CHAPTER 1

INTRODUCTION

Power flow is a function of transmission line impedance, the magnitude of the sending and receiving end voltages, and the phase angle between the voltages. By controlling one or a combination of the power flow arguments, it is possible to control the active, as well as the reactive power flow in the transmission line. In the past, power systems were simple and designed to be self-sufficient. Active power exchange of nearby power systems was rare as AC transmission systems cannot be controlled fast enough to handle dynamic changes in the system and, therefore, dynamic problems were usually solved by having generous stability margins so that the system could recover from anticipated operating contingencies.

Today, it is possible to increase the system loadability and security by using a number of different approaches. It is a usual practice in power systems to install shunt capacitors to support the system voltages at satisfactory levels. Series capacitors are used to reduce transmission line reactance and thereby increase power transfer capability of lines. Phase shifting transformers are applied to control active power flows in transmission lines by introducing an additional phase shift between the sending and receiving end voltages.

In past days, all these devices were controlled mechanically and were, therefore, relatively slow. They are very useful in a steady state operation of power systems but from a dynamical point of view, their time response is too slow to effectively damp transient oscillations. If mechanically controlled systems were made to respond faster, power system security would be significantly improved, allowing the full utilization of system capability while maintaining adequate levels of stability. The advances in the field of power electronics led to a new approach introduced by the Electric Power Research Institute (EPRI) in the late 1980, called Flexible AC Transmission Systems or simply FACTS, it was an answer to a call for a more efficient use of already existing resources in present power systems while maintaining and even improving power system security. In [1], the authors introduced this new concept, initiating a new direction in power system research.

1.1 Basic Principles of Active and Reactive Power Flow Control

Active 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.

The simple model shown in Figure 1.1 is used to facilitate the understanding of the basic issues in power flow control and to introduce the basic ideas behind Voltage Source Converter (VSC) based FACTS controllers, [2]. 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". The sending and receiving ends are connected by an equivalent reactance, assuming that the resistance of high voltage transmission lines is very small. The receiving end is modeled as an infinite bus with a fixed power phase angle of 0 ^{0}.

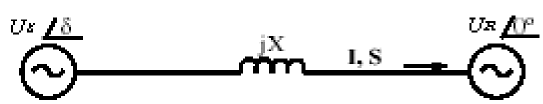

Figure 1.1 Model for calculation of real and reactive power flow

Complex, active power P_R and reactive power Q_R flows in this transmission system are defined respectively, as follows:

$$S_R = P_R + jQ_R = U_R I^* \tag{1.1}$$

$$P_R = \frac{U_s U_R}{X}\sin(\delta) \tag{1.2}$$

$$Q_R = \frac{U_s U_R \cos(\delta) - U_R^2}{X} \tag{1.3}$$

Similarly, for the sending end:

$$P_S = \frac{U_s U_R}{X}\sin(\delta) \tag{1.4}$$

$$Q_S = \frac{U_s^2 - U_s U_R \cos(\delta)}{X} \tag{1.5}$$

where U_S and U_R are the magnitudes ,in RMS values, of sending and receiving end voltages, respectively, while δ is the phase-shift between sending and receiving end voltages (Power Angle).

The equations for sending and receiving active power flows, P_S and P_R, are identical because the system is assumed to be a lossless line. Figure 1.2, shows the maximum active power transfer occurs, at a power, or load angle, equal to 90^0. Maximum power occurs at a different angle if the transmission losses are included. The system is stable or unstable depending on whether the derivative $\frac{dp}{d\delta}$ is positive or negative. The steady state limit is reached when the derivative is zero (maximum power).

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 to make the system able to handle disturbances such as load changes, faults, and switching operations.

