Chapter – 1

INTRODUCTION

1.1 OVERVIEW

In a three phase ac power system active and reactive power flows from the generating station to the load through different networks buses and branches. The flow of active and reactive power is called power flow or load flow. Power flow studies provide a systematic mathematical approach for determination of various bus voltages, their phase angle active and reactive power flows through different branches, generators and loads under steady state condition. Power flow analysis is used to determine the steady state operating condition of a power system. Power flow analysis is widely used by power distribution professional during the planning and operation of power distribution system. The major problems faced by power industries in establishing the match between supply and demand are:

• Transmission & Distribution supply the electric demand without exceeding the thermal limit.

• In large power system, stability problems causing power disruptions and blackouts leading to huge losses.

These constraints affect the quality of power delivered. However, these constraints can be suppressed by enhancing the power system control. One of the best methods for reducing these constraints is FACTS devices.

With the rapid development of power electronics, Flexible AC Transmission Systems (FACTS) devices have been proposed and implemented in power systems. FACTS devices can be utilized to control power flow and enhance system stability. Particularly with the deregulation of the electricity market, there is an increasing interest in using FACTS devices in the operation and control of power systems. A better utilization of the existing power systems to increase their capacities and controllability by installing FACTS devices becomes imperative. FACTS devices are cost effective alternatives to new transmission line construction.

Reactive power compensation is provided to minimize power transmission losses, to maintain power transmission capability and to maintain the supply voltage. Series compensation is control of line impedance of a transmission line; with the change of impedance of a line either inductive or capacitive compensation can be obtained thus facilitating active power transfer or control. Thyristor Controlled Series Capacitor (TCSC) is a variable impedance type series compensator and is connected in series with the transmission line to increase the power transfer capability, improve transient stability, reduce transmission losses and damped power system oscillations. Shunt compensation is used to increase the steady-state transmittable power and to control the voltage profile along the line. Unified power flow controller (UPFC) is the most comprehensive multivariable flexible ac transmission system (FACTS) controller. Simultaneous control of multiple power system variables with UPFC posses enormous difficulties. In addition, the complexity of the UPFC control increases due to the fact that the controlled and the control variables interact with each other. UPFC which consists of a series and a shunt converter connected by a common dc link capacitor can simultaneously perform the function of transmission line real/reactive power flow control in addition to UPFC bus voltage/shunt reactive power control [1] - [4].

1.2 FLEXIBLE AC TRANSMISSION SYSTEM

The concept of Flexible AC Transmission Systems (FACTS) was first defined by N.G. Hingorani, in 1988 [5]. A Flexible Alternating Current Transmission System (FACTS) is a system comprised of static equipment used for the AC transmission of the electrical energy. It is meant to enhance controllability and increase power transfer capability of the network. It is generally a power electronic-based device. FACTS is defined by the IEEE as “a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability” [6]. The primary advantage of FACTS devices, over its conventional counterpart is the rapid control of current, voltage and/or impedance. The conventional solutions such as capacitor, reactor and phase shifting transformers are normally less expensive than FACTS devices, but limited in their dynamic behavior and are less optimal. The review of various FACTS devices is summarized in Chapter 4.

1.3 LOAD FLOW SOLUTIONS

Load flow studies are the backbone of power system analysis and design. Load flow studies are necessary for planning, economic scheduling and exchange of power between utilities. In addition, power flow analysis is required for many analyses such as transient stability and contingency studies. The load flow solution gives the nodal voltages and phase angles and hence the power injection at all the buses and power flows through interconnecting transmission lines. Load flow equations are nonlinear and can be solved by an iterative method. In this thesis Newton Raphson method is used, as the number of iterations is independent of the size of the system, and convergence characteristic is independent of selection of slack bus. Details of Newton Raphson method, load flow solution with UPFC are discussed in chapter 5.

Chapter : 2

LITERATURE REVIEW

2.1 INTRODUCTION

The brief review on the placement of FACTS devices is presented here. The concept of FACTS and FACTS controllers was first defined by Hingorani, 1988 in [5]. FACTS usually refer to the application of high-power semiconductor devices to control different parameters and electrical variables such as voltage, impedance, phase angles, currents, reactive and active power [7]-[8]. FACTS can provide versatile benefits to transmission utilities such as control of power flow, increasing capabilities of lines to their thermal limits, reducing loop flows, providing greater flexibility [9-10].The value of FACTS application lies mainly in the ability of the transmission system to efficiently transmit power or to transfer power under contingency conditions [11]. FACTS technology is a collection of controllers that can be applied to control electrical variables and parameters. In general FACTS controllers can be divided into four categories:

(1) Series controllers mainly TCSC and SSSC,

(2) Shunt controllers mainly STATCOM and SVC,

(3) Series-series controllers such as IPFC and

(4) Combined series-shunt controllers such as UPFC [1]-[4].

Recently, the steady state performance of power system has become a matter of grave concern in system operation and planning. As the power system becomes more complex and more heavily loaded, it can be operated in unstable or insecure situations like the cascading thermal overloads, the frequency and voltage collapse. For a secure operation of the power system, it is essential to maintain the required level of security margin [12]-[14]. Then, power system controllability is required in order to utilize the available network capacitance adequately. The development of FACTS devices based on the advance of semiconductor technology opens up new opportunities for controlling the load flow and extending the loadability of the available transmission network. The UPFC is one of the family members of FACTS devices for load flow control, since it can either simultaneously or selectively control the active and reactive power flow along the lines [15]-[16]. Several papers have been published about finding the optimal location of the UPFC with respect to different purposes and methods [17]-[18]. In [17], augmented Lagrange multiplier method is applied to determine the optimal location of the UPFC to be installed. Although multi operating conditions can simultaneously be taken into consideration, the operating condition must be preassigned.

FACTS devices can be embedded into power flow equations with modification of the network admittance matrix and the Jacobian matrix. Radman and Raje discussed power flow calculation of power system with multiple flexible AC transmission system (FACTS controller) by modifying and adding new entries in Jacobian equation with no FACTS controller and considered three major FACTS controllers STATCOM, SSSC and UPFC. Esquiuel and Acha considered the issue of controllable branch model suitable for assessing the steady state response of FACTS devices and presented nodal admittance model for series compensators, phase shifter and unified power flow controller.

2.2 Organization of the Project:

- Chapter 1 gives a brief introduction about the project,
- Chapter 2 gives a brief literature review,
- Chapter 3 deals with the description of power flow control and its limitations,
- Chapter 4 gives a brief overview about FACTS Technology and different FACTS controllers,
- Chapter 5 gives an overview about Unified Power Flow Controller – operation and characteristics of UPFC,
- Chapter 6 description of Newton-Raphson algorithm with UPFC,
- In chapter 7 a standard IEEE-5 bus and IEEE-30 bus network with UPFC is considered as a case study to analyze the power flow of the network, MATLAB is used to simulate the same and in Chapter 8 the final conclusion of project is given.

Chapter 3

LOAD FLOW CONTROL IN POWER SYSTEMS

3.1 Power System Operation

A power system is a large interconnected network with components converting non-electrical energy into the electrical form to meet the demanded high quality power supply to the end users. A power system is an electrical network divided into three sub-systems. The three sub-systems are the generation stations, the transmission systems and the distributed systems. Electric power produced by a generator unit transmitted from generators to loads by transmission system. The transmission systems are the connecting link between generating stations and the distributed systems that leads to other power system over interconnections as shown in the block diagram in Figure3.1.

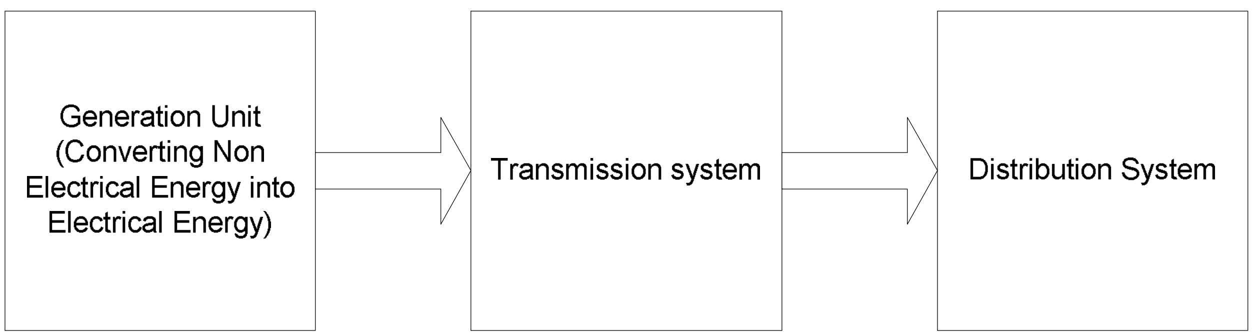


Figure 3.1: Block Diagram of Power System Operation

3.1.1 Generation Unit:

The generation unit includes the generating plants that produce energy fed through the transformers to a high voltage transmission network interconnecting to other generating plants. It converts non-electrical energy such as coal, water, natural gas, hydroelectric, solar and geothermal sources etc., into electrical energy.

Transmission Systems: In transmission systems, electricity generated from power generation unit is transferred to substations. It performs voltage transformation, power switching, measurement and control.

3.1.2 Distribution Systems:

This is the final stage in the delivery of electricity to the end users. A distribution system carries electricity from the transmission system and delivers it to the end users.

3.2 Power Flow Control

Today most of the electrical power systems in the world are widely interconnected due to economic reasons to reduce the cost of electricity and to improve system stability and reliability. Because of the increasing complexity of power system design, the challenge to meet the high quality power supply in a power system is highly desirable. The factors considered for the smooth functionality of power system operation and control as follows:

- Power system operating in a synchronous mode maintains the power quality with a controlled phase between all the interconnected networks.
- The voltage level in a power system should maintain within limits. Any variations in the voltage level cause damage to electric motors and dielectric components, which is not acceptable and leads to overloading of many electric components.
- Transmission lines of power systems should operate with minimum losses by using the most efficient transmission paths capable of handling the loads.
- In practical power engineering it is not possible to operate a power system without any single faults. When faults naturally occur protective relaying systems are used to detect the faults and restore the system operation.
- Whenever there are disturbances in the power system because of system failure, the part of the system that remains operable may not have sufficient capacity to serve the loads without becoming overloaded. In such cases, the major control objective of power system is to manage the overloads that may results from disturbances to the normal operation of the system.

3.3 Power System Limitations:

Theoretically, power engineers have taken lot of measures to avoid the limitations and maintain the power system to work with stability and reliability. However, it is very hard to predict the power system limitations that affect the system operation. Following are the some of the limitations considered in power system: Thermal, Voltage and Transient Stability limits.

Thermal limit: Thermal limits are due to the thermal capability of power systems. As power transfer increases, current magnitude increases which is key to thermal damage.

For example, in a power system, the sustained operation of units beyond the maximum operation limits will result in thermal damage.

Voltage limit: Power systems are designed to operate at a nominal supply voltage. Variations in nominal voltage can adversely affect the performance as well as cause serious damage to the system. Current flowing through the transmission lines may produce an unacceptably large voltage drop at the receiving end of the power system. This voltage drop is primarily due to the large reactive power loss, which occurs as the current flows through the systems.

Transient Stability: It is defined as the ability of power system to maintain synchronism when it is subjected to severe transient disturbance. In general, power systems with long transmission lines are most susceptible to transient instability. The best way to analyze the transient stability limit is to study the change of rotor angle of all synchronous machines connected to the system after the system subjected to large disturbance.

3.4 Power Controlling Devices:

To overcome the above limitations, power system engineers introduced the concept of advanced controller devices that provide techniques to maintain system stability and reduce losses. Different types of power controlling devices are as follows:

3.4.1 Phase Shifting Transformer (PST):

Generally, transformers transport electric power between different voltage levels of a power system. It may also used to control the phase displacement between the input voltage and current phase by an angle adjusted by means of a tap changer. Such special transformers are termed as Phase Shifting Transformer (PST). PSTs used to control the power flow through a specific line and line losses in a complex transmission network.

Disadvantages: The speed of the phase shifting transformers to change the phase angle of the injected voltage is very slow and limited to issues with short-circuit current protection. In conclusion, PSTs applied in power system are very limited with slow requirements under steady state system conditions.

3.4.2 High Voltage Direct Current (HVDC):

HVDC systems introduced in 1950's play an important role to improve the reliability of the power system in addition to the power transfer operations. It is the feasible way to interconnect two asynchronous networks, reduce fault currents, power system reliability and utilize long cable circuits.

Basic functionality of HVDC system is to convert electrical current from AC to DC terminal at the transmitting end and from DC to AC terminal at the receiving end. Converting AC to DC terminal referred as rectifier and DC to AC terminal referred as inverter terminal.

