controlled FACTS controllers, static var compensator (SVC), thyristor controlled series capacitor (TCSC) and phase shifter, employ conventional thyristors in circuit arrangements that are operated by sophisticated controls. All these controllers govern one of the parameters controlling the power flow in the transmission system, the SVC for voltage, TCSC for transmission line impedance and phase shifter for transmission phase angle. All of these have a common characteristic that the necessary reactive power required for the line is generated or absorbed by the traditional capacitor or reactor banks and the thyristor switches are used only for the combined reactive impedance these banks present to the ac system. The basic operating principles and characteristics of these conventional FACTS controllers are summarized below.

1.4.3 *Static VAR Compensator*

A shunt-connected static var compensator employs thyristor-switched capacitors (TSC's) and thyristor-controlled reactors (TCR's). With proper coordination of the thyristor capacitor switching and reactor control, the reactive power output can be varied continuously between the capacitive and inductive ratings of the equipment. The compensator is normally operated to regulate the voltage at the bus. The maximum obtainable capacitive current decreases linearly with system voltage since SVC becomes a fixed capacitor when the maximum capacitive output is reached. Therefore, the voltage support capability of the conventional thyristor-controlled static var compensator rapidly deteriorates with decreasing system voltage. In addition to voltage support, SVCs are also employed for transient and dynamic stability. One of the configuration using a fixed capacitor with a thyristor controlled reactor is shown in Figure 1.13. Static var compensators are extensively employed in electric utility systems.

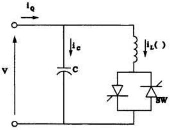


Figure 1.13 Fixed capacitor-Thyristor controlled reactor type SVC

1.4.4 Thyristor Controlled Series Capacitor

The basic TCSC module comprises of series capacitor in parallel with a TCR. A metal oxide varistor, essentially a resistor is connected across the series capacitor to prevent the occurrence of high capacitor over-voltages. The degree of series compensation in the capacitive operating region is increased by increasing the thyristor conduction period and thereby the current in the TCR. The principle of variable series compensation is to simply increase the fundamental frequency across a fixed capacitor in a series compensated line. In a thyristor switched capacitor (TSC) scheme, the amount of series compensation is controlled by increasing or decreasing the number of capacitor banks in series. TCSC configuration uses thyristor-controlled reactors (TCRs) in parallel with segments of a capacitor as shown in Figure 1.14. The TCSC can be continuously controlled in the capacitive or inductive zone. The impedance of the transmission line can be adjusted using TCSC to meet the performance requirements.

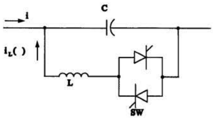


Figure 1.14 Thyristor Controlled Series Compensator Scheme

1.4.5 Phase Shifter

The principles for using a phase shifting transformer with a thyristor tap-changer are well established. Mostly phase shifters with a mechanical tap-changer provide quadrature voltage injection. A thyristor controlled phase shifting transformer consists of a shunt connected excitation transformer (ET), a series insertion transformer and a thyristor switch arrangement connecting a selected combination of tap voltages to the secondary of the insertion transformers. The phase angle between the voltage injected by the phase shifter and the line current is arbitrary, determined by the parameters of the overall system. The thyristor controlled phase-shifting transformer could be used to regulate the transmission angle to maintain balanced power flow in multiple transmission paths. In general, the phase shifter exchanges real and reactive power with the ac system through the series insertion transformer. A thyristor controlled phase shifting arrangement is shown in Figure 1.15.

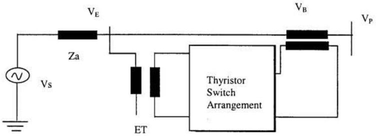


Figure 1.15 Schematic diagram of a phase shifter [2]

1.4.6 Converter Based FACTS Controllers

The second group of FACTS controllers employs self commutated voltage source converters to realize rapidly controllable, static synchronous ac voltage or current sources. This approach including thyristor switched capacitors and thyristor controlled reactors generally provides better performance characteristics and are applicable for transmission voltage, line impedance, and angle control as compared to conventional compensation methods. It has the unique potential to exchange real power directly with the ac system in addition to provide independently controllable reactive power compensation, there by giving a powerful option for power flow control.

Some of the recently proposed FACTS controllers employing switching converter based synchronous voltage sources are, the Static Synchronous Compensator (STATCOM), the Static Synchronous Series Compensator (SSSC), the unified Power flow controller (UPFC)

1.4.7 Static Synchronous Compensator (STATCOM)

The basic operating behavior of STATCOM is similar to a synchronous condenser. If the synchronous voltage source (SVS) is used for reactive shunt compensation like a static var compensator; the source of dc energy can be replaced by a small dc capacitor as shown in Figure 1.16. The steady state power exchanges between the SVS and the ac system is only reactive.

The converter can charge the capacitor to the required voltage level when SVS is used for reactive power generation. The converter absorbs a small amount of real power from the ac system to replenish its internal losses and keep the capacitor voltage at the desired level. The ability of the STATCOM to produce full capacitive output current at low system voltage also makes it highly effective in improving the transient stability. The control mechanism can be used to increase or decrease the capacitor voltage and thereby the amplitude of the output voltage of the converter, for the purpose of controlling the var generation or absorption.

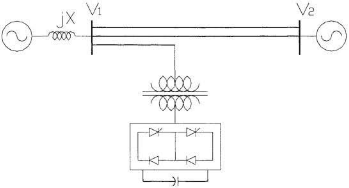


Figure 1.16 Static Synchronous Compensator [1]

1.4.8 Static Synchronous Series Compensator (SSSC)

A voltage source inverter could be used in series with the transmission line. This device is called static synchronous compensator as shown in Figure 1.17. An SSSC is capable of interchange of active and reactive power with the system. The injected voltage could be controlled in magnitude and phase if sufficient energy source is provided. The SSSC behaves like a controllable series capacitor and a controllable series reactor. The basic difference is that the voltage injected by the SSSC is not related to the line current and can be independently controlled.

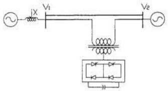


Figure 1.17 Static Synchronous Series Compensator [2]

1.4.9 Unified Power Flow Controller (UPFC)

The unified power flow controller utilizes the synchronous voltage source (SVS) concept for providing a uniquely comprehensive capability for transmission system control. It can provide the functional capability of independently controlling both the real and reactive power flow of the line.

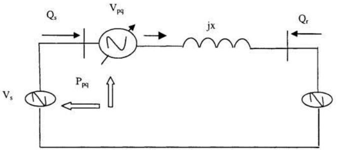


Figure 1.18 Two machine system with the Unified Power Flow Controller [2].

As shown in Figure 1.18, UPFC is represented by a controllable voltage source in series with the line. The voltage injected by the UPFC in series with the line is V_{pq} ($0 \leq V_{pq} \leq V_{pqmax}$) at angle ρ ($0 \leq \rho \leq 360^{o}$). The line current flows through the series voltage source, V_{pq} and result in exchange of real and reactive power. This implies that voltage source V_{pq} generally exchanges both real and reactive power with the transmission line. A converter-based SVS can internally generate or absorb the reactive power, but the real power it exchanges with, must be supplied to, or absorbed from its dc terminals. The available source of power is the sending-end generator. The shunt converter is assumed to be operated at unity power factor, as its main function is to transfer the real power demand of the series converter to the sending end generator. It is reasonable to stipulate that the sending-end generator must provide the SVS exchanges with the transmission line to accomplish the desired flow of power. A possible practical implementation of this coupling is a back-to-back converter arrangement, in which the shunt series connected converter, provides the real power (from the sending-end bus) the series -connected converter exchanges with the line. The basic block diagram of the Unified Power flow controller as shown in Figure 1.19.

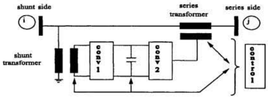


Figure 1.19 Unified Power Flow Controller

1.5 Summary

This chapter has focused on the basics of the AC power transmission to provide a necessary background for understanding the power electronics based devices. Before the advent of FACTS technology, the transmission capability of transmission lines was increased by traditional line compensation techniques. The main objective of FACTS is to increase the useable transmission capacity of lines and control the flow of power. The arrangement of voltage source converters in FACTS devices can provide individual voltage, impedance and angle regulation or, alternatively real and reactive power flow control and thus can adapt to short term contingencies and future system modifications. The installation of FACTS controllers particularly the converter types with multiple power flow control capability has revolutionalized the field of power transmission and distribution. Economic evaluation and practical considerations suggest that FACTS devices have significant capability to enhance the operation of a power system by overcoming some of the traditional limits.

1.6 Objective and Organization of the thesis

The objective of this thesis is to develop and verify a model for FACTS device used in controlling the power flow in energy systems. The model is intended to be simple in realization, easy to implement and applicable to different power system configurations. In this thesis, the terms FACTS Controllers and FACTS devices are used interchangeably.

Chapter 2 of this thesis presents the fundamentals of UPFC, principle of operation of UPFC, various converter topologies and control modes of UPFC. A detailed analysis of converter switching technique has been demonstrated with simulation results. Chapter 3 discusses the injection model of UPFC. The UPFC model used in the simulation is derived and explained. The UPFC model has been included in a Newton-Raphson load flow algorithm. Chapter 4 illustrates the application of UPFC for power flow control. The UPFC has been used to reduce overloads in a transmission line and improve the voltage at the buses. Various test systems have been used to show the effectiveness of the UPFC. Chapter 5 discusses the area of available transmission capability in electric power systems. A number of methods to calculate transfer capability have been discussed. The effect of UPFC is studied and demonstrated with different power systems. The results clearly illustrate the effectiveness of UPFC in enhancing the Available Transfer Capability of power systems. In Chapter 7, the summary of the thesis highlighting the contribution of the research and suggestions for future work are outlined.

Chapter 2

The Unified Power Flow Controller

2.1 Introduction

The power transmitted over a transmission line is a function of the line impedance, the magnitude of sending-end voltage, receiving-end voltage and the phase angle between the voltages. As presented in chapter 1, traditional techniques of reactive line compensation and step like voltage adjustment are generally used to alter these parameters to achieve optimal power transmission control.

The unified power flow controller (UPFC) is a member of the group of FACTS devices which utilizes synchronous voltage source concept for providing a comprehensive capability for transmission system control. Within the structure of traditional power transmission concepts, the UPFC is able to control simultaneously or selectively all the parameters affecting power flow in transmission line. It can also provide the unique capability of independently controlling both the real and reactive power flow in the transmission line. These basic features make the unified power flow controller the most powerful device presently available for transmission system control. This chapter presents operating characteristics and features of the UPFC. The various features have been supported by simulation results.

2.2 Operating principles and characteristics of UPFC

The unified power flow controller employs two switching converters, which are considered as voltage source inverters using gate turn off (GTO) thyristor switches, as illustrated in Figure 2.1. These converters, labeled "Converter 1" and "Converter 2" are operated from a common dc link provided by a dc storage capacitor. This arrangement functions as an ideal ac to ac power converter in which the real power can freely flow in either direction between the ac terminals of the two converters and each converter can independently generate reactive power at its own ac output terminal.

Converter output provides the main function of the UPFC by injecting an ac voltage V_{pq} $(0 \leq V_{pq} \leq V_{pqmax})$ at phase angle $\rho(0 \leq \rho \leq 360^{o}$)at the power frequency, in series with the line with an insertion series transformer. This injected voltage can be considered essentially as an ac synchronous voltage source. The transmission line current flows through the voltage source resulting in real and reactive power exchange between it and the ac system. The real power exchanged at the ac terminal (i.e., at the terminal of the series insertion transformer) is converted by the converter into dc power which appears at the dc link as positive or negative real power demand. The reactive power exchanged at the ac terminal is generated internally by the converter.

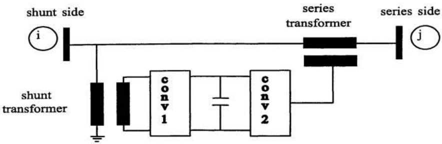


Figure 2.1: Basic circuit arrangement of the UPFC

The basic function of converter 1 is to supply or absorb the real power demanded by converter 2 at the common dc link. This dc link power is converted back to ac and coupled to the transmission line via a shunt connected transformer. Converter 1 can also generate or absorb controllable reactive power, if it is required and thereby it can provide independent shunt reactive compensation for the line. There is a closed path for the real power exchanged by the action of series voltage injection through converters 1 and 2 back to the line. The reactive power exchanged is supplied or absorbed locally by converter 1 and 2 back to the line.

Converter 1 can be operated at a unity power factor or can exchange reactive power with the line independent of any reactive power exchange by converter 2. Hence there is no reactive power flow through the UPFC.

