Chapter-1
Introduction

1.1 VOLTAGE STABILITY CONCEPTS

One of the most fundamental concepts in AC power transmission is stability. It is the property of the power system that enables its operation in the intended mode where power flows through entire network and the power angles have their magnitude within specified limits. This maintains synchronism between the synchronous machines (chief sources of power generation) and also ensures that the system voltage and currents do not exceed the rated values. Stability of an AC power system is also denoted by its capability to recover from planned and unplanned electrical disturbances and outages, viz. switching operation, faults, and variation in load demand etc.

Conventionally, power system stability has been classified in the different categories, viz. steady state, transient and dynamic stability. Steady state stability is the capability of the power system to remain in synchronism when the power flow is gradually increased. Steady state stability limit may be defined as the limit of maximum power flow beyond which instability occurs and the synchronous generators supplying powers through the line, loses synchronism. On the other hand, transient stability of a power transmission system is its inherent ability to recover normal operation following sudden and/or severe disturbances (e.g. the fault). Transient stability limit is characterised by the highest magnitude of power flow just prior to transient disturbance for which system can remain in synchronism once the transient fault is withdrawn or cleared. Again, dynamic stability is the capacity of a system to recover normal operation following a specific minor disturbance. Dynamic stability is frequently expressed in terms of rate of damping of components of performance parameters like voltages, currents, torque (or load) and angles of synchronous machines.

In addition to power flow (or angle) stability; voltage stability is also major criterion for successful AC power transmission. Transmission lines are frequently subjected to under-voltage and over-voltage problems and their performance is thus affected. Heavy loading is one of the prime reasons of under voltage. Open conductors, high resistance fault, starting of large motors are other sources of under-voltage. In reactive power constrained systems, heavy loading may create under-
voltage problems particularly affecting the performance of induction motors. Under-voltage during heavy loading condition also increases series reactive loss and under extreme conditions may lead to voltage instability. Voltage instability is characterised by a state of system when the receiving end voltage drops abnormally thus drawing high current from source and even when the power demand starts going down, the bus voltage goes on declining and the power angle between the two bus voltages may exceed their rated values for stable power transfer.

Owing to the risk of flashover and insulation failure, over-voltage is also treated as a dangerous operating condition. Ferranti effect and over capacitive compensation of any line are the commonest causes of steady state over-voltage in transmission lines. Switching faults and lightening are the conditions causing transient over-voltages.

1.2 VOLTAGE COLLAPSE PHENOMENA

Angle stability had been the primary concern of utilities for many decades. In eighties due to the declining investments in new generation and transmission facilities and because of growth of load demand, the system became stressed particularly the reactive power handling capability got affected resulting in a new phenomena named voltage stability. The role of reactive power in maintaining proper voltage profile in the system began receiving attention and initially being treated as a static concept, the importance of dynamics of machines, exciters, tap changers as well as dynamics of load were found to affect voltage stability significantly [1.12-1.14, 1.23, 1.59].

J. Deuse et al shows some examples of dynamic simulations of voltage phenomena using a new general purpose stability program (EUROSTAG) covering the classical fields of transient, mid-term and long-term stability, and also the quasi steady state conditions of a power system [1.12, 1.13].

Morison et al discussed voltage stability analysis of power systems using static and dynamic technique. Using a small test system, results of time domain simulations were presented to clarify the phenomenon of voltage stability for better understanding and modeling requirements. The same system was then analyzed using static approach in which modal analysis was performed using system conditions (or snapshots, which approximate different stages along the time trajectory). The results obtained using the static and dynamic methods were compared and were shown to be consistent [1.14].
However, system voltage instability can well be treated as a dynamic phenomenon \[1.13, 1.21, 1.23, 1.37\] and frequently in weak power system dynamic load increase or line tripping may create conditions, which would lead to voltage instability. The voltage collapse phenomenon is also to some extent dependent on load characteristics. Therefore load modeling plays a key role in voltage stability assessment \[1.33, 1.48, 1.53\]. Researchers have proposed a number of techniques to analyse voltage collapse phenomenon \[1.35\].