HVDC Applications: These provide high power flow transfers over long distance using fewer transmission lines than AC transmission lines, with lower system losses by increasing the dc voltage level. HVDC underground cables have no restricted limitation over the distance as in case of ac cables. HVDC cables used with voltage source converter based HVDC transmission systems are lighter and more flexible.

HVDC transmission systems used in interconnections between asynchronous networks provides more reliable system operation. Many asynchronous interconnections exist in North America between the eastern and western interconnected systems, between the Electric Reliability Council of Texas Disadvantages: HVDC system generates harmonics that effect on the power quality of a power system. Normal operation of HVDC requires a reactive power to support hence large reactive source should be installed at the converter stations.

3.4.3 Flexibility of AC Transmission Systems (FACTS):

The world's electrical power systems today are widely interconnected due to economic reasons to reduce the cost of electricity and to improve the reliability of the system. These interconnected networks are difficult to operate and cannot utilize the full potential of a transmission system. In order to overcome these limitations, power systems came up with the concept of mechanical controllers in the past but these mechanical controllers had numerous intrinsic problems. Later power system engineers introduced the concept of power electronic devices to control the power system limitations known as Flexible AC Transmission System (FACTS) devices.

FACTS Applications:

In interconnected as well as in long transmission power systems technical problems occur which limits the load ability and reliability of the system. The best devices for the use in complex systems are the phase angle regulator, the controlled series compensator, especially when gate turn of thyristor technology with unified power flow controller. In long-distance transmission, TCSC or SSSC offers advantages comparing effectiveness against the rating, complexity and costs.

Chapter 4

FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEMS

4.1 INTRODUCTION

According to the IEEE definition, FACTS is defined as *"The Flexible AC Transmission System(FACTS) is a new technology based on power electronic devices which offers an opportunity to enhance controllability, stability and power transfer capability of AC Transmission Systems"* [19].

Power systems today are highly complex and the requirements to provide a stable, secure, controlled and economic quality of power are becoming vitally important with the rapid growth in industrial area. To meet the demanded quality of power in a power system it is essential to increase the transmitted power either by installing new transmission lines or by improving the existing transmission lines by adding new devices. Installation of new transmission lines in a power system leads to the technological complexities such as economic and environmental considerations that includes cost, delay in construction as so on. Considering these factors power system engineers concentrated the research process to modify the existing transmission system instead of constructing new transmission lines. Later they came up with the concept of utilizing the existing transmission line just by adding new devices, which can adapt momentary system conditions in other words, power system should be flexible [20].

In this research process, in late 1980s Electric Power Research Institute (EPRI) came up with the concept of Flexible AC Transmission Systems (FACTS) technology, which enhances the security, capacity and flexibility of power transmission systems. It was the new integrated concept based on power electronic switching device and dynamic controllers to enhance the system utilization and power transfer capacity as well as the stability, security, reliability and power quality of AC transmission Systems. The controllers designed based on the concept of FACTS technology known as FACTS controllers.

4.2.1 POWER SYSTEM STABILITY

Modern Electric Power system is a complex network of synchronous generators, transmission lines and loads. With changes in generation schedules and load, the system characteristics will vary. Electrical Utilities started as stand-alone systems and with increasing growth in the neighboring utilities and upon their addition to the network began to form high interconnected systems. This facilitated the need to draw on each other's generation reserves in required times. The interconnection improved reliability but has given birth to instability issues as the disturbances can propagate through the system. Depending on the magnitude of disturbance the system can become transiently unstable. A good power system should have the ability to regain its normal operating conditions even after the disturbance, as the ability to supply uninterrupted electricity determines the quality of a power system. Stability of a power system is considered as a very important aspect for research.

Power system stability can be defined as the ability of synchronous machines to remain in synchronism with each other following a major disturbance. The possible disturbances being the line faults, generator, line outages, load switching and etc. Stability is characterized by the capability of power system to remain in synchronism for the possible disturbances. The stability studies are classified into steady state stability, transient stability and slowly growing stability depending on the order of magnitude and type of disturbance. The transient stability of a system can be improved by using FACT Controllers.

4.2.2 BASIC PRINCIPLE OF ACTIVE AND REACTIVE POWER FLOW CONTROL

Active (real) and reactive power in a transmission line depend on the voltage magnitudes and phase angles at the sending and receiving ends as well as line impedance. To understand the basic concept behind the FACTS controllers a simple model is considered as shown in Fig 4.1.The sending and receiving end voltages are assumed to be fixed and can be interpreted as points in large power systems where voltages are stiff". Assuming that the resistance of high voltage transmission lines are very small, there is equivalent reactance connected in between sending and receiving ends. The receiving end is modelled as an infinite bus with a fixed angle of zero degree.

$$S_R = P_R + jQ_R = V_R I^* \qquad 4.2.1$$

$$\mathrm{P_R} = \frac{V_S V_R}{X} \sin\delta \qquad 4.2.2$$

$$\mathrm{Q_R} = \frac{V_S V_R \cos\delta - V_R^2}{X} \qquad 4.2.3$$

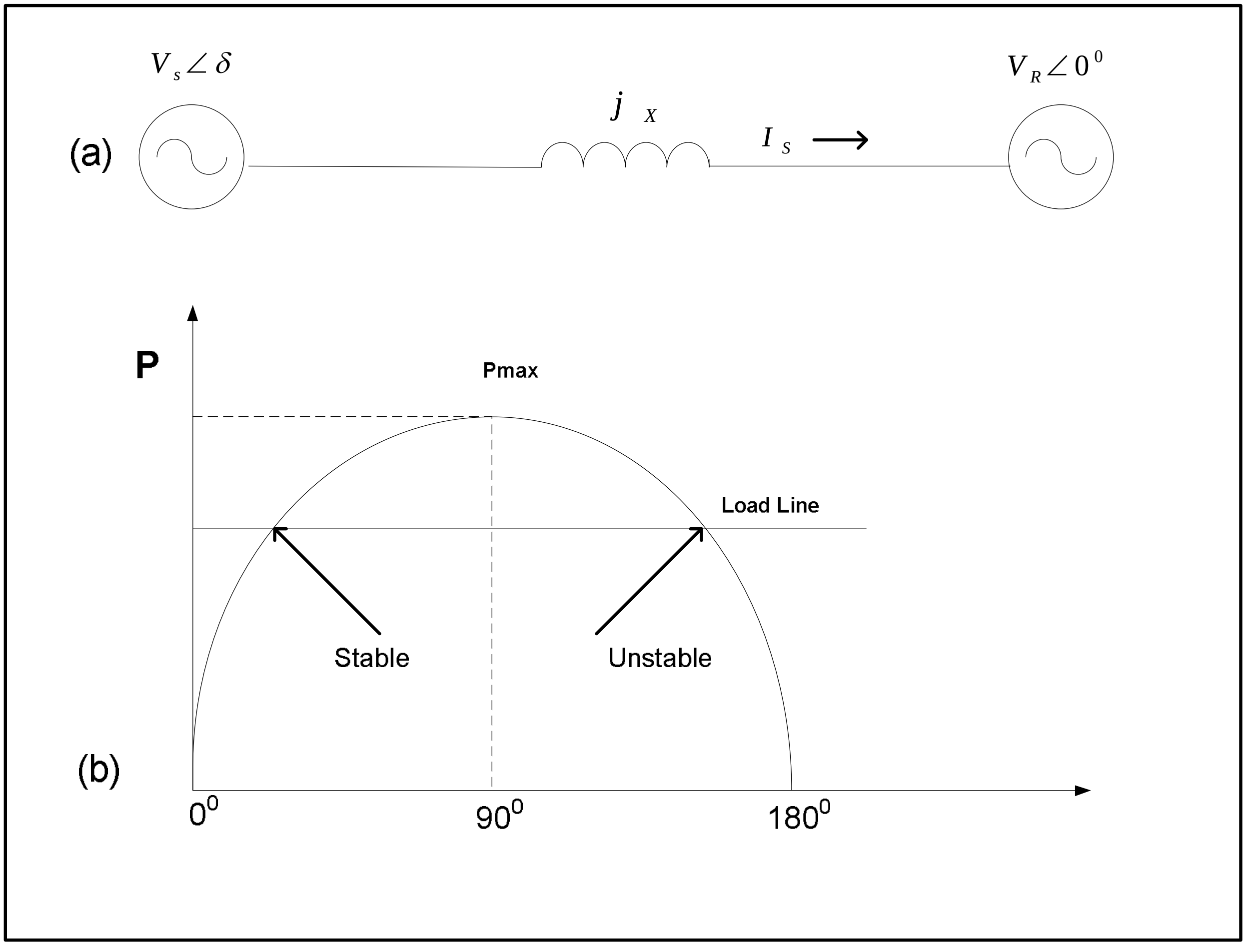


Fig.4.1:Model for Calculation of Real and Reactive Power flow [16]

Similarly for the sending end;

$$P = \frac{V_S V_R}{X} \sin\delta - P_{\max} \sin\delta \qquad 4.2.4$$

$$Q_S = \frac{V_S^2 - V_S V_R \cos\delta}{X} \qquad 4.2.5$$

Where V_S and V_R are the magnitudes (in RMS values) of sending and receiving end voltages, respectively, where δ is the phase-shift between sending and receiving end voltages.

The system is assumed to be a lossless system and so the equations for sending and receiving active power flows, P_S and P_R, are equal. The maximum active power transfer occurs, for the given system, at a power or load angle δ equal to 90° which can be seen in the figure 4.1. Maximum power occurs at a different angle if the transmission losses are included. The system is stable or unstable depending on whether the derivative $dP/d\delta$ is positive or negative. The steady state limit is reached when the derivative is zero.

In practice, a transmission system is never allowed to operate close to its steady state limit, as certain margin must be left in power transfer in order for the system to be able to handle disturbances such as load changes, faults, and switching operations. The intersection between a load line representing sending end mechanical (turbine) power and the demand line defines the steady state value of δ . The angle can be increased by a small increase in mechanical power at the sending end. With increasing load demands the angle goes beyond 90° and results in less power transfer. This accelerates the generator and further increases the angle making the system unstable. However, the increased angle δ increases the electric power to correlate the mechanical increased power. The concepts of dynamic (small signal stability) or Transient (large signal stability) are used to determine the appropriate margin for the load angled.

By the IEEE definition, "dynamic stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance such as a fault or loss of generation". Typical power transfers correspond to power angles below 30°; to ensure steady state rotor angle stability, the angles across the transmission system are usually kept below 45°.Inspecting the equations little deeper reveals that the real or active power transfer depends mainly on the power angle and also reactive power requirements in both sending and receiving ends typically require high power transfers. From this information we can conclude that reactive power transfer depends mainly on voltage magnitudes, with flows from the highest voltage to the lowest voltage, while the direction of active power flow depends on the sign of the power angle.

Another interesting observation is on the dependability on reactance. The maximum power transfer Pmax and the angle between two ends vary upon variation of reactance. The regulation of power flow is also possible by varying the sending and receiving end voltages. For a given power flow, a change of X also changes the angle between the two ends. Regulating the magnitudes of sending and receiving ends voltages, V_S and V_R, respectively, can also control power flow in a transmission line. From the equations of reactive power 4.1.4 & 4.1.5, it can be concluded that the regulation of voltage magnitude has much more influence over the reactive power flow than the active power flow.