The functional capability of the unified power flow controller from the traditional transmission concept is based on shunt compensation, series compensation and phase shifting. The UPFC can fulfill all these functions and thereby meet multiple control objectives by adding the injected voltage V_{pq} with appropriate amplitude and phase angle, to the terminal voltage V. Using phasor representation, the basic UPFC control functions are illustrated in Figure 2.2.

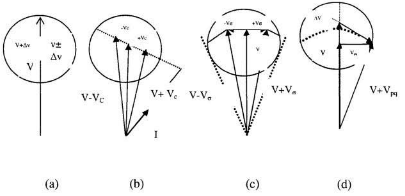


Figure 2.2 Phasor diagram showing control capability of UPFC [1]

Figure 2.2 (a) shows terminal voltage regulation similar to that which can be obtained with a transformer tap-changer having infinitely small steps. $V_{pq}=\Delta V$ is injected in-phase (or anti-phase) with V.

Figure 2.2 (b) shows series reactive compensation where $V_{pq}=V_C$ is injected in quadrature with line current I. The series voltage injected in the transmission line can be varied in proportion to the line current to imitate the compensation obtained with a series capacitor or reactor.

Figure 2.2 (c) shows phase angle regulation. $V_{pq}=V_\sigma$ is injected at an angle with respect to V_s that achieves the desired phase shift without any change in magnitude. This mode can function as a phase angle regulator.

Multi function power flow control is executed by simultaneous terminal voltage regulation, series capacitive compensation and phase angle as shown in Figure 2.2 (d) where $V_{pq}=\Delta V+V_c+V_\sigma$. All the parameters controlling the flow of power in the transmission line can be controlled simultaneously. The powerful features of the UPFC can be used to maintain real and reactive power flow in the line at desired levels. The UPFC controls the magnitude and angular position of the injected voltage so as to maintain or vary the real and reactive power flow in the line to satisfy load demand and system operating conditions.

2.3 Real and Reactive Power Control using UPFC

A simple two machine system with sending-end voltage V_s, receiving-end voltage V_r, and line impedance X is shown in Figure 2.3 (a). Figure 2.3 (b) shows the system voltages in the form of a phasor diagram with transmission angles δ and $|V_s|=|V_r|=V$.

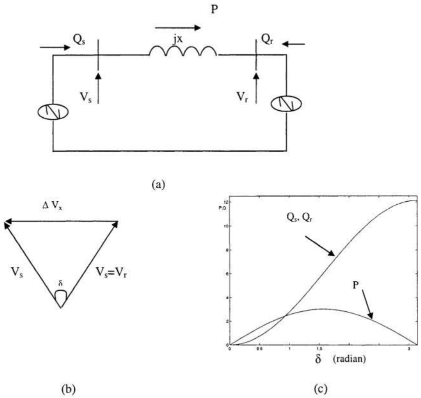


Figure 2.3 (a) A simple two machine system (b) Related voltage phasor, (c) Real and reactive power versus transmission angle.

In Figure 2.3 (c) the transmitted power P (P= $\{V^2/X\}$ sin δ) and the reactive power $Q=Q_s=Q_R$ (Q= $\{V^2/X\}$ {1-cosδ}) supplied at the ends of the line are shown plotted as a function of the angle δ (i.e., $0 \leq \delta \leq 90^o$). The elementary system of Figure 2.3 (a) has been used as a building block to explain the capability of the UPFC to control the real power P and reactive power Q_s and Q_R, at the sending-end and the receiving end of line respectively.

Figure 2.4 shows the power system of Figure 2.3 (a) included with a UPFC. The UPFC is represented by a controllable voltage source in series with the line which, as explained in the previous section, can generate or absorb reactive power from the sending-end generator. The voltage injected by the UPFC in series with the

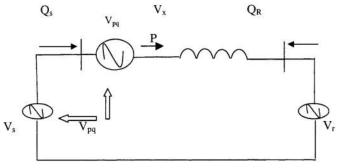


Figure 2.4 Two machine system with the Unified Power Flow Controller [2].

line is represented by V_{pq} having magnitude V_{pq} ($0 \leq V_{pq} \leq V_{pqmax}$) and angle ρ ($0 \leq \rho \leq 360^{o}$). The line current flows through the series voltage source, V_{pq}, and results in both real and reactive power exchange with the line. To represent the UPFC properly, the series voltage source is designed to generate only the reactive power Q_{pq} it exchanges with the line. Thus the real power P_{pq} it exchanges with the line is assumed to be transferred to the sending end generator as if a perfect exchange for real power flow between it and the sending end generator exists. This is compatible with the UPFC structure in which the dc link between the two voltage source converters maintains a bi-directional coupling for real power between the injected series voltage and the sending bus. In Figure 2.4 the shunt reactive compensation capability of the

UPFC is not utilized. The UPFC shunt inverter is assumed to operate at unity power factor. Its main function is to transfer the real power demand of the series inverter to the sending end generator. The operating principle of the UPFC is explained with the help of a simple two bus power system [6].

2.3.1 UPFC in a two-bus power system

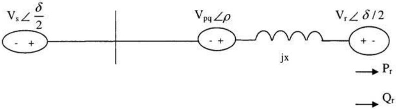


Figure 2.5 Conceptual representation of UPFC in a two-Bus Power System

The power flow control capability of the UPFC can be illustrated by the real and reactive power transmission characteristics of the simple two machine system shown in Figure 2.5. The system consists of sending and receiving end voltage sources. A voltage of appropriate magnitude V_{pq} and phase angle ρ is added to the (Sending-end) terminal voltage V_s.

The system voltages in phasor form are defined below:

$$V_r = V e^{-j\delta/2}$$

$$V_s = V e^{j\delta/2}$$

$$V_{pq} = V_{pq} e^{j\rho}$$

The complex power flow is given by $V_r I_r^*$ and can be written as P_r+jQ_r, where * means the conjugate. Current flowing through the line is given by

$$I_r = \frac{V_S + V_{pq} - V_r}{jX} \tag{2.1}$$

Substituting the value of I_r in $V_r I_r^*$

$$P_r+jQ_r = V_r \left(\frac{V_S + V_{pq} - V_r}{jX}\right)^* \tag{2.2}$$

Taking V_r inside the equation

$$P_r+jQ_r = \left(\frac{V_r^* V_s + V_r^* V_{pq} - V_r^* V_r}{jX}\right)^* \tag{2.3}$$

Substituting the value of voltage in equation (2.3) gives

$$P_r+jQ_r = \left(\frac{V^2 e^{j\delta} + VV_{pq} e^{j\left(\frac{\delta}{2}+\rho\right)} - V^2}{jX}\right)^* \tag{2.4}$$

Expressing $e^{j\delta}$ as $\cos\delta + j\sin\delta$ and expanding equation 2.4 gives

$$P_r+jQ_r = \left(\frac{V^2(\cos(\delta) + j\sin(\delta)) - V^2 + VV_{pq}\cos(\frac{\delta}{2}+\rho) + jVV_{pq}\sin(\frac{\delta}{2}+\rho)}{jX}\right)^* \tag{2.5}$$

Taking the conjugate of equation 2.5 gives

$$P_r+jQ_r = \left(\frac{V^2\cos(\delta) + VV_{pq}\cos(\frac{\delta}{2}+\rho) - V^2 - j(V^2\sin(\delta) + VV_{pq}\sin(\frac{\delta}{2}+\rho))}{-jX}\right) \tag{2.6}$$

Separating the real and imaginary parts of equation 2.6 the following equation. is obtained.

$$P_r+jQ_r=\left(\frac{V^2\sin(\delta)}{X}+\frac{VV_{pq}\sin(\frac{\delta}{2}+\rho)}{X}\right)+j\left(\frac{-V^2}{X}(1-\cos(\delta))+\frac{VV_{pq}\cos(\frac{\delta}{2}+\rho)}{X}\right) \quad (2.7)$$

P_r and Q_r can be separately written as

$$P_r=\frac{V^2\sin(\delta)}{X}+\frac{VV_{pq}\sin(\frac{\delta}{2}+\rho)}{X} \quad (2.8)$$

$$Q_r=\frac{-V^2}{X}(1-\cos(\delta))+\frac{VV_{pq}\cos(\frac{\delta}{2}+\rho)}{X} \quad (2.9)$$

$$P_o(\delta)=\frac{V^2}{X}\sin(\delta) \quad (2.10)$$

and $Q_o(\delta)=\frac{-V^2}{X}(1-\cos(\delta))$ (2.11)

are the real and reactive powers characterizing the power transmission of the uncompensated system at a given angle δ. Since angle ρ is freely variable between 0 and 2π at any transmission angle δ ($0\leq\delta\leq\pi$), with these capabilities of the UPFC explained above, the conventional terms of series compensation, phase shifting, etc. become irrelevant; the UPFC simply controls the magnitude and angular position of injected voltage.

It can be observed from Figure 2.4 that the transmission line sees V_s+V_{pq} as the effective sending end voltage. The UPFC affects the voltage (both its magnitude and angle) across the transmission line and thus it is able to control, by varying the magnitude and angle of V_{pq}, the transmission real power as well as the reactive power demand of the line at any given transmission angle between the sending -end and receiving-end voltages.

Figure 2.6 shows the controllable area of real power P and reactive power demand Q attained with the UPFC for the voltage injected at different angles $\delta=0^o$, $\delta=30^o$, $\delta=60^o$, $\delta=90^o$. The centers of control regions are defined by the $P_o(\delta)$, $Q_{or}(\delta)$ coordinates. Figure 2.6(a) illustrates the case when the transmission (phase) angle is zero ($\delta=0$). As $V_{pq}=0$ is zero, P, Q_r and Q_s are all zero. The circle is the locus of all values of real power P and reactive power Q_r obtained for a fixed value of injected voltage phasor rotated at full revolution of $(0\leq\rho\leq360^o)$. The area within this circle defines all P and Q_r values obtainable by controlling the magnitude V_{pqmax} and angle ρ of phasor V_{pq}.

The circle in the $\{P, Q_r\}$ plane defines all P and Q_r values attainable with the UPFC of a given rating. As an example, the UPFC with the voltage rating of V_{pq} p.u is able to establish V_{pq} p.u. power flow in either direction, without imposing any reactive power demand on either the sending-end or the receiving-end generator. The UPFC can also force the system at one end to supply reactive power for, or absorb that from, the system at the other end [7].

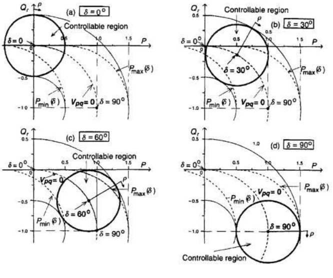


Figure 2.6 Control region of the attainable real power P and receiving-end reactive power demand Q_r with a UPFC-controlled transmission line at $\delta=0^o$ (a) $\delta=30^o$ (b) $\delta=60^o$ (c) $\delta=90^o$ (d) [1]

2.4 Converter Topologies

Converters are used to convert dc power into ac power at desired output voltage and frequency. The force commutated inverters can be classified into current source converters and voltage source converters. The two basic categories of self commutating converters are explained below.

The current source converter converts power between an adjustable current source and a single or three phase load. Since the input power is usually supplied at a constant voltage, the converter system consists of the two stages.

Figure 2.7 shows that the current source receives power from a fixed voltage ac or dc bus and supplies an adjustable dc current at the output terminals. This stage employs a controlled bridge rectifier or a dc chopper. The current source converter is connected with the "current source". It converts the dc current at the input to an ac current at the output terminals. The dc current always flows in one direction and power flow would reverse with change in direction of dc current. The amplitude of the ac current can be controlled only indirectly by controlling the magnitude of the dc input current produced by the current source.

Figure 2.7 shows the converter box with a simple symbol because the current source converter may be based on diodes, conventional thyristors or the turn off devices.

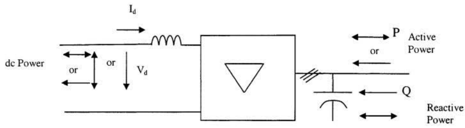


Figure 2.7 Current Sourced Converter[1]

Converters fed by a dc source with small internal impedance are called voltage sourced converters. Converters employing thyristors connected in bridge configuration are called bridge converters.

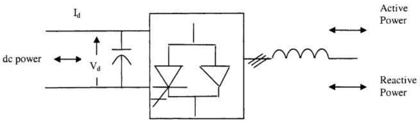


Figure 2.8 Voltage Sourced Converter [1]

Figure 2.8 shows the basic operation of a voltage sourced converter. The structure of the converter shows a box with a gate turn-off thyristor and diode. The input side of the converter has single polarity supported by a capacitor. The size of the capacitor is very large to accommodate currents that accompany the switching sequence of the converter. The voltage of the capacitor is kept constant. The dc current can flow in either direction and it can exchange dc power with the connected dc system in either direction. The generated ac voltage connects to the ac system through an inductor.