M. A. Pai et al reviewed the basic concepts of structural stability theory and demonstrated its application to multimachine power systems. Specifically, a connection between structural stability and bifurcation theory was established and they examined the effects of nonlinear loads as well as different sizes of induction motor loads on the structural stability limits. Detailed generator models were used in the study throughout. They concluded that in studying structural stability, load modeling is a crucial factor and needs more research \[1.33\].

In the literature, most available approaches to the voltage stability problem are either static or quasistatic, which do not take load dynamics into account. C. Dingguo and R. R. Mohler presented a survey of those approaches, made a comparison between them, and pointed out the possible consequences of not considering load dynamics, which at worst can be a complete voltage collapse. Based on this observation, modeling of load dynamics was considered in their paper, and neural networks including recurrent neural networks were applied for load modeling. Furthermore, they presented the strategies, for the first time, to incorporate the neural-network-based load model into static and dynamic voltage stability analysis. The computation of the relevant sensitivity was carried out for the neural-network-based load model, and the results were used in the popular modal analysis. The proposed methods were tested on both the IEEE 14-bus system and real data \[1.53\].

Conceptual and theoretical backgrounds of the voltage instability problems have also been established \[1.10, 1.12, 1.20, 1.24, 1.32, 1.34\] covering both the static and dynamic aspect of the problem \[1.16, 1.18, 1.47\].

T. Lie et al developed two methods of determining weak transmission stability boundaries based on the strong controllability and observability properties of power systems. This theory had been applied to a dynamical model of the generators and network. It was established that the network and generator states associated with a cluster of generators and load buses surrounded by weak transmission boundaries are
strongly controllable and observable for a single measurement and control at
generators or load buses in that bus cluster. Such a bus cluster is called a *control area*. Two methods of determining control areas, where strong controllability and
observability hold, were developed. Both methods attempt to determine weak
transmission stability boundaries that encircle control areas. The groups of generators
being identified, as the method described in [1.10] uses a rms coherency measure
evaluated for the set of all inertial load flow contingencies to determine groups of
coherent generators.

B. Lee et al have provided a tutorial introduction to the small-disturbance
voltage-stability analysis as applied to the structure-preserving power system model.
Salient features of this approach are inclusion of both dynamic and static models that
are relevant to voltage stability. The effect of load dynamics and generator current
limits had also been considered. Realistic load increases and a generation sharing
scheme with relevant limits were included. For a given load increase and generation
sharing scenario, all possible critical points that may lead to voltage instability were
systematically traced and identified [1.32].

Power systems in developing countries being basically ‘weak’ in nature, they
suffer from high nodal reactances, erratic outages, non-uniform load demand,
unplanned load growth and possess high susceptibility to real and reactive power
changes. They also have less number of EHV lines, lesser telemetering and advanced
control facilities, lower spinning reserve and financial constraints. The loadability
being lower, these systems are usually reactive power constrained and are
conventionally termed as *Longitudinal Power Supply (LPS) Systems* [1.21]. Further,
the continuous interconnection of these power networks, due to economical and
environmental measures, has led to increasingly complex operating problems [1.32].

The problem of voltage control and voltage stability in longitudinal power
supply (LPS) system has attracted much attention since last decade [1.1, 1.12, 1.14,
1.15, 1.17, 1.22, 1.37, 1.40] but its occurrence might not have been directly linked
with ‘angle instability’ [1.12, 1.14]. Voltage stability being one of the prime
requirements for proper control and assessment of security of LPS systems, it hinges
on the coordinated response of all voltage and reactive power status throughout the
network and it is very sensitive to changes in real and reactive power demands [1.22,
1.25, 1.37]. Studies of voltage collapse [1.11, 1.38] clearly indicate that voltage
instability becomes almost certain following large contingencies.
R. Yokoyama et al presented a flexible approach to a coordinated control of voltage and reactive power in order to enhance voltage security of an electric power system. The control strategy is expressed by simple rules, which measure the proximity of system state to certain operating conditions, and utilize linear equations to obtain the effective control models. The desired control actions are determined by considering several criteria at the same time. The procedure had been applied to a model system in order to verify its effectiveness. The simulation results showed the advantages of this approach over conventional expert systems for voltage-reactive power control [1.11].

