CHAPTER 1

INTRODUCTION

1.1 RESEARCH MOTIVATION

Electricity is a very useful and popular energy form which plays an increasing role in our modern industrialized society. Scarcity of natural resources, the ubiquitous presence of electrical power make it desirable and continuous increase in demand, causing power systems to operate close to their stability and thermal ratings. All the latter mentioned reasons together with the high penetration of Distributed Resources (DR) and higher than ever interest in the quality of delivered energy are the driving forces responsible for extraordinary changes taking place in the electricity supply industry, worldwide.

Against this background of rapid changes, the expansion programs for many utilities are being thwarted by variety of environmental and regulatory pressures, that prevent the building of new transmission lines and electricity generating plants, the construction of which is becoming increasingly difficult. The one-line diagram shown in Figure 1.1 illustrates the Electrical Power System (EPS) and its major components: Generation, Transmission and Distribution systems. Electrical power is generated at power stations predominantly by synchronous generators that are mostly driven by steam or hydro turbines. Hence, the electric power generated at any such station usually has to be transmitted over a great distance, through the transmission systems, to the distribution systems. The distribution networks
distribute the energy from the transmission grid or small/local DR to customers.

Figure 1.1 A simplified one-line diagram of the power systems

The term quality of delivery, which appears in the title of thesis, refers to the ability of the various components – generation, transmission and distribution – to deliver the product (electric power) to any point of consumption in the amount and at the quality demanded by the customer. The three components – generation, transmission and distribution – have different influences, individual and sometimes common, on the level of the quality of delivery. Some of these problems are related to power transmission systems and some of them to power distribution systems, but all are fundamental from the point of view of quality of delivered power. It is to be noted that even if Power Quality (PQ) is mainly a distribution problem, the power transmission system may also have an impact on the PQ issues. Therefore, the term quality of delivery will be treated in this thesis as a matter of two issues, related to
limitations of the transmission systems as well as to PQ problems of the distribution systems.

An in-depth analysis of the options available for maximizing existing transmission and distribution resources, with high levels of stability and PQ, points in the direction of power electronics. Two kinds of power electronics applications gaining importance in power systems are well defined: active, reactive power control and power quality improvement. The first application known as Flexible Alternating Current Transmission System (FACTS), where the latest power electronic devices and methods is used to control the transmission side of the network. The second application known as Custom Power Devices (CPD), which focuses on the distribution system supplying the energy to end-users and is a technology created in response to reports of poor power quality of supply affecting factories, offices and homes.

The characteristics of a given power system evolve with time, as load grows and generation is added. If the transmission facilities are not upgraded sufficiently the power system becomes vulnerable to steady-state and transient stability problems, as the stability margin becomes narrower. The limitation of the transmission system can take many forms and may include one or more of the following characteristics, namely steady state stability, voltage stability, transient stability and dynamic stability. Of the above mentioned limitations, the transient stability enhancement through UPFC, the most versatile FACTS device, will be treated in this thesis. Also this thesis aims to develop a comprehensive mathematical model of different FACTS devices for power system steady state operation.

The PQ, at distribution level, broadly refers to maintaining a near sinusoidal power distribution bus voltage at a rated magnitude and frequency. In addition, the energy supplied to a customer must be uninterrupted. Modeling and simulation of different Custom Power Devices have been
attempted to enhance the reliability and quality of power delivery in distribution networks.

1.2 OBJECTIVE OF THE THESIS

On the basis of the above discussion it can now be stated that the major objective of this thesis is to present the solutions to transmission and distribution systems for the improvement in quality of delivery of the electric energy in Electric Power Systems. Accordingly, the scope of the present work is shown in Figure 1.2.

![Figure 1.2 Scope of the present investigation](image_url)

The specific objectives are as follows:

- To develop a comprehensive mathematical model of FACTS devices namely Static Var Compensator (SVC), Thyristor controlled Series Capacitor (TCSC), Static Synchronous Compensator (STATCOM) and Unified Power Flow Controller (UPFC) for power flow control.
• To investigate the effectiveness of the model developed and test for its convergence in load flow studies.

• To develop a dynamic mathematical model of UPFC for transient stability studies.

• To propose suitable controllers and examine their ability in damping of electromechanical oscillations in a power system.

• To develop an electromagnetic transient model and control strategy for Distribution Static Var Compensator (D-SVC) and Custom Power Devices, namely Distribution Static Compensator (D-STATCOM), Dynamic Voltage Restorer (DVR) and Solid State Transfer Switch (SSTS) to enhance the reliability and quality of power delivery in distribution networks.

