CHAPTER 1

INTRODUCTION

1.1 GENERAL

Power system is a complex interconnected network comprising of generation, transmission and distribution systems. The generation system converts energy from one of the naturally available forms to electrical form. Transmission system transmits bulk power from major generating stations to the main load centres in power system. It constitutes the backbone of an integrated power system and operates at high voltage levels. The distribution system forms the final stage in the transfer of power to the individual customers at lower voltage levels. The systems in addition are incorporated with switchgears such as circuit breakers, isolators, fuses and lightning arresters to ensure satisfactory operation and protection. They are monitored at energy control centres, which are equipped with on-line computers to process the signals received through remote acquisition systems and analyse the performance for safe, reliable and economic operation of the system.

The network is expanding everyday with increase in demand, and to meet this situation, either new installation of power generating stations and transmission lines are required or the operation of existing infrastructure has to be extended to its limits. Laying of new lines or installation of new generating stations imposes many environmental and economical constraints. As a result, the existing transmission lines are more heavily loaded than ever before. In steady state operation of heavily loaded power systems, the main problems are increased losses, poor voltage profile, unwanted loop flows and line overloads.

In addition, the system under such a state imbibes substantially different response to disturbances from that of non-stressed systems and therefore even a relatively smaller disturbance may upset the system. Besides progressive energy demands and depletion of the existing generation and transmission resources evolve a new type of problem, referred to as voltage instability or voltage collapse in power systems. The phenomenon of voltage instability in power systems is characterised by a monotonic voltage drop, which is slow at first, becomes abrupt after some time and generally triggered by some form of disturbance such as loss of generation, transmission lines or transformers or a change in the operating conditions, that create an increased demand for reactive power, which is in excess of what the system is capable of supplying. A large disturbance on a stressed system results in a loss of equilibrium, at which the generation and load do not meet, and the power system can no longer operate normally and leads to cascaded outages (Kundur 1993; Taylor 1994).

The main factor causing voltage instability is the inability of the power system in meeting the reactive power demand at heavily stressed systems, and this prevents it from maintaining the desired voltages. The other factors contributing to voltage collapse are generator reactive power/voltage control limits, load characteristics, characteristics of reactive power compensating devices, the action of transformer with load tap changers, cutbacks in system maintenance, workforce downsizing and unpredicted power flow patterns.

Voltage stability (VS) assumes extreme significance in the operation and planning of the present day power systems. When a power system is operating close to its stability limits, it is essential for the system operators to inherit clear knowledge about the operating states. The philosophy is to identify tools that can enhance their understanding of where the system is operating with respect to the point of voltage collapse. VS margin is directly assessed by the plots of PV or QV curves obtained from a series of load flow solutions based on continuation method or repeated power flow method (Lee et al 2010; Da Costa et al 2010). In addition, a number of VS indices, which provide an indirect relative measure of proximity to voltage instability, such as voltage collapse proximity indicator (VCPI) (Bedoya et al 2008; Chakravorty and Das 2001; Haque 2006; Kessel and Glavitsch 1986; Sinha and Hazarika 2000; Wang et al 2009; De Souza 2000), the minimum singular value of power flow jacobian matrix (Basa and Crow 1996), the loading margin (Jeyasurya 1994), the fuzzy based approach (Berizzi et al 2009) and artificial neural network (ANN) based strategies (Chakrabarti 2008; Kamalasadan et al 2009; Modi et al 2008;Taghi et al 2008) are available in the literature to estimate the proximity of the power system to voltage collapse. However, most of these methods involve a rigorous procedure and hence are suitable only for off-line studies (Lee et al 2010; Da Costa et al 2010; Kundur 1993).

Voltage collapse can appear quite abruptly in systems or sub-systems due to the continuously-changing operating conditions and various unforeseen factors associated with large power systems and hence offline stability studies can no longer be sufficient to ensure a secure operation of the power system. Online VS analysing tools that use real-time direct measurements are envisioned to quickly detect the potentially dangerous situations of voltage instability and offer guidance to the operators to steer the system away from a possible voltage collapse. Online VS monitoring is becoming an integral part of the modern day Energy Management Systems.

When the operating state is near instability region, the main objective is prevention of voltage collapse. It is therefore appropriate that efficient and economically justified solution techniques for avoiding voltage instability problems be developed. Optimal real and reactive power dispatch and the installation of reactive power sources at appropriate buses can minimise the losses, enhance the voltage profile and improve the voltage stability. The other methods require control over line parameters. Several attempts had been made to use capacitor banks in power systems for power factor correction, feeder voltage control (Kundur 1993; Taylor 1994), loss minimisation (EL-Dib et al 2008; Bhattacharya and Goswami 2009; Chiou et al 2006; Das 2008; Haghifam and Malik 2007; Huang et al 2008; Khodr et al 2008; Prasad et al 2007;Rao and Narasimham 2008; Tabatabaei and Vahidi 2011; Venkatesh and Ranjan 2006), and reconfiguration (Ahmed and Wafa 2011; Niknam 2011) which are in practice. A host of algorithms for enhancing the VS of transmission system by optimal capacitor placement (CP) (El Arini 2000; Satpathy et al 2004) and loss minimisation (Jasmon and Lee 1991; Kashem and Moghaavvemi 1998) are in vogue. There are efforts to enhance VS of distribution systems through network reconfiguration that alters the topological structure of the distribution feeders by rearranging the status of switches (Sahoo and Prasad 2006; Sivanagaraju et al 2005; Venkatesh and Ranjan 2003).

