# CHAPTER 1

# INTRODUCTION

Around the globe, the demand for power is increasing sharply. The main reason is exorbitant growth witnessed in the industrial sector. This growth necessitates the expansion in transmission interconnection. This transmission interconnection reduces the production cost and increases the efficiency in power system operation. This interconnected transmission networks are subjected to greater stress both in the bundled and unbundled power systems. Any violation in power flow limit even for short duration may lead to undesirable effects in the operation of power system.

Restriction imposed on the construction of new facilities due to increasingly difficult economic, environmental and social problems have led to much more intensive shared use of the existing transmission facilities. Moreover, the construction of high voltage transmission lines is expected to increase by only 6 percent during the next decade, whereas power demand is expected to increase by almost 20 percent. Hence, there is a lag of constructing new transmission lines.

Scheduling of generators is the primary means for adjusting power flow through the network where the energy consumptions are rising sharply. Scheduling of generators limits the transmission power flow control. Thus, new controllers must be developed that will allow transmission providers to control the grid directly.

These concerns have motivated the development of strategies and methodologies for better utilization of available transmission facilities and employing FACTS devices is one such option.

FACTS devices provide new control facilities both in steady state power flow control and dynamic stability control. The possibility of controlling power flow in an electric power system without generation rescheduling or topological changes can improve the performance considerably.

The insertion of such devices seems to be a promising strategy for improving all round performance of power system. Therefore, rugged design of FACTS controllers for increasing operational flexibility and versatility becomes essential.

## 1.1 FACTS CONTROLLERS AND ITS TYPES

FACTS controller is defined as a power electronic based system and other static equipments that provide control of one or more AC transmission system parameters.

There are three main types of compensation in the FACTS devices.

- Shunt compensation
- Series compensation
- Combined shunt-series compensation

In all the above types, there are two types of FACTS controllers. They are:

- Thyristor based FACTS controllers
- VSC based FACTS controllers

Some of the types of thyristor based FACTS controllers are

- SVC
- Thyristor Controlled Series Capacitors(TCSC)
- Thyristor Controlled Phase Angle Regulator(TCPAR)

Types of FACTS controllers based on the VSC are:

- STATCOM
- SSSC
- UPFC

STATCOM is a shunt connected device, whose capacitive or inductive output current can be controlled independently of AC system voltage.

SSSC is a series connected device, whose output voltage is in quadrature with line current, and controllable independently for the purpose of increasing or decreasing the line reactive voltage drop and thereby controlling the transmitted electric power.

UPFC is a combination of STATCOM and SSSC, which are coupled via a common dc link, to allow bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM. The converters are controlled to provide concurrent real and reactive series line compensation, without an external electric source.

In all the above VSC based FACTS devices, STATCOM is the best device because of its size and easy control.

## 1.2 ADVANTAGES OF VSC BASED STATCOM OVER SVC

- STATCOM maintains the reactive power support even when the terminal voltage decreases.
- It has increased transient rating in both inductive and capacitive regions
- Size of the STATCOM is smaller than SVC for the same kVAR rating.
- STATCOM has no capacitor or reactor banks and hence cost is also less
- It can support at a very low system voltage even at 0.15 p.u.
- The overload capability is about 20% for several cycles in both inductive and capacitive regions

## 1.3 BENEFITS OF FACTS CONTROLLERS

The possible benefits of FACTS controllers include

- Increases power transfer capability of the transmission system
- Direct control of real and reactive power
- Provides dynamic reactive power support and voltage control
- Damps power system oscillations
- Improves system stability

By introducing fast active power electronic switches, the transmission line can be operated nearer to its thermal rating. By introducing fuzzy, ANNC and ANFIS approaches for the design of controllers, speed of response and operational flexibility of FACTS controllers are substantially enhanced.

## 1.4 BASIC PRINCIPLES OF ACTIVE AND REACTIVE POWER FLOW CONTROL

A simple model is given in Figure 1.1 in order to know the basic issues of power flow control.

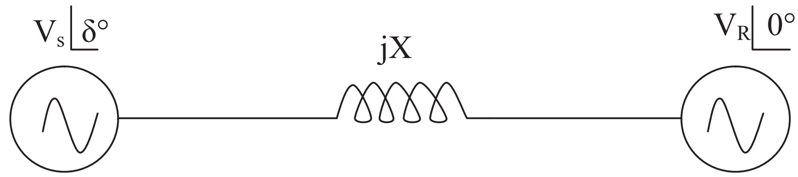


**Figure 1.1 Model of power system**

The sending end and receiving end voltages are assumed to be fixed. The sending and receiving ends are connected by an equivalent reactance 'X' by assuming the resistance of high voltage transmission line as zero. The receiving end is modelled as an infinite bus with a fixed angle of 0°. The sending end phase angle is of δ°. $V_S$ and $V_R$ are the sending end voltages. The power angle curve of this model is shown in Figure 1.2.