4.3 Introduction to FACTS controllers:

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

- First Generation of FACTS Controllers: Static Var Compensator (SVC) and Thyristor Controlled Series Compensator (TCSC)
- Second Generation of FACTS Controllers: Static Synchronous Series Compensator (SSSC) and Static Synchronous Compensator (STATCOM)
- Third Generation of FACTS Controllers: Unified Power Flow Controller (UPFC)
- Fourth Generation of FACTS Controllers: Interline Power Flow Controller (IPFC) and Generalized Power Flow Controller (GUPFC)

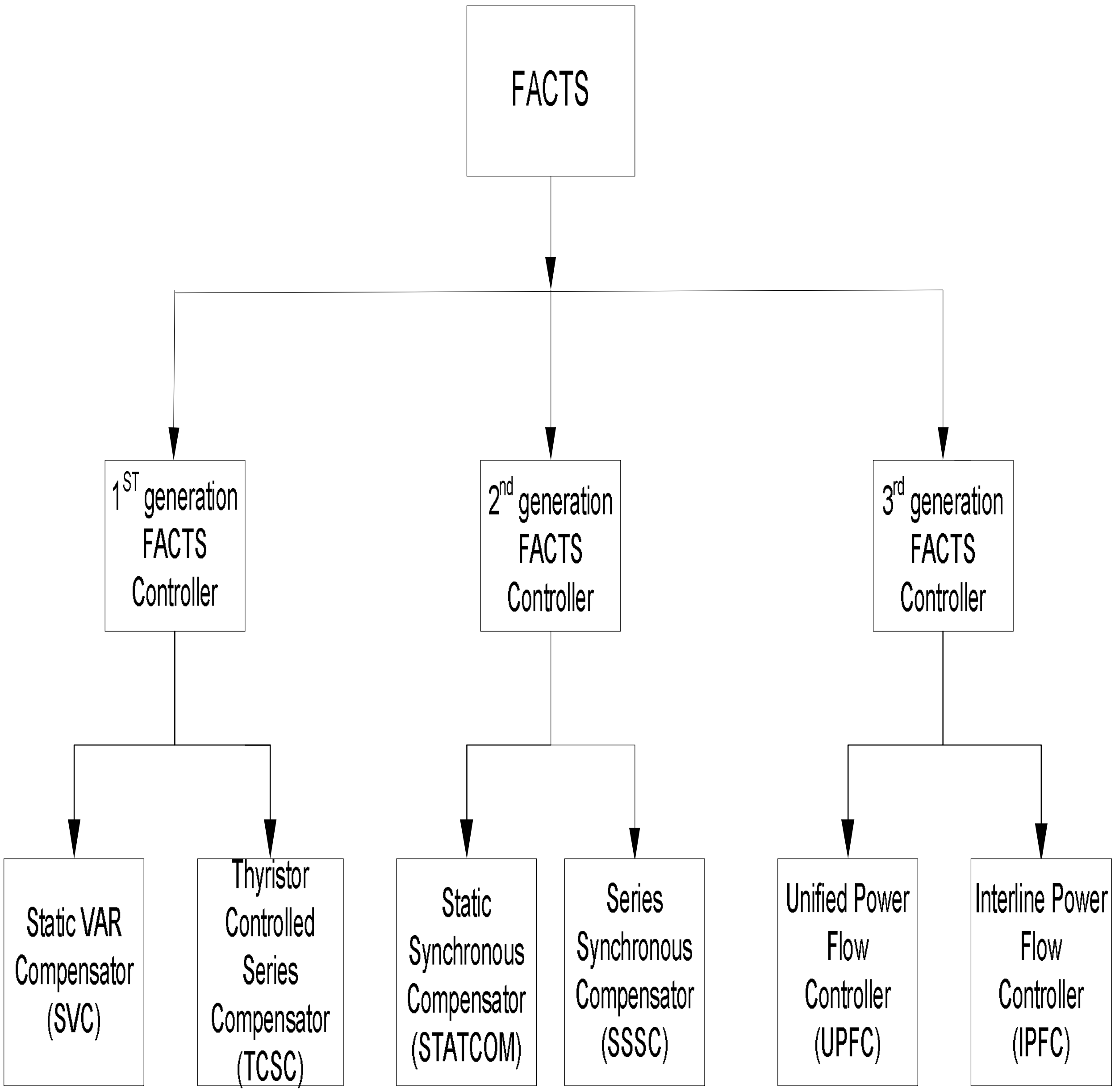


Figure 4.2: Block Diagram of FACTS Controllers

4.4 Different FACTS Controllers

4.4.1 First Generation of FACTS Controllers:

These categories of controllers are designed based on thyristor based FACTS technology.

4.4.1.1: Static Var Compensator (SVC):

It is the first device in the first generation of FACTS controller introduced to provide fast-acting reactive power compensation in the transmission network.

Circuit Description: Static Var Compensator as shown in Fig 4.3 composed of thyristor controlled reactor (TCR), thyristor switched capacitor (TSC) and harmonic filters connected in parallel to provide dynamic shunt compensation. The current in the thyristor controlled reactor is controlled by the thyristor valve that controls the fundamental current by changing the fire angle, ensuring the voltage limited to an acceptable range at the injected node. Current harmonics are inevitable during the operation of thyristor controlled rectifiers, thus it is essential to have filters to eliminate harmonics in the SVC system. The filter banks not only absorbs the risk harmonics but also produce the capacitive reactive power.

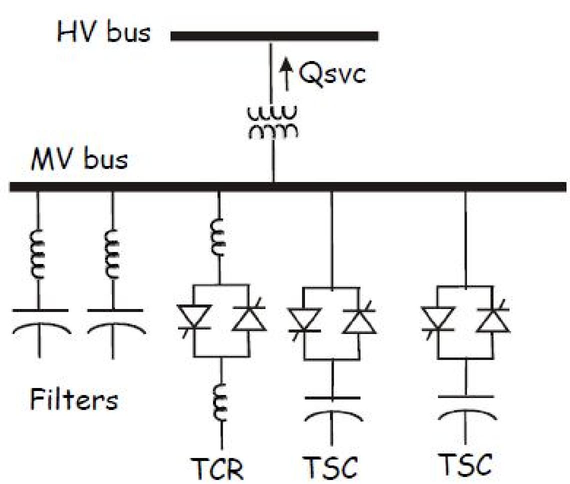


Figure 4.3: Circuit Diagram of Static Var Compensator (SVC)

Characteristics of SVC: SVC placed in a transmission network provides a dynamic voltage control to increase the transient stability, enhancing the damping power oscillations and improve the power flow control of the power systems.

In real time scenario, it effectively controls the reactive power, improves the power factor, reduces the voltage levels caused by the nonlinear loads, improves the power quality and reduces the energy consumption.

The main advantage of SVC application is to maintain bus voltage approximately near a constant level in addition used to improve transient stability. It is widely used in metallurgy, electrified railway, wind power generation etc.

4.4.1.2 Thyristor Controlled Series Compensator (TCSC):

It is designed based on the thyristor based FACTS technology that has the ability to control the line impedance with a thyristor-controlled capacitor placed in series with the transmission line. It is used to increase the transmission line capability by installing a series capacitor that reduces the net series impedance thus allowing additional power to be transferred.

Circuit Description: TCSC device consists of three main components: Capacitor bank, bypass inductor and bidirectional thyristors SCR1 and SCR2 as shown in the Fig 4.4.

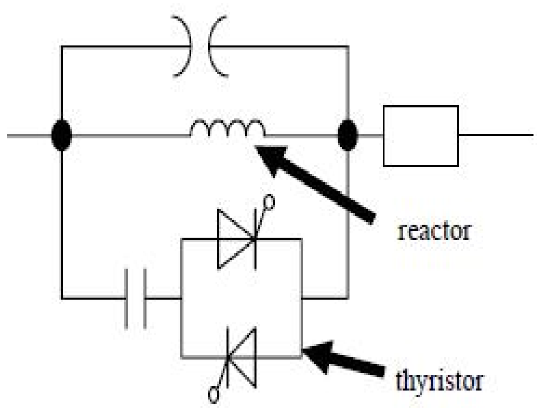


Figure 4.4: Circuit Diagram of Thyristor Controlled Series Compensator (TCSC)

Characteristics of Thyristor Controlled Series Compensator (TCSC): TCSC placed in a transmission network provides the power flow control in a power system improving the damping power oscillation and reduces the net loss providing voltage support.

The thyristors in TCSC device offers a flexible adjustment with the ability to control the continuous line compensation. TCSC controllers effectively used for solving power system problems of transient stability, dynamic stability, steady state stability and voltage stability in long transmission lines.

4.4.2: Second Generation of FACTS Controllers:

These categories of controllers are designed based on voltage source converter FACTS technology.

4.4.2.1: Static Synchronous Series Compensator (SSSC):

Static Synchronous Series Compensator is based on solid-state voltage source converter designed to generate the desired voltage magnitude independent of line current.

Circuit Description: SSSC consists of a converter, DC bus (storage unit) and coupling transformer as shown in Figure 4.5. The dc bus uses the inverter to synthesize an ac voltage waveform that is inserted in series with transmission line through the transformer with an appropriate phase angle and line current. If the injected voltage is in phase with the line current it exchanges a real power and if the injected voltage is in quadrature with line current it exchanges a reactive power. Therefore, it has the ability to exchange both the real and reactive power in a transmission line.

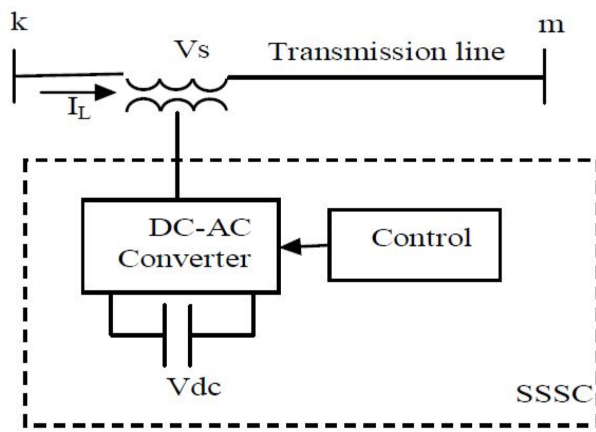


Fig. 4.5: Block Diagram of Static Synchronous Series Compensator SSSC)

Characteristics of SSSC: SSSC in a transmission network generates a desired compensating voltage independent of the magnitude of line current, by modulating reactive line impedance and combining real and reactive compensation it can provide high damping of power oscillation. The capability of SSSC to exchange both active and reactive power makes it possible to compensate both the reactive and the resistive voltage drop thereby maintains a high effective X/R ration independent of degree of series oscillation.

All the above features of SSSC attract the FACTS device for power flow control, damping of power oscillations and transient stability.

4.4.2.2: Static Synchronous Compensator (STATCOM):

It is designed based on Voltage source converter (VSC) electronic device with Gate turn off thyristor and dc capacitor coupled with a step down transformer tied to a transmission line as shown in Fig 4.6. It converts the dc input voltage into ac output voltages to compensate the active and reactive power of the system. STATCOM has better characteristics than SVC and it is used for voltage control and reactive power compensation.

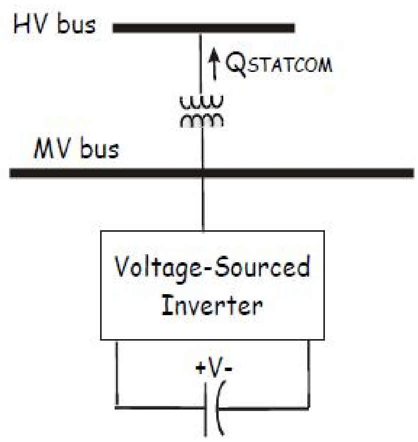


Figure 4.6 : Circuit Diagram of Static Synchronous Compensator (STATCOM)

Characteristics of Static Synchronous Compensator (STATCOM): STATCOM placed on a transmission network improve the voltage stability of a power system by controlling the voltage in transmission and distribution systems, improves the damping power oscillation in transmission system, provides the desired reactive power compensation of a power system[21].

4.4.3: Third Generation of FACTS Controllers:

The third generation of FACTS controllers is designed by combining the features of previous generation's series and shunt compensation FACTS controllers.

4.4.3.1: Unified Power Flow Controller (UPFC):

It is designed by combining the series compensator (SSSC) and shunt compensator (STATCOM) coupled with a common DC capacitor. It provides the ability to simultaneously control all the transmission parameters of power systems, i.e. voltage, impedance and phase angle.

Circuit Description: As shown in Fig 4.7 it consists of two converters – one connected in series with the transmission line through a series inserted transformer and the other one connected in shunt with the transmission line through a shunt transformer. The DC terminal of the two converters are connected together with a DC capacitor. The series converter control to inject voltage magnitude and phase angle in series with the line to control the active and reactive power flows on the transmission line. Hence the series converter will exchange active and reactive power with the line.

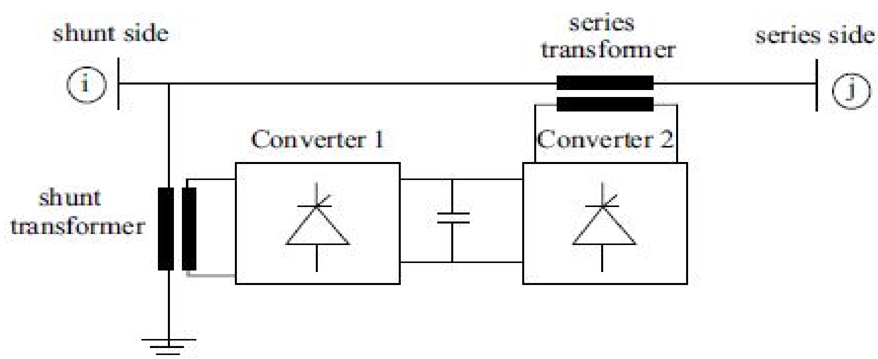


Figure 4.7: Circuit Diagram of Unified Power Flow Controller (UPFC)

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

4.4.4: Convertible Static Compensator (CSC):

It is the latest generation and most recent development in the field of FACTS controllers. It has the ability to increase the power transfer capability and maximize the use of existing transmission line.