The voltage source is interfaced with the transmission line through an insertion transformer in a UPFC. The main advantage is its capability to transfer power in either direction. The UPFC employs two three phase voltage source converters, one connected in series and other in shunt with the line. With these converters, the ac output voltage magnitude, phase angle and the frequency can be controlled, by varying the width of the voltage pulses, and/or the amplitude of the dc bus voltage. Another approach is to have multiple pulses per half cycle, and then vary the width of the pulses to vary the amplitude of the ac voltage. The main reason for doing so is to be able to vary the ac output voltage and to reduce the low order harmonics [8].

2.5 Control Circuit

Control circuit constitutes a major part of the complete UPFC device. The control circuit is divided functionally into internal (converter) control and external control. The internal control operates the two converter so as to produce the desired injected voltage. In this section a brief introduction is given to the techniques a voltage source converter employs to generate variable ac output voltage. The technique is based on pulse width modulation. The capability of injecting voltage with specified magnitude and angle in series with the transmission line lies with the UPFC. The voltage is generated from the voltage sourced converter using sinusoidal pulse width modulation (SPWM) technique, a control within the inverter and is also known as duty-cycle regulation. This method of regulation of voltage employs variation of the conduction time per cycle to alter the rms output voltage of the inverter. It is required to vary the magnitude of the ac output voltage without having to change the magnitude of the dc voltage. The three phase converter can accomplish the desired criteria. With these converters the ac output voltage can be controlled by varying the width of the voltage pulses, and/or by varying the amplitude of dc bus voltage.

The sinusoidal pulse width modulation has been explained with reference to control requirements of the circuit. In this method, the firing instants of the GTO's of the converters are decided by the interactions of rectified sinusoid voltage of amplitude A_2 with a triangular wave of amplitude A_1. Both these waveforms are synchronized with respect to the mains supply. The output voltage is varied by changing the amplitude of the rectified sinusoid or the ratio A_2/A_1 as it would change the width of the pulse. The ratio A_2/A_1 is called the modulation index. The triangular wave can be timed to have either peak or zero with the zero of the sinusoid [9]. As an example, the following section explains how a voltage sourced converter can be used to generate and control the voltage which is injected in to the transmission line through an insertion transformer.

2.5.1 Voltage Source Converter Using SPWM

To demonstrate the concept of voltage sourced converter, the circuit in Figure 2.9 has been simulated using PSCAD/EMTDC simulation software [10]. The basic building block to simulate a voltage sourced converter is the generation of firing pulses for the GTOs connected in the circuit. Figure 2.9 shows the system used for generating the pulse width modulated signal for the voltage sourced converter. The three sinusoidal signals separated by 120^0 are generated using built-in basic PSCAD blocks and are compared with a triangular wave using a triangular wave generator. Both the signals are compared using a comparator.

The output of the comparator with a desired modulation index is a Pulse width modulated signal fed to the GTO's of the three phase voltage source converter. Figure 2.10 shows the complete system for generating the variable voltage through a voltage sourced converter.

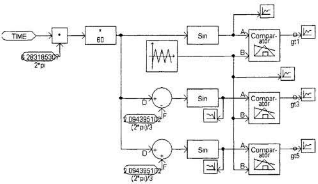


Figure 2.9: Circuit arrangement for SPWM

Figure 2.10 consists of a rectifier, a d.c source and a voltage sourced converter. In general, the input voltage from a three phase source operating at 60 Hz frequency is fed to the three phase full wave rectifier; it is made up of diodes connected in parallel and gives six pulse ripples at the output voltage. The diodes are numbered in order of conduction sequences, as 12, 23, 34, 45, 56 and 61. The pair of diodes which are connected between the pair of supply lines having the highest value of line-to-line voltage would conduct. The output of the rectifier is fed to the inverter. The voltage source converter is made up of an asymmetric turn-off device such as GTO with a parallel diodes connected in reverse. Some turn-off devices, such as the IGBT's and IGCT's, may have a parallel reverse diode built in as a part of complete integrated device for suitable voltage source converters as shown in Figure 2.10. However, for high power converters, provision of separate diodes is advantageous. In real time, there would be several turn off device

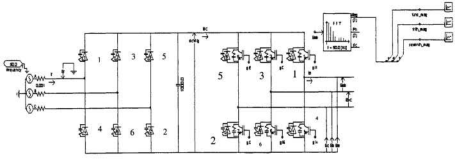


Figure 2.10 Circuit arrangement for generation of injected voltage.

units in series for high voltage applications.. The gating signals of three phase inverters should be advanced or delayed by 120^0 with respect to each other in order to obtain three-phase balanced voltages [11]. Each GTO conducts for 180^0 and three GTO remain on at any instant of time. A three-phase inverter may be considered as three single-phase inverters and the output of each single phase inverter is shifted by 120^0. Inverter output voltage can be controlled by introducing ac regulator between the inverter and the load. This method has the drawback that it gives a high harmonic content. Hence, the output voltage is controlled by varying the pulse width of the gating signals.

An important advantage of this scheme is that at low output voltages, the relative harmonic content does not increase. The output of the voltage sourced converter has been shown in Figure 2.11. The first plot in Figure 2.11 is the inverter output current I_a in phase A, the second plot shows the inverter output voltage of phase a-b, E_{ab}, and the third plot shows the phase voltage E_a of the inverter. If the dc input

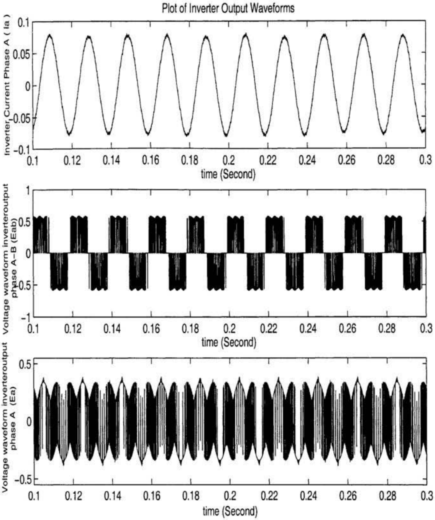


Figure 2.11 Plot of inverter output waveforms

voltage to the inverter is varied to compensate for source voltage fluctuations, the inverter can be designed for the maximum value of output voltage desired [12].

2.5.2 Control of Shunt and Series Converter

The circuit arrangement of two coupled converters offers series voltage injection along with independently controllable reactive power exchange and facilitates several control modes for the UPFC. Reactive shunt compensation and free control of series voltage injection are the options to the approach selected for power flow control.

The shunt inverter is operated in such a way so as to draw controlled current from the ac bus. The current reference is chosen to satisfy the shunt reactive power reference and (in UPFC configuration) to provide any real power needed to balance the real power of the series inverter. A small amount of real power is also drawn to meet the power losses of the inverter and magnetics. The shunt reactive power reference can be either capacitive or inductive. In var control mode, the simple var request is maintained by the control system regardless of bus voltage variation. The magnitude and angle of the voltage injected in series with the line is controlled by the series converter.

The series inverter generates a voltage vector (across the line-side terminal of the insertion transformer) with magnitude and phase angle requested by the reference input. In automatic power flow mode, series injected voltage is determined automatically and continuously by a vector control system to ensure that the desired values of real and reactive power (P and Q) (looking in to the transmission line) are maintained despite system changes. The basic function of series compensation is to control the magnitude of the injected voltage in proportion to the line current, so that series insertion emulates reactive impedance when viewed from the line. The injected voltage is controlled with respect to the input bus voltage so that the output bus voltage is phase shifted relative to the input voltage by an angle specified by the reference input [13].

2.6 Summary

This chapter has presented the details of UPFC. Compared to other power flow control devices, such as STATCOM, TCSC etc, UPFC is unique in its capability to control both real and reactive power in a transmission system. Various control features of UPFC with voltage control techniques have been discussed with supporting simulations results. The features provided by UPFC can be effectively used to control power flow over long distance high voltage transmission lines.

Chapter 3

Modeling of Unified Power Flow Controller for Load Flow Studies

3.1 Introduction

In this chapter, a general model is derived for the unified power flow controller. This model which is referred to as injection model is helpful in understanding the impact of UPFC on a power system. This model can easily be implemented in existing power system analysis programs, particularly for load flow studies. This chapter presents the incorporation of the derived UPFC model for load flow analysis studies.

Few models have been developed for the UPFC to study its effect on power system. With such a comprehensive control capability, UPFC has the ability to provide real time control of power flows within a power system to meet predefined operating target. This may be very helpful in the continuing deregulation of power industry. Power systems connected with UPFCs can precisely control the power exchanged in power transactions.

This approach of modeling incorporates, a series reactance together with a set of active and reactive power injections at each end of the series reactance. These powers are expressed as function of the terminal, nodal voltages, and the voltage of a series source which represents the UPFC series converter.

3.2 *Injection Model of Series Controllable Device*

Figure 3.1 shows the equivalent circuit diagram of a series controllable device (SCD) or a series connected voltage source, which is located between nodes i and j in a power system. A UPFC injects a voltage V_{se} in series with the transmission line through a series transformer. The active power P_{se} involved in the series injection is taken from the transmission line through a shunt transformer (i.e. P_{sh}).

The UPFC generates or absorbs the needed reactive power (i.e. Q_{se} and Q_{sh}) locally by the switching operation of its converters, while there is no transfer of reactive power through the dc link. In Figure 3.1 x_s is the effective reactance of the UPFC seen from the transmission line side of the series transformer. The shunt converter must supply or absorb the required amount of active power to the series converter via the DC link. Typically this amount is less than the MVA rating of the converter which allows the shunt converter to provide reactive power compensation to the sending end. In this manner the converters of the UPFC may generate or absorb reactive power internally. Figure 3.2 shows the vector diagram of a series controllable device [14].

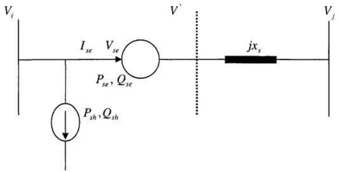


Figure 3.1: Equivalent circuit diagram of a Series Controllable Device

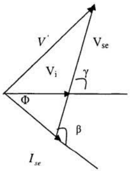


Figure 3.2: Vector diagram of the Series Controllable Device

3.2.1 Injection model of UPFC

To obtain an injection model for a UPFC, the series part of the UPFC as shown in Figure 3.3 is considered first.

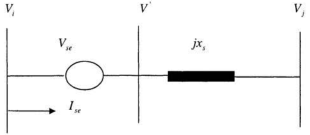


Figure 3.3 Representation of the series connected voltage source

The series connected voltage source is modeled by an ideal series voltage V_{se} which is controllable in magnitude and phase, that is, $V_{se} = rV_i e^{j\gamma}$ where $0 \le r \le r_{\max}$ and $0 \le \gamma \le 2\pi$. V' represents a fictitious voltage behind the series reactance.

$V' = V_{se} + V_i$ (3.1)

The injection model is obtained as shown in Figure 3.4 by replacing the voltage source V_{se} by a current source $I_{inj} = -jb_s V_{se}$ in parallel with x_s. Note that $b_s = 1/x_s$.

The current source I_{inj} corresponds to injection powers S_i and S_j which are defined by

$$S_i = V_i(-I_{inj})^* \tag{3.2}$$

$$S_j = V_j(I_{inj})^*$$

The injection power S_i and S_j are simplified as

$$\begin{aligned} S_i &= V_i\left(jb_s rV_i e^{j\gamma}\right)^* \\ &= -rb_s V_i^2 \sin(\gamma) - jrb_s V_i^2 \cos(\gamma) \end{aligned} \tag{3.3}$$

$$\begin{aligned} S_j &= V_j\left(-jb_s rV_i e^{j\gamma}\right)^* \\ &= rb_s V_i V_j \sin(\theta_{ij}+\gamma) + jrb_s V_i V_j \cos(\theta_{ij}+\gamma) \end{aligned} \tag{3.4}$$

where $\theta_{ij} = \theta_i - \theta_j$

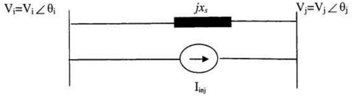
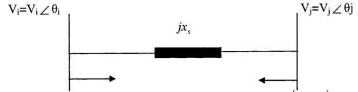


Figure 3.4: Replacement of the series voltage source by a current source.