T. Van Cutsen and C. D. Vournas [1.38] reviewed the general methodology of analyzing voltage stability in the mid-term and in the transient time scale. They demonstrated how a simplified simulation of the mid-term dynamics only could be combined with the analysis of ‘snapshots’ using a linearised model for the transient dynamics. Finally it points out how the stability of mid-term dynamics can be predicted using constant power loads in a transient time scale modeling.

Nowadays it is well appreciated that maintenance of good voltage profile is not alone sufficient to guarantee for voltage stability for changes in the network. M. K. Paul showed that when the characteristic of the composite load of a typical utility system is taken into account, large disturbance voltage stability is assured by the existence of the stable equilibrium state of the post-disturbance system, as determined from the standard power flow model. When the load contains static components, stability limits extend considerably. The exact limit for such loads can also be determined from a power flow model, properly modified to reflect the static component of the load. In specific situations, when the bulk of the load is composed of fast response loads, a correct assessment of voltage stability would require comprehensive analyses, employing detailed dynamic models of all system components. The use of the conventional power flow model may lead to considerable error [1.6].

1.3 STATIC VOLTAGE STABILITY AND LOAD FLOW STUDY

Voltage stability has long been categorised as a phenomenon that could be investigated using load flow methods [1.2, 1.28]. Newton-Raphson (N-R) load flow technique and Fast Decoupled Load Flow (FDLF) technique are widely accepted in load flow algorithm and it can even be well utilised in order to check the system
performance including system stability on off-line basis. The solution of the load flow equations is usually assumed to be the steady state solution of the power system. It is similar to the equilibrium point of the differential algebraic power system model during nominal load condition. The solutions may diverge once the power system is stressed [1.41]. Earlier researches have also indicated that when the voltage collapse region is approached, the load flow algorithm converges slowly or not at all and it becomes very difficult to find step-size to be used for next iteration [1.17].

P.W. Sauer [1.2] et al have established a relationship between a detailed power system dynamic model and a standard load flow model. The linearised dynamic model was examined to show how the load-flow Jacobian appears in the system dynamic state Jacobian for evaluating steady-state stability. Two special cases were given for the situation when singularity of the load-flow Jacobian implies singularity of the system dynamic state Jacobian.

T. J. Overbye and R. P. Klump [1.41] developed a method for reliably determining the set of low-voltage solutions, which are closest to the operable power flow solution. These solutions are often used in conjunction with techniques such as energy methods and the Voltage Instability Proximity Index (VIPI) for assessing system voltage stability. They presented an algorithm, which provides good initial guesses for these solutions. The results are demonstrated on a small system and on larger systems with up to 2000 buses. The development of the physical concepts and mathematical backgrounds of voltage stability has been done with basis on load flow solution feasibility [1.27], optimal power flow [1.49], bifurcation technique [1.9, 1.26] and singularity of Jacobian [1.2] etc.

As power systems become more heavily loaded, system operation will be increasingly constrained by contingent cases where the power flow equations have no real solutions. Since such cases often represent the most severe threat to system operation, it is critical that a computationally efficient method be developed to provide optimal control recommendations to mitigate these cases. T. J. Overbye developed such an algorithm. He quantified the degree of unsolvability using the distance in parameter space between the desired operating point and the closest solvable point. The sensitivity of this measure to different system controls was then calculated. These sensitivities were used to determine the best way to mitigate the contingency. The dynamic consequences of loss of solution were also discussed. The
method was demonstrated on a small system as well as on the IEEE 118 bus case [1.27].

V. Ajjarapu and B. Lee [1.9] presented a tutorial introduction to bifurcation theory and the applicability of this theory to study nonlinear dynamical phenomena in a power system network was explored. Systematic application of the theory revealed the existence of stable and unstable periodic solutions as well as voltage collapse. A particular response depends on the value of the parameter under consideration. It had been shown that voltage collapse is a subset of overall bifurcation phenomena a system may experience under the influence of system parameters. A low dimensional center manifold reduction was applied to capture the relevant dynamics involved in the voltage collapse process. The study also emphasises the need for the consideration of nonlinearity, especially when the system is highly stressed.