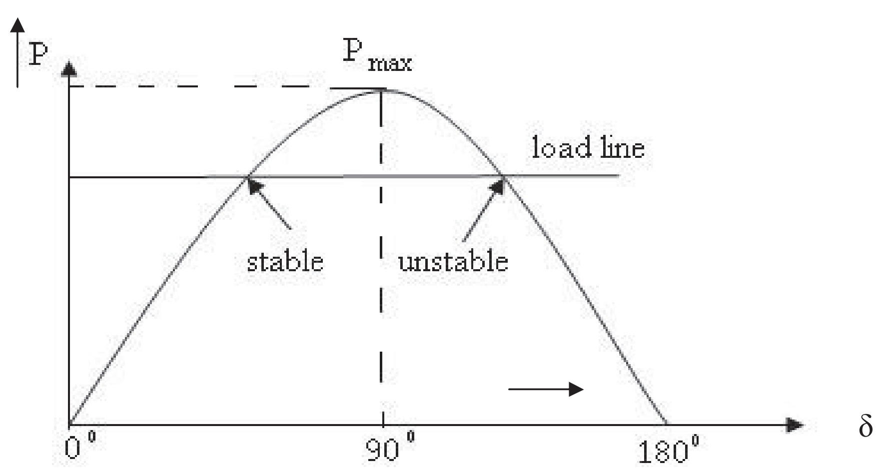


**Figure 1.2 Power angle curve for Figure 1.1**

where ‘P’ is the power and ‘$P_{max}$’ is the maximum power flowing across the line. Active and reactive power flow in this transmission system are given in the following Equations (1.1) to (1.5).

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

$$P_R = V_S V_R \sin\delta \tag{1.2}$$

$$Q_R = \frac{V_S V_R \cos\delta - V_R^2}{X} \tag{1.3}$$

$$P_S = V_S V_R \sin\delta = P_{max} \sin\delta \tag{1.4}$$

$$Q_S = \frac{V_S^2 - V_S V_R \cos\delta}{X} \tag{1.5}$$

where $V_S$ and $V_R$ are the magnitudes of sending and receiving end voltages respectively, while $\delta$ is the phase shift between sending and receiving end voltages. $Q_s$ and $Q_R$ are the sending end and receiving end reactive power respectively. ‘X’ is the reactance of the transmission line.

If the system is a lossless system, the equations for sending and receiving active power flow $P_S$ and $P_R$ are equal. From Figure 1.2, the maximum active power transfer occurs for the given system at load angle $\delta$ equal to 90°. Maximum power does not occur at 90° when the losses of the transmission line are included. The system stability depends on whether the derivative $dP/d\delta$ is positive or negative. The steady state limit is reached, when the derivative is zero.

A small disturbance in the transmission system leads to instability, when it is allowed to operate closer to its steady state limit. So, certain margin must be left in power transfer as cushion. A small increase of electrical power at the receiving end may increase in mechanical power at the sending end which increases the angle. For an angle above 90°, the demand gets increased which results in less power transfer. This accelerates the generator and further increases the angle. This makes the system completely unstable.

By the IEEE definition, dynamic stability is the ability of the power system to maintain synchronism under small disturbance. Transient 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. In order to increase the steady state rotor angle stability, the power angle is kept below 30°.

From Equations (1.2) and (1.4) it is understood that the real power transfer depends mainly on the power angle. The Equations (1.3) and (1.5) show that the reactive power requirements at both ends are more at high angles and high power transfers. It is also concluded that the reactive power transfer depends mainly on voltage magnitudes. Reactive power flows from the high voltage magnitude to the low voltage magnitude. The active power flows from higher power angle to the lower power angle.

## 1.5 FLEXIBLE AC TRANSMISSION SYSTEM (FACTS)

The IEEE definition of FACTS controller is described as follows:

A power electric based system and other static equipments that provide control of one or more AC transmission system parameters.

FACTS controllers are introduced in the transmission system in order to improve the all round performances of the power system. Equations from (1.2) to (1.5) show that the power flow in the transmission line depends on X, the magnitude of $V_R$, and $V_S$. The FACTS controllers are used to control any of these parameters in real-time and thus, vary the transmitted power according to system conditions. The FACTS controllers are designed to act quickly within the certain limits to increase the transient and dynamic stability and to damp the system oscillations. From the Equations (1.3) and (1.5), it can be concluded that the regulation of voltage magnitude mainly depends on the reactive power flow than the active power flow.

In 1990s, the power systems were simple and designed to be self-sufficient .In those days, the interconnected transmission system did not have any active power exchange. Hence, the AC transmission systems could not be controlled faster to handle the dynamic changes in the system. In order to solve these problems, the stability margins are widened, so that the system could recover from anticipated operating contingencies.

The power system is installed with shunt capacitors to support the system voltages at satisfactory levels. Series capacitors are used to reduce transmission line reactance and thereby the power transfer capability of lines is increased. Phase shifting transformers are applied to control power flows in transmission lines by introducing an additional phase shift between the sending and receiving end voltages.

In olden days, all these devices were controlled mechanically and were, therefore, relatively slow. They are very useful in a steady state operation of power systems. During dynamic conditions, these controllers are slow in effectively damping transient oscillations. If the mechanically controlled systems are made to respond faster, the system security gets improved by allowing the full utilization of system capability. This concept and 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 FACTS.

## 1.6 TYPES OF COMPENSATIION

The three main types of compensation are shunt compensation, series compensation and shunt-series compensation.