Figure 3.5 shows the injection model of the series part of the UPFC (series connected voltage source) as two dependent loads.

$$\begin{aligned} &P_i = -real(S_i)\ , \quad Q_i = -imag(S_i) \\ &P_j = -real(S_j), \quad Q_j = -imag(S_j) \end{aligned} \tag{3.5}$$



$$P_i = rb_s V_i^2 \sin\gamma \qquad P_j = -rb_s V_i V_j \sin(\theta_{ij} + \gamma)$$

$$Q_i = rb_s V_i^2 \cos\gamma \qquad Q_j = -rb_s V_i V_j \cos(\theta_{ij} + \gamma)$$

Figure 3.5: Injection model of the series part of the UPFC

3.3 The UPFC Model

The series connected voltage source injects a voltage in the transmission line resulting in exchange of active power. The shunt connected voltage source is used mainly to provide the active power which is injected to the network through the series connected voltage source.

$$P_{conv1} = P_{conv2} \tag{3.6}$$

Equation 3.6 is valid when the losses of the UPFC are neglected. The apparent power supplied by the series voltage source converter is calculated as

$$S_{se} = V_{se} I_{se}^{*} = re^{j\gamma} V_i \left(\frac{V' - V_j}{jx_s} \right)^{*} \tag{3.7}$$

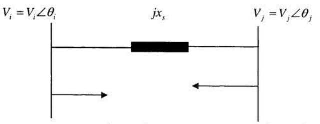
Active and reactive power supplied by the series voltage source are given as

$$P_{se} = rb_s V_i V_j \sin(\theta_{ij} + \gamma) - rb_s V_i^2 \sin(\gamma) \tag{3.8}$$

$$Q_{se} = -rb_s V_i V_j \cos(\theta_{ij} + \gamma) + rb_s V_i^2 \cos(\gamma) + r^2 b_s V_i^2 \tag{3.9}$$

3.3.1 The injection model

Assuming an ideal UPFC (i.e. losses are neglected in the UPFC), $P_{sh}=P_{se}$. For the UPFC, Q_{sh} is independently controllable, and it is assumed that $Q_{sh}=0$. Q_{sh} can also have a nonzero value. The injection model of the UPFC is constructed from the series connected voltage source model shown in Figure 3.5 by adding $P_{sh}+jQ_{sh}$ to bus i. The model shows that the net active power exchange with the power system is zero as expected for a lossless UPFC. Figure 3.6 shows the injection model of the UPFC.



$$P_{si} = rb_s V_i V_j \sin(\theta_{ij} + \gamma) \qquad P_{sj} = -rb_s V_i V_j \sin(\theta_{ji} + \gamma)$$

$$Q_{si} = rb_s V_i^2 \cos\gamma \qquad Q_{sj} = -rb_s V_i V_j \cos(\theta_{ij} + \gamma)$$

Figure 3.6 Injection model of the UPFC

In Figure 3.6

$$\begin{aligned} P_{si} &= rb_s V_i V_j \sin(\theta_{ij} + \gamma) \\ P_{sj} &= -P_{si} \\ Q_{si} &= rb_s V_i^2 \cos(\gamma) \\ Q_{sj} &= -rb_s V_i V_j \cos(\theta_{ij} + \gamma) \end{aligned} \tag{3.10}$$

where r *and* γ and are control variables of UPFC.

For the purpose of developing a control strategy for the UPFC it is useful to apply the following control variables [15]:

$$r\sin(\theta_{ij} + \gamma) = r\cos(\gamma)\sin(\theta_{ij}) + r\sin(\gamma)\cos(\theta_{ij}) = u_1 \mathrm{Sin}\ \theta_{ij} + u_2 \mathrm{Cos}\ \theta_{ij} \tag{3.11}$$

$$r\cos(\theta_{ij} + \gamma) = r\cos(\gamma)\cos(\theta_{ij}) - r\sin(\gamma)\sin(\theta_{ij}) = u_1 \mathrm{Cos}\ \theta_{ij} + u_2 \mathrm{Sin}\ \theta_{ij} \tag{3.12}$$

where $u_1 = r\cos(\gamma)$, $u_2 = r\sin(\gamma)$

$$r = \sqrt{u_1^2 + u_2^2} \quad \text{and} \quad \rho = \arctan\left(\frac{u_2}{u_1}\right) \tag{3.13}$$

Substituting (3.11) and (3.12) into (3.10), the following is obtained :

$$\begin{aligned} P_{si} &= b_s V_i V_j (u_1 \sin\theta_{ij} + u_2 \cos\theta_{ij}) \\ P_{sj} &= -P_{si} \\ Q_{si} &= u_1 b_s V_i^2 \\ Q_{si} &= -b_s V_i V_j (u_1 \cos\theta_{ij} - u_2 \sin\theta_{ij}) \end{aligned} \tag{3.14}$$

The reactive power delivered or absorbed by converter 1 is independently controllable by UPFC and can be modeled as a separate controllable shunt reactive source. It is assumed that $Q_{conv1}=0$.

The model shows that the net active power interchange of UPFC with the power system is zero, as expected for a lossless UPFC. It is assumed that converter 1 only delivers active power flow. In this way, the VA rating of converter 1 is selected as:

$$S_{conv1}=\max|P_{conv1}(\gamma)| \qquad \gamma_{min}<\gamma<\gamma_{max},\ r=r_{max}$$

However, this capacity is only utilized for a certain operating condition and for the rest of the time, there is some available capacity. This remaining capacity can be utilized if converter 1 delivers or absorbs reactive power. At any operating point (r,γ), the reactive power available is

$$Q_{conv1}(r,\gamma) = [(S_{conv1})^2-(P_{conv1}(r,\gamma))^2]^{0.5} \qquad (3.15)$$

The UPFC's injection model has been used by enabling three parameters to be controlled at the same to time to get the desired control, namely the shunt reactive power, Q_{conv1}, magnitude r, and the angle γ of the series injected voltage [16]. The various modes of UPFC operation are explained in the following section.

3.3.2 Modes of Operation

Bus voltage magnitude can be supported at both sides of UPFC. At the series side, voltage V_j is supported through r-loop with appropriate adjustment of angle γ. At the shunt side, V_i-feedback enables support through Q_{conv1}-loop. If losses are neglected, the active power requirement is equal for both converters

$$P_{conv1}=P_{conv2}=\mathrm{Re}\left(V_{se}I_{ij}^{*}\right) \qquad \text{(equation 3.8)}$$

$$=rb_sV_iV_j\sin\left(\theta_{ij}+\gamma\right)-rb_sV_i^2\sin(\gamma)$$

Thereby, the nominal rating S_{conv1} of the shunt converter 1 is given as the maximum reactive power demanded by the injected series voltage source $\max\left|P_{conv1}(r,\gamma)\right|$. Since this MVA capacity is not always fully utilized, there usually remains some capacity available for producing reactive power and thereby controlling the voltage V_i. Thus, during the simulation it is necessary to check for maximum available reactive capacity $\max\left|Q_{conv1}\right|$

$$\max\left|Q_{conv1}\right|=\sqrt{S_{con1n}^{2}-P_{conv1}^{2}(r,\gamma)} \qquad (3.16)$$

Series compensation mode of the UPFC could be attained by setting angle γ to $\gamma=\pi/2$. The voltage is injected in qudarature with the current I_{ij}. The current I_{ij} is generally defined as

$$I_{ij}=(V_i-V_j)/jX_s=[(P_{conv2}+jQ_{conv2})/V_s]^* \qquad (3.17)$$

but this expression is not very convenient due to division by r (V_s=rV_i) which could take zero value. In the series compensation mode, the following relation is applied instead [14].

$$I_{ij} = \frac{\sqrt{P_{i1}^2 + (Q_{i1} - Q_{conv1})^2}}{V_i} \tag{3.18}$$

Phase shifting mode of the UPFC could be achieved by operating it as a phase angle regulator (PAR). Voltage is injected with respect to V_s that achieves the desired σ phase shift without any change in magnitude. Thus the UPFC can function as a perfect phase shifter. From the practical view point, it is also important to note that, in contrast to conventional phase shifters, the ac system does not have to supply the reactive power the phase shifting process demands since it is internally generated by the UPFC converter[17] .

3.4 UPFC Injection Model For Load Flow Studies

The UPFC injection model can be easily implemented in load flow programs. If a UPFC is located between node i and node j in a power system, the admittance matrix must be modified to consider the new bus (corresponding to V' in Figure 3.3) and include the reactance X_s of the UPFC. The Jacobian matrix is modified by the addition of appropriate injection powers.

The model is implemented in a full Newton-Raphson program. Newton Raphson method is found to be more efficient and practical. There are two equations for each load bus and one equation for each voltage controlled bus. Expanding the power flow equations in Taylor's series results in the following set of linear equations

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \\ \cdot \\ \Delta P_n^{(k)} \\ \Delta Q_2^{(k)} \\ \cdot \\ \cdot \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2^{(K)}}{\partial \delta_2} & \frac{\partial P_2^{(K)}}{\partial |V_n|} \\ \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial |V_n|} \\ \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \frac{\partial Q_n^{(K)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \cdot \\ \cdot \\ \Delta \delta_n^{(k)} \\ \Delta |V_2^{(k)}| \\ \cdot \\ \\ \Delta |V_n^{(k)}| \end{bmatrix} \tag{3.19}$$

In the above equation, bus 1 is assumed to be the slack bus. ΔPn and ΔQn are the difference between the scheduled and calculated values, known as power residuals. The matrix which contains the partial derivatives is called the Jacobian matrix. Elements of the Jacobian matrix are the partial derivatives of power flow equations evaluated at $\Delta\delta_i^{(k)}$ and $\Delta|V_i^{(k)}|$. The Jacobian matrix gives the linearised relationship between small changes in voltage angle $\Delta\delta$n and voltage magnitude $\Delta|$Vn$|$. In short form, it can be written as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ J & L \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V / V \end{bmatrix} \tag{3.20}$$

The state variables corresponding to the UPFC are combined with the network voltage magnitudes and angles in a single frame of reference for a unified solution through Newton-Raphson method. The UPFC equations are combined with the linearised system of equations corresponding to the rest of the network. The resulting system equation is represented as

[f (X)]=[J][ΔX]

where J is the Jacobian matrix and [ΔX] is the mismatch vector.

Equation 3.10 is included in the power mismatch equations.

$\Delta P(i) = \Delta P(i) - P_{si}$

$\Delta P(j) = \Delta P(j) - P_{sj}$ (3.21)

$\Delta Q(i) = \Delta Q(i) - Q_{si}$

$\Delta Q(i) = \Delta Q(i) - Q_{sj}$

The change is reflected in the ΔX vector. The original dimensions of the mismatch vector are not altered at all. The Jacobian matrix is modified by addition of appropriate injection powers. The Jacobian matrix is modified as given in Table 3.1.

Table 3.1 Modification of Jacobian matrix

$H_{(i,i)} = H^o(i,i) - Q_{sj}$ $H_{(i,j)} = H^o(i,j) + Q_{sj}$ $H_{(j,i)} = H^o(j,i) + Qsj$ $H_{(j,j)} = H^o(j,j) - qsj$	$N_{(i,i)} = N^o(i,i) - P_{sj}$ $N_{(i,j)} = N^o(i,j) - P_{sj}$ $N_{(j,i)} = N^o(j,i) + P_{sj}$ $N_{(j,j)} = N^o(j,j) + P_{sj}$
$J_{(i,i)} = J^o(i,i)$ $J_{(i,j)} = J^o(i,j)$ $J_{(j,i)} = J^o(j,i) - P_{sj}$ $J_{(j,j)} = J^o(j,j) + P_{sj}$	$L_{(i,i)} = L^o(i,i) + 2Q_{si}$ $L_{(i,j)} = L^o(i,j)$ $L_{(j,i)} = L^o(j,i) + Q_{sj}$ $L_{(j,j)} = L^o(j,j) + Q_{sj}$

The flow chart for performing the load flow after including the UPFC model is given in Figure 3.7.

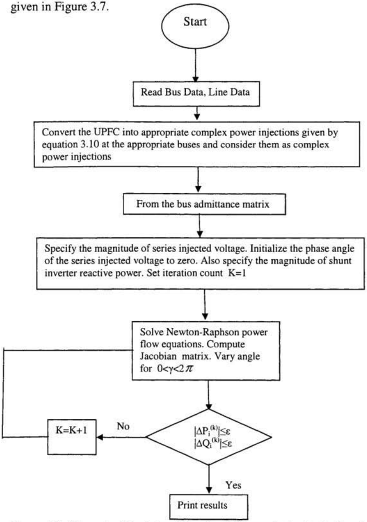


Figure 3.7 Flow chart for determining Load flow solution including the UPFC model.

The elements of the Jacobian are calculated from the above equations. The Jacobian is used to compute the Δ X vector. The new voltage and magnitude are computed and the process is continued until the residuals ΔPi and ΔQi are less than the specified tolerance.