The different control strategies such as generation and energy transfer rescheduling, bringing standby generators on-line, switching capacitor banks, reduction of MV set point and other reactive power controls are exhausted, the only alternative way is load curtailment at some weak buses to avoid voltage collapse. Insufficient load shedding (LS) however may not eliminate voltage instability problem. On the other hand, excessive LS tend to curtail the load too much to end up with an imminent power outage problem. Though extensive research is in progress on under-frequency LS, (Chuvychin et al 1996; Hsu et al 2008; Huang and Huang 2000; Kottick 1996; Mingchui et al 2008; You 2003), relatively a little contribution is reported on the effect of LS on power systems to avoid voltage instability(Arnborg et al 1997; Arya et al 2005; Echavarren et al 2006; El-Sadek et al 1999; Feng et al 1998; Otomega et al 2007;Tuan et al 1994; Sadati et al 2009; Sasikala and Ramaswamy 2011). A combination of these corrective methods are often tried: e.g., tap changer blocking to slow down the system degradation and allow some time for another action, may be load shedding.

The recent developments in power electronics have introduced Flexible AC Transmission Systems (FACTS) that include Thyristor Controlled Series Compensator (TCSC), Static VAR Compensator (SVC), Static Synchronous Compensator (STATCOM), Unified Power Flow Controller (UPFC), Static Synchronous Series Compensator (SSSC), Thyristor Controlled Phase Angle Regulator (TCPAR) etc., These devices can facilitate the control of power flow, increase the power transfer capability, improve the security and enhance the stability of the power systems. They allow the operation of the power systems more flexible, secure and economical through controlling various electrical parameters of transmission circuits. However, the decision on the size, the locations and their parameters is of great significance in obtaining the benefits of the FACTS devices (Gotham and Heydt 1988; Hingorani and Gyugyi 2000).

The placement of FACTS devices can be described as an optimization problem with an objective of minimizing a cost function while satisfying system constraints. The aim of this problem may be to reduce the power loss, lower the installation cost, minimize the voltage magnitude deviation and maximize the voltage stability margin. The constraints may include power flow and security limits under normal and contingent conditions. Owing to rigorous constraints, the FACTS placement problem may be a non-convex and nonlinear problem, and becomes the most challenging optimization problem in power systems.

Numerous methods for obtaining the solution of FACTS placement problem have been suggested in recent years. (Abido 2009; Blanco et al 2011; Chatterjee and Ghosh 2011; Gitizadeh et al 2012; Besharat, and Taher 2008; Zhang et al 2007; Zhu et al 2010; Khederzadeh and Ghorbani 2012; Ara et al 2012; Magaj and Mustafa 2011; Malihe et al 2007;Ishimaru et al 2002; Phadke et al 2012; Minguez et al 2007; Saravanan et al 2007; Senthil Kumar and Gokulakrishnan 2011; Jiang et al 2011; ShanmukhaSundar and Ravikumar 2012; Singh et al 2007; Grbex et al 2001; Szuvovivski et al 2012; Vilmair et al 2011; Shao and Vittal 2006; Wibowo et al 2011; Jiang et al 2010; Chang 2012; Yousefi et al 2012) The solution techniques may be classified as conventional methods, intelligent searches and fuzzy set applications. The conventional methods include linear programming, nonlinear programming, mixed-integer nonlinear programming, etc. The intelligent-search-based methods such as simulated annealing, genetic algorithm (GA), evolutionary algorithm and particle swarm optimization (PSO) have received widespread attention as possible techniques to obtain the global optimum solution. The fuzzy set theory has been applied to address uncertainties in objectives and constraints. In the light of the fact that there are no known ways to find the exact global solution for this complicated optimization problem, there is always a need to develop better methods with a view of obtaining the global best solution.

Recently, a biogeography based optimization (BBO) algorithm has been suggested for solving optimization problems (Simon 2008). It is based on the mathematics of biogeography that studies the geographical distribution of biological organisms. In this approach, problem solutions are represented as islands or habitats and sharing of features between solutions is represented as immigration and emigration between islands. It has been applied to several optimization problems such as optimal reactive power control (Bhattachary and Chattopadhyay 2010), economic load dispatch (Bhattacharya and Chattopadhyay 2010) and power flow (Rarick et al 2009).