4.4.4.1: Interline Power Flow Controller (IPFC):

It is designed based on Convertible Static Compensator (CSC) of FACTS Controllers. As shown in Fig 4.8, IPFC consists of two series connected converters with two transmission lines. It is a device that provides a comprehensive power flow control for a multi-line transmission system and consists of multiple number of DC to AC converters, each providing series compensation for a different transmission line. The converters are linked together to their DC terminals and connected to the AC systems through their series coupling transformers. With this arrangement, it provides series reactive compensation in addition any converter can be controlled to supply active power to the common dc link from its own transmission line.

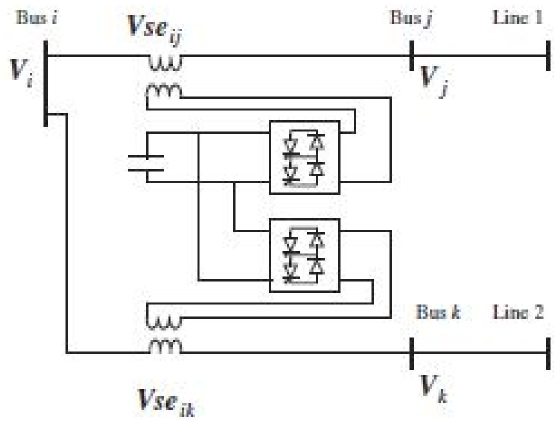


Figure 4.8: Circuit Diagram of Interline Power Flow Controller [21]

Characteristics of IPFC: To avoid the control of power flow problem in one system with synchronous of power in other system, installation of IPFC system in additional parallel inverter is required to meet the active power demand.

4.4.4.2: Generalized Unified Power Flow Controller (GUPFC):

It has been proposed to realize the simultaneous power flow control of several transmission lines. It is designed by combining three or more dc to ac converters working together extending the concepts of voltage and power flow control of the known two-converter UPFC controller to multi voltage and power flow control. The GUPFC shown in Fig 4.9 consists of three converters, one

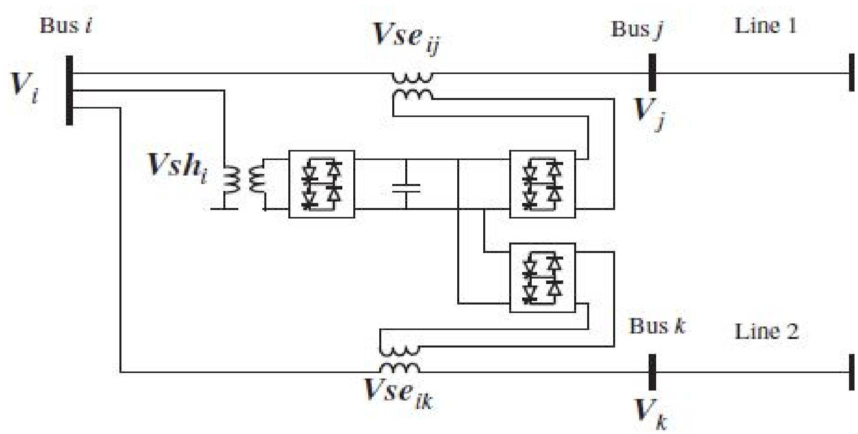


Figure 4.9: Circuit Diagram of Generalized UPFC

4.5 Advantages of FACTS controllers in Power Systems:

- Power system stability: Instabilities in power system are created due to long length of the transmission lines, interconnected grid, changing system loads and line faults in the system. These instabilities results in reduced transmission line flows or even tripping of the transmission. FACTS devices stabilize transmission systems with increased transfer capability and reduced risk of transmission line trips.
- Power Quality and Reliability: Modern power industries demand for the high quality of electricity in a reliable manner with no interruptions in power supply including constant voltage and frequency. The change in voltage drops, frequency variations or the loss of supply can lead to interruptions with high economic losses. Installation of TCSC at the distribution system without increasing the short circuit current level considerably increase the reliability for the consumer.
- Environmental Benefits: The construction of new transmission line has negative impact on the economical and environmental factors. Installation of FACTS devices in the existing transmission lines makes the system more economical by reducing the need for additional transmission lines. For example, In Sweden, eight 400 kV systems run in parallel to transport power from north to south. Each of the transmission systems are equipped with FACTS. Studies show that four additional 400kV transmission systems would be necessary if FACTS were not utilized on the existing system.
- Flexibility: The construction of new transmission lines take several years but the installation of FACTS controllers in a power system requires only 12 to 18 months. It has the flexibility for future upgrades and requires small land area.
- Reduced maintenance cost: Maintenance cost of FACTS controllers are less compared to the installation of new transmission lines. As the number of transmission line increases, probability of fault occurring in a line also increases resulting in system failure. By utilizing the FACTS controllers in a transmission network, power system minimizes the number of line faults thus reducing the maintenance cost.

Chapter 5

THE UNIFIED POWER FLOW CONTROLLER

5.1 INTRODUCTION

Gyugyi in 1991 proposed the Unified Power Flow Controller. It is the most versatile and complex power electronic device and member of third generation FACTS Controller introduced to control the power flow and voltage in the power systems. It is designed by combining the features of second-generation FACTS controllers – Series Synchronous Compensator (SSSC) and Static Synchronous Compensator (STATCOM). It has the ability to control active and reactive power flow of a transmission line simultaneously in addition to controlling all the transmission parameters (voltage, impedance and phase angle) affecting the power flow in a transmission line.

5.2 UPFC Circuit Description

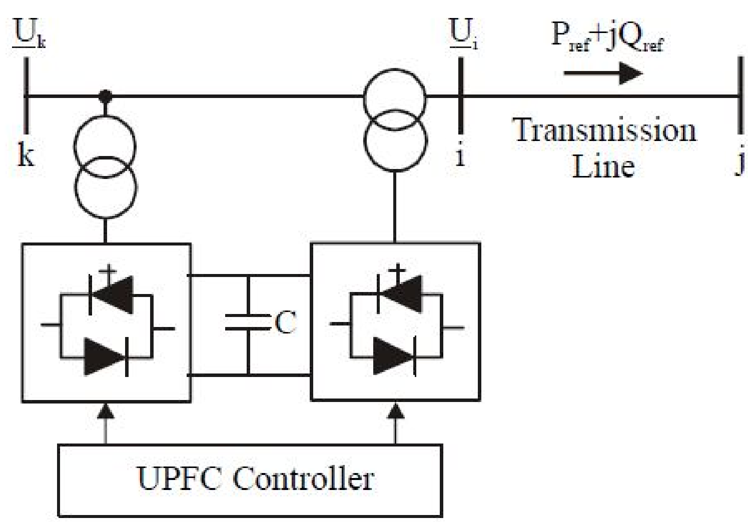


Figure 5.1: Unified Power Flow Controller

The above figure 5.1 taken from reference [22] gives a clear description about how UPFC controller connected to a transmission line. It consists of two back-to-back self-commutated voltage source converters - one converter at the sending end is connected in shunt as shunt converter and the other converter connected in between sending and receiving end bus in series as series converter. One end of the both the converters are connected to a power system through an appropriate transformer and other end connected with a common DC capacitor link [22].

5.3 Operation of UPFC:

This arrangement of UPFC ideally works as a ideal ac to dc power converter in which real power can freely flow in either direction between ac terminals of the two converters and each converter can independently generate or absorb reactive power at its own AC output terminal. The main functionality of UPFC provided by shunt converter by injecting an ac voltage considered as a synchronous ac voltage source with controllable phase angle and magnitude in series with the line. The transmission line current flowing through this voltage source results in real and reactive power exchange between it and the AC transmission system. The inverter converts the real power exchanged at ac terminals into dc power which appears at the dc link as positive or negative real power demand.

Operation of two converters:

Series converter Operation: In the series converter, the voltage injected can be determined in different modes of operation: direct voltage injection mode, phase angle shift emulation mode, Line impedance emulation mode and automatic power flow control mode. Although there are different operating modes to obtain the voltage, usually the series converter operates in automatic power flow control mode where the reference input values of P and Q maintain on the transmission line despite the system changes.

Shunt converter operation: The shunt converter operated in such a way to demand the dc terminal power (positive or negative) from the line keeping the voltage across the storage capacitor Vdc constant. Shunt converter operates in two modes: VAR Control mode and Automatic Voltage Control mode. Typically, Shunt converter in UPFC operates in Automatic voltage control mode.

5.4 Equivalent Circuit Operation of UPFC:

As shown in Fig 5.2, the two-voltage source converters of UPFC can modeled as two ideal voltage sources one connected in series and other in shunt between the two buses. The output of series voltage magnitude V_{se} controlled between the limits $V_{se\min} \leq V_{se} \leq V_{se\max}$ and the angle θ_{se} between the limits $0 \leq \theta_{se} \leq 2\Pi$ respectively. The shunt voltage magnitude V_{sh} controlled between the limits $V_{sh\min} \leq V_{sh} \leq V_{sh\max}$ and the angle between $0 \leq \theta_{sh} \leq 2\Pi$ respectively. Z_{se} and Z_{sh} are considered as the impedances of the two transformers one connected in series and other in shunt between the transmission line and the UPFC as shown in the Fig 5.2 which is the UPFC equivalent circuit.

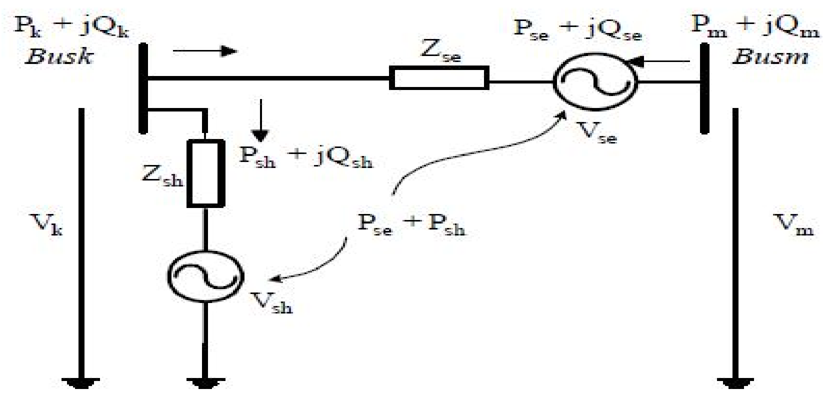


Figure 5.2: Equivalent circuit of UPFC

The ideal series and voltage source from the Fig 5.2 can written as

$$V_{se} = V_{se}(\cos\theta_{se} + j\sin\theta_{se}) \qquad 5.3.1$$

$$V_{sh} = V_{sh}(\cos\theta_{sh} + j\sin\theta_{sh}) \qquad 5.3.2$$

The magnitude and the angle of the converter output voltage used to control the power flow mode and voltage at the nodes as follows:

1. The bus voltage magnitude can be controlled by the injected a series voltage V_{se} in phase or anti-phase.
2. Power flow as a series reactive compensation controlled by injecting a series voltage V'_{se} in quadrature to the line current.

3. Power flow as phase shifter controlled by injecting a series voltage of magnitude V''_{se} in quadrature to node voltage θ_m.