1.3 ORGANISATION OF THE THESIS

This thesis is organized in six chapters.

Chapter 1 presents the problem under investigation, objectives of the present work, scope, organization of the thesis and previous investigations reported in the literature.

Chapter 2 starts with a discussion on FACTS devices, principle of operation and its appropriateness for overcoming limitations in transmission systems i.e. power flow control issues. Considering the practical application of the FACTS controller, it is of importance to investigate the benefits and to model these devices for power system steady state operation. The comprehensive modeling of most popular FACTS devices namely SVC, TCSC, STATCOM and UPFC were developed for power flow studies. The
effectiveness of modeling and convergence is tested with a five bus study system without any FACTS devices and further analyses it with different FACTS controllers. The *de facto* standard Newton-Raphson method is used to solve the nonlinear power flow equations. The effectiveness of Power flow model of various FACTS devices are also tested with IEEE 30 Bus system for power system steady state operation.

Unified Power Flow Controller for damping the electromechanical oscillations in a power system is attempted in chapter 3. A dynamic model of Unified Power Flow Controller has been developed. The control strategy is based on d-q axis theory. Two types of controllers are proposed for UPFC, namely GA tuned Proportional Integral and Single–Input Fuzzy Logic Controller. The above schemes are implemented on Single Machine Infinite Bus system to carry out transient stability studies.

Chapter 4 addresses the power quality issues, its impact on the modern industry and Var compensation in the power distribution section. An electromagnetic transient model of Fixed Capacitor/ Thyristor Controlled Reactor arrangement of the D-SVC is developed and applied to the study of transients due to load variations

Chapter 5 presents an electromagnetic transient model and analysis of different Custom Power Devices, namely Distribution Static Compensator, Dynamic Voltage Restorer and Solid State Transfer Switch for enhancing the reliability and quality of power in low voltage distribution networks.

Chapter 6 presents the highlights of work, summary and conclusion obtained from the present investigation. The scope for future work for enhancement in quality of delivery is also presented. The references are listed at the end.
1.4 LITERATURE REVIEW

This section reviews the recent approaches for modeling and control of FACTS devices for power system steady state operation, followed by reviews of modeling and control of UPFC for enhancement of power system stability. Finally, literature surveys have done for various custom power devices for power quality and reliability improvement in distribution systems.

1.4.1 Modeling of FACTS Devices for Power Flow Studies

Power flow constitutes perhaps the most important study in the planning and expansion of power systems. It is also the study frequently done by the utilities in operation as well as in planning. The purpose of the study is to compute the steady state operating condition of the system i.e. voltage magnitude and phase angle at the buses. From these values, other quantities like the line flows (MW and MVAR), real and reactive power supplied by generators and loading of transformers etc., can be calculated. Overloaded conditions as well as poor voltages existing in parts of the system can be detected.

The origins of the formulation of the power flow problem and the solution based on the Newton–Raphson’s technique are back to the late 1960s. Since then, a huge variety of studies have been presented about the solution of the power flow problem, addressing starting initial guess, computational efficiency, ill-conditioned cases and robustness, multiple solutions and unsolvable cases. Though, lot of research papers are available in the area of load flow studies, only a handful of literature is available for positive sequence power flow incorporating FACTS controllers.

Fuerte-Esquivel et al (1998) presented the methodology used in the development of a new generation of software suitable for the analysis and control of large-scale power networks containing FACTS-controlled branches. Newton-Raphson load flow is used to emphasis the benefits and drawbacks introduced by the object-oriented technology when applied to number-crunching power engineering solutions.

A comprehensive load flow model for the TCSC is presented by Fuerte-Esquivel et al (2000 a). In this model the state variable is the TCSC’s firing angle, which is combined with the nodal voltage magnitudes and angles of the entire network in a single frame of reference for a unified iterative solution through a Newton-Raphson method. Fuerte-Esquivel et al (2000 b) discussed a load flow model for UPFC, where it can be set to control active and reactive powers and voltage magnitude in any combination.

Marcelo Jose et al (2004) described a new methodology to evaluate the area interchange control in a power flow problem using the Newton-Raphson method. The great advantage of this methodology in comparison with others is that the Jacobian matrix becomes sparser and the multiple regulating buses at a given area are easily represented.