1.2 OBJECTIVE OF THE RESEARCH WORK

The main objective of the present investigation is to develop a new strategy to improve voltage profile, enhance voltage stability and minimise network loss through placing FACTS devices. The exercise is to identify precise locations, predict the appropriate FACTS device and determine optimal parameters to ensure enhanced system performance through a suitable optimisation technique.

1.3 LITERATURE REVIEW

The recent research work carried out in the area of VS, loss minimisation, voltage profile enhancement and preventive strategies to avoid voltage instability are outlined.

1.3.1 Voltage Stability

A VS index (VSI) for radial distribution systems has been detailed in (Chakravorty and Das 2001). This indicator has been found to use the terminal node voltages and the line real and reactive power flows to compute the index value of a line. The node at which the value of indicator is minimum, has been identified the most sensitive node to voltage collapse.

Increasing the loadability of power systems which, in turn, can be linked to voltage collapse occurrences. As voltage collapses may be caused by insufficiency of reactive power support, and considering that reactive power can be locally supplied, for instance, by shunt capacitors or FACTS devices have been explained in (Antonio at al 2004). Local control actions on the system loadability are carried out in two steps. First, by using the tangent vector technique, two important areas of the power system are identified: the critical area under the point of view of voltage collapse, and the area most sensitive to active power losses reduction. Second, once these two areas are identified, an optimization technique takes place to optimize the amount of shunt reactive power compensation that should be available in each bus.

A linear VSI has been suggested to faithfully determine the distance to voltage collapse of radial distribution systems (Haque 2006). This index has been found to exhibit almost a linear characteristic in the entire operating region. The value close to zero has been found to indicate the proximity to voltage collapse and that close to one, the most stable state. The simplicity of numerical computation and ease of expressiveness of the results are the advantages of this method.

A fast method for computing minimum VS margin has been developed (Bedoya et al 2008). This method has been found to obtain the minimum VS margin unlike other methods that may cause voltage instability corresponding to the unexpected load increase at some buses. This offers VS margin for a predefined direction of load increase. The minimum VS margin along with the direction of load increase for which it occurs besides the usual VS margin have been found to initiate preventive measures.

An online VSI, called equivalent node voltage collapse index, generated by recognising the weakest node and local voltage phasors has been suggested (Wang et al 2009). This method has been found to produce very accurate results, owing to the fact that the impacts of grid systems find a place in the equivalent system model.

A fuzzy logic based method for online assessment of voltage security of the current operating point has been presented (Berizzi et al 2009). This method uses a few of the most suitable voltage security indices as inputs and has been found to exploit the human expertise in synthesising the information imbibed in the indices with a view to assess the voltage security.

Bifurcation theory has been employed to qualitatively explain the mechanisms of voltage stability problems occurring in electric power systems by relating the voltage collapse and voltage oscillatory problems to the appearance of saddle node and Hopf bifurcations, respectively. The results obtained by bifurcation analysis have revealed the existence of degenerate Hopf bifurcations when two parameters of the system are varied simultaneously; however, the mechanisms of voltage stability problems when the system is operating near these kinds of bifurcations have not yet been investigated. The authors (Armenta et al 2013) assessed the voltage stability of a power system which is affected by the presence of codimension-2 degenerate Hopf bifurcations. From the multi parameter bifurcation analysis, the existence of degenerate Hopf bifurcation points is identified and a trajectory stability diagram is then computed for classifying the type of degenerate Hopf bifurcations. This classification is used for establishing the voltage dynamics' behaviour when the power system is operating near these bifurcations. Finally, the application of a Stat Com is proposed to eliminate sustained voltage oscillations and the appearance of degenerate Hopf bifurcations.

With regard to widespread use of distributed generation in distribution network, its technical impacts in distribution network should be thoroughly analyzed. Simultaneous placement of distributed generation (DG) and capacitor is considered in radial distribution network with different load levels in (Saijadi et al 2013). The active and reactive power loss, energy loss is reduced then the voltage profile has been improved. Also effect of capacitor and DG on voltage stability improvement has been considered. Memetic algorithm is used to find optimal solutions. This algorithm is combinatorial form of local search and genetic algorithm.

Static and dynamic VAR planning based on the reactive power margin for enhancing dynamic voltage stability of distribution networks with distributed wind generation has been detailed in (Roy et al 2013). Firstly, the impact of high wind penetration on the static voltage stability of the system is analysed and then the effect of composite loads on system dynamics is presented through an accurate time-domain analysis. A new index, reactive power loadability (*Q*-loadability), is used to measure the vulnerability of the network to voltage collapse. Compensating devices are located using *Q*-loadability to increase the system voltage stability limit. Finally, a cost-effective combination of shunt capacitor bank and distribution static compensator (D-STATCOM) is determined through static and dynamic analyses to ensure voltage stability of the system after a sudden disturbance for different wind penetration levels.