### 1.6.1 Shunt Compensation

Mechanically switched capacitors and reactors together with synchronous compensator have been employed to increase the steady state power transmission. They control the voltage profile along the transmission lines. It is known that both the transient and steady state stability of a power system can be enhanced, if the compensation devices react quickly by using solid-state thyristor switches and electronic control. This leads to the development of modern SVC, TCSC and TCPAR and many other FACTS controllers. Figure 1.3 shows the block diagram of shunt compensation

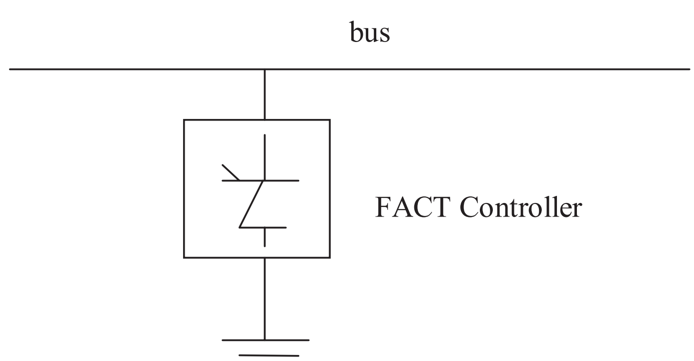


**Fig.1.3 block diagram of shunt compensation**

The capacitor banks in a SVC are rated for full capacitive output, whereas the reactor banks are rated for full inductive output. The coupling transformers are rated to withstand the sum of the maximum capacitive and inductive output. It should be noted that the SVC capacity for compensation is determined only by the size of its reactive components. A SVC can control only one of the three principal parameters voltage or phase angle or impedance, which determines the power flow in AC power systems.

### 1.6.2 Series Compensation

In series compensation, the power system parameter, the reactive impedance is controlled to control the line power flow. Series capacitive impedance was initially introduced to decrease the total line reactance and thus increases the power on the line..

In the 1980s, by using the power semiconductor switches, the controllable series reactive power compensation was achieved using TCSC controller. In this controller, one or more capacitor banks, each shunted with a thyristor-controlled reactor were employed. It increases the maximum transmittable power and reduces the effective reactive power loss. By using TCSC, the power transfer control can be done continuously rather fast and it very useful in dynamically controlling the power system oscillations. Figure 1.4 shows the block diagram of series compensation.

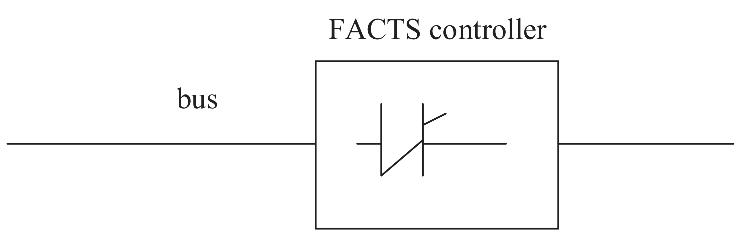


**Fig. 1.4 block diagram of series compensation**

The Thyristor Controlled Reactor (TCR) is used to alter the low frequency impedance of the TCSC and to prevent sub synchronous resonance. In 1992, Gate turn off Thyristor Controlled Series Capacitor (GTCSC) was proposed. In both schemes, the objective is to control the capacitive impedance by appropriate switching of the semiconductor devices.

### 1.6.3 Combined Shunt-Series Compensation

TCPAR is used to control the power flow in a transmission line by controlling the magnitude of the injected voltage component in quadrature to the line current, which controls the phase angle between the sending and receiving end voltages. It is made up of two thyristor controlled tap changing transformers and it results in high series impedance. TCPAR can consume significant amounts of reactive power at high power transfer levels. Hence, a large power source must be located close to this device to get adequate voltage regulation during contingencies.

## 1.7 VSC BASED FACTS CONTROLLERS

A normal thyristor can block high voltage in the off-state and carry large currents in the on-state with only small on-state voltage drop. The draw backs of using thyristors are:

- It changes from on-state to off-state, when the current drops below the holding current
- Separate commutation circuits are needed to turn off the thyristors.

Therefore, the thyristors are not suitable for switched mode applications. With the development of high voltage and high current IGBT, it becomes possible to overcome this deficiency. Like the normal thyristor, a gate current can turn on the IGBT, while to turn it off, gate pulse is removed. Using these IGBTs, the VSC has been developed.

### 1.7.1 STATCOM

The STATCOM is based on the principle that a voltage source converter generates a controllable AC voltage source behind a transformer leakage reactance, so that the voltage difference across the reactance produces active and reactive power exchange between the STATCOM and the transmission network. By injecting a current of variable magnitude in quadrature with the line voltage, the STATCOM can inject reactive power into the power system. VSC employs converters with IGBT, back to back diodes and a DC capacitor to generate a synchronous voltage of fundamental frequency, controllable magnitude and phase angle. If a VSC is connected to the transmission system via a shunt transformer, it can generate or absorb reactive power from the bus to which it is connected. Such a controller is called STATCOM and is used for voltage control in transmission systems. It is also defined as a static synchronous generator operated as a shunt-connected static VAR compensator whose capacitive or inductive output current can be controlled independent of the AC system voltage.

### 1.7.2 SSSC

A VSC is employed as a series device by connecting it to the transmission line via a series transformer. The SSSC can generate a controllable compensating capacitive or inductive voltage. Thus, it controls the transmittable power.

This controller can also generate or absorb reactive power from the line to which it is connected and in that way changes the series impedance of the line. It is equivalent to a variable series capacitor or inductor and therefore can be used to control the power flow in the transmission line. The dynamic behavior of the SSSC can be enhanced by including the energy absorbing devices across the capacitor. This energy storing devices provide additional temporary real power compensation to increase or decrease momentarily the overall real voltage drop across the line.