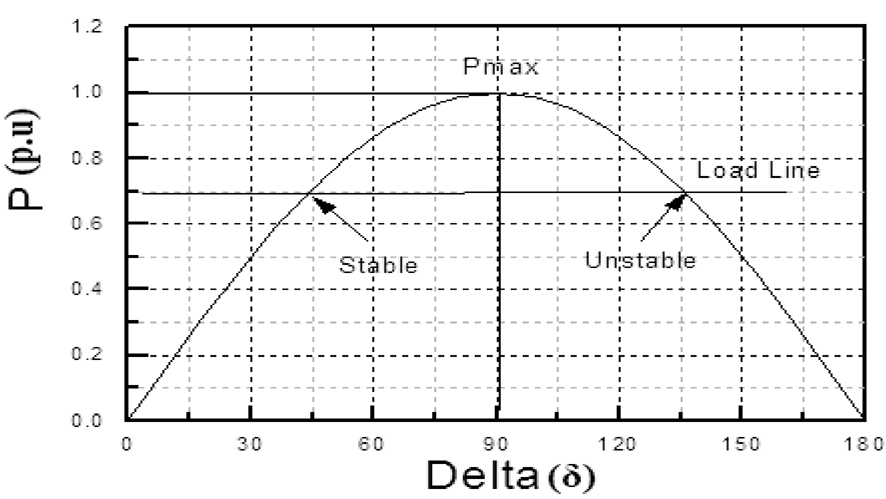

Figure 1.2 Power angle curve

As can be seen in Figure 1.2, the intersection between a load line representing sending end mechanical (turbine) power and the electric load demand line defines the steady state value of δ; a small increase in mechanical power at the sending end increases the angle. For an angle above 90^0, increased demand results in less power transfer, which accelerates the generator, and further increases the angle, making the system unstable; on the left side intersection, however, the increased angle increases the electric power to match the increased mechanical power. In determining an appropriate margin for the load angle δ, the concepts of dynamic or small signal stability and transient or large signal stability are often used. According to the IEEE definition, dynamic stability is the ability of the power system to maintain synchronism under small disturbance, whereas transient stability is the ability of a power system to maintain synchronism when subjected to a severe transient disturbance such as a fault or loss of generation [2].

Closer inspection of equations (1.2) and (1.4) shows that the real or active power transfer depends mainly on the power angle; inspection of equations (1.3) and (1.5) shows that the reactive power requirements of the sending and receiving ends are excessive at high angles and high power transfers. It is also possible to 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 flows depends on the sign of the power angle.

Equations from (1.2) to (1.5) show that the power flow in the transmission line depends on the transmission line reactance, the magnitudes of sending and receiving end voltages and the phase angle between the voltages. The concepts behind FACTS controllers are to enable control of these parameters in real-time and, thus, vary the transmitted power according to system conditions. The ability to control power rapidly, within appropriately defined boundaries, can increase transient and dynamic stability, as well as the damping of the system. For example, an increase or decrease of the value of transmission line reactance X, as can be seen from equations (1.2) and (1.4), increases or decreases the value of maximum power transfer P_{max}. 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, U_S and U_R, respectively, can also control power flow in a transmission line. However, these values are subject to tight control due to load requirements that limit the voltage variations to a range between 0.95 and 1.05 p.u. and hence cannot influence the power flows in a desired range. From the equations of reactive power flow, (1.3) and (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.

1.2 FACTS Devices

The voltage stability problem resulting from transmission system may be, at least partly, improved by use of equipment well-known as FACTS controllers .It is possible to design a power electronic equipment of high rating and high voltage systems. The de-regulation of power network will probably imply new loading conditions and new power for situations as the development of these devices. Lately some concerns are raised as to show FACTS capabilities in open access environment [3, 4].

1.2.1 Definition of FACTS

According to IEEE, FACTS, which is the abbreviation of *Flexible AC Transmission Systems,* is defined as follows [5]:

Alternating current transmission systems incorporating power electronics based and other static controllers to enhance controllability and power transfer capability.