Selvan and Swarup (2006) developed power flow software using object-oriented design patterns. Important patterns such as iterator, decorator and template method are utilized to develop a comprehensive power flow analysis program, including FACTS devices such as SVC, TCSC, STATCOM
and UPFC. Joao Passos Filho et al (2009) described a methodology to identify potential conflicts among power flow control devices that may slow down or impair convergence. The proposed methodology is based on the eigen value analysis of the sparse Jacobian matrix associated with the Newton’s power flow with controls.

Federico Milano (2009) has given a novel perspective on the formulation of the power flow problem and proposes an efficient method for solving ill-conditioned cases. But it fails to incorporate FACTS devices in the mathematical model, which is the future of power system transmission in deregulation environment.

Hence, power flow programs are under continuous improvement, with the implementation of models for new devices, control strategies and system operating requirements. The power flow controls, special equipments and limits, that can be modeled in a production-grade program have been attempted in this present work. Newton- Raphson’s load flow programs have been developed using MATLAB for SVC, TCSC, STATCOM and UPFC which includes comprehensive control facilities and yet exhibits very strong convergence characteristics.

1.4.2 Modeling of UPFC for Power Systems Stability Studies

While the major advantage of FACTS devices is flexible power scheduling under various (changing) operating conditions, the fast controllability also ensures improvement of security of power systems, where system stability is threatened. Small signal stability of power systems that implies the ability of the power systems to maintain synchronism under small disturbances that are always present (due to small perturbations in the system load) is well researched. Transient stability of power system and its
improvement by suitable control of UPFC, the most versatile FACTS device is discussed in the present work.

Transient stability is concerned with the stability of power systems when subjected to severe or large disturbance such as a fault in a line followed by its clearing. Transient stability depends on the location and nature of disturbance in addition to initial operating point. Instability results in loss of synchronism leading to separation of generators that are protected by out of step relays. Large excursions in the rotor angles imply that, it is not possible to apply linear system theory. Since, nonlinear system analysis is not generally feasible, numerical methods are used to simulate the system to predict system stability for accurate result. The recent trend is to apply different intelligent controller technique for enhancement of transient stability. In the literature various modeling of UPFC are proposed to solve the different type of problem such as voltage stability enhancement, damping torsional oscillations, power system voltage control and power system stability improvement. These methods include current injection as well as power injection method.

Gyugyi et al (1995) proposed a novel approach in which solid state synchronous voltage sources are employed for the dynamic compensation and real time control of power flow in transmission system. Comparison of the synchronous voltage source approach with the more conventional compensation method of employing thyristor-switched capacitors and reactors shows its superior performance, smaller physical and potentially lower overall cost. Also the authors showed that the UPFC is able to control both the transmitted real power and independently, the reactive power flows at the sending end and the receiving end of the transmission line. The unique capabilities of the UPFC are integrated into a generalized power flow
controller that is able to maintain prescribed and independently controllable real power and reactive power in the line.

Padiyar and Kulkurni (1998), proposed a cascade PI controller structure for shunt inverter of Unified Power Flow Controller which can be used for STATCOM. Dai et al (1999) focused on an improved structure of Artificial Neural Network (ANN) $\alpha^{th}$-order inverse as TCSC controller for increase in transient stability. The ANN $\alpha^{th}$-order inverse, consisting of a single static ANN and a number of integrators is used to eliminate the nonlinearities of the power system. An additional linear feedback controller is designed to enhance the stability of the linearised system.

Hingorani and Gyugyi (2000) presented the basic concept about FACTS devices. This book discusses all the Power Electronic devices, which can be used to control the basic power system parameters (voltage, current and impedance). The authors describe the basic concepts of the proposed generalized P and Q controller and compare it with the more conventional power flow controllers, such as Thyristor-controlled Series Capacitor and Thyristor- controlled phase angle regulator.

A linearized Phillips–Heffron model of a power system installed with a UPFC is discussed by Wang (2000). Two applications based on the Phillips–Heffron model are demonstrated: 1) Study on the effect of UPFC DC voltage regulator on power system oscillation stability; 2) Selection of damping control signal for the design of UPFC damping controller. Zhengyu Huang (2000) proposed a new power frequency model for unified power flow controller including its dc link capacitor dynamics. Four principal control strategies for UPFC series element and their impacts on system stability are discussed.
Karl Schoder et al (2000) proposed transient stability enhancement through UPFC. A fuzzy logic based controller using active power flow along the transmission line as supplementary control signal is used. Fuzzy logic controller simulating an SVC device in power system transient stability analysis is proposed by Valle et al (2001).