### 1.7.3 UPFC

A UPFC can control transmission line impedance, voltage and phase angle. It has the capability of controlling with two-degrees of freedom. It can control inverter output voltage magnitude and phase angle. This new device offers the ability to control voltage magnitude in the system, controls power flow in both steady-state and dynamic conditions and allows secure loading of transmission lines up to their full thermal capability.

A combination of STATCOM and SSSC, which are coupled via a common DC link to allow bi-directional flow of real power between the series output terminals of the SSSC and the shunt output terminals of STATCOM. They are controlled to provide concurrent real and reactive series line compensation without an external electric energy source. The UPFC can control concurrently or selectively, the transmission line voltage, impedance and angle and thus controls the real and reactive power flow in the line. It may also provide independently controllable shunt reactive compensation.

In order to improve the performance of both active and reactive power regulation, the UPFC is integrated with STATCOM, SSSC and a Battery Electrical Energy Storage (BEES) device or Superconducting Magnetic Energy Storage (SMES) device in parallel with their DC capacitor. It can provide simultaneous real time control of real and reactive power on the transmission line and thus shunt input voltage support and DC link capacitor voltage regulation are provided.

## 1.8 BASIC TERMINOLOGIES

The important terminologies used in this work have been explained in the following section.

### 1.8.1 dSPACE

dSPACE stands for Digital Signal Processor Advanced Control Engineering. It demonstrates high-end control development from block diagram design to on line controller optimization. It is possible to test even the most complex control systems in real time using dSPACE. It is possible to implement the simulink model of any system on dSPACE real time hardware within seconds and to observe the effects of parameter changes on system's behavior.

### 1.8.2 Sine Triangular Pulse Width Modulation (SPWM)

It is a technique used to generate the PWM pulses. Here, the high frequency carrier wave (normally 2 kHz to 20 kHz) is compared with the sine wave of 50Hz and according to that the PWM wave forms have been generated.

### 1.8.3 Modulation index

The modulation index (K) is defined by the following formula

$$K = \frac{\text{magnitude of the modulating signal}}{\text{magnitude of the carrier signal}}$$

Here the modulating signal is the sine wave and the carrier wave is a triangular wave of 20 kHz.

### 1.8.4 Phase angle or Firing angle

It is an angle between the converter output voltage and the 3 phase bus voltage. It is mentioned in degree. The maximum value of firing angle is limited from -25° to +25° for safer operation.

### 1.8.5 Phase Locked Loops (PLL)

It is a circuit used to synchronize the converter output to the bus voltage.

### 1.8.6 Power Transfer Capability

It is defined as the amount of electric power that can be transferred over the interconnected transmission network or particular path or interface in a reliable manner, while meeting all of a well defined pre- and post-contingency system conditions from a specified set.

### 1.8.7 Intelligent Power Module (IPM)

It consists of 3 arm IGBTs bridge converter with anti-paralleled diodes. One more IGBT is paralleled to AC supply to prevent the remaining 6 IGBTs from over current. This entire arrangement is molded on a single module which has 7 PWM signal points and has terminals which sense the device temperature, fault current and short circuit across the AC supply. It also prevents from the fault by sensing the above parameters.

### 1.8.8 Opto Isolator

It is an IC which is used to isolate the PWM signals with the power supply signals. Totally, 7 opto isolators are provided for isolation. It consists of photo diodes and photo transistors.

### 1.8.9 Fuzzy controller

It is a controller whose inputs are fuzzified. The outputs of the controller are defuzzified. These controllers are used, when there is no linear relation between the inputs and the output.

### 1.8.10 ANNC

It is expanded as Artificial Neural Network Controller. The training data for the inputs and output are taken from the PI controller data. According to the inputs and output, it creates an artificial network. This controller output is used to vary the duty cycle of the 'α' through switches S1 and S2.

### 1.8.11 ANFIS

It is expanded as Adaptive Neuro-Fuzzy Inference System. It contains the characteristics of fuzzy and ANNC.

### 1.8.12 Fluke power quality analyzer

It is a Fluke company make 200MHz power quality analyzer. It is used to measure the SPWM signals generated by the DSP TMS320F2407 kit.

### 1.8.13 Duty cycle (D)

It is defined by the following Formula

$$D = \frac{T_{on}}{T_{on+T_{off}}}$$

where

$T_{on}$ is the on time of the pulse width

$T_{on} + T_{off}$ is the total time period(T) of the pulse width

## 1.9 LITERATURE SURVEY

Publications on the topic relevant to FACTS controllers are too numerous. Only those important publications which are directly related with the work have been referred and presented in this thesis. Literature survey is presented under the following topics.

### 1.9.1 Introduction to FACTS Controllers

Hingorani (1993) and (1998) introduced different FACTS controllers such as phase angle regulator, static VAR compensator, sub-synchronous resonance damper and static condenser to improve all round performance of power system. It has also been stated that the improvement of power semiconductors is held up as a major factor to the increased importance in future power system. Using power electronic circuits, the line parameters such as the phase angle, the line end voltages and the impedance can be controlled at a faster rate.

Arindam Ghosh et al (1995) used power electronic devices to enhance both system stability and power transfer limits using a linearized discrete model. Matsuno et al (2002) had proposed various types of FACTS controllers such as SVC, STATCOM and variable speed pumped storage (VSPS). They studied their necessity, technical problems in developing the FACTS controllers, and their solutions.