UPFC power Equations:

Based on the equivalent circuit as shown in Fig 5.2, the active and reactive power equations can be written as follows:

At node k:

$$\begin{aligned} P_k &= V^2{}_k G_{kk} + V_k V_m (G_{km} \cos(\theta_k - \theta_m) + B_{km} \sin(\theta_k - \theta_m)) \\ &+ V_k Vse(G_{km} \cos(\theta_k - \theta_{se)} + B_{km} \sin(\theta_k - \theta_{se})) \\ &+ V_k V_{sh} (G_{sh} \cos(\theta_k - \theta_{sh}) + B_{sh} \sin(\theta_k - \theta_{sh})) \end{aligned} \quad 5.3.3$$

$$\begin{aligned} Q_k &= -V^2{}_k B_{kk} + V_k V_m (G_{km} \sin(\theta_k - \theta_m) - B_{km} \cos(\theta_k - \theta_m)) \\ &+ V_k V_{se} (G_{km} \sin(\theta_k - \theta_{se}) - B_{km} \cos(\theta_k - \theta_{se})) \\ &+ V_k V_{sh} (G_{sh} \sin(\theta_k - \theta_{sh}) - B_{sh} \cos(\theta_k - \theta_{sh})) \end{aligned} \quad 5.3.4$$

At node m:

$$\begin{aligned} P_m &= V^2{}_m G_{mm} + V_m V_k (G_{mk} \cos(\theta_m - \theta_k) + B_{mk} \sin(\theta_m - \theta_k)) \\ &+ V_m V_{se} (G_{mm} \cos(\theta_m - \theta_{se}) + B_{mm} \sin(\theta_m - \theta_{se})) \end{aligned} \quad 5.3.5$$

$$\begin{aligned} Q_m &= -V^2{}_m B_{mm} + V_m V_k (G_{mk} \sin(\theta_m - \theta_k) - B_{mk} \cos(\theta_m - \theta_k)) \\ &+ V_m V_{sh} (G_{mm} \sin(\theta_m - \theta_{se}) - B_{mm} \cos(\theta_m - \theta_{se})) \end{aligned} \quad 5.3.6$$

Series converter:

$$\begin{aligned} P_{se} &= V^2{}_{se} G_{mm} + V_{se} V_k (G_{km} \cos(\theta_{se} - \theta_k) + B_{km} \sin(\theta_{se} - \theta_k)) \\ &+ V_{se} V_m (G_{mm} \cos(\theta_{se} - \theta_k) + B_{mm} \sin(\theta_{se} - \theta_m) \end{aligned} \quad 5.3.7$$

$$\begin{aligned} Q_{se} &= -V^2{}_{se} B_{mm} + V_{se} V_k (G_{km} \sin(\theta_{se} - \theta_k) - B_{km} \cos(\theta_{se} - \theta_k)) \\ &+ V_{se} V_m (G_{mm} \sin(\theta_{se} - \theta_m) - B_{mm} \cos(\theta_{se} - \theta_m)) \end{aligned}$$

$$P_{sh} = -V^2{}_{sh} G_{sh} + V_{sh} V_k (G_{sh} \cos(\theta_{sh} - \theta_k) + B_{sh} \sin(\theta_{sh} - \theta_k) \quad 5.3.8$$

$$Q_{sh} = V^2{}_{sh} B_{sh} + V_{sh} V_k (G_{sh} \sin(\theta_{sh} - \theta_k) - B_{sh} \cos(\theta_{sh} - \theta_k)) \quad 5.3.9$$

Where;

$$Y_{kk} = G_{kk} + jB_{kk} = Z^{-1}{}_{se} + Z^{-1}{}_{sh} \quad 5.3.10$$

$$Y_{mm} = G_{mm} + jB_{mm} = Z^{-1}{}_{se} \quad 5.3.11$$

$$Y_{km} = Y_{mk} = G_{km} + jB_{km} = -Z^{-1}{}_{se} \quad 5.3.12$$

$$Y_{sh} = G_{sh} + jB_{sh} = -Z^{-1}{}_{sh} \quad 5.3.13$$

Assuming a free converter loss operation, the active power supplied to the shunt converter P_{sh} equals to the active power demanded by the series converter P_{se}.

$$P_{se} + P_{sh} = 0 \quad 5.3.14$$

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

$$P_{sh} + P_{se} = P_k + P_m = 0 \quad 5.3.15$$

The UPFC power equations linearised and combined with the equations of the AC transmission network. For the cases when the UPFC controls the following parameters:

(1) voltage magnitude at the shunt converter terminal

(2) active power flow from bus m to bus k and

(3) reactive power injected at bus m, and taking bus m to be PQ bus.

5.5 ADDITIONAL FEATURES OF UPFC

UPFC can be controlled by using following objectives simultaneously in the power systems:

- Regulating power flow through a transmission line
- Minimizing the power losses without generator rescheduling.

Dynamic Security: In the past years, preventive control has been considered as the only strategy to control the dynamic security of the power systems, since the instability in the system occurs rapidly and no manual intervention is possible. Preventive control obtained by rescheduling of active power is generally of higher cost than the one obtained by economic dispatch. UPFC controllers can control the security of the network under the large disturbances associated to generation and load.

Comparison of UPFC with other FACTS devices:

Conventional thyristor-controlled power flow controllers employ the traditional power system compensation in which mechanical switches are replaced by thyristor valves. Each scheme is devised to control a particular system parameter affecting power flow. Thus, static var compensators are applied for reactive power and voltage control, controllable series compensators for line impedance adjustment, and tap-changing transformers for phase-shift. Each of these is a custom-designed system with different manufacturing and installation requirements. They have inherent limitations with regard to manufacturing and installation complexity, physical size and relatively high overall cost.

Practically, the unified power flow controller makes it possible to handle the power flow control and transmission line compensation problems uniformly, using solid-state voltage sources instead of switched capacitors and reactors or tap changing transformers. UPFC minimizes the installation labor requirements, and makes the capital cost primarily dependent on the cost of the solid-state components, which are decreasing trend with advancement of technology.

Chapter 6

NEWTON RAPHSON ALGORITHM AND FLOW CHART

6.1 Introduction

From the mathematical modeling point of view, the set of nonlinear, algebraic equations that describe the electrical power network under the steady state conditions are solved for the power flow solutions. Over the years, several approaches have been put forward to solve for the power flow equations. Early approaches were based on the loop equations and methods using Gauss-type solutions. This method was laborious because the network loops has to be specified by hand by the systems engineer. The drawback of these algorithms is that they exhibit poor convergence characteristics when applied to the solution of the networks. To overcome such limitations, the Newton-Raphson method and derived formulations were developed in the early 1970s and since then it became firmly established throughout the power system industry.

In this project a Newton Raphson power flow algorithm is used to solve for the power flow problem in a transmission line with UPFC as shown in the flow chart in Fig 6.1.

6.2: Steps to Solve the Newton-Raphson Algorithm

Step 1: Read the input of the system data that includes the data needed for conventional power flow calculation i.e. the number and types of buses, transmission line data, generation, load data and location of UPFC and the control variables of UPFC i.e. the magnitude and angles of output voltage series and shunt converters.

Step 2: Formation of admittance matrix Y_{bus} of the transmission line between the bus i and j.

Step 3: Combining the UPFC power equations with network equation, we get the conventional power flow equation:

$$P_i + jQ_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \angle(\theta_{ij} - \delta_i + \delta_j) + P'_i + jQ'_i \qquad 6.1.1$$

Where $P'_i + Q'_i =$ active and reactive power flow due to UPFC between the two buses.

$P_i + jQ_i =$ Active and reactive power flow at the i^{th} bus.

$V_i \angle \delta_i =$ Voltage and angle of i^{th} bus

$V_j \angle \delta_j =$ Voltage and angle at j^{th} bus

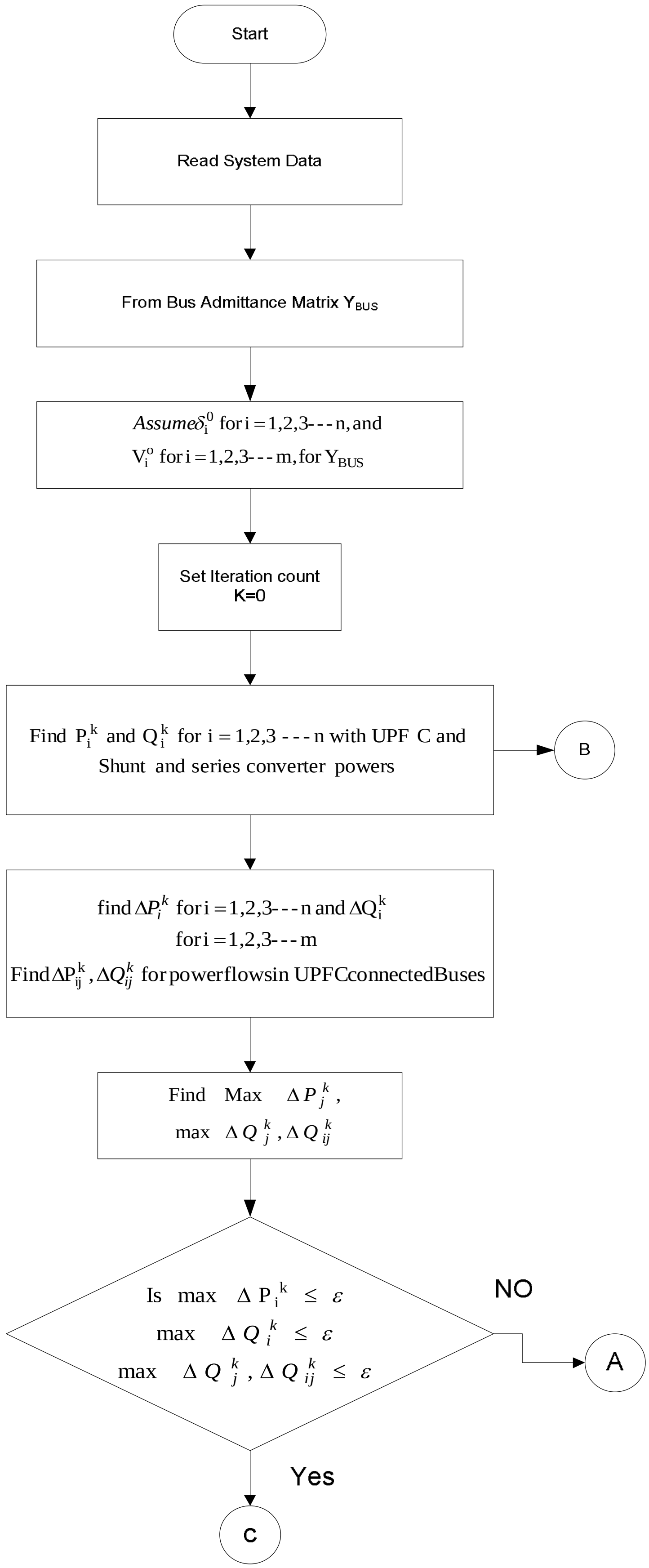
Step 5 : The conventional jacobian matrix are formed ($P^k{}_i$ and $Q^k{}_i$) due to the inclusion of UPFC. The inclusion of these variables increases the dimensions of the jacobian matrix.

Step 6: In this step, the jacobian matrix is modified and power equations are mismatched ($\Delta P^k{}_i$, $\Delta Q^k{}_i$ for i=2, 3,…, m and $\Delta P^k{}_{ii}$, $\Delta Q^k{}_{ii}$).

Step 7: The busbar voltages are updated at each iteration and convergence is checked.

If convergence is not achieved in the next step the algorithm goes back to the step 6 and the jacobian matrix is modified and the power equations are mismatched until convergence is attained.

Step 8: If the convergence achieved in Step 7, the output load flow is calculated for PQ bus that includes the Busbar voltages, generation, transmission line flow and losses.


Start
Read System Data
From Bus Admittance Matrix Y_{BUS}
$Assume\delta_i^0$ for i = 1,2,3---n, and
V_i^o for i = 1,2,3---m, for Y_{BUS}
Set Iteration count
K=0
Find P_i^k and Q_i^k for i = 1,2,3 ---n with UPF C and
Shunt and series converter powers
B
find ΔP_i^k for i = 1,2,3---n and ΔQ_i^k
for i = 1,2,3---m
Find ΔP_{ij}^k, ΔQ_{ij}^k for powerflowsin UPFCconnectedBuses
Find Max ΔP_j^k,
max ΔQ_j^k, ΔQ_{ij}^k
Is max $\Delta P_i^k \leq \varepsilon$
max $\Delta Q_i^k \leq \varepsilon$
max ΔQ_j^k, $\Delta Q_{ij}^k \leq \varepsilon$
NO
A
Yes
C