3.5 Summary

In this chapter a general UPFC model has been presented . This model has been included in a Newton-Raphson load flow algorithm. The model of the UPFC and control equations are discussed. The UPFC model is very flexible, and it takes into account the various UPFC operating modes as well as interaction with the network. Load flow studies using the model are presented in the next chapter.

Chapter 4

Control of Power System Operation using Unified Power Flow Controller

4.1 Introduction

In interconnected power systems, electric power flows through high voltage transmission lines that connect generating stations and load centers. With the changing structure of the electric industry, it is likely that some of the transmission lines are overloaded and some transmission lines carry power well below their capacity. As discussed before, FACTS devices have the potential to control power flow in a power system. Specifically, this chapter illustrates the effectiveness of UPFC for power flow control.

The UPFC model derived in the previous chapter has been used to perform load flow studies. Four standard power system study systems are used to demonstrate the effectiveness of UPFC.

4.2 5 Bus system

In order to investigate the feasibility of the proposed model, a standard five-bus power system [18] shown in Figure 4.1 is used. The network has been modified to include a UPFC in line 1-3 near bus 3. An additional node Nbus (6) is used to consider the UPFC model. The UPFC is used to change the power flow in the transmission line between bus 1 and bus 3 from 72 MW to 98 MW. By increasing this power flow, the loading in the line between bus 1 and bus 2 is reduced. In addition, the voltage at bus 3 is improved to 1 per unit.

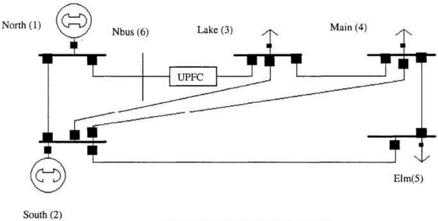


Figure: 4.1 Five Bus System [18]

Table 4.1 presents the relevant load flow results. Table 4.1 shows that the UPFC is effective in controlling the power flow through the transmission line and improving the voltage at the load bus.

Table 4.1 Comparison between power flow results with and without UPFC

Power flows &	V_1=1.06	V_2=1.0	V_3=.9433	V_4=.9469	V_5=.9554	V_6=.9433
Voltages	P_{1-2}=142.64	P_{2-3}=47.55	P_{3-4}= -7.51	P_{4-5}= -2.62	P_{2-5}=64.41	P_{6-3}=67.98
Without UPFC	P_{1-6}=72.45	P_{2-4}=46.35				
Power flows &	V_1=1.06	V_2=1.0	V_3=1.00 *	V_4=.9931	V_5=.9714	V_6=1.0122
Voltages	P_{1-2}=116.28	P_{2-3}=36.53	P_{3-4}=5.94	P_{4-5}=2.66	P_{2-5}=59.21	P_{6-3}=91.78
with UPFC	P_{1-6}=98.70**	P_{2-4}=37.24				

Voltages (V) in per unit

Power Flow (P) in MW

* Bus Voltage (Per unit) improved using UPFC

** Line flow (MW) at desired value with UPFC

UPFC parameters: $|V_{se}| = 0.12$; $\gamma = 90^{\circ}$

V_{se} is the induced series voltage. The magnitude of V_{se} is controllable by UPFC. If we define $r=|V_{se}|/|V_i|$. , then $o<r<r_{max}$. The angle γ is controllable by UPFC from 0 to 2π. The parameters of UPFC have been selected to achieve the desired power flow. The maximum value of the injected voltage is the input to the

system and the angle is varied from zero to 2π. With this the control area of the power flow can be determined. In this example UPFC has been used for relieving the overload in the system. It can also be used for voltage control on the selected bus. For controlling the voltage at a particular bus the voltage is injected in phase or antiphase with the voltage depending upon the requirement [19].

Figure 4.2 shows the influence of UPFC on active power flow of the line for variation of γ from zero to 2π and r from zero to r_{max}. The real power is a function of the injected voltage and angle. The power through the line changes as the injected voltage and the angle at which the voltage is injected in the transmission line is changed.

Figure 4.3 shows the change of reactive power flow of the line for a change in the injected voltage and angle. Controlling the injected voltage and its angle can control the flow of reactive power through the transmission line [20].

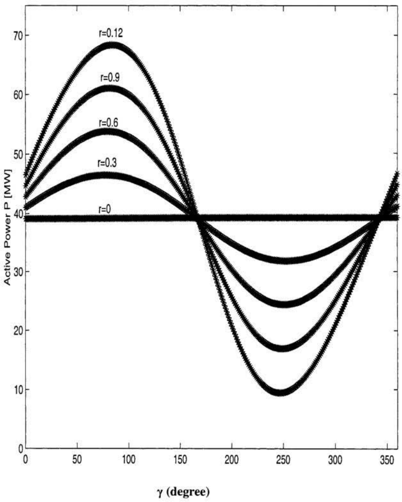


Figure. 4.2 Variation of P against r and γ

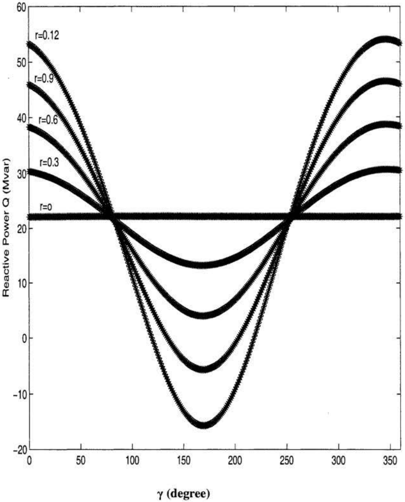


Figure. 4.3 Variation of Q against r and γ

4.3 IEEE-24 Bus Reliability test system

Figure 4.4 shows the single line diagram of the 24 bus IEEE reliability test system [21]. The transmission lines are at two voltages 230 kV and 138 kV. The peak load of the system is 2850 MW. The system total installed capacity is 3405 MW. The generation dispatch used in the base case is given in Table 4.2.

Table 4.2 IEEE 24 Bus Reliability System generation dispatch

Bus No.	22	18	21	15	16	23	1	2	13	7
MW	300	400	400	155	155	660	152	152	472	4

The 230 KV system is the top part of Figure 4.4 with 230/138 KV tie station at Buses 11, 12 and 24. One of the lines (8-9) in the system is in over loaded state with low voltage at bus 8. It is desired to relieve the overload from the line in the system; one of the ways is to use a load sharing device or install new transmission line. The UPFC has been installed in this system and is used to boost the voltage at Bus 8 and relieve the overload from line 8 to 9 and increase the line flow between line 8 to 10. The original network has been modified to include a UPFC in line 8-10 near bus 10. An additional node Nbus (25) is used to consider the UPFC model. It is decided to change the power flow in the transmission line between bus 8 and bus 10 from 145 MW to 171 MW and improve the voltage at Bus 8. By increasing this power flow, the loading in the line between bus 8 and

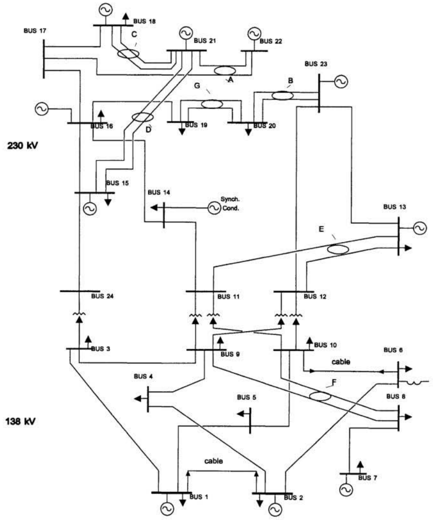


Figure 4.4: Single line diagram of the 24-Bus Reliability Test System bus 9

is reduced. In addition, the voltage at bus 8 is also improved. Table 4.3 presents the relevant load flow results with and without UPFC. This table shows that the UPFC is effective in controlling the power flow through the transmission line and improving the voltage at the bus. From Table 4.3 it is seen that the voltage has improved at bus 8 from 0.94 p.u to 0.99 p.u and power flow has changed in the transmission line (8-10) from 145 MW to 171 MW.

Table 4.3 Comparison between power flow results with and without UPFC

Power flows & Voltages Without UPFC	V_9=0.94 P_{8-9}=152	V_8=.94 P_{8-10}=145	V_6=1.03 P_{2-6}= 41.70	V_7=1.01 P_{8-7}=126.47	V_5=.99 P_{5-10}=21.13	V_1=1.01 P_{1-2}=18.06
Power flows & Voltages with UPFC	V_9=.952 P_{8-9}=125	V_8=.99* P_{8-25}=171.4** P_{25-10}=185	V_6=1.04 P_{2-6}=44.74	V_7=1.01 P_{8-7}=123.89	V_5=.997 P_{5-10}=17	V_1=1.06 P_{1-2}=15.91

Voltages (V) in per unit

Power Flow (P) in MW

* Bus Voltage (Per unit) improved using UPFC

** Line flow (Mega Watt) at desired Value Using UPFC

UPFC parameters: $|V_i|$ =0.12; γ=90°

4.4 IEEE 30 Bus test system

Figure 4.5 shows the single line diagram of IEEE 30 bus test system [22]. The system contains 30 buses, 41 transmission lines and 6 generators. One of the lines (Bus 1 – Bus 3) in the system is overloaded. It is desired to relieve the overload from line 1 to 3 using the UPFC. By increasing the power flow in the line between bus 1 and bus 2, the line between bus 1 and bus 3 is relieved of the overload. An UPFC placed between line 1 and 2 is used to change the power flow in the transmission line between bus 1 and bus 2 from 177 MW to 200 MW. An additional node Nbus (31) is used to consider the UPFC model.

By injecting the voltage of suitable magnitude, the flow in the line between bus 1 and bus 2 has been changed and the line between bus 1 and bus 3 has been relieved of the overload. Table 4.4 presents the relevant load flow results with and without UPFC. This table also shows that the UPFC is effective in controlling the power flow through the transmission line. Many operating conditions have been investigated to achieve the optimal operation of the system with UPFC. Table 4.4 shows the change in the power flow in the line 1 to 2. Initial power flow through the line was 177 MW. With UPFC placed in the line, power flow in the line has increased to 200 MW and line 1 to 3 is relieved of the overload.

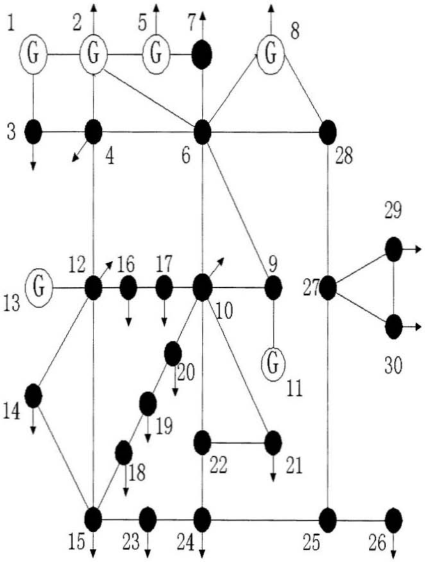


Figure 4.5: Single line diagram of the 30 Bus test system

Table 4.4 Comparison between power flow results with and without UPFC

Power flows & Voltages Without UPFC	V_1=1.06 $P_{1\text{-}2}$=177.24	V_2=1.04 $P_{2\text{-}4}$=45.45	V_3=1.03 $P_{1\text{-}3}$= 83.83	V_4=1.02 $P_{3\text{-}4}$=78.60	V_5=1.01 $P_{2\text{-}5}$=82.78	V_6=1.01 $P_{2\text{-}6}$=61.92
Power flows & Voltages With UPFC	V_1=1.06 $P_{1\text{-}31}$=200* $P_{31\text{-}2}$=190	V_2=1.04 $P_{2\text{-}4}$=55	V_3=1.04 $P_{1\text{-}3}$=63.33	V_4=1.02 $P_{3\text{-}4}$=59.31	V_5=1.01 $P_{2\text{-}5}$=85.92	V_6=1.0 $P_{2\text{-}6}$=69.1

Voltages (V) in per unit

Power Flow (P) in MW

* Line flow (Mega Watt) at desired Value Using UPFC

UPFC parameters: $|V_{se}|$ =0.1; γ=90°

4.5 39- Bus New England test system

Figure 4.6 shows the 39-bus New England test system which consists of 46 transmission lines, 10 generators and 12 transformers. The system component data is as shown in Table 4.5. The power system base case load flow summary is shown in Table 4.6.