Schauder and Mehta (1993) discussed the Advanced Static VAR Compensator (ASVC) using self commutating inverter. They have also introduced two types of inverters for STATCOM and analyzed. Singh et al (2009) proposed a fast acting static STATCOM, which was used as the state-of-the-art dynamic shunt compensator for reactive power control in transmission and distribution system.

Mohagheghi et al (2003) introduced a nonlinear identification of STATCOM connected to a power system using Continually Online Trained (COT) Artificial Neural Networks (ANNs).

Jianye Chen et al (2006) focused on a new kind of STATCOM, where thyristors instead of self-commutated devices are used as switching devices.

Hinton et al (2001) had given some guidelines on the principles of design for replaceable control components to improve the performance for a FACTS controller.

El Moursi et al (2006), (2010) and (2011) proposed a reactive power controller for STATCOM and SSSC and introduced a Coordinated Voltage Control Scheme for SEIG-based Wind Park Utilizing Substation STATCOM.

### 1.9.2 Modelling Of STATCOM

FACTS controllers have been modelled using different modeling analysis. Voltage source converter model, frequency model and ‘dq’ model are some of the FACTS controller models.

Li Xiaolu et al (1998) had given a simplified fundamental frequency model of FACTS controller and its simulation results. This model inherently incorporates the thyristor triggering logic and the synchronization system.

Kumkratug et al (2002) proposed a versatile mathematical model of a FACTS controller in a single machine infinite bus system. The model consists of a simple voltage source whose magnitude and angle depend on the control parameters.

Yankui Zhang Lee et al (2006) modelled the STATCOM based on the power injection model. In this model, PWM control and phase control strategies were made. They also presented the operating limit for these control strategies by considering the steady state losses of the STATCOM. They used IEEE 300 bus and 30 bus system to verify the effectiveness and performances of this model.

Lehn et al (1998 and 2002) designed a discrete linear time varying model of the three-phase VSC and they have given the experiment evolutions of STATCOM. Hung-chi et al (2006) employed the inner loop, passivity-based control by using energy shaping and damping injection techniques to produce the proper switching function for VSC based STATCOM.

Yhang Shung Lee et al (2002) designed a STATCOM controller for power system stabilization with sub-optimal control. Nitus Voraphonpiput (2005) et al proposed a mathematical model of STATCOM based on space vector theory. The voltage equations are transformed into the synchronous rotating reference frame (dq-axis).

Yidan Li et al (2008) presented a new dc voltage balance control method that combines the phase shifting technique and SPWM strategy for the control of H-bridge DC capacitor voltages in STATCOM.

Hannan et al (2009) modelled the STATCOM using dynamic phasor model to investigate the performances of STATCOM for power quality analysis. They also modelled based on Electro Magnetic Transient (EMT) using MATLAB/simulink and PSCAD and compared the results.

Elmoursi et al (2006) investigated the dynamic operation of STATCOM based on a new model for combined reactive power support and voltage stabilization. They proposed the model based on the decoupled current control strategy using MATLAB/simulink. Suul (2010) proposed a control method for limiting the torque of grid-connected cage induction machine during the recovery process after grid faults, by using a STATCOM connected at the machine terminals.

Clandio et al (2003) modelled STATCOM accurately based on the voltage and angle stability studies of power system. These models are validated by means of electro magnetic transient program (EMTP) simulation on a test system and then implemented into two different programs for voltage and angle stability studies.

Wang (2003) derived the dynamic model of a multi-machine power system with STATCOM and other FACTS devices. Amit Jain (2003) and (2006) modelled a STATCOM and gave a control scheme for fast voltage regulation. Yukimori Kishida et al (2009) introduced a STATCOM using the new concept of an inverter system with controlled gradational voltage.

### 1.9.3 Development of STATCOM

In order to analyze the dynamic performance of the FACTS devices, a proto type hardware setup is needed along with the software simulation. It is also useful to predict the device performance in the actual power system operation.

Lehn et al (1998) developed a new approach for the dynamic control of FACTS apparatus, such as the STATCOM and UPFC, which utilizes Voltage Source Inverters (VSI) as the main building block. The control concept is based on a linearization of the 'dq' inverter model.

Singh et al (2002) implemented a DSP-based 3-phase STATCOM using a fuzzy logic. They introduced two different types of current control techniques namely, direct and indirect current control for the compensator. They conducted the experimental tests on the compensator with both techniques and compared the results.

Varma et al (2011) presented a novel optimal utilization of photovoltaic solar system as STATCOM for voltage regulation and power factor correction during both nighttime and daytime. Dong et al (2004) developed a laboratory setup of STATCOM, SSSC and UPFC and tested their performances.

Doval (2003) presented the PWM STATCOM using pole assignment control method. He developed a proto type model of STATCOM with DSP as controller and obtained the results for both leading and lagging VAR compensation. Yasuyuki Miyazaki (2002) developed a STATOCM using real time digital simulator with 50 microseconds time step. He also simulated the STATCOM using MATLAB/simulink and compared the results obtained in both cases.

Keyou Wang et al (2009) presented the development of a FACTS Interaction Laboratory (FIL) to interface a real-time power system simulator with multiple FACTS/UPFC devices via Hardware-In-Loop (HIL) to study their dynamic responses and test control approaches.