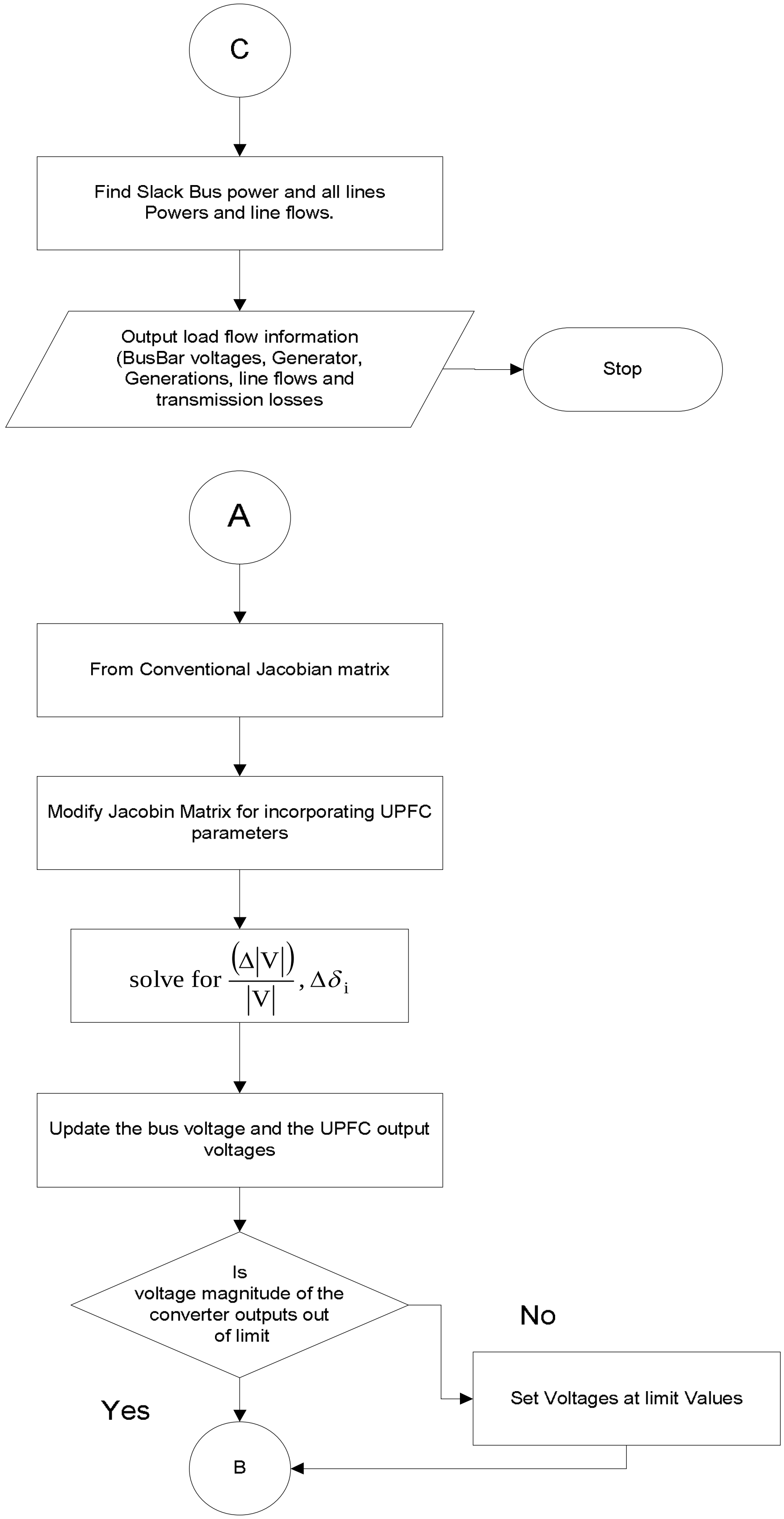


Figure 6.1: Flow Chart for load flow by Newton Raphson with UPFC [18]

Chapter 7

CASE STUDY OF A NETWORK WITH UNIFIED POWER FLOW CONTROLLER

7.1 INTRODUCTION:

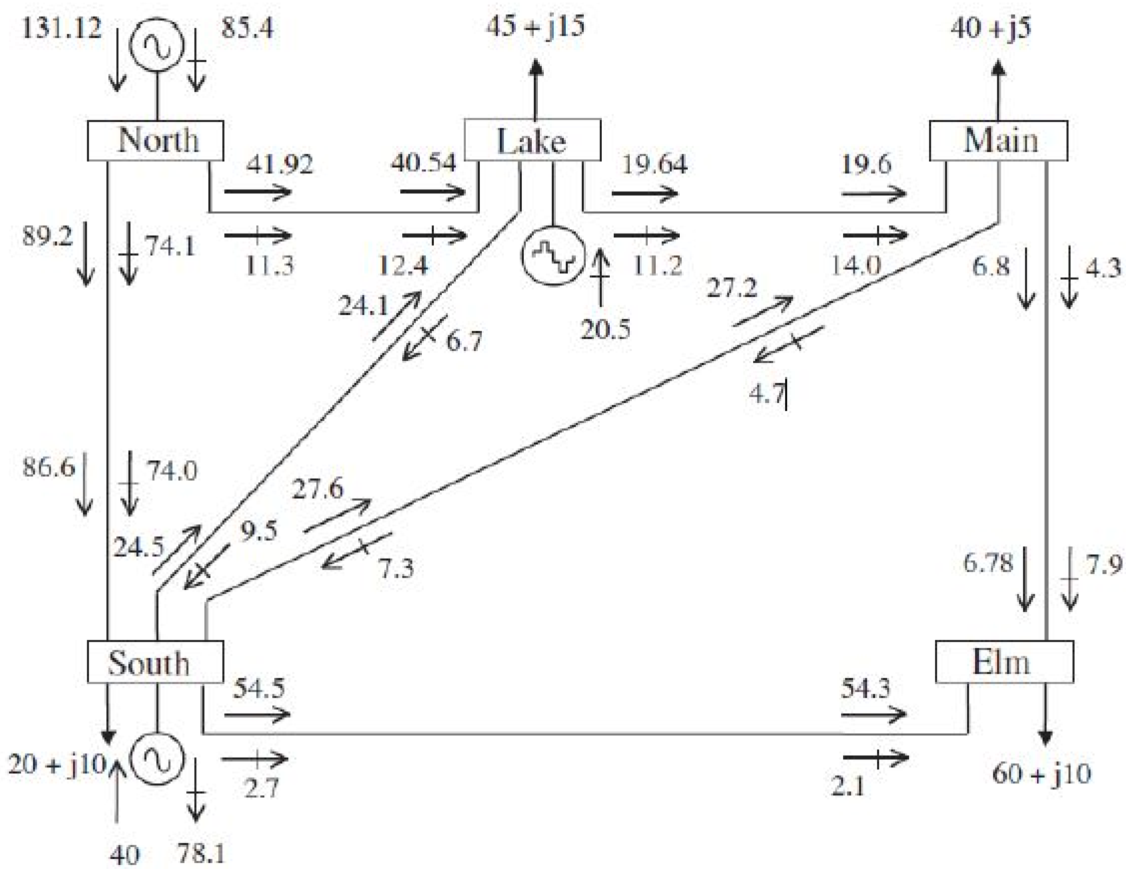


Figure 7.1: A Standard 5-Bus Network with UPFC

In this case, I considered an IEEE standard 5- bus network with UPFC to study the power flow control of a power system. For the analysis as shown in Fig 7.1, bus 1(North) considered as slack bus, buses 2(South) and 3(Lake) as voltage control buses and buses 4(Main), 5(Elm) as load buses. To include a unified power flow controller an additional bus 6 placed in between buses 3 and 4 in the network. It maintains the active and reactive powers leaving the UPFC towards the bus 4. The UPFC shunt converter is set to regulate bus 3 nodal voltage magnitude at 1 p.u.

Explanation of MATLAB program using Newton-Raphson algorithm with Unified Power Flow Controller

- Program in the Appendix incorporates the UPFC model with the Newton-Raphson power flow algorithm.
- In the main program, the functions used are PowerFlow data, UPFC data.
- The functions Power Flow data is used to read the network data and the UPFC data is used to read the UPFC data. Admittance matrix called to solve for the formation of YBus and the UPFC NewtonRaphson function called to solve the nodal voltage magnitude and phase angle for the number of iterations.

- PQ UPFC Power called to solve for the active and reactive power at sending and receiving end bus with UPFC.
- In the main UPFC Newton-Raphson program, the function UPFC data added to read the UPFC data, UPFC PQ flow data called used to calculate the power flow and losses in the UPFC.
- By using the UPFC power equations from UPFC data with network equations from PowerFlow data, UPFC calculated powers are obtained.
- Power mismatches are calculated with UPFC and the Jacobian matrix is attained because of the inclusion of UPFC.
- As per the flow chart 6.1 from Chapter 6 convergence is checked for the power mismatches.
- If the convergence limit is not achieved, the Jacobian matrix modified by adding UPFC elements and power mismatches are calculated. This step continues until convergence is attained.
- Once the convergence is achieved the reactive and active power controlled in terms of Jacobian terms are calculated.
- Once the reactive and active power terms calculated the UPFC state variables are updated and check for the voltage source limits.

By solving the program in steps with all the parameters included I got the following results, which I formulated in the tables below. I cross checked the results obtained against the IEEE test case results and observed that the power flows in the UPFC network differ with respect to the power flow without UPFC. Table 7.2.1 represents the bus voltage network without UPFC. Table7.2.2 represents the bus voltage network with UPFC. Table 7.2.3 represent the line flows calculated for the network with and without UPFC. From Table 7.2.3 the line flow in the transmission line with the UPFC in between the bus 3-4 has increased from -0.19016 to -0.4062. The increase is in response to the large amount of active power demanded by the UPFC series converter. The negative sign represent the direction of the flow from the shunt converter end to the series converter. The maximum amount of active power exchanged between the UPFC and the AC system depend on the robustness of UPFC shunt bus and bus 3. Since UPFC generates its own reactive power, the generator at bus 1 decreases it reactive power generation and the generator connected at bus 2 increases its absorption of the reactive power.

7.1.1 BUS DATA

Table 7.1.1 below displays the bus data characteristics of the transmission system discussed above. Column 1 of Table 7.1.1 outlines the bus number and column 2 contains the bus code. Columns 3 and 4 show the voltage magnitudes in p.u. and phase angle in degrees. Columns 5 and 6 outline the size of the active and reactive loads connected to the corresponding buses in MW and MVAR. Columns 7 through to 10 are MW, MVAR, minimum MVAR and maximum MVA of generation, in that order. The bus code entered in column 2 is used for identifying load, voltage-controlled, and slack buses as outlined below;

- code "1" is used for the slack bus.
- code"2" is used for the voltage controlled buses.
- code "3" is used for load buses.

7.1.2 LINE DATA

Table 7.1.2 below displays the line data characteristics of the transmission system discussed above. Columns 1 and 2 of Table 7.1.2 outline the corresponding line bus numbers. Columns 3 through to 5 contain the line resistance, reactance, and one half of the total line charging susceptance in per unit on the MVA base of 100MVA.

Table: 7.1.1 BUS DATA

Bus No.	**Bus Code**	**Voltage Mag.**	**Angle Degree**	**Load MW**	**Load MVAR**	**Gen. MW**	**Gen. MVAR**	**Qmin**	**Qmax**
1	**1**	**1.06**	**0**	**0.0**	**0.0**	**0.0**	**0.0**	**-500**	**500**
2	**2**	**1.0**	**0**	**20.0**	**10.0**	**40.0**	**0.0**	**-300**	**300**
3	**3**	**1.0**	**0**	**45.0**	**15.0**	**0.0**	**0.0**	**0**	**0**
4	**3**	**1.0**	**0**	**40.0**	**5.0**	**0.0**	**0.0**	**0**	**0**
5	**3**	**1.0**	**0**	**60.0**	**10.0**	**0.0**	**0.0**	**0**	**0**

Table 7.1.2 : LINE DATA

Bus nl	Bus nr	R	X	B
1	2	0.02	0.06	0.06
1	3	0.08	0.24	0.05
2	3	0.06	0.18	0.04
2	4	0.06	0.18	0.04
2	5	0.04	0.12	0.03
3	4	0.01	0.03	0.02
4	5	0.08	0.24	0.05

7.2 Results

7.2.1 A 5-Bus Network Bus Voltage without UPFC:

For iterations = 6

	Bus Voltage without UPFC				
Nodal Voltage	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
Magnitude(p.u)	1.06	1.06	0.981	0.9993	0.9647
Phase angle(deg)	0.00	-1.986	-4.22	-4.60	-5.0169

Table 7.2.1 : Bus Voltage without UPFC

7.2.2 A 5-Bus Network Bus Voltage with UPFC :

For iterations = 6

	Bus Voltage with UPFC				
Nodal voltage	**Bus 1**	**Bus 2**	**Bus 3**	**Bus 4**	**Bus 5**
Magnitude(p.u)	**1.0600**	**1.0000**	**1.0100**	**1.0178**	**0.9717**
Phase angle(deg)	**0**	**-2.0612**	**-3.3498**	**-3.8986**	**-5.7649**

Table 7.2.2: Bus Voltage with UPFC

7.2.3 Line Flow with and without of UPFC for the 5-bus Network:

Buses	**Line Flows without UPFC**		**Line Flow with UPFC**	
	P (MW)	**Q (MVAR)**	**P (MW)**	**Q (MVAR)**
1-2	**-0.8043**	**-0.7108**	**0.6215**	**-0.0335**
1-3	**-0.4027**	**-0.1621**	**-0.2182**	**-0.1668**
2-3	**-0.2418**	**-0.0033**	**-0.0901**	**-.02081**
2-4	**-0.2651**	**-0.0079**	**-0.2061**	**-0.2270**
2-5	**-0.5217**	**-0.0473**	**-0.5122**	**-0.3839**
3-4	**-0.19016**	**-0.0655**	**-0.4062**	**-0.0216**
4-5	**-0. 04561**	**-0.0508**	**-0.09601**	**-0.0138**