Table 4.5: New England 39- bus power system component data

Buses	39
Generators	10
Bus shunts	0
Lines	46

Table 4.6: New England 39-bus power system base case

	Real Power (MW)	Reactive Power (Mvar)
Total generation	6192.8	1256.3
Total load	6150.1	1408.9
Losses	42.74	-152.56

The system shown in Figure 4.6 has one of the lines (16-15) in overloaded state. It is desired to relieve the overload from the line by installing a UPFC in the system. By increasing the power flow in the line between bus 16 and bus 17, overload in line between bus 16 and bus 15 can be relieved. An additional node Nbus (40) is added to include the UPFC model.

The UPFC has been placed between bus 16 and 17 near bus 16. By injecting voltage of suitable magnitude in the transmission line the flow in the line between bus 16 and bus 17 has been changed to 312 MW and line flow between bus 16 and bus 15 has been reduced to 180 MW from the initial flow of 287 MW. By pushing more power through the transmission line the unused capacity of the transmission lines can be used. The transmission limits for this system are chosen arbitrarily.

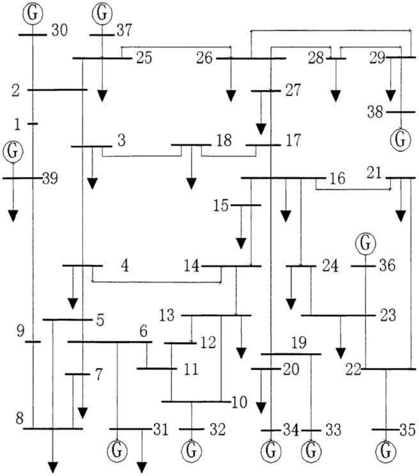


Figure 4.6 Single line diagram of the 39-bus power system

Table 4.7 Comparison between power flow results with and without UPFC

Power flows & Voltages Without UPFC	V_{16}=1.0427 P_{17-16}=205.78	V_{15}=1.0242 P_{16-15}=287.77	V_{14}=.9962 P_{15-14}= 33.5	V_{13}=0.989 P_{14-13}=297.52	V_{11}=.9849 P_{11-10}=344.6
Power flows & Voltages With UPFC	V_{16}=1.0423 P_{17-40}=312.3* P_{40-16}=313.03	V_{15}=1.0265 P_{16-15}=180.79	V_{14}=.997 P_{15-14}= 140	V_{13}=0.9896 P_{14-13}=327.40	V_{11}=.9893 P_{11-10}=317.2

Voltages (V) in per unit

Power Flow (P) in MW

* Line flow (MW) at desired value Using UPFC

UPFC parameters: $|V_{se}|$ =0.09; γ=270°

4.6 Summary

This chapter illustrates the effectiveness of the UPFC in controlling power flow in a power system. It has been shown that the UPFC can be used to reduce overloads in the transmission line and improve the voltage at the buses. The power flow control range on one or a set of transmission lines in the system can be precisely computed. It can be concluded that by diverting the flow of power from overloaded lines to under loaded lines the unused transmission capacity of the lines can be used effectively. The strong control capability of the UPFC to control bus voltage and power flows offers a great potential in solving many of the problems facing the electric utilities in a competitive environment.

Chapter 5

Available Transfer Capability Enhancement Using Unified Power Flow Controller

5.1 Introduction

A fuller understanding of transmission capacity is taking on greater importance in planning and operating electric power systems. This is due to at least three distinct reasons: (1) The actual expansion of transmission grid is severely limited by environmental constraints; (2) In a changing industry, system inputs such as generation and demand may have significantly different patterns than in a regulated industry; (3) There have been many recent developments in technologies capable of varying transmission characteristics in a flexible manner.

While these reasons may not appear to be directly inter-related, they all demonstrate the crucial role of the transmission grid in flexible energy management. It is the presence of the transmission grid that makes the economics of power industry deregulation a qualitatively different problem than the deregulation problem of many other industries.

5.2 Various notions of transfer capability

Describing and quantifying transmission capability in a meshed power system network is elusive [23]. It is difficult to pin down. Somewhat analogous to the traffic capability of large city, every vehicle is going somewhere but not all have the same destination. Some have the same origin but follow different paths while others have identical final end but come from different sources. Clearly, some circuits can become highly congested under certain conditions, thereby limiting the flow in specific directions.

5.2.1 What is Available Transfer Capability ?

One concept of available transmission capability (ATC) in a power system is defined as the amount that the power injection in a bus in a power system can be changed without violating any operating constraints in the system [23]. ATC is important for both economic and engineering reasons. All transmission grids are limited in the amount of power they can transmit. As discussed earlier, these limits can be thermal limits, steady state stability limits etc.

In a deregulated market it is important to know how much a power company can change their injections and maintain a stable operating point. If one power company increases its injections, that action may cause the flows on transmission lines somewhere in the system to increase with the result that another company cannot increase its injections in a way it desires.

Grid owners are very interested in ATC issues, e.g., how much their grid can transmit, where are the weak links in the grid, how much can the transmitted power increase before they have to invest in new equipment etc. Other questions of concern to grid owners are how other companies power transmission will influence the ATC in the grid.

5.3 Definitions used in the industry

First contingency incremental transfer capability [24]**:** It is the amount of power, incremental above normal base power transfer that can be transferred over the transmission network in a reliable manner, based on the following conditions:

- With all transmission facilities in service, all facility loadings are within normal ratings and all voltages are within normal limits.
- The bulk power system is capable of absorbing the dynamic power swings and remains stable following a disturbance resulting in loss of any single generating unit, transmission circuit or transformer.
- After the dynamic power swings following a disturbance resulting in a loss of any single generating unit, transmission circuit or transformer, but before operator-directed system adjustments are made, all transmission facility loadings are within emergency ratings and all voltages are within emergency limits.

This indicates how much the power transmission can be increased without any changes in the system and still keep the system inside all security and stability limits. A loss of some equipment will not cause any collapse.

Second contingency incremental transfer capability: It is the amount of power, incremental above normal base power transfer that can be transferred over the transmission network in a reliable manner, based on the following conditions:

- With all transmission facilities in service, all facility loadings are within normal ratings and all voltages are within normal limits.
- The bulk power system is capable of absorbing the dynamic power swings and remains stable following a disturbance resulting in a sequential and overlapping outage of two facilities - either being a generating unit, transmission circuit or transformer - with system adjustments made between the two outages are required.
- After the dynamic power swings following a disturbance resulting in a loss of the second facility - either a generating unit, transmission circuit or transformer- but before further operator-directed system adjustments are made, all transmission facility loadings are within emergency ratings and all voltages are within emergency limits.

If two outages of equipment occur, the system must still be able to handle the power transmission. With adjustments, the system can be held inside the safety limits

Installed incremental transfer capability: It is the amount of power, incremental above normal base power transfers that can be transferred over the transmission network without giving consideration to the effect of transmission facility outages. All facility loadings are within normal ratings and all voltages are within normal limits.

This definition applies to normal operation and not to any contingency, and states how much the transmission of power can be increased.

5.4 Methods of calculating ATC

The first step in calculating ATC is the determination of total transfer capability (TTC). TTC is the largest flow through the selected interface which causes no thermal overloads, voltage limit violations, voltage collapse and /or other system security problems such as transient stability [25]. The ATC for the selected interface is the TTC minus base case flow and appropriate transmission margins. The transmission margin included in calculation of ATC is transmission reliability margin (TRM), it is the portion of TTC that can not be used for reservation of firm transmission service because of uncertainties in system operation. ATC determination requires consideration of generation dispatch, system configuration, scheduled transfers, system contingencies and projected customer demand. Few of the methods available for ATC calculation are summarized below.

Single linear step ATC [26]: The single linear step approach is the most common ATC method and duplicates the ATC analysis done by many reliability organizations. This method of ATC analysis uses only information about the present system state and sensitivities about the present system state. These sensitivities are embodied in power transfer distribution factor (PTDF) calculations. A power transfer distribution factor is a measure of the sensitivity of a flow to an injection or extraction at a given location. There are two types of PTDFs: operating point dependent, which come from the load flow, and traditional PTDFs, which are derived from the DC power flow model. In any case, the PTDFs take into account at the same time injection and extraction of power at some points or at specific group of points defining the transfer. There is no need to run the power flow. The idea behind the PTDFs is to use the linear sensitivity instead of nonlinear power flow solution to arrive at the transfer limits quickly. A PTDF is measured with respect to a slack bus or a location.

Consider a transmission line with a limit of 10 MW and present loading of 5 MW and a PTDF of 10%. The estimated maximum transfer without causing overload on line is: Transfer limitation = (Limit –Present loading)/PTDF= (10-5)/0.1=50 MW. Line Outage Distribution Factors (LODFs) are a sensitivity measure of how a change in a line's status affects the flows on other lines in the system. On an energized line, the LODF calculation determines the percentage of the present line flow that will be shown up on other transmission lines after the outage of the line. When including contingency analysis, then OTDF (Outage Transfer Distribution Factor) and linearized estimates of post-outage flows are used to determine the Transfer Limitation. Transfer Limitation = (Limit – Post Outage Loading) / OTDF. If the transfer limitation for all lines during each contingency is determined, then the ATC is equal to the smallest transfer limitation.

Continuation Power Flow Analysis (CPF) [3] **:** It is well known that the Jacobian matrix of the power-flow equations becomes singular at the voltage stability limit. Conventional load flow algorithms are prone to convergence problems at operating conditions near the voltage stability limit. The continuation power-flow analysis overcomes this problem by reformulating the load flow equations so that they remain well conditioned at all possible loading conditions [3]. This approach uses an iterative process where, from a known initial solution, the solution for a specified pattern of load increase can be obtained. Specifically for ATC calculations, continuation power flow method can be used to specify the desired generation and load pattern increase and determine the power flow solution at the point where a thermal or voltage stability limits the transfer. Compared to applying standard load flow algorithms repeatedly, continuation power flow method makes it possible to include voltage stability as well.

Optimal Power flow based method [27]: The general formulation of an optimal power flow problem is

$$\text{Minimize} \quad \sum_{i=1}^{NG} F(PGi) \tag{5.1}$$

Subject to the constraints

$$g_o(x, u) = 0 \tag{5.2}$$

$$h_o(x, u) \leq 0 \tag{5.3}$$

The most common objective is the minimization of the total fuel cost. The equality constraints (equation 5.2) ensure that the load flow equations are satisfied. Equation (5.3) specifies the inequality constraints like the limit on power flow through transmission lines, bus voltage, real and reactive power limits of generation etc. This formulation can be easily modified for ATC computation. The objective function will be the transfer between the source and sink areas and this will be maximized subject to both equality and inequality constraints. Thermal limits and voltage limits can be easily included in the inequality constraints. However including stability and voltage collapse condition is a great challenge.

Repeated Power Flow (RPF) : RPF enables transfers by increasing the load (only real) at every load bus in the sink area and increasing the injected real power at the generator buses in the source area in incremental steps until limits are incurred [28].

In order to compute ATC from one location (Bus A) to another location (Bus B) and ATC's for selected transmission paths between them, the following procedure is used. Bus A and Bus B are any two different buses in the system

1) Select a case from the list of cases to be studied.

2) Establish and solve the base case power flow in which the system load is supplied without violating any transmission limits. Obtain the base case, flows on selected transmission paths.
3) Use RPF to make a step increase in power transfer. Increase the generation (source at the bus A). Increase the real load at bus B (sink) by same amount.
4) Establish and solve the power flow.
5) Check the solution up to step 2, whether any limit is violated. If there is any violation, decrease the transfer power by the minimum amount necessary to eliminate the violation and then go to step 6. If no limit is violated, go to step 3.
6) Compute the ATC level. This is the ATC value for the selected case.
7) Select the next case and return to step 2. If all cases have been selected, go to step 8.
8) Compute the ATC for the source/sink transfer case. It is the minimum value of all ATC levels.

In the research presented in this thesis ATC is calculated using repeated power flow. The reason for using this method is that RPF can be easily done using available load flow software. The results are illustrated for a 6 bus system shown in Figure 5.1, which contains 11 transmission lines and 3 generators [29]. The system component data is shown in Table 5.1. The power system base case is shown in Table 5.2.