Pavel Zuniga Haro et al (2009) developed a novel switching function model for the static synchronous compensator, the static synchronous series compensator, and the UPFC devices based on a multi-pulse voltage-sourced converter topology for 6-12-pulse configurations.

Suresh et al (2010) developed a VSC with PWM functionality which results in avoiding over-currents and trips of the STATCOM during and after system faults, and ensures that the STATCOM functionality improves a lot by supplying required VAR support, when it is most required. Ding Lijie et al (2010) presented a high capacity static VAR system for SVC or STATCOM placed on transmission path of power system.

Majumder et al (2006) validated the controller in real time using a detailed model of the power system implemented using Linux PC based multi-processor technology. Christian Dufour et al (2005) developed a real-time simulation of a 48-pulse GTO STATCOM static compensator with RT-LAB Electrical System Simulator using Linux PC-based multi-processor technology.

Xu (2001) addressed key issues surrounding the development of STATCOM. The STATCOM is based on a conventional six-switch bi-directional VSC topology using insulated gate bipolar transistors. They also implemented the system's control, incorporating a VAR calculator and synchronization, on a digital signal-processing board to achieve excellent overall performance.

Venkata Dinavahi et al (2004) presented the design and implementation details of a real-time digital simulator for a VSC based distribution STATCOM (D-STATCOM) power system. They designed a modular approach utilizing distributed digital signal processor/field-programmable gate array resources of a digital processing platform. They validated this design by using an experimental setup of a 5-kVA D-STATCOM system.

Yuang Shang Lee (2002) designed a STATCOM for power system stabilization to increase the damping of electromechanical and exciter modes of the power system. Bhim Singh et al (2012) developed a new configuration of STATCOM with constant DC-link voltage for voltage regulation. This STATCOM consists of eight sets of two level double way VSCs each with two six pulse VSC.

### 1.9.4 Intelligent Controllers Design for VSC Based STATCOM

To improve the performance of the FACTS devices, intelligent controllers have been introduced. The introduction of these controllers increases the speed of the controlling action and increases the stability.

Salman Mohagheghi et al (2005) modelled a multi-machine power system with fuzzy controller and STATCOM using Real Time Digital Simulator (RTDS). Mak (2000) designed a fuzzy controller for STATCOM to enhance the interconnected power system stability. He modelled the STATCOM using power frequency model with conventional controllers. The main control is for voltage regulation and the supplementary control is for damping inter area power oscillations.

Gwang Won Kim et al (2005) presented an Artificial Neural Network (ANN) based coordination control scheme for Under Load Tap

Changing (ULTC) transformer and STATCOM. Derment Zoglou (2011) developed a STATCOM with fixed gain PID controller and multiple stage lead-lag compensators for improving further the dynamic impact. The sustainability and effectiveness of the result are tested by performing digital simulations.

Olamaei (2012) developed advanced controllers for FACTS devices such as STATCOM for improving the power quality regarding to wind forms. Ajami et al (2011) developed a hybrid Fuzzy/LQR (Linear Quadratic Regulator) control method which was used to minimize the cost function in order to achieve the optimal tradeoff, for 3-level STATCOM control and applied for damping oscillations caused by Sub-Synchronous Resonance (SSR). The Fuzzy logic is used to design of control system in outer loops of controller and designed supplementary controller for damping oscillation in STATCOM.

Salman Mohagheghi1 et al (2004, 2005 and 2006) designed a STATCOM using a Mamdani fuzzy controller and compared its performance with a conventional fine tuned PI controller. They also proposed modified Takagi-sugeno fuzzy logic controllers for STATCOM and implemented the hardware model.

Jegadeesan et al (2011) designed STATCOM with the application of the intelligent techniques such as a combination of neural network and fuzzy logic. The performance of the new Neuro- Fuzzy controller was evaluated in a single machine infinite bus power system subjected to various transient disturbances which exhibited a superior damping performance in comparison to the proportional-integral as well as the mamdani type fuzzy controller.

Rachid Dehini et al (2011) designed a STATCOM which regulated the voltage and corrected the power factor at the Point of Common Coupling (PCC) by injecting reactive power. They investigated that the ability of fuzzy logic to handle rough and unpredictable real world data made it suitable for a wide variety of applications, especially, when the models or processes were too complex to be analyzed by classical methods. They also investigated the application of a fuzzy controller for controlling the DC capacitor voltage under steady and transient condition using MATLAB / simulink and verified the performance of the fuzzy controller.

Aman Ganesh et al (2010) designed a STATCOM using the artificial neural network model for defining the switching criterion of the VSC for the STATCOM in order to reduce the Total Harmonic Distortion (THD) of the injected line current at the PCC.

Amer et al (2011) designed an ANN control of STATCOM to improve the damping of power systems. They proposed a control algorithm for a Single Machine-Infinite Bus (SMIB) and multi-machine power system that include a Superconducting Generator (SCG). They designed ANN-STATCOM based on Proportional Integral Derivative (PID) by means of minimization of the system's deviations. They compared the damping provided by the ANN-STATCOM controller with a fixed-parameter PID-STATCOM controller.

Morsy (2011) proposed a Fuzzy-PI controller which had a nonlinear and robust structure for control of D-STATCOM's d and q-axis currents. They simulated a Fuzzy-PI current controlled D-STATCOM by MATLAB/Simulink software. They observed the dynamic response of D-STATCOM by changing the reference reactive current. They compared the results with conventional PI controller.