C. A. Canizares [1.26] discussed the relation between bifurcations and power systems stability through a thorough analysis of several examples, to clarify some ideas regarding the usefulness and limitations of bifurcation theory in network studies and operation, particularly in voltage stability related issues. Different types of load models were used in a sample system to analyse their effect on system stability and bifurcation. The Ecuadorian National Interconnected System (SNI in Spanish) was used to depict and discuss the effect of load modeling in saddle-node bifurcation analysis of real power systems.

1.4 VOLTAGE STABILITY INDICATORS AND VOLTAGE STABILITY MARGINS

For the past decade, electric utilities have paid attention to the problem of voltage instability due to the increasing loads and lack of transmission capability. Several power utilities even experienced voltage collapse. Therefore, investigation of a reliable approach for identifying the weakest bus/area, which causes voltage collapse, is extremely important. Methods employed for dealing with the problem of voltage collapse can be divided into two groups: the dynamic approaches and the static approaches [1.66]. The impacts of characteristics of generators, compensators, loads and on-load-tap-changers (OLTCs) are investigated in the dynamic approaches. These methods are based on the bifurcation theory, energy function and the theory of minimum singular value etc. On the other hand, each operating point could be computed with a proper static approach, since voltage instability can be considered as
a long term dynamical phenomenon. In these methods, the stability indices are achieved to show the viability of the system at the present condition by sensitivities. The critical point is obtained through the sensitivity.

At the present time, it has been an accepted proposition that that singularity of the Jacobian in the load flow solution indicates critical state of voltage [1.2] and the voltage stability index can be obtained from feasibility of the solution to power flow equations for each of the buses [1.18] on off-line basis. The achievements lie in the domain of static model as well as on dynamic voltage collapse models [1.14, 1.16, 1.18, and 1.34]. These models predict the proximity of the system near critical state and determine the reactive reserves etc. However, it is not usually frequently explored about the margin or proximity to the stability limit that is of concern to any system operator. In the operation of longitudinal power supply (LPS) system it is very much pertinent to investigate about voltage stability and security margins [1.17, 1.19, 1.24, 1.35, 1.41, 1.54]. Voltage stability problem can be effectively tackled by the inherent robustness of the system [1.39], which manifests some resistance to voltage collapse. Different voltage stability indicators (to forecast secured voltage stable states of a particular load bus) have also been developed during last two decades of the last century [1.18, 1.36]. Many researchers have proved that sensitivity analysis is as an efficient tool to assess voltage stability [1.7, 1.27, 1.29, 1.42]. Efforts have been made to determine suitable voltage stability indices to identify the weak/weakest bus in power system responsible for voltage collapse [1.10, 1.5, 1.25, 1.25, 1.52].

M. Begovic and A. Phadke [1.7] investigated the effects of static compensation on voltage stability boundary. For a class of voltage instabilities, which correspond to static bifurcations of load flow equations, minimum singular values of Jacobian matrix and total generated reactive power were calculated as indicators of stability margin, and sensitivity methods were used for reactive support allocation. Improvement in stability margin under progressive loading was investigated on a 39-bus test system for different allocations and amounts of reactive support with reactive generation capabilities taken into account.

A. C. Zambroni and V. H. Quintana [1.24] described that voltage collapse is associated with stress conditions of power systems. Control actions must provide the desired results; otherwise system may operate in an unknown condition. It had been shown that this unknown condition is associated with two regions of operation and the boundary between them. The boundary between the two regions was related to a
singular load-flow Jacobian. To identify the critical bus, a reduction of the load-flow Jacobian in relation to each load bus was developed. To reduce the computational burden associated with large power networks, network partitioning was proposed which was based on voltage variation at each load bus in relation to load variation at the other load busses. Comparison between the proposed method and network partitioning (using Sanchis’ method) was made and the weak area of a power system was identified in the network partitioning (a weak area was defined as the area that contains the critical bus of the power network). To calculate the margins for each load bus of the weak area, the relation between load variation at each load bus and voltage magnitude and phase angle variations at the critical bus was normalised, one by one. The busses strongly connected