Table 5.1: 6- bus power system component data

Buses	6
Generators	3
Lines	11

Table 5.2: 6-bus power system base case

	Real Power (MW)	Reactive Power (Mvar)
Total generation	218	179.8
Total load	210	210
Losses	7.88	-30.05

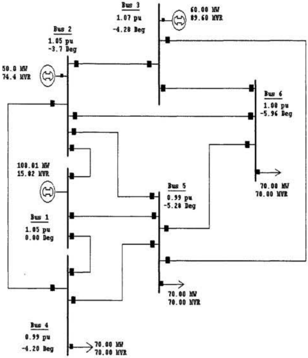


Figure: 5.1 Single line diagram of 6-bus power system [29]

The ATC is calculated between bus 2 and bus 6. To calculate ATC between the two buses the generation at bus 2 is increased and the load is also increased by the same amount at bus 6. The power flow is run and flows on all transmission lines are monitored. If the power flow (MW) exceeds the MW limit of the transmission line there would be no more transfer of power between the two buses, otherwise again an incremental amount of power transfer is performed between the two buses till any of the transmission line reaches its MW limit. In this case line 1-5 reaches its limit when 52.49 MW is transferred between bus 2 and bus 6. Any additional amount of transferred power beyond this value would cause an overload on the line. The difference between power flows computed after increasing generation and load, and base case gives the required ATC between the two buses. Applying the proposed method, ATC can be found by taking the difference of the increased generation or load from the base case. The results are shown in Table 5.3. The above case is also explained with details of possible transactions. The single linear step ATC is obtained using an option available with the PowerWorld simulator.

Table 5.3: ATC results for 6-Bus System

From	To	ATC with single linear step ATC	ATC with Repeated Power Flow
2	6	52.49 MW	47 MW
3	5	41.59 MW	40 MW

Figure 5.2 shows the base case loading of the system. When a transfer of 52.49 MW is obtained between bus 2 and bus 6, line 1-5 reaches its MW limit; this is the maximum amount of power that can be transferred between the two buses. ATC of 52.49 MW means that this is the maximum amount of power that can be transferred between two buses(in this case buses 2 and 6) so that no transmission line is overloaded. Figure 5.3 shows that line 1-5 reaches its MW limit when 52.49 MW is transferred between bus 2 and bus 6.

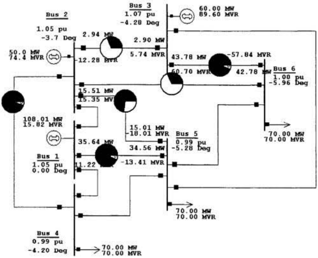


Figure 5.2: Single line diagram of 6 bus system in normal state

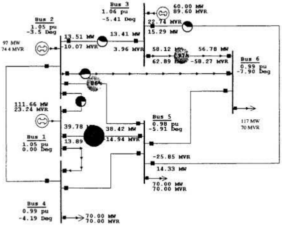


Figure 5.3: Single line diagram of 6 bus system showing line 1-5 operating near its thermal limit.

One more transaction has been considered between bus 3 and bus 5. To calculate ATC between the two buses the generation at bus 3 is increased and load is also increased by the same amount at bus 5. The power flow is run and flows on all transmission lines are monitored. Transfer of power would change the flow of power in the transmission lines. Figure 5.4 shows the base case loading of the system when no power is being transferred. When a transfer of 41.59 MW is performed between bus 3 and bus 5, line 1-5 reaches its MW limit; this is the maximum amount of transfer that can be performed between the two buses and is the ATC. Figure 5.5 shows that

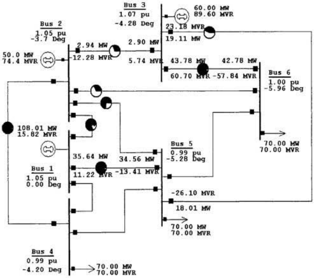


Figure 5.4: Single line diagram of 6 bus system in normal state

line 1-5 reaches near its MW limit if power of 41.59 MW is pushed through the transmission line. The concept can be further explained by a simple example of 6 bus system. Consider that a consumer at bus 6 wants to purchase power from a generating station in the system. There are two generators near bus 6, one is at bus 2 and the other at bus 3. Assume that Generation cost is cheaper at bus 2 as compared to generation at bus 3. The maximum power transfer from generator to the bus is limited by the MW limit of the lines. One option with the consumer is to purchase power from bus 2; which can be up to a maximum of 52.49 MW. If this consumer tries to purchase more power, the transmission lines in the path or somewhere else in the system would get overloaded.

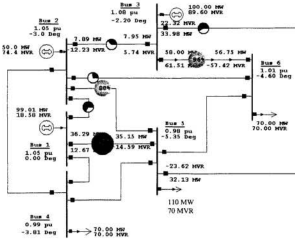


Figure 5.5: Single line diagram of 6 bus system in overloaded state

Thus, after purchasing the limited amount of power from generator at bus 2 the consumer has to look for another generating company which could supply power as per the consumer's requirement, or to purchase power from bus 3 (2^{nd} generator) which is costly, or purchase power from some other connected network.

This motivates competition among the generating companies to provide power at a cheaper cost and in a reliable manner. A generation company can increase the cost and the consumer would have to pay more price if the consumer does not find any other source to fulfill the requirements.

5.5 ATC enhancement using UPFC

As presented in chapter 4, UPFC's can control power flow in a system. They can be used to increase ATC. UPFC can be effectively used to relieve the loading of the transmission line which has reached its limit. The UPFC is placed in a suitable location and its parameters are determined so that power flow can be redirected. The UPFC has been simulated using the injection model and a new load flow solution is determined. With the UPFC, the generation and load are increased till the transfer is limited by the constraint. A commercially available load flow program Power World Simulator [30] has been used to determine the desired ATC in the system without the UPFC. The increase in the ATC achieved using the UPFC for different power systems are discussed in the next section.

5.6 Application to sample power systems

The proposed method has been applied to three sample power systems. The ATC of the transmission system is illustrated using IEEE Reliability Test System [21]. The system has 24 buses, 10 generators and 38 transmission lines. The second system is the 39-bus New England test system, which contains 46 transmission lines, 10 generators and 12 transformers. The third system studied is a model of BC Hydro's 196-bus power system. The system has been derived from a Western Systems Coordination council 8313-bus power system file. This system has twenty two 500 KV lines. A detailed description of this system has been discussed in a separate section. The base case load flow study was performed on all the systems considered, and it was found that some of the lines were overloaded. Thus, it was decided to install the UPFC in the overloaded transmission line or the adjoining line. Voltage violation has not been taken into account while relieving the overload. ATC has considered only those transmission lines which reached their limit because of transfer between the buses. A Newton-Raphson ac load flow program has been developed in Matlab [31] for the load flow studies.

5.6.1 IEEE 24-Bus Reliability test system

Figure 5.6 shows the single line diagram of the 24 bus IEEE reliability test system [21]. The transmission lines are at two voltages 230 kV and 138 kV. The peak load of the system is 2850 MW. The system total installed capacity is 3405 MW. The generation dispatch used in the base case is given in Table 5.4.

Table 5.4: IEEE 24 Bus Reliability System generation dispatch

Bus No.	22	18	21	15	16	23	1	2	13	7
MW	300	400	400	155	155	660	152	152	472	4

The 230 KV system is the top part of Figure 5.6 with 230/138 KV tie station at Buses 11, 12 and 24. This generation dispatch was assumed to remain unchanged when the ATC was calculated. ATC has been computed for two pair of buses (one at a time); Buses 23 and 15, Buses 10 and 3 in the system. The ATC computed for two pairs of buses has been shown in Table 5.5. ATC has been determined by using

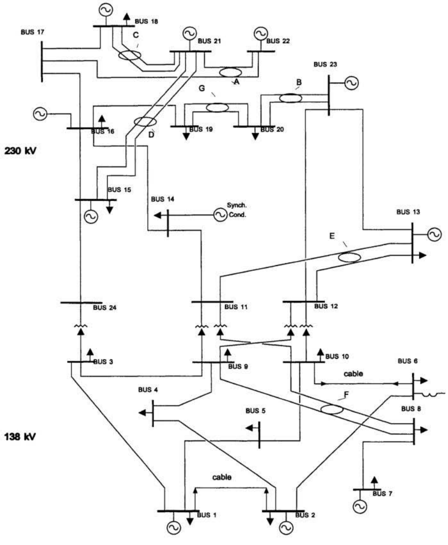


Figure 5.6: Single line diagram of the 24-Bus Reliability Test System

repeated load flow and single linear step ATC. Despite the fact that Bus 10 has no generator, it is the major channel for transfer of power from one system to the other. The most limiting element for the case in which the ATC has been computed from Bus 23 to Bus 15 is line 15-16. Generator has been connected to bus 23 and load has been connected to bus 15. The transfer was performed between these two buses and the flow on this line (15-16) was found equal to its line rating of 500 MW.

Any additional amount of power transfer beyond this value would cause an overload on line 15-16. For transfer of power between bus 10 and bus 3, the most limiting element is line 8-10. The same procedure is followed to determine the ATC between the bus 8 and bus 10. The results in Table 5.5 have been verified using the load flow option of a continuation power flow program [32]. RPF enables transfer by increasing the real load at the desired load bus and injecting the real power at generator buses in the source area in incremental steps until limits are reached. By installing a UPFC in the limiting line, the flow of power from overloaded lines is diverted to under loaded lines and still more power could be pushed through the line. The results in Table 5.6 show the change in ATC with UPFC at different location in the system using repeated power flow (RPF). Comparing the results in Table 5.5 and Table 5.6 it is seen that there has been considerable increase of power transfer between the two buses with the use of UPFC. The ATC in the base case for transfer between bus 23 and bus 15 is 816 MW and has been increased to 920 MW using UPFC which is a considerable increase in the power transfer. Simulation studies also show that the effect of UPFC has been significant on high voltage transmission lines.

Table 5.5: Base Case ATC Results for 24 Bus power system

From Bus	To Bus	ATC with Repeated Power Flow	ATC with Single Linear Step ATC	Transmission Line at Limit	
23	15	840 MW	816 MW	15-16	500 MW
10	3	250 MW	262.6 MW	10-3	175 MW

Table 5.6: ATC Results with UPFC

From Bus	To Bus	Location Of UPFC	ATC
23	15	15-16	920 MW
		15-21	895 MW
		15-24	880 MW
10	3	8-10	410 MW
		8-9	367 MW
		8-7	340 MW

5.6.2 39-Bus New England test system

Figure 5.7 shows the 39-bus New England test system, which consists of 46 transmission lines, 10 generators and 12 transformers. The system component data is as shown in Table 5.7. The power system base case load flow summary is shown in Table 5.8.

Table 5.7: New England 39- bus power system component data

Buses	39
Generators	10
Lines	46

Table 5.8: New England 39-bus power system base case

	Real Power (MW)	Reactive Power (Mvar)
Total generation	6192.8	1256.3
Total load	6150.1	1408.9
Losses	42.74	-152.56

Table 5.9 shows that the most limiting element for the case in which ATC was computed from bus 30 to bus 7 is line 2-3. When the transfer was performed between bus 30 and 7 the line 2-3 was found to be equal to the line rating of 500 MW. The maximum power that can be transferred between two buses without any violation of transmission constraint was found to be 230 MW. Any additional amount of transferred power beyond this value would overload this line. The results in Table 5.10 show the increase in ATC with UPFC installed in the limiting lines. By installing a UPFC in the limiting line power can be diverted

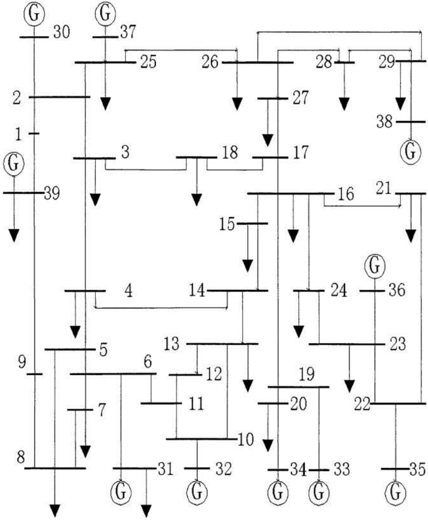


Figure 5.7: Single line diagram of the 39-bus power system

to other under loaded lines and still more power can be pushed through the limiting line which would eventually increase the power transfer between the buses. The ATC in the base case for transfer between bus 30 and bus 7 is 207 MW and by installing a UPFC between the lines the ATC has been increased to 380 MW. The transmission line limits have been chosen arbitrarily. With UPFC the ATC has been increased considerably.

Table 5.9: Base Case ATC Results for 39- Bus power system

From Bus	To Bus	ATC with Repeated Power Flow	ATC with Single Linear Step ATC	Transmission Line at Limit	
30	7	230 MW	207 MW	2-3	500 MW
34	18	495 MW	480 MW	17-16	500 MW
30	25	250 MW	232.5 MW	2-30	500 MW

Table 5.10: ATC Results with UPFC

From Bus	To Bus	Location of UPFC	ATC
30	7	2-3	380 MW
34	18	17-16	750 MW
30	25	2-30	440 MW

5.6.3 An overview of 196-bus BC Hydro power system

One of the power system models used in the research is BC Hydro 196-bus power system [33]. In this power system, most of the available sources of hydroelectric power are distant from the southwest part of the province, where most of the demand is located.