Resul Coteld et al (2011) designed an inverter based D-STATCOM to improve the power quality issues in distribution systems. They proposed a fuzzy-PI controller which has a nonlinear and robust structure for control of D-STATCOM's d and q-axis currents. They also simulated fuzzy-PI current controlled D-STATCOM using MATLAB/Simulink software.

Mehdi Nikzad et al (2011) presented the application of STATCOM to enhance damping of low frequency oscillations at a single-machine infinite-bus power system installed with a STATCOM as a case study. They considered Artificial intelligence methods like Fuzzy Logic schemes and Genetic Algorithms optimization to design STATCOM supplementary damping controller. They simulated using MATLAB/simulink and compared these two methods in damping of power system oscillations.

Sharma et al (2011) described the damping of power system oscillations of the single machine and multi- machine power system using STATCOM with combined PI and Fuzzy Logic controlled voltage regulator. The proposed controller was used to damp the power system oscillations and to regulate the bus bar voltage at which STATCOM is connected. They compared the performance of the proposed controller with combined conventional PI voltage regulator and fuzzy logic controller on a Western System Coordinating Council (WSCC) 3-phase 9-bus system through simulation by using MATLAB.

Al-Mawsawi et al (2004) described a modern approach of controlling the power flow in AC transmission lines. They installed the STATCOM device on one line of the two parallel transmission lines to design the controllers for such a system using EMTP. They designed with two types of controllers, PI with gain scheduling and fuzzy logic. They tested and compared the dynamic performance of the two controllers.

## 1.10 RESEARCH GAP IDENTIFIED FROM LITERATURE SURVEY

From the literature survey, it is found that numbers of controllers have been suggested for the STATCOM. The controller for the STATCOM has been designed and simulated using different simulation software. There is a lack of proto type model of power system with intelligent controllers for STATCOM. There is also a lack of clear comparison of performance of different controllers in dSPACE environment, which is a real time simulation software and has lot of advantages over other simulation software. This research aims at covering this gap, by introducing intelligent controllers such as fuzzy, ANNC and ANFIS controllers for STATCOM which is connected to the transmission line. From these controllers, the best controller has been suggested when STATCOM is subjected to different loading conditions.

## 1.11 PRESENT WORK

Details about the work carried out in this work are described below:

### 1.11.1 Simulink Model of STATCOM

STATCOM modeling is done by connecting a VSC in parallel with the capacitor. The capacitor acts as the voltage source. This voltage source converter is connected to a line through the shunt transformer and capacitor filter. The VSC is modelled by connecting IGBT’s with anti-parallel diodes. The SPWM generator is used to generate the gate pulses.

The real and the reactive power flows are measured by the load. The power flow without connecting STATCOM are measured and these values are compared with the power flow after connecting the STATCOM.

### 1.11.2 State Space Modelling of STATCOM

The state space equation of the STATCOM is obtained from its equivalent circuit. By defining a proper synchronous reference frame, the dynamic model of STATCOM can be simplified. The reference frame coordinate is defined in which the d-axis is always coincident with the instantaneous system voltage vector and the q-axis is in quadrature with it. This transformation of phase variables to instantaneous vectors can be applied to voltages as well as to currents.

The closed loop operation of STATCOM is first tested with a PI controller and then based on the error, change in error and output of the PI controller. A Mamdani based fuzzy controller is designed with proper ranges for the linguistic variables namely error, change in error and output. Training the neural network with error, previous error and output of PI controller, a neuron controller is designed. The implementation of different controllers for closed loop STATCOM control is also done.

### 1.11.3 Simulink Model of STATCOM in dSPACE

The dSPACE layout of STATCOM is created in SIMULINK environment and the variable parameters such as load real and reactive power are made as knob, so that, they can be varied by adjusting the knob, while the simulation is running. Using the plotter instrument, the waveforms of the $P_S$, $Q_S$, $P_R$, $Q_R$ and $Q_{STAT}$ are plotted. By varying the knob of real and reactive power, the values of $P_s$, $Q_s$, $P_R$, $Q_R$ and $Q_{STAT}$ are changed during the simulation. This can also be done in the real time environment. In such cases, the control law is designed in simulink and executed in real time using the dSPACE DS1104 DSP board.

### 1.11.4 Development of STATCOM

The STATCOM is connected at the middle of the transmission line with the LC filter. VSC is modelled in Intelligent Power Module (IPM). The IPM consists of 7 IGBT. 6 IGBTs are for conversion purpose and one IGBT is connected in parallel with AC source, which protects the 6 IGBTs, when fault occurs. It gets turned on and makes short circuit when fault occurs. 7 IGBTs and anti-paralled diode are completely moulded and extended with cooling fins. A sine triangular PWM is generated from the DSP. In order to bring it to sine waveform, a LC filter is connected to filter out the content of carrier wave with the frequency of 20 kHz. The inductance of shunt transformer will act as a 'L' for the LC filter.

dSPACE converts the MATLAB/Simulink model into the DSP code. The backend tool of the dSPACE software is based on MATLAB/Simulink model. The dSPACE layout of STATCOM model is created in SIMULINK environment. Then, this model layout is converted into DSP code which runs in the in-built TMS320F240 DSP processor in the dSPACE controller. A dSPACE connector panel (CLP1104) ports provide easy access to all input and output signals of the DS1104 board. It has 8 DACs, 8 ADCs and digital I/O ports.