Voltage stability imposes important limitations on the power systems operation. Adequate voltage stability margin needs to be obtained through the appropriate scheduling of the reactive power resources. The main countermeasures against voltage instability could be distinctly classified into preventive and corrective control actions. A preventive countermeasure to improve the voltage stability margin through the management of the reactive power and its reserve has been discussed (Mousavi et al 2013). The voltage and reactive power management is studied from the generator's point of view to maximize effective generator reactive power reserve (EGRPR). Detailed model of the generators including the armature and field current limits, as well as the switch mode between the voltage control and the reactive power limitations are considered to maximize the reactive power capability of the generators in emergency states. One-stage and two-stage optimization approaches are utilized to find the optimum solution.

Chaos and voltage collapse exist in power systems due to critical loading and disturbing of energy (DE). These phenomena cause instability in power system operation and must be avoided. An ANFIS-based composite controller-static var compensator (CC-SVC) was proposed to control both chaotic oscillations and voltage collapse in this work (Ginarsa et al 2013). The ANFIS-based CC-SVC was proposed which is more efficient than Mamdani fuzzy logic controller. Adaptive network parameters were obtained through a training process. The controller parameters were automatically updated by off-line training. The load voltage was held to a set value by adjusting the supplied reactive power. When the reactive load was increased, the SVC susceptance and reactive power supplied by the SVC also increased.

A new hybrid fuzzy multi-objective evolutionary algorithm (HFMOEA) based approach for solving complex multi-objective, mixed integer nonlinear problems such as optimal reactive power dispatch considering voltage stability (ORPD-VS) has been detailed (Saraswat, and Saini 2013). In HFMOEA based optimization approach, the two parameters like crossover probability (P_C) and mutation probability (P_M) are varied dynamically through the output of a fuzzy logic controller. The fuzzy logic controller is designed on the basis of expert knowledge to enhance the overall stochastic search capability for generating better pareto-optimal solution. The performance of HFMOEA is tested on five benchmark test problems such as ZDT1, ZDT2, ZDT3, ZDT4 and ZDT6 as suggested by Zitzler, Deb and Thiele; Secondly, HFMOEA is applied to multi-objective ORPD-VS problem. In both the cases, the optimization results obtained from HFMOEA are analysed and compared with the same obtained from two versions of elitist non-dominated sorting genetic algorithms such as NSGA-II and MNSGA-II in terms of various performance metrics.

An Adaptive Neuro-Fuzzy Inference System (ANFIS) method based on the Artificial Neural Network (ANN) is applied to design a Static Synchronous Series Compensator (SSSC)-based controller for the improvement of transient stability in this work (Swasti et al 2013). The ANFIS controller combines the advantages of a fuzzy controller as well as the quick response and adaptability nature of an ANN. The ANFIS structures were trained using the generated database by the fuzzy controller of the SSSC. It is observed that the proposed SSSC controller improves greatly the voltage profile of the system under severe disturbances.

1.3.2 Loss Minimization

A single dynamic data structure for an evolutionary programming algorithm that handles the problems of sizing of capacitors simultaneously while considering transformer taps, existing reactive power sources and reconfiguration options, accounting for different load levels and time durations has been proposed (Venkatesh and Ranjan 2006). It has been found to allow the real time sizing of reactive power sources in one computation cycle rather than two cycles of the existing approaches.

A computationally efficient methodology for the optimal location and sizing of static and shunt switched capacitors in radial distribution systems has been suggested (Khodr et al 2008). It has been formulated as the maximisation of savings with a view to reduce the energy losses and eliminates the costs due to investment deferral in the expansion of the network, and solved as a mixed-integer linear problem iteratively.

A PSO based solution technique for finding the optimum location and sizing of the shunt compensation devices in transmission systems have been outlined (EL-Dib et al 2008). The problem has been formulated as an integer nonlinear optimization problem with an objective to improve VS and maintain acceptable VP of the system.

A GA based fuzzy multi-objective approach for determining the optimal values of fixed and switched shunt capacitors to improve the VP and maximise the net savings in a radial distribution system has been presented (Das 2008). The twin objectives, i.e. maximisation of net savings and minimisation of node's voltage deviations have been first fuzzified and then integrated into a fuzzy objective function through appropriate weights. GA has thereafter been applied for obtaining the optimum values of shunt capacitors.

A fuzzy based approach for identification of probable capacitor nodes of radial distribution system has been developed (Bhattacharya and Goswami 2009). New membership functions have been formulated, where the active power is an exponential function of the nodal active power and branch power loss, while the reactive membership function has been expressed as a function of nodal reactive power and branch reactive power loss. Simulated Annealing (SA) technique has been employed for final sizing of the capacitor banks.

A methodology based on fuzzy decision making for the optimal location and sizing of shunt capacitors in radial distribution systems with objectives of minimizing the cost of peak power, reducing energy loss and improving voltage profile has been outlined in (Tabatabaei and Vahidi 2011). The bacteria foraging algorithm (BFA) has been utilized in solving the multi-objective optimisation problem and determining the optimal nodes for CP.