The application of Takagi-Sugeno type fuzzy logic controllers for UPFC voltage source inverter control in a multi-machine power system environment is proposed by Mishra et al (2000). Keri et al (1999) proposed a set of equations for a system including the UPFC, an equivalent two bus power network. The UPFC provides a full dynamic control of transmission parameters - voltage, line impedance and phase angle. A new numerical method tested with MATLAB model has been successfully validated with Electro Magnetic Transient Program (EMTP).

Sadeghzadeh et al (1998) presented an on-line fuzzy control scheme applied on the super-conducting magnetic energy storage (SMES) and Static Synchronous Series Compensator (SSSC) units to increase lines transfer capacity. The control strategy attempts to suppress the line power swings caused by unwanted disturbances. The SMES and SSSC units can be installed at an intermediate point of transmission line and are controlled locally.

Kumkratug and Haque (2003) proposed a simple mathematical model of UPFC in a single-machine infinite-bus (SMIB) system. The presented UPFC model can work as SSSC and STATCOM which depends on the control strategy of UPFC. The UPFC and the downstream side of the network was replaced by a dependent voltage source. The magnitude and angle of the voltage source depend on the UPFC control parameters and downstream side network parameters. In fact, a SMIB system with a UPFC is modeled as a single-machine finite-bus system.
Kannan et al (2004) proposed a new real and reactive power coordination controller for a unified power flow controller. The basic control for the UPFC is such that the series converter of the UPFC controls the transmission line real/reactive power flow and the shunt converter of the UPFC controls the UPFC bus voltage/shunt reactive power and the DC link capacitor voltage. In steady state, the real power demand of the series converter is supplied by the shunt converter of the UPFC. In order to avoid instability/loss of DC link capacitor voltage during transient conditions, a new real power coordination controller has been designed.

In the existing fuzzy logic controllers (FLC), input variables are mostly the error and the change-of-error regardless of complexity of controlled plants. Either control input $u$ or the change of control input $\Delta u$ is commonly used as its output variable. A rule table is then constructed on a two-dimensional (2-D) space. This scheme naturally inherits from conventional proportional-derivative (PD) or proportional-integral (PI) controller. Observing that 1) rule tables of most FLC have skew-symmetric property and 2) the absolute magnitude of the control input $|u|$ or $|\Delta u|$ is proportional to the distance from its main diagonal line in the normalized input space. Byung-Jae Choi et al (2000) derived a new variable called the signed distance, which is used as a sole fuzzy input variable in the simple FLC called single-input FLC (SFLC). The SFLC has many advantages like, the total number of rules is greatly reduced compared to existing FLC and hence, generation and tuning of control rules are much easier. The control performance is nearly the same as that of existing FLC, which is revealed via computer simulations for the non-linear systems namely Magnetic-levitation system and Inverted pendulum system.

Dash et al (2004) presented a paper on the design of a non-linear variable-gain fuzzy controller for a unified power flow controller to enhance
the transient stability performance of power systems. The fuzzy controller uses a numerical consequent Takagi-Sugeno type rule base, which can be either linear or non-linear producing control-gain variation over a very wide range. This type of fuzzy control is expected to be more robust and effective in damping electromechanical oscillations of the power systems in comparison with the conventional PI regulators used for UPFC control.

Maintaining dynamic security of a power system subjected to large disturbances is of utmost importance. Fast and accurate online detection of instability is essential in initiating certain emergency control measures. Padiyar and Krishna (2006) proposed an accurate technique for the online detection of loss of synchronism based on voltage and current measurements in a line. The technique makes use of the concept of potential energy in a line. The conditions for the system instability are derived from energy function analysis.

Guo et al (2009) proposed a controller which is a non-linear dynamic control that translates the desired system level control into gating control. Ideally, the system level control set points would not be constant power flows (or current injections), but would be time varying, in order to achieve the desired system response (i.e., oscillation damping). The paper asserts that a linear control (such as the PI control) is inadequate to track a moving target due to the requirement that it be tuned for different operating conditions and requires a much larger number of parameters. The proposed non-linear control has the advantages of rapid tracking and is independent of tuning, but difficult to implement in a real power system.

The literature review reveals that there exists a need for dynamic modeling of UPFC with suitable effective controllers, to damp out electromechanical oscillations as well as to improve the power system
stability. However, both STATCOM and UPFC modeling are based on conventional PI or Fuzzy controllers by which electromechanical damping oscillations were reduced. Design and tuning of such controllers are complex and more time consuming. The method used in the present work reduces the time for tuning the parameters as well as performance has been improved due to the use of SFLC controller. The modeling technique used here is simple and takes into account the dynamics of shunt transformer elements as well as the effect of DC voltage capacitor.