### 1.11.5 Design of Different Controllers for STATCOM

The real time performance analysis of STATCOM with PI controller is done by giving a load disturbance. In order to control $V_{pcc,}$ its value is received in the dSPACE environment through one ADC. The command to change the phase angle 'α' so as to change the $V_{pcc}$ is given to the I/O pins of the dedicated DSP TMS320F2407 through DAC from the dSPACE.

Once the PI controller for STATCOM has been built in simulink block-set, machine codes that run on the inbuilt DSP processor are generated by the dSPACE controller. During the experiment, dSPACE DS1104 provides a reference $V_{pcc}$ as a knob for the user to change its value online. Thus, it is possible for the user to view the process in real time, while the experiment is in progress. The $V_{pcc}$ and the load current value are taken from the ADCs. The PI controller gives the output to DAC which is used to change the phase angle of the injected voltage by STATCOM till it reaches the reference values. In the PI controller, the values $K_p$ and $K_i$ are set as 0.1 and 500 respectively.

In ANNC, a two layer feed forward neural network is constructed with two neurons in the input layer and one neuron in the output layer. As the inputs to the controller are the error and the change in error, two neurons are used for input layer. The neurons are biased. The activation functions used for the input and output neurons are pure linear and tangent sigmoid respectively. A supervised back propagation neural network-training algorithm is used with a fixed error goal.

In fuzzy, a Sugeno type fuzzy controller is constructed. It uses singleton membership functions for the output variables. The Sugeno type controller is used because it can easily be implemented in any embedded system and it simplifies calculations. Thus, real time operation can be easily achieved.

The error and change in error of $V_{pcc}$ are fuzzified. Seven linguistic fuzzy sets with triangular membership function are used. The seven sets used for fuzzy variables ‘error’ and ‘change in error’ are Negative Big (NB), negative medium (NM), Negative Small (NS), Zero (Z), Positive Big (PB), Positive Medium (PM), and Positive Small (PS). The reverse of fuzzification is called defuzzification. Weighted average method of defuzzification which is suitable for Sugeno type controllers is used in this work. The defuzzified output is the duration of the pulse. Totally, 49 rules have been formed.

In ANFIS controller, in the input side, 5 membership functions are used with triangular membership function. Sugeno type fuzzy inference is also used. The network is trained for an error goal of 0.0005. It takes 200 epochs to get that error goal. The output from the ANFIS is used to vary the phase angle ‘α’

### 1.11.6 Comparison of the Performances of Different Controllers for STATCOM

The real time performances of STATCOM using PI, fuzzy, ANNC and ANFIS controllers in dSPACE environment are analyzed. The performance of STATCOM is analyzed by giving load disturbance. It is observed that the STATCOM under ANFIS controller has less peak overshoot and steady state error and responses faster than PI, fuzzy and ANNC controllers. Hence, ANFIS controller is performing better than PI, fuzzy and ANNC controllers. It also proves that using dSPACE, experimental verification of real time control system can be easily achieved.

It further proves that the ANFIS controller performs better than the other three controllers in trajectory tracking method.

## 1.12 OBJECTIVES OF THE THESIS

The main objectives of the present work are:

- To model STATCOM in MATLAB/simulink

- To create a state space model of STATCOM with PI, fuzzy and ANNC controllers and comparing the performances of these controller under different loading conditions.
- To develop a proto type model of STATCOM
- To implement different controllers such as PI, fuzzy, ANNC and ANFIS for STATCOM in dSPACE environment.
- Comparing the performance of these controllers under load disturbance conditions and suggesting the best controller out of these four controllers.

## 1.13 THESIS ORGANIZATION

This thesis has been organized into six chapters and the details are given below.

Chapter 1 introduces the basic principles of active and reactive power flow control and basic operating principles of conventional FACTS controllers such as simple inductor and capacitor banks. It also introduces the new power electronics based FACTS controllers such as SVC, Thyristor Switched Capacitor (TSC). Nowadays the new and modern VSC based FACTS controllers are also dealt in this chapter.

The STATCOM concept and its simulink model are explained in chapter 2. In this chapter, a power system is modelled with and without the STATCOM controller. For that, a VSC based STATCOM is modelled. A sine triangular PWM is generated for the gating signals of IGBT. The STATCOM performance is studied for different cases. Results obtained in various cases are shown and discussed.

Chapter 3 presents the state space modeling of STATCOM. For this model, the proto type hardware parameters such as transmission line inductance, transmission line resistance, DC capacitance and real power loss represented by $R_{dc}$ are taken. The state matrix is developed based on these values. Three type of controllers such as PI, fuzzy and ANNC are designed. The data for inputs and output for ANNC are taken from conventional PI controller. Their performances are compared for sudden change in the load current. Results are obtained in various cases and they are compared.

Chapter 4 describes the hardware development of STATCOM. It deals with the construction of IPMs, DSP program to generate sine triangular PWM pulses, shunt transformer, filter design and the protection circuits of the IPM. The control pulse to vary the firing angle and modulation index is generated from the dSPACE model.

Chapter 5 deals with the design of PI, fuzzy, ANNC and ANFIS controllers for STATCOM under dSPACE environment. Under various loading conditions, the results are derived and they are compared.

Chapter 6 provides the concluding remarks from the work carried out and also lists the suggestions for future research in this area of work.