Table7.2.3: Line Flow with and without UPFC

7.3: Case Study of IEEE-30 Bus Network:

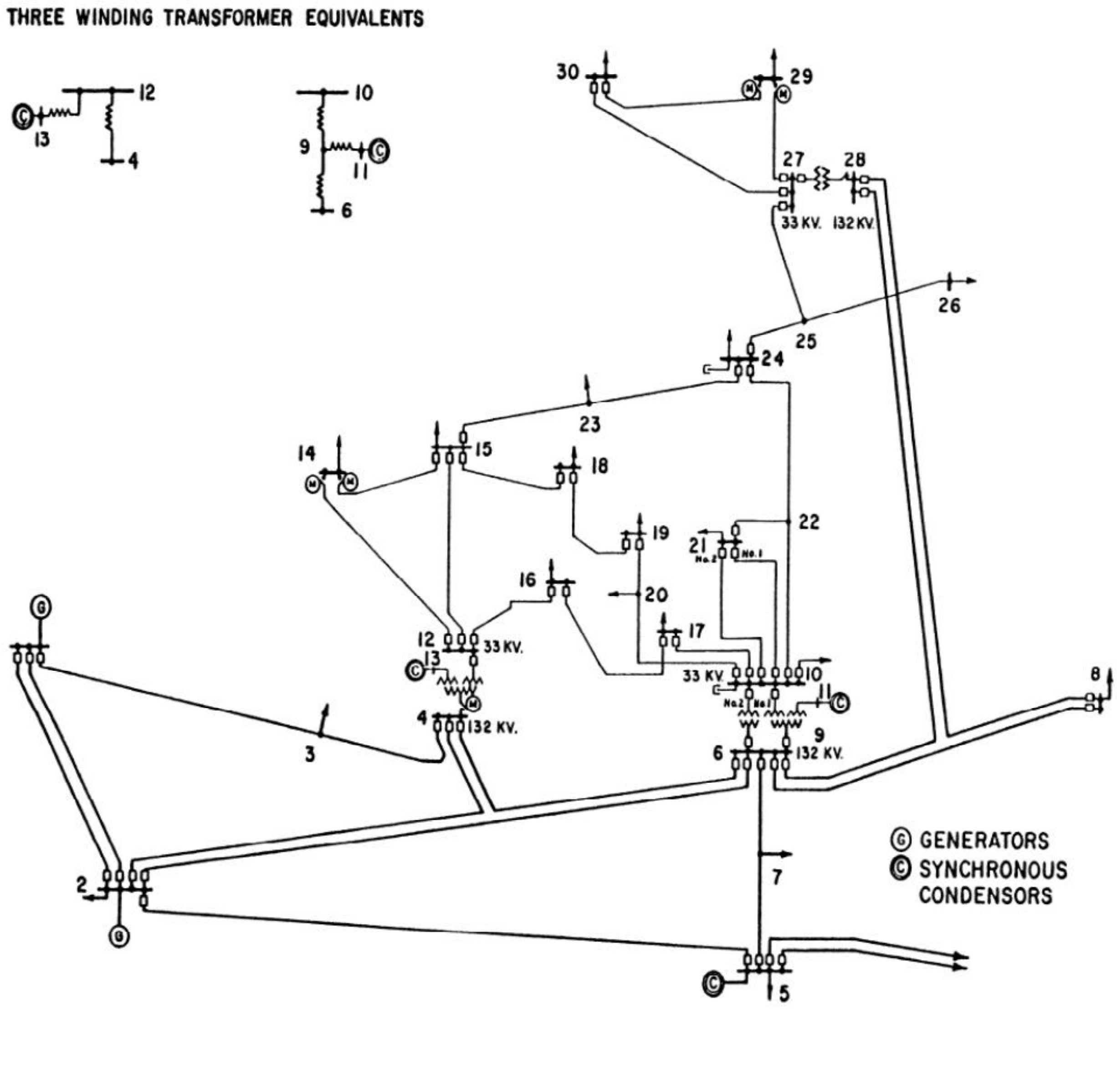


Fig.7.2 IEEE-30 bus Test System

A single line diagram of IEEE-30 bus test system is shown in fig. 7.2. This system consists of five generator buses (bus no.-2,5,8,11,13), one slack bus (bus no.-1) and twenty seven load buses (bus no.-2,3,4,5,6,7,8,9,10,12,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30).

7.4.1 BUS DATA

Table 7.3.1 below displays the bus data characteristics of the transmission system discussed above. Column 1 of Table 7.3.1 outlines the bus number and column 2 contains the bus code. Columns 3 and 4 show the voltage magnitudes in p.u. and phase angle in degrees. Columns 5 and 6 outline the size of the active and reactive loads connected to the corresponding buses in MW and MVAR. Columns 7 through to 10 are MW, MVAR, minimum MVAR and maximum MVA of generation, in that order. The bus code entered in column 2 is used for identifying load, voltage-controlled, and slack buses as outlined below;

1 – This code is used for the slack bus.

2 – This code is used for the voltage controlled buses.

3 – This code is used for load buses.

7.4.2 LINE DATA

Table 7.3.2 below displays the line data characteristics of the transmission system discussed above. Columns 1 and 2 of Table 7.3.2 outline the corresponding line bus numbers. Columns 3 through to 5 contain the line resistance, reactance, and one half of the total line charging susceptance in per unit on the MVA base of 100MVA.

Table : 7.3.1; Bus Data

Bus NO.	Bus Code	Voltage Magnitude	Angle Degree	Load MW	Load MVAR	Gen. MW	Gen. MVAR	Q_{Min}	$Q_{Max.}$
1	1	1.06	0	0.0	0.0	0.0	0.0	0	0
2	2	1.043	0	21.70	12.7	40.0	0.0	-40	50
3	3	1.0	0	2.4	1.2	0.0	0.0	0	0
4	3	1.06	0	7.6	1.6	0.0	0.0	0	0
5	2	1.01	0	94.2	19.0	0.0	0.0	-40	40
6	3	1.0	0	0.0	0.0	0.0	0.0	0	0
7	3	1.0	0	22.8	10.9	0.0	0.0	0	0
8	2	1.01	0	30.0	30.0	0.0	0.0	-10	40

9	**3**	**1.0**	**0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0**
10	**3**	**1.0**	**0**	**5.8**	**2.0**	**0.0**	**0.0**	**0**	**0**
11	**2**	**1.08**	**0**	**0.0**	**0.0**	**0.0**	**0.0**	**-6**	**24**
12	**3**	**1.0**	**0**	**11.2**	**7.5**	**0.0**	**0.0**	**0.0**	**0.0**
13	**2**	**1.071**	**0**	**0.0**	**0.0**	**0.0**	**0.0**	**-6**	**24**
14	**3**	**1.0**	**0**	**6.2**	**1.6**	**0.0**	**0.0**	**0**	**0**
15	**3**	**1.0**	**0**	**8.2**	**2.5**	**0.0**	**0.0**	**0**	**0**
16	**3**	**1.0**	**0**	**3.5**	**1.8**	**0.0**	**0**	**0**	**0**
17	**3**	**1.0**	**0**	**9.0**	**5.8**	**0.0**	**0.0**	**0**	**0**
18	**3**	**1.0**	**0**	**3.2**	**0.9**	**0.0**	**0.0**	**0**	**0**
19	**3**	**1.0**	**0**	**9.5**	**3.4**	**0.0**	**0.0**	**0**	**0**
20	**3**	**1.0**	**0**	**2.2**	**0.7**	**0.0**	**0.0**	**0**	**0**
21	**3**	**1.0**	**0**	**17.5**	**11.2**	**0.0**	**0.0**	**0**	**0**
22	**3**	**1.0**	**0**	**0.0**	**0.0**	**0.0**	**0.0**	**0**	**0**
23	**3**	**1.0**	**0**	**3.2**	**1.6**	**0.0**	**0.0**	**0**	**0**
24	**3**	**1.0**	**0**	**8.7**	**6.7**	**0.0**	**0.0**	**0**	**0**
25	**3**	**1.0**	**0**	**0.0**	**0.0**	**0.0**	**0.0**	**0**	**0**
26	**3**	**1.0**	**0**	**3.5**	**2.3**	**0.0**	**0.0**	**0**	**0**
27	**3**	**1.0**	**0**	**0.0**	**0.0**	**0.0**	**0.0**	**0**	**0**
28	**3**	**1.0**	**0**	**0.0**	**0.0**	**0.0**	**0.0**	**0**	**0**
29	**3**	**1.0**	**0**	**2.4**	**0.9**	**0.0**	**0.0**	**0**	**0**
30	**3**	**1.0**	**0**	**10.6**	**1.9**	**0.0**	**0.0**	**0**	**0**

Table 7.3.2: Line Data

Bus nl	Bus nr	R	X	1/2B
1	2	0.0192	0.0575	0.0264
1	3	0.0452	0.1852	0.0204
2	4	0.0570	0.1737	0.1840
3	4	0.0132	0.0379	0.0042
2	5	0.0472	0.1983	0.0209
2	6	0.0581	0.1763	0.0187
4	6	0.0119	0.0414	0.0045
5	7	0.0460	0.1160	0.0102
6	7	0.0267	0.0820	0.0085
6	8	0.0120	0.0420	0.0045
6	9	0.0	0.2080	0.0
6	10	0.0	0.5560	0.0
9	11	0.0	0.2080	0.0
9	10	0.0	0.1100	0.0
4	12	0.0	0.2560	0.0
12	13	0.0	0.1400	0.0
12	14	0.1231	0.2559	0.0
12	15	0.0662	0.1304	0.0
12	16	0.0945	0.1987	0.0
14	15	0.2210	0.1997	0.0
16	17	0.0824	0.1923	0.0
15	18	0.1073	0.2185	0.0
18	19	0.0639	0.1292	0.0

19	**20**	**0.0343**	**0.0680**	**0.0**
10	**20**	**0.0936**	**0.2090**	**0.0**
10	**17**	**0.0324**	**0.0845**	**0.0**
10	**21**	**0.0348**	**0.0749**	**0.0**
10	**22**	**0.0727**	**0.1499**	**0.0**
21	**22**	**0.0116**	**0.0236**	**0.0**
15	**23**	**0.1000**	**0.2020**	**0.0**
22	**24**	**0.1150**	**0.1790**	**0.0**
23	**24**	**0.1320**	**0.2700**	**0.0**
24	**25**	**0.1885**	**0.3292**	**0.0**
25	**26**	**0.2554**	**0.3800**	**0.0**
25	**27**	**0.1093**	**0.2087**	**0.0**
28	**27**	**0.0000**	**0.3960**	**0.0**
27	**29**	**0.2198**	**0.4153**	**0.0**
27	**30**	**0.3202**	**0.6027**	**0.0**
29	**30**	**0.2399**	**0.4533**	**0.0**
8	**28**	**0.0636**	**0.2000**	**0.0214**
6	**28**	**0.0169**	**0.0599**	**0.065**

Results: 7.5

7.5.1 IEEE-30 Bus Voltage

Without UPFC			With UPFC		
Bus No.	VM (p.u.)	VA (p.u.)	Bus No.	VM (p.u.)	VA (p.u.)
1	1.0600	0.0000	1	1.0600	0.0000
2	1.043	-5.5020	2	1.0430	-5.5090
3	1.020.64	-7.9900	3	1.0260	-8.0600
4	1.0122	-9.6500	4	1.0190	-9.7340
5	1.0100	-14.4200	5	1.0100	-14.4230
6	1.0082	-11.3600	6	1.0100	-11.4180
7	1.0007	-13.1400	7	1.0020	-13.1700
8	1.0100	-12.1500	8	1.0100	-12.1550
9	1.0091	-14.6600	9	1.0210	-14.7510
10	0.9860	-16.4400	10	0.9960	-16.5370
11	1.0564	-14.6600	11	1.0820	-14.7510
12	1.0051	-15.9100	12	1.0290	-16.189
13	1.0375	-15.9100	13	1.0710	-16.1890
14	0.9884	-16.8600	14	1.0130	-17.1780
15	0.9826	-16.9000	15	1.0070	-17.3080
16	0.9895	-16.4300	16	1.0070	-16.6170
17	0.9814	-16.6700	17	0.9940	-16.7830
18	0.9709	-17.5100	18	0.9910	-17.7860
19	0.9673	-17.6600	19	0.9840	-17.8650
20	0.9712	-17.4200	20	0.9860	-17.5930
21	0.9726	-16.9200	21	0.9890	-17.2200