1.4.3 Modeling of Custom Power Devices

With the emergence of computers, sensitive loads and modern communications, a reliable electricity supply with high quality voltage has become a necessity. A few years back, the main concern of consumer of electricity was reliability of supply per se. It is however not only simple supply reliability that consumers want today, they want an ideal AC line supply, i.e. a pure sine wave of fundamental frequency and in addition, a rated peak voltage. Unfortunately the actual AC line supply that we receive differs from this ideal. There are many ways in which the lack of quality power affects customers. Voltage sags and dips can cause loss of production in automated processes and can also force a computer system or data processing system to crash.

Voltage sag is one of the most important power quality problems challenging the utility industry. Voltage sags can be compensated for by voltage and power injection into the distribution system. By injecting voltage with a phase advance with respect to the sustained source-side voltage, reactive power can be utilized to help voltage restoration. Hence, the consumption of real power, from the perspective of the energy supply device, can be reduced. This energy-saving voltage injection comes at the expense of
an increased voltage injection magnitude, load power swing, phase shift and discontinuity of voltage wave-shape (Choi et al 2000).

Fitzer et al (2002) suggested that during the transient period at the start of voltage sag, a DVR injection transformer can experience a flux-linkage that is up to twice its nominal steady-state value. In order to prevent the transformers from saturating, it is normal to choose a rating flux that is double that of the steady-state limit. Fitzer et al (2004) proposed a voltage sag detection technique for a DVR by matrix method. The paper also illustrates that the matrix method returns results that can be directly interpreted, whereas other methods such as the wavelet transform return results that can be difficult to interpret.

The main aim of the DVR is to regulate the voltage at the load terminal irrespective of sag/swell, distortion, or unbalance in the supply voltage. The DVR is operated in such a fashion that it does not supply or absorb any active power during the steady-state operation (Ghosh et al 2004). Hence, a DC capacitor rather than a DC source can supply the voltage source inverter realizing the DVR.

Domijan et al (2005) presented a simulation study about the coordination and interaction of advanced power electronic devices working in close electrical proximity. In particular, three major Power Quality Devices (PQDs)-an advanced static VAR compensator, a dynamic voltage restorer, and a high-speed transfer switch as well as their combined performance are modeled and studied in detail using ATP-EMTP.

Kincic et al (2005) proposed that when load centers require Static VAR Systems (SVS) for regulated voltage control, the strategy of using many, small, distributed SVS located at distribution buses is more
advantageous than a few large bulk SVS located at the transmission or subtransmission bus. The advantages are (i) standby to meet N-1 reliability criterion is reduced; (ii) costly high voltage transformers are no longer needed because the SVS can be connected directly to the low voltage distribution buses; (iii) distribution-side voltage support is more effective so that the total MVAR requirement of the distributed SVS is less.

In order to restore the load voltage, dynamic voltage restorer, which is installed between the supply and a sensitive load, should inject voltage and active power from DVR to the distribution system during voltage sag. Due to the limitation of energy storage capacity of DC link, it is necessary the minimize energy injection from DVR. A new concept of restoration technique is suggested to inject minimum energy for a given apparent power of DVR (Banaei et al 2006).

Elnady and Salama (2005) introduced a method for the mitigation of the voltage sag and voltage flicker by using Kalman filter in a D-STATCOM. The Kalman filter is used as a tool to extract both the instantaneous envelope of the voltage sags and to extract the instantaneous flicker level of the voltage flicker.

Blazic and Papic (2006) presented a D-STATCOM control algorithm which enables separate control of positive and negative-sequence currents and decoupled control of d and q-axes current components. The algorithm is based on the developed mathematical model in the d-q coordinates for a D-STATCOM operating under unbalanced conditions. The problem of dc-side voltage ripple and ac-side harmonics generation due to unbalanced voltages/currents is solved by using switching function modulation, enabling the use of a relatively small capacitor on the dc side. But the control algorithm is not tested for high-power applications.
1.5 SUMMARY

The problem under investigation, literature review, objectives of the present work, the scope and organization of the thesis were discussed.

On the basis of the above literature survey, it is clear that there is ample scope for further research in finding simple and workable solution to the improvement in quality of delivery of the electric energy in Electric Power Systems.

The next Chapter presents a discussion on FACTS devices, principle of operation and modeling of FACTS Devices for Steady State Operations.