1.3.3 Reconfiguration

A multi-objective algorithm based on honey bee mating optimisation for distribution feeder reconfiguration problem with objectives of decreasing the real power loss, minimizing the number of switching operations and reducing the voltage deviations at each node has been suggested (Niknam 2011). Conventional algorithms for solving the multi-objective optimisation problems and to convert the multiple objectives into single objective uses a vector of user-predefined weights but this algorithm has been found to utilize the concept of Pareto optimality. A fuzzy-based clustering technique has been used in order to control the size of the repository.

A meta-heuristic approach by integrating load flow with known heuristic search methodology for determining the minimum loss configuration of a radial distribution system has been detailed in (Ahmed and Wafa 2011). The technique has been formulated in two parts, while the first determines the best switching combinations in all loops with minimum computational effort and the other relates the power loss and voltage profile calculation of the best switching combination that has been found in part one by the load flow. The load flow has been found to follow changes in system structure by creating directed graph for the distribution network in each reconfiguration phase, thus avoiding creation of unconnected branches or forming closed loops. The tie branches and its neighbouring branches have been considered in its attempt to generate the switching combination and the best combination among them has been found with less computational effort.

A network reconfiguration algorithm for VS enhancement through loss reduction for radial distribution system has been described in (Sivanagaraju et al 2005). The load flow technique has been extended to compute VSI at every node and identify the most sensitive node to voltage instability and further modified to search for optimal configuration of the network.

A fuzzy genetic approach for reconfiguration of radial distribution network so as to maximise the VS for a specific set of nodes has been suggested in (Sahoo and Prasad 2006). It has been found to involve a mechanism for selection of the best set of branches to be opened, one from each loop such that the reconfigured network possesses the desired performance. The fuzzy GA that uses a suitable coding and decoding scheme for maintaining the radial nature of the network at every stage of genetic evolution and fuzzy rule based mutation controller has been found to perform an efficient search.

1.3.4 Load Shedding

An efficient LS scheme that determines the location and amount of load to be shed to avoid voltage collapse has been outlined (Tuan et al 1994). It is based on a sensitivity matrix that couples the shed able load and voltage instability indicator.

A Hopfield neural network based LS algorithm to avoid risk of voltage instability under emergency condition has been described (Arya et al

2005). The minimum eigen value of load flow has been selected as the proximity indicator. The sensitivity relations have been derived between indicator changes and load shed at a bus and the buses having large sensitivities. The amount of load to be shed has been decided so as to maintain a threshold value of the indicator and ensured that all load bus voltages to remain within limits.

A LP-based optimisation algorithm to compute the amount and location of minimum LS to improve the load margin to voltage collapse has been presented (Echavarren et al 2006). The problem has been devised with an objective of minimising the total system demand along with the constraints of power balance equation, generation and demand limits. It has been found to provide a target improvement of the load margin.

An under-voltage LS scheme that uses a set of distributed controllers, each monitoring transmission voltage, controlling a group of loads, acting in closed-loop and adjusting its action to the voltage evolution, against long term voltage instability has been outlined (Otomega et al 2007). This scheme has been found to be robust with respect to behavioural uncertainties and operational failures, besides being able to adjust to the disturbance location and severity.

An under voltage LS approach based on hybrid PSO based SA optimisation technique has been briefed (Sadati et al 2009). This approach has been formulated based on the concept of static VS margin and its sensitivity at the maximum loading point or the collapse point. This scheme has been found to consider both technical and economical aspects of each load by incorporating the sensitivities of the VS margin into the traditional cost based objective function and found to offer a global optimum solution in minimum runs.

Two elegant load shedding algorithms for avoiding voltage collapse have been developed in (Sasikala and Ramaswamy 2011). These fuzzy based approaches have been coined to improve VP, in addition enhancing VS. The first method has been tailored to identify the most appropriate locations and use an analytical procedure to compute the shed able load, while the second directly predicts the amount of load to be shed at the critical buses. In spite of the fact that both the schemes have been focussed to improve the bus VP, in addition to enhancing VS, still the second formulation offers an added weight in terms of its lower execution time and lesser extent of LS.

1.3.5 FACTS Devices

A GA based strategy that seeks the optimal location of multi-type FACTS devices in a power system has been outlined in (Grbex et al 2001). The method uses four different FACTS devices and provides the location of the devices, their types and their values.

Power system stabilizing control has an important role in maintaining synchronism in power systems during major disturbances resulting from sudden changes of load and configuration. A linear matrix inequality strategy that treats the load changes as a system uncertainty for the design of robust TCSC controller to suppress disturbances in power systems has been outlined in (Ishimaru et al 2002). H_∞ control is adopted as the methodology of the robust controller design along with a linear matrix inequality (LMI), which solves the Lyapunov inequality without the weighting coefficients.