1.2.2 FACTS categories and their functions

FACTS controllers are classified into two distinctly different technical approaches, both resulting in a comprehensive group of controllers able to address targeted transmission problems. These two groups are described below [6]:

i- Thyristor controlled FACTS controllers:

This group of controllers employs conventional thyristors with fast response and operated by sophisticated control. Each one of these controllers can act on one of the three parameters determining power transmission as follows:

a. Static VAR Compensator (SVC)
b. Thyristor Controlled Series Capacitor (TCSC)
c. Phase Shifting Transformer (PST).

ii- Converter-based FACTS controllers:

In which power switching converters such as voltage or current sources can be used to absorb or generate reactive power, rather than exchanging active power with the network if supplied by DC source and this type include the following:

a. Static synchronous compensator (STATCOM).
b. Static synchronous series compensator (SSSC).
c. Unified power flow controller (UPFC).

1.2.3 Possible benefits of FACTS technology

Within the basic system security guidelines, the FACTS devices enable the transmission system to obtain one or more of the following benefits:

i-Power Flow Control

Today, electric distribution systems are normally designed based on a (n-1)-security criterion. This means that the system must have enough security margins to operate even if one of the elements, e.g. a transmission line, fails. With congested inter-regional links this normally leads to the maximum allowed transfer capacity being considerably below the maximum physically possible power flow. In [7], the authors propose using a TCSC to relieve line overloads during contingencies, which increases the reliability of the whole system. They demonstrate the feasibility with different configurations on a 14-bus network. In addition, they clarify that not only network configuration and parameters influence functionality of the controllable devices but also influence load and generation patterns. Therefore accurate load and generation forecasts are an important part in the decision to invest in FACTS devices.

Installing a TCSC or an UPFC at one end of a parallel path the security of the system can be increased considerably, especially the loss of load probability, is demonstrated in [8].

ii- Stability

There are more publications available concerning increased stability due to FACTS devices, than there are about using FACTS devices for power flow control. Reference [9] explains that the voltage stability can be effectively improved by installing an UPFC using a three-machine system.

Control Lyapunov functions can be used for controlling series devices for system damping only by using locally measurable signals [10]. However, under certain circumstances (the controller is not properly designed), it is possible that a change in controller reference values can excite inter-area modes.

On the other hand, the authors of [11] suggest that UPFC controllers using global information are more effective for power system damping enhancement than those using local information. They argue that global information has stronger observability for power system oscillations than local information.

FACTS can also be used to improve power quality, such as reducing voltage dips, phase shifting etc. In [12], there is a good overview including simulation results where an UPFC is used to reduce voltage dips and harmonics at a specific node.

iii- Transfer Capacity

In the new world of liberalized electricity markets system operators have no longer direct means (neither in short nor long term) to control the power flow by generator dispatch, since the generating companies decide how much energy they want to produce when and where. This implies changes in the geographic generation-load pattern and results in the need to change network topology, since certain paths will get congested, and consequently energy trading transactions can sometimes be interdicted. For the system operator there are two fundamentally different solutions:

First, the transmission system operator could try to alleviate the problem by giving incentives to reduce the loading of the congested path. This could be to give price signals based on the geographical locations (using Locational Marginal Prices) to encourage investments into generating units in high price areas and at the same time, discourage new loads in the same areas.

Second, the transmission system operator could invest in the physical transmission network, either by reinforcing the network by building new transmission lines or adding flexible devices to leverage and control power flow. But very often, especially in highly populated regions, building new lines is not feasible due to environmental and political concerns. However, as shown in [13, 14], it is possible to use FACTS (TCSC or UPFC) to improve network performance and thus reduce load or generation curtailments and, at the same time, reduce system losses by minimizing loop flows.

iv- Reliability

Electric power distribution system reliability is defined as the ability to deliver uninterrupted service to customers. The authors of [15] show that it is possible to increase reliability for consumers considerably by installing TCSC at the distribution delivery point without increasing short circuit current levels. They also suggest a method to determine the change in loss of load probability and loss of load expectation. They show that the installation of the UPFC in one of two different parallel transmission lines significantly improves the reliability of the network fed by those two lines.

v-Power Quality

In a distribution system unbalance will increase losses and may cause adverse effects on industrial machines and generators. Presently, feeder switching through manual or automatic control to reduce the unbalance of the load is used among industry. The authors in [16] present a mathematical model for computer simulation and control of a delta-connected SVC to achieve the purpose restoring the balanced operation.