Figure 5.8 shows the entire 500kV network and the sub transmission network of the major load centers of Lower Mainland (around the city of Vancouver) and the south part of Vancouver Island (around the city of Victoria). The transmission network is interconnected with the Trans-Alta Utilities system in the province of Alberta, the West Kootenay power and Light System in the southeast part of British Columbia, and the interconnected Western system of the U.S.A in the south. Figure 5.9 shows the geographic location of BC Hydro transmission network.

The major generation system of BC Hydro consists of those on the Peace and Columbia rivers. (Table 5.11 shows the information of the main power plants of BC Hydro power system). The Peace River System (G.M Shrum and Peace Canyon generating stations), located at the northern part of the Province, has a generating capacity of 3400 MW. The majority of this capacity is transmitted about 1000 km through 500 kV transmission lines to the load centers.

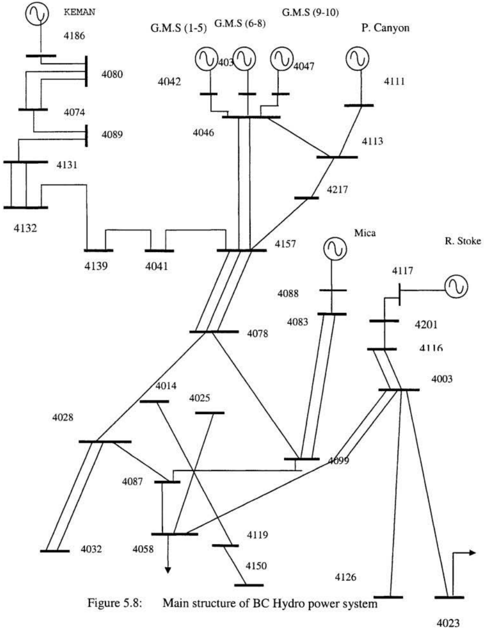


Figure 5.8: Main structure of BC Hydro power system

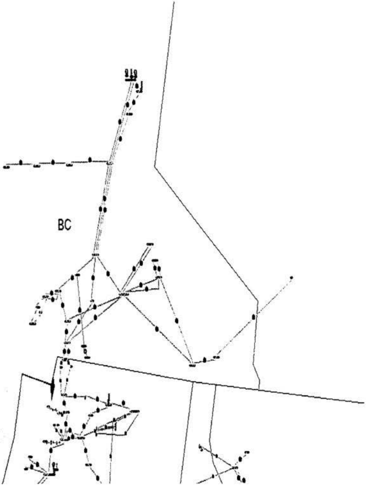


Figure 5.9 Geographic location of BC Hydro transmission network

Table 5.11: BC Hydro main power plant summary [33]

Power Station Name	Type (Hydro or Thermal)	Capacity (MW)	Bus Number	Power Generation (MW)	Power Generation (Mvar)	Terminal Voltage (P.U / kV)	Voltage Angle (Degree)
Burrard	Thermal	912	4015	0	-138.32	0.965 / 15.9	-36.40
Cheakmus	NA*	NA	4026	144.00	18.74	1.02 / 14.1	-24.25
Gorden M. Shrum (G. M. S)	Hydro	2730	4042	1122.00	-205.35	0.978 / 13.5	-1.23
			4043	663.39	261.67	1.049 / 14.5	-2.24
			4047	400.00	-96.9	0.979 / 13.5	-2.65
Kootenay Canal	Hydro	549	4064	529.00	-46.76	0.969 / 13.4	4.52
Kelly L. k	NA	NA	4069	0	21.55	1.014 / 12.7	-25.64
L. M. EQIV	NA	NA	4081	209.00	8.53	1.00 / 13.8	-32.99
Mica	Hydro	1736	4088	1700.00	38.58	0.961 / 15.4	6.50
Peace Canyon	Hydro	700	4111	530.00	23.15	0.985 / 13.6	-3.47
Revel Stoke	Hydro	1843	4117	1818.75	105.00	1.009 / 16.1	0
Seven Mile	Hydro	594	4130	590.00	-19.86	0.985 / 13.6	-1.02
V. I. T	NA	NA	4140	0	-36.09	1.006 / 12.7	-45.84
			4141	0	-36.09	1.023 / 13.0	-45.87
VA. IS. EQ	NA	NA	4142	279.00	-28.06	1.00 / 13.8	-40.17
Whatshan	NA	NA	4153	55.00	9.93	1.05 / 14.5	-9.84
Willston	NA	NA	4154	0	-67.5	0.928 / 11.6	-19.32
DMRSVC	NA	NA	4182	0	150.5	1.119 / 21	-42.22
Kemano	NA	NA	4186	810	294.69	1.078 / 14.9	-4.93
Bridge River	Hydro	480	4210	175.00	2.30	1.02 / 14.1	-15.76
			4211	200.00	2.30	1.023/ 14.1	-18.45
Data from Powerworld Viewer				Data from 196-bus load flow			

*NA : Not Available

The Columbia River System (Mica, Revelstoke, Seven Miles and Kooteny Canal generating stations), located in the south of interior region of the province, has a generating capacity of 4730 MW at distances ranging from 200 to 500 km from the load centers. The transfer over part of the 500 kV network feeding the Lower Mainland and Vancouver Island is limited by voltage stability [33].

The BC Hydro power system data file used in the research is generated using the power system model for the WSCC (Western Systems Coordination Council)

8313-bus power system file. Table 5.12 shows the power system component data, and Table 5.13 shows the WSCC 8313-bus power system base case load flow summary. The data were obtained from the web site: http://www.ferc.fed.us/f75/f715.htm. This data is for the 1998 summer loading condition.

One of the procedures for the derivation of the 196-bus BC Hydro power system data file is explained below [33]:

(1) Obtain the basic power system parameters (bus data and transmission line data) from WSCC.RAW file on the above website and change it to CDF (IEEE Common Data Format) file.

(2) Find the 11 tie transmission lines connecting BC Hydro power system to the other subsystems and all the power transferred through the tie lines using Powerworld Viewer software (test edition), which is available on web site: http://www.powerworld.com.

(3) Cut off all the tie transmission lines between BC Hydro and all the other subsystems, and install the equivalent real power and reactive power exchange through the tie lines on the buses in BC Hydro accordingly.

(4) Change initial values for iteration in the new BC Hydro power system data file so that the initial values are close to the converged value for power flow. Thus, the final equivalent BC Hydro 196-bus power system CDF data file is obtained. Table 5.14 shows the BC Hydro 196-bus power system component data. Table 5.15 shows the BC Hydro 196-bus power system base case load flow.

Table 5.12: WSCC 8313- bus power system component data

Buses	8313
Generators	1320
Bus shunts	1059
Lines	7767
Transformers	2951
Phase Shifters	16
DC Converters	6

Table 5.13: WSCC 8313-bus power system base case

	Real Power (MW)	Reactive Power (Mvar)
Total generation	132686.78	25619.00
Total load	127642.73	31644.42
Losses	4557.74	59391.75

Table 5.14: BC Hydro 196- bus power system component data

Buses	196
Generators	20
Lines	316

Table 5.15: BC Hydro 196-bus power system base case

	Real Power (MW)	Reactive Power (Mvar)
Total generation	8246.1	-145.2
Total load	6384.8	3052.5
Losses	392.3	-7094.83

The ATC computed between five pair of buses (one at a time) are shown in Table 5.16. For the base case the ATC has been calculated using repeated power flow and single linear step ATC. Table 5.16 shows that the most limiting element for the case in which ATC was computed from bus 4043 to bus 4114 is line 4097-4114. The flow on this line was found equal to the line rating of 110 MW. In case of repeated power flow the transfer is performed between bus 4043 and bus 4114, bus 4043 is considered as a generator and bus 4114 is considered as a load. The maximum power that can be transferred between the two buses without any violation of transmission constraint was found to be 80 MW.

Any additional amount of power beyond this value would cause an overload on line 4097-4114. By installing a UPFC in the overloaded line more power can be transmitted by diverting the flow from overloaded lines to under loaded lines (where transmission capacity is not being fully utilized). Table 5.17 shows a considerable increase in ATC by using UPFC in transmission line. The base ATC from bus 4043 to bus 4114 has been increased to 160 MW. The same pattern of increase has followed the other transfers presented in Table 5.17. It is possible to arrive at an optimal location of UPFC by analyzing the sensitivity of the UPFCs to the power transfer in the system [34]. These studies show that the UPFC has been able to increase the power transfer to a considerable amount.

Table 5.16: Base Case ATC Results for 196 Bus power system

From Bus	To Bus	ATC with Repeated Power Flow	ATC with Single Linear Step ATC	Transmission Line at Limit	
4043	4114	80 MW	78.06 MW	4097-4114	110 MW
4210	4258	115 MW	97 MW	4014-4210	200 MW
4130	4252	105 MW	92.66 MW	4129-4130	675 MW
4088	4144	440 MW	420 MW	4083-4088	1828 MW
4047	4163	160 MW	149.82 MW	4046-4047	630 MW

Table 5.17: ATC Results with UPFC

From Bus	To Bus	Location of UPFC	ATC
4043	4114	4097-4114	160 MW
4210	4258	4014-4210	230 MW
4130	4252	4129-4130	200 MW
4088	4144	4083-4088	688 MW
4047	4163	4046-4047	270 MW

5.7 Summary

The chapter has reviewed the area of transmission capability in electric power systems A number of methods to calculate transfer capability have been discussed. Improvement of transfer capability is an important topic in the current deregulation environment. Fast power flow control capabilities offered by FACTS provide a powerful tool for system operation in a open access environment.

Bottlenecks in the transmission system can be mitigated by proper placement of suitable FACTS systems. They enable steady-state optimization of system resources in order to alleviate overloads, reduce losses and achieve optimal generation dispatch. The UPFC has been used to enhance the available transmission capability of the transmission system. By shifting power flow from overloaded to underloaded transmission lines, FACTS devices can increase the capacity of individual transmission corridors. The effect of UPFC is studied and demonstrated with different power systems. The results clearly illustrate the effectiveness of UPFC in enhancing the Available Transfer Capability of power systems.

Chapter 6

Conclusion and Future Work

6.1 Contributions of the research

The interconnected power system is designed and operated to transfer large quantities of electricity over long distances. There is a need to improve the performance of existing power system and use the available resources of power in an optimal manner. Flexible A.C Transmission system has played a major role in relieving these basic problems of transmission resulting in efficient, transmission and distribution of power. UPFC is one of the most powerful devices currently used for power flow control in electrical utilities.

This thesis has presented the modeling and application of unified power flow controller in power systems. The two applications discussed are control of power flow and increase of available transfer capability in power system using unified power flow controller. Various power flow control devices have been discussed in the introduction with a detailed analysis of UPFC. Operation of UPFC is based on the principle of voltage injection in the transmission line with an insertion transformer. The basic configuration of UPFC consists of voltage source converters connected in shunt and series with the transmission line. The converters have been simulated using PSCAD software in order to investigate the behavior of the voltage injected in the transmission line.

Appropriate model for UPFC has been developed and analyzed for incorporation in power flow program. The model has been incorporated in a Newton-Raphson power flow program. The model is based on a series control device and can provide the necessary functional flexibility for power flow control. This approach of modeling has the option of power flow and voltage control simultaneously. All these different modes can also be controlled separately. Various features of UPFC have been explained with reference to the control capability of UPFC and its effect on the system.

A detailed study has been carried out on various test power systems to show the power flow control features of UPFC. The UPFC has been used to relieve the overload from the transmission lines. Application of UPFC has been demonstrated in the area of available transfer capability. Various methods of calculating ATC have been investigated. ATC of some small systems have been evaluated using Powerworld software and repeated power flow method.

UPFC has played a major role by diverting the flow of power and increasing the available transfer capability of the system. The results for ATC, calculated without UPFC have been verified using different methods of calculating ATC. UPFC has been used to increase the ATC by installing it at suitable locations in the power system. The simulations and analysis were carried out on IEEE test systems and BC-Hydro 196

Bus system. The results show that ATC has been considerably improved with UPFC and has improved the performance of power system.

A recent study by the department of energy in U.S.A [35], presented the need to incorporate innovative technologies for electric power transmission. The research presented in this thesis has the potential to be a part of the new technology expected to meet the challenges in electric power transmission

6.2 Suggestions for Future Work

The location of UPFC as presented in the studies of this thesis has been decided arbitrarily. It is possible to investigate the application of optimization methods to decide the location of the UPFC to meet a specific objective with the lowest possible cost.

The work reported in this thesis can be extended in the following areas:

- To observe the impact of UPFC on damping of electro mechanical oscillations.
- Control of UPFC for transient stability improvement
- Investigate the effectiveness of multiple UPFCs in an interconnected power system
- To observe the effectiveness of UPFC for voltage stability analysis.

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