An efficient LP based optimal power flow algorithm for corrective FACTS control with an objective of maximizing the loadability on highly loaded transmission lines has been suggested in (Shao and Vittal 2006). The method relives voltage violations besides eliminating overloads under contingencies.

An application of PSO technique to find the optimal location with minimum cost of installation of FACTS devices and to improve system loadability has been suggested in (Saravanan et al 2007). While finding the optimal location, thermal limit for the lines and voltage limit for the buses are taken as constraints. TCSC, SVC and UPFC have been considered in the FACTS placement problem.

The SVC placement problem has been formulated as a mixed integer non convex nature of nonlinear programming problem that includes binary variables with a view to maximize the loading margin of a transmission network in (Minguez et al 2007). A base case and different contingency cases have been considered and solved using Benders decomposition technique.

A method involving normal forms of diffeomorphism to determine the optimal SVC allocation to enhance the voltage stability of power systems has been presented in (Zhang et al 2007). It makes use of the nonlinear participation factors, in which the nonlinearity of power systems can be taken into consideration. As a result, the most suitable location where the SVC should be used in power system can be determined, even for the cases in which the system is characterized with strong nonlinearity.

A reactive power spot price index has been suggested for optimal placement of SVCs in power systems (Singh et al 2007). The index has been defined in terms of the reactive power spot prices and computed at each bus based on the reactive power spot price under different loading conditions for the system intact and critical line outage contingency cases. The algorithm places SVC at a bus having the highest value of the index.

A method to seek the optimal location of several SVCs in a power system based on their primary function has been suggested in (Malihe et al 2007). This method uses power system stability as an index for optimal allocation of the controllers. First, several SVCs are placed optimally based on nodal analysis and genetic algorithm in a power system. After placing the SVCs based on their primary functions, the most appropriate input signal for supplementary controller is also selected. The frequency response characteristics of the system for all located SVCs are determined in selecting the best input signals.

A method based on real power performance index and reduction of total system VAR power losses to determine the optimal location of TCSCs has been outlined in (Besharat, and Taher 2008) with a view to relieve congestion besides minimizing the TCSCs cost in deregulated environment.

The performance of unified power flow controller has been investigated in controlling the flow of power over the transmission line in (Mubeen et al 2008). Voltage sources model has been utilized to study the behaviour of the UPFC in regulating the active, reactive power and voltage profile. The equations involving UPFC and the power balance equations of the network have been combined into one set of non-linear algebraic equations and solved using Newton Raphson technique.

The current status of power system stability enhancement using FACTS controllers have been discussed in (Abido 2009). The essential features of FACTS controllers and their potential to enhance system stability have also been addressed. Performance comparison of different FACTS controllers has been reviewed. The likely future direction of FACTS technology, especially in restructured power systems have been discussed as well. Different applications of the first and second generation FACTS devices over the last two decades have been reviewed.

The steady-state modeling of Static VAR Compensator (SVC) and Thyristor Controlled Series Compensator (TCSC) for power flow studies has been represented and discussed in (Hassan and Cheng 2009). Firing angle model for SVC for controlling the voltage at which it is connected and the firing angle model for TCSC for controlling the active power flow of the line to which TCSC is installed have been developed. The proposed models take firing angle as state variable in power flow formulation. The effectiveness of the proposed models have been studied through solving power flow equations in the presence of SVC and TCSC using Newton-Raphson technique.

An application of coordinated SVC as additional control in reactive power optimization problem has been reported and analyzed the impact on system loss minimization and voltage improvement in (Zhu et al 2010). Unlike the general SVC, the coordinated SVC model controls internal, local and remote devices simultaneously.

A comprehensive set of dynamic regulation models for voltage source converter (VSC) based FACTS controllers with a view to improve the capability of a power transfer path have been described in (Jiang et al 2010). It has been shown that the benefits of FACTS controllers are proportional to the MVA ratings and the benefits of multiple FACTS controllers are cumulative. Furthermore, coupling of dc buses allow active power circulation between multiple VSC FACTS controllers may offer additional improvement in transfer capability.

An optimal allocation method for FACTS devices for market-based power systems considering congestion relief and voltage stability has been presented in (Wibowo et al 2011). The purpose of the FACTS devices installation is to provide benefit for all entities accomplished by both minimizing annual device investment cost and maximizing annual benefit defined as difference between expected security cost with and without FACTS devices installation. It accurately evaluates the annual cost and benefits obtainable by FACTS devices installation by formulating a large-scale optimization problem that contains power flow analyses for a large number of system states representing annual power system operations. Dynamic state transitions caused by specified contingencies are also simulated in the optimization problem to evaluate the effect of FACTS control actions as well as the other coordinated controls. The expected cost consists of operating cost under normal and contingency states along with their related probabilities to occur. Maximizing social welfare is the objective for normal state while minimizing compensations for generations re-scheduling and load shedding as well as maximizing social welfare are the objectives in case of contingency. Although installation cost of FACTS devices is required, they are useful as cost free means, which can reduce effectively the annual costs for generations re-scheduling and load shedding.