1.2.4 Power system performance and FACTS application

Vast amount of work has been reported in the literature of FACTS application to enhance the power system performance in both steady state and transient conditions.

In [17], an approach is examined for identifying the most effective FACTS Controllers, locations, types and ratings that increase asset utilization of power systems. The approach is a combined static/dynamic procedure based on the use of a continuation power flow, an optimal power flow and an eigenvalue analysis.

In [18], improvement of power system dynamics is examined by the use of UPFC, TCPST and TCSC. Models suitable for incorporation in dynamic simulation programs for studying angle stability are analyzed. A control strategy for damping of electromechanical power oscillations using an energy function method is derived. The achieved control laws are shown to be effective for damping of both large signal and small signal disturbances.

In [19], an active approach is described to series line compensation, in which SSSC is used to provide controllable series compensating voltage over an identical capacitive and inductive range, independently of the magnitude of the line current.

In [20], methods are presented to study the application of controllable series capacitors for damping power system electromechanical oscillations.

In [21], effectiveness in suppressing power system oscillations of both Static Var Compensator (SVC) and Phase Shifter (PS) are investigated by analyzing their damping torque contributions to the power system.

In [22], a quantitative measurement is provided for the benefit that a UPFC can provide to increase power transfer between two large power systems.

In [23], the location of SVC is determined by using a tool based on the determination of critical modes in the vicinity of the point of collapse. System participation factors for the critical mode are used to determine the most suitable sites for system compensation.

In [24], enhancement of Egyptian power system stability is achieved by using power system stabilizers controlled by local control signals. Feasibility and benefits of using the new adaptive Neuro-Fuzzy logic controls to create new control signals for those conventional power system stabilizers or for an appropriately sized, judiciously located SVC are studied.

In [25], an algorithm of a unified power flow controller is suggested. Through this suggested algorithm, the UPFC is able to control both real and reactive power flow of a transmission line independently.

In [26], comprehensive development procedures and final forms of mathematical models of UPFC are provided for steady state, transient stability and eigenvalue studies.

In [27], UPFC is investigated to enhance the transient stability margin of a longitudinal system. The basis for determination of the suitable damping strategy and for determination of the optimal UPFC parameters is a mathematical model, which describes the interdependence between longitudinal transmission system parameters, operating conditions and UPFC parameters in the form of analytical equations.

In [28], the multi-rate method is applied to the problem of simulating the dynamics of a power system which contains fast components such as induction machine load and FACTS devices.

In [29], A new special stability control termed CAPS (CAPacitor bank series group Shorting), is provided to improve power system stability by exploiting the time-over voltage capability of large shunt capacitor banks. During low voltage emergencies, several series groups of wye-connected capacitor banks are shorted to increase reactive power output.

In [30], the problem of controlling and modulating the power flow of long transmission lines using a series-connected Solid-State Synchronous Voltage Source (SVS) is addressed. The results from these studies demonstrate the effectiveness of the proposed approach in regulating the line power and, also, in providing power modulation that can enhance the dynamic and transient performance of the line.

1.3 Objectives of the Thesis

As mentioned in the previous sections, FACTS devices can be effectively utilized for the steady-state power flow control and dynamic control of power systems. The proposal of the thesis is to give an overview of FACTS technology with emphasis on the following three topics in detail:

a- Modeling of Static VAR Compensator(SVC) under Steady state and transient conditions.

b- Implementation of SVC in a power system to improve the steady state voltage stability.

c- Implementation of SVC in a power system to improve the transient stability.

1.4 Thesis Outline

Chapter 1: Introduces FACTS devices, their types and their benefits. It includes a Survey of the previous work in FACTS, the thesis objectives and the thesis outline.

Chapter 2: Introduces power system problems and solution by FACTS.

Chapter 3: Investigates the application of SVC to enhance the steady state voltage stability margin of different power systems.

Chapter 4: Investigates the application of SVC to enhance the transient stability margin of different power systems.

Chapter 5: Presents the conclusions and contributions of this thesis with future recommendations.