22	0.9730	-16.9000	22	0.9910	-17.2700
23	0.9689	-17.2000	23	1.0000	-18.0470
24	0.9596	-17.2200	24	1.0000	-18.6680
25	0.9644	-16.8700	25	0.9830	-15.5680
26	0.9458	-17.3400	26	0.9640	-16.0180
27	0.9765	-16.3600	27	0.9870	-15.4230
28	-16.36	-12.0100	28	1.0080	-119700
29	1.0045	-17.7200	29	0.9670	-16.7460
30	0.9556	-18.69	30	0.9550	-17.6980

Table : 7.5.2 : Line Flow Without UPFC for IEEE-30 BUS TEST SYSTEM

Buses	Sending End		Receiving End	
	P(MW)	Q(MVAR)	P(MW)	Q(MVAR)
1-2	178.10	-20.74	-172.62	34.24
1-3	83.17	6.80	-80.36	2.50
2-4	45.67	4.10	-44.56	-2.67
3-4	77.96	-3.70	-77.19	5.48
2-5	83.26	2.82	-80.24	7.64
2-6	61.99	2.29	-59.93	1.99
4-6	70.87	-9.59	-70.27	11.19
5-7	-13.96	13.36	14.13	-13.95
6-7	37.30	-2.78	-36.93	3.05
6-8	29.76	-12.94	-29.64	12.96
6-9	28.10	0.33	-28.10	1.29
6-10	15.81	4.71	-15.81	-3.22
9-11	0.00	-22.93	0.00	24.00
9-10	28.10	21.64	-28.10	-20.28

4-12	**43.29**	**5.18**	**-43.29**	**-0.43**
12-13	**0.00**	**-23.25**	**0.00**	**24.00**
12-14	**7.84**	**2.91**	**-7.75**	**-2.73**
12-15	**17.44**	**8.60**	**-17.19**	**-8.11**
12-16	**6.81**	**4.68**	**-6.74**	**-4.54**
14-15	**1.55**	**1.13**	**-1.55**	**-1.12**
16-17	**3.24**	**2.74**	**-3.23**	**-2.71**
15-18	**5.87**	**2.39**	**-5.82**	**-2.30**
18-19	**2.62**	**1.40**	**-2.62**	**-1.39**
19-20	**-6.88**	**-2.01**	**6.90**	**2.05**
10-20	**9.19**	**2.95**	**-9.10**	**-2.75**
10-17	**5.79**	**3.13**	**-5.77**	**-3.09**
10-21	**15.62**	**10.51**	**-15.49**	**-10.23**
10-22	**7.51**	**4.92**	**-7.45**	**-4.80**
21-22	**-2.01**	**-0.97**	**2.01**	**0.97**
15-23	**4.67**	**4.34**	**-4.63**	**-4.26**
22-24	**5.44**	**3.83**	**-5.39**	**-3.74**
23-24	**1.43**	**2.66**	**-1.41**	**-2.63**
24-25	**-1.90**	**-0.33**	**1.90**	**0.34**
25-26	**3.55**	**2.37**	**-3.50**	**-2.30**
25-27	**-5.45**	**-2.71**	**5.50**	**2.80**
28-27	**18.81**	**7.81**	**-18.81**	**-6.18**
27-29	**6.20**	**1.20**	**-6.11**	**-1.51**
27-30	**7.11**	**1.69**	**-6.93**	**-1.36**
29-30	**3.71**	**0.61**	**-3.67**	**0.54**
8-28	**-0.36**	**1.80**	**0.37**	**-3.95**
6-28	**-19.24**	**-2.50**	**-19.18**	**-3.86**

Table : 7.5.3 : Line Flow With UPFC for IEEE-30 BUS TEST SYSTEM

Buses	Sending End		Receiving End	
	P(MW)	Q(MVAR)	P(MW)	Q(MVAR)
1-2	178.97	-20.94	-173.44	34.61
1-3	82.65	12.48	-79.82	-3.11
2-4	45.85	11.23	-44.67	-9.56
3-4	77.42	1.91	-76.65	-0.10
2-5	83.53	2.80	-80.49	7.74
2-6	62.36	3.60	-60.27	0.78
4-6	70.01	-32.91	-69.30	34.93
5-7	-13.71	13.84	13.89	-14.42
6-7	37.05	-4.85	-36.69	5.13
6-8	29.84	-18.71	-29.69	18.76
6-9	27.65	-6.49	-27.65	8.15
6-10	15.49	2.14	-15.49	-0.80
9-11	0.00	-30.06	0.00	31.68
9-10	27.65	21.91	-27.65	-20.60
4-12	43.71	-5.41	-43.71	10.38
12-13	0.00	-37.15	0.00	39.01
12-14	7.72	4.36	-7.63	-4.16
12-15	17.74	9.56	-17.49	-9.06
12-16	7.05	5.36	-6.98	-5.21
14-15	1.43	0.23	-1.42	-0.22
16-17	3.48	3.41	-3.46	-3.36

15-18	**6.01**	**2.67**	**-5.96**	**-2.58**
18-19	**2.76**	**1.68**	**-2.75**	**-1.67**
19-20	**-6.75**	**-1.73**	**6.76**	**1.77**
10-20	**9.05**	**2.66**	**-8.96**	**-2.47**
10-17	**5.56**	**2.47**	**-5.54**	**-2.44**
10-21	**15.38**	**9.80**	**-15.27**	**-9.55**
10-22	**7.35**	**4.46**	**-7.30**	**-4.35**
21-22	**-2.23**	**-1.65**	**2.23**	**1.65**
15-23	**4.70**	**4.10**	**-4.66**	**-4.02**
22-24	**5.07**	**2.70**	**-5.03**	**-2.64**
23-24	**1.46**	**2.42**	**-1.45**	**-2.40**
24-25	**-2.22**	**-1.66**	**2.24**	**1.68**
25-26	**3.55**	**2.37**	**-3.50**	**-2.30**
25-27	**-5.79**	**-4.05**	**5.84**	**4.16**
28-27	**19.16**	**2.12**	**-19.16**	**-0.67**
27-29	**6.26**	**-3.25**	**-6.15**	**3.46**
27-30	**7.06**	**-0.25**	**-6.90**	**0.55**
29-30	**3.75**	**2.54**	**-3.70**	**-2.45**
8-28	**-0.31**	**1.42**	**0.31**	**-3.58**
6-28	**19.54**	**-7.80**	**-19.47**	**1.46**

Chapter 8

CONCLUSION

This project deals with the case study of power flow control with the Unified Power Flow Controller (UPFC) that is used to maintain and improve power system operation and stability. This paper presents the power flow operation of power systems and its limitations, different devices to control the power flow with the existing transmission lines, types of FACTS controllers used in the power system, basic characteristics and operation of UPFC, Newton Raphson flow chart and algorithm with UPFC and a case study to study the power flow control with UPFC.

The Unified Power Flow Controller provides simultaneous or individual controls of basic system parameters like transmission voltage, impedance and phase angle there by controlling the transmitted power. In this project, a IEEE-5 bus network & a IEEE-30 bus network is considered and power flow program with UPFC is simulated in MATLAB. Simulation results have shown that controller exhibits good damping characteristics for different operating conditions. This feature to control simultaneously all the transmission parameters cannot be accomplished with the mechanical and other FACTS devices.

The results obtained in this project can further improved by:

• To consider the effect of different input signals such as line current, difference in sending and receiving bus voltages phase angles, etc., on the damping controller performance.

•To include more than one UPFC for the advanced features in the power systems.

• Coordinating the UPFC with mechanical and other FACTS controllers.

APPENDIX

```
% - - - Main UPFC Program

PowerFlowsData; %Function to read network data

UPFCdata; %Function to read the UPFC data

[YR,YI] = YBus(tlsend,tlrec,tlresis,tlreac,tlsuscep,tlcond,shbus,...

shresis,shreac,ntl,nbb,nsh);

[VM,VA,it,Vcr,Tcr,Vvr,Tvr] = UPFCNewtonRaphson(tol,itmax,ngn,nld,...

nbb,bustype,genbus,loadbus,PGEN,QGEN,QMAX,QMIN,PLOAD,QLOAD,YR,YI,...

VM,VA,NUPFC,UPFCsend,UPFCrec,Xcr,Xvr,Flow,Psp,PSta,Qsp,QSta,Vcr,...

Tcr,VcrLo,VcrHi,Vvr, Tvr,VvrLo,VvrHi,VvrTar,VvrSta);

[PQsend,PQrec,PQloss,PQbus] = UPFC_PQflows(nbb,ngn,ntl,nld,genbus,...

loadbus,tlsend,tlrec,tlresis,tlreac,tlcond,tlsuscep,PLOAD,QLOAD,...

VM,VA);

[UPFC_PQsend,UPFC_PQrec,PQcr,PQvr] = PQUPFCpower(nbb,VA,VM,NUPFC,...

UPFCsend,UPFCrec,Xcr,Xvr,Vcr,Tcr,Vvr,Tvr);

%Print results

it;%Number of iterations

VM ;%Nodal voltage magnitude (p.u.)

VA=VA*180/pi; %Nodal voltage phase angles (deg)

Sources=[Vcr,Tcr*180/pi,Vvr,Tvr*180/pi]; %Final source voltage parameters

UPFC_PQsend;

UPFC_PQrec;

%Carry out iterative solution using the Newton–Raphson method
```

```
function [VM,VA,it,Vcr,Tcr,Vvr,Tvr] = UPFCNewtonRaphson(tol,itmax,...

ngn,nld, nbb,bustype,genbus,loadbus,PGEN,QGEN,QMAX,QMIN,PLOAD,...

QLOAD,YR,YI,VM,VA, NUPFC,UPFCsend,UPFCrec,Xcr,Xvr,Flow,Psp,PSta,...

Qsp,QSta,Vcr,Tcr,VcrLo,VcrHi,Vvr,Tvr,VvrLo,VvrHi,VvrTar,VvrSta)

% GENERAL SETTINGS

flag = 0;

it = 1;

% CALCULATE NET POWERS

[PNET,QNET] = NetPowers(nbb,ngn,nld,genbus,loadbus,PGEN,QGEN,...

PLOAD,QLOAD);

while ( it < itmax && flag==0 )

% CALCULATED POWERS

[PCAL,QCAL] = CalculatedPowers(nbb,VM,VA,YR,YI);

% CALCULATED UPFC POWERS

[PspQsend,PspQrec,PQcr,PQvr,PCAL,QCAL] = UPFCCalculatedpower...

(nbb,VA, VM,NUPFC,UPFCsend,UPFCrec,Xcr,Xvr,Vcr,Tcr,Vvr,Tvr,PCAL,...

QCAL);

% POWER MISMATCHES

[DPQ,DP,DQ,flag] = PowerMismatches(nbb,tol,bustype,flag,PNET,QNET,...

PCAL,QCAL);

% UPFC POWER MISMATCHES

[DPQ,flag] = UPFCPowerMismatches(flag,tol,nbb,DPQ,VM,VA,NUPFC,Flow,...

Psp,PSta,Qsp,QSta,PspQsend,PspQrec,PQcr,PQvr);
```

```
if flag == 1

break

end

% JACOBIAN FORMATION

[JAC] = NewtonRaphsonJacobian(nbb,bustype,PCAL,QCAL,DPQ,VM,VA,YR,YI);

% MODIFICATION OF THE JACOBIAN FOR UPFC

[JAC] = UPFCJacobian(nbb,JAC,VM,VA,NUPFC,UPFCsend,UPFCrec,Xcr,...

Xvr,Flow,PSta,QSta,Vcr,Tcr,Vvr,Tvr,VvrSta);

% SOLVE JOCOBIAN

D = JAC\DPQ';

% UPDATE THE STATE VARIABLES VALUES

iii = 1;

for ii = 1: nbb

VA(ii) = VA(ii) + D(iii);

VM(ii) = VM(ii) + D(iii+1)*VM(ii);

iii = iii + 2;

end

% UPDATE THE TCSC VARIABLES

[VM,Vcr,Tcr,Vvr,Tvr] = UPFCUpdating(nbb,VM,D,NUPFC,UPFCsend,PSta,...

QSta,Vcr,Tcr,Vvr,Tvr,VvrTar,VvrSta);

%CHECK VOLTAGE LIMITS IN THE CONVERTERS

[Vcr,Vvr] = UPFCLimits(NUPFC,Vcr,VcrLo,VcrHi,Vvr,VvrLo,VvrHi);

it = it + 1;end
```

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