Efficient and well-timed investments in electric transmission networks that cope with the large ongoing power market uncertainties are currently an open issue of significant research interest. Strategic flexibility for seizing opportunities and cutting losses contingent upon an unfavorable unfolding of the long-term uncertainties is an attribute of enormous value when assessing irreversible investments. In this sense, FACTS devices appear as an effective manner of adding flexibility to the transmission expansion planning. An investment valuation approach which properly assesses the option value of deferring transmission lines investments whereas gaining flexibility by investing in FACTS devices has been proposed in (Blanco et al

2011). The flexibility provided by FACTS installation-option to abandon and relocate is assessed through a real option valuation approach based on the novel least square Monte Carlo method.

The dynamic behavior of two different FACTS devices; the interline power-flow controller and the UPFC in a benchmark system have been discussed in (Jiang et al 2011). The small-signal model of the interline power-flow controller is developed and validated using detailed electromagnetic transients simulation. Using this model, the damping capabilities of the interline power-flow controller and the UPFC are compared and rationalized. From a small-signal dynamics point of view, it is shown that the series branches of these devices essentially segment the network creating a new structure. This structure change may be used to effectively improve system damping without requiring the design of a tuned feedback controller. The two series branches of the interline power-flow controller (IPC) in contrast to the single series branch of UPFC permit more opportunities for network segmentation and has greater potential for improving the system's dynamic performance.

The increasing power demand has led to the growth of new technologies that play an integral role in shaping the future energy market. Keeping in view of the environmental constraints, grid connected wind turbines are promising in increasing system reliability. The impact of FACTS controllers on the stability of power systems connected with wind energy conversion systems has been studied in (SenthilKumar and Gokulakrishnan 2011). The wind generator model considered is a variable speed doubly fed induction generator model. The stability assessment is made first for a three phase short circuit without FACTS controllers in the power network and then with the FACTS controllers. It yields information on the impact of faults on the performance of induction generators/wind turbines, transient rating of the FACTS controllers for enhancement of rotor speed stability of induction generators and angle stability of synchronous generators.

UPFC is used for controlling the real and reactive power in transmission lines and bus voltages simultaneously and independently. An additional task of UPFC is to increase transmission capacity as a result of power oscillation damping. The effectiveness of this controller depends on its optimal location and proper signal selection in the power system network. A residue factor, based on the relative participation of the parameters of UPFC controller to the critical mode, has been proposed to find the optimal location of the UPFC controllers and eigenvalue analyses are used to assess the most appropriate stabilizing signals for supplementary damping control of UPFC to damp out the inter-area mode of oscillations in (Magaj and Mustafa 2011). The residue factor combines the linearized differential algebraic equation model of the power system and the UPFC output equations. While for signal selection a right-half plane zeros (RHP zeros) and Hankel singular value (HSV) are used as tools to select the most receptive signal to a mode of the inter-area oscillations.

A GA based OPF model to allocate TCPST at congested transmission systems has been outlined in (Vilmair et al 2011). The GA allocates the TCPST and the OPF adjusts the phase shifter’s taps. The methodology minimizes the installation costs of the equipment and total system overload. The method involves a strategy to elect the most favorable substations to the devices allocation.

A pole placement technique for power system stabilizer and TCSC based stabilizer using simulated annealing algorithm has been described in (Chatterjee and Ghosh 2011). The design problem is formulated as an optimization problem where SA is applied to search for the optimal settings. A pole placement-based objective function to shift the dominant eigen values to the left in the *s*-plane is considered. The method provides efficient damping of low frequency oscillations besides improving the voltage profile of the system under severe disturbances.

A GA based optimal power flow method to allocate voltage regulators (VRs) and capacitor banks simultaneously for effective control of voltage magnitude, reactive power and power factor has been presented in (Szuvovivski et al 2012). The GA allocates the capacitor banks and voltage regulators and the OPF is responsible for the solution of the power balance equations, tap adjustments of the VRs that assure the voltage level for the diverse load curve and for the attainment of the nominal current of the allocated voltage regulators.

A method using multi-objective optimization technique to investigate the influence of switching losses on TCSC optimum allocation in power systems has been developed in (Gitizadeh et al 2012). The method minimizes voltage deviations and the system cost that includes cost of active power losses, investment cost of devices and active power generation cost in the peak load. It involves multi-objective Artificial Bee Colony to obtain Pareto optimal solutions.

An optimal power flow solution for enhancement of system performance without sacrificing the security of the system via optimal location and optimal sizing of TCSC has been developed in (Shanmukha Sundar and Ravikumar 2012). Thermal Capacity Index and Contingency Capacity Index are proposed for placing the TCSC at appropriate location under normal and network contingency conditions. Once the location to install

TCSC is identified, the optimal setting of TCSC is determined through the use of linear programming technique.

The location and sizing of FACTS controllers for voltage stability enhancement is an important consideration for practical power systems. A strategy for placement and sizing of shunt FACTS controller using Fuzzy logic and Real Coded Genetic Algorithm has been proposed in (Phadke et al 2012). A fuzzy performance index based on distance to saddle node bifurcation, voltage profile and capacity of shunt FACTS controller has been developed. The technique finds the most effective location and optimal size of the shunt FACTS device.

A two-step market clearing procedure for transmission lines congestion management in a restructured market environment using a combination of demand response and FACTS devices has been formulated in (Yousefi et al 2012). In the first step, generation companies bid to the market for maximizing their profit, and the ISO clears the market based on social welfare maximization. Network constraints including those related to congestion management are represented in the second step of the market-clearing procedure. A re-dispatch formulation using mixed integer optimization technique for the second step in which demand responses and FACTS device controllers are optimally coordinated with conventional generators.

Appropriate models of FACTS shunt-series controllers for multi-objective optimization have been developed and a multi-objective optimization methodology to find the optimal location of FACTS shunt-series controllers has been presented in (Ara et al 2012). The objective functions are the total fuel cost, power losses, and system loadability with and without minimum cost of FACTS installation. The ε-constraint approach is implemented for the multi- objective mathematical programming formulation, including the FACTS shunt-series controllers. The solution procedure uses nonlinear programming and mixed-integer nonlinear programming to solve the optimal location and setting of FACTS incorporated in the optimal power-flow problem considering these objective functions and improving the power system operation.

Independent controllability over each compensated line of a multiline system can be achieved by utilizing multiline VSC-based FACTS controllers. While VSC-based multiline FACTS controllers emerged as an opportunity to control two independent ac systems, the main constraints and limitations that are presented to the conventional transmission-line protection systems need to be investigated. The impacts of voltage source converter - based FACTS controllers on distance relays while controlling the power flow of compensated lines have been evaluated and analyzed for different fault types and locations in (Khederzadeh and Ghorbani 2012).

Proper installation of FACTS in existing transmission networks can improve transmission system loading margin (LM) to a certain degree and reduce network expansion cost. Under each contingency with high risk index (RI) value, the nodal analysis technique is used to determine the buses that need static VAR compensator (SVC) installation, and with maximum LM and minimum SVC installation cost composed into the multi-objective function. The optimal LM enhancement problem has been formulated as a multi-objective optimization problem and solved by using the fitness sharing multi-objective particle swarm optimization algorithm for a Pareto front set in (Chang 2012). In the Pareto front set for each considered contingency, the solution with the largest performance index value is determined for SVC installation. Finally, an SVC installation scheme derived from the union of the

SVC installations for all considered contingencies is recommended for LM enhancement.

The use of Power System Analysis Toolbox has been studied for improving voltage stability of the existing transmission systems. The enhancement of voltage stability using FACTS controllers such as Static Var Compensator (SVC) device through the continuation power flow methods with increasing load levels and with different contingencies has been investigated in (Nagesh and Puttaswamy 2012). A simple method for identifying the weak bus and optimal value of reactive power support needed have also been discussed.

The mathematical models for TCSC have been established and the Optimal Power Flow problem with these FACTS-devices has been formulated and solved by Newtons with an objective of relieving the congestion in the system and recovering the investment on TCSC in (Lakdja et al 2012)

FACTs technology allows a better utilization existing transmission and generation reserve margins in the deregulated electricity market for various stability margins. The steady state models of SVC (Static VAR Compensator), TCSC (Thyristor Controlled Series Compensator) and TCPAR (Thyristor Controlled phase angle regulator) have been investigated for load flow environment with a view of improving transmission capabilities to reduce the system losses besides enhancing the loadability of the power system in (Hassan et al 2013).

1.4 THESIS SKETCH

This thesis comprises six chapters. A general introduction to power system network and a review of VS problems are presented in the first chapter. The need for newer solution methods is brought out in the same chapter. It also surveys the recent work carried out in the area of VS and enumerates the aim of this work.

The existing techniques for VS studies and the general corrective measures to be taken to circumvent voltage instability are outlined in second chapter.

The various types of FACTS devices and their mathematical modelling have been described in chapter three.

Elegant method involving BBO for minimising the network loss, improving VP and enhancing VS through FACTS placement has been proposed in chapter four.

The results for four cases with different objectives on three standard IEEE test systems have been presented to exhibit the superiority of the proposed method (PM) in chapter five.

The concluding remarks of the method discussed in chapter four and the direction for future work that can be done based on the techniques suggested in this report form part of the sixth chapter. It also includes the limitations of this dissertation.

1.5 SUMMARY

In this chapter, the general introduction of the power system, VS problem and the need for corrective measures have been outlined. A review of the research work carried out in the same area in recent years and the objective of this work along with the thesis sketch have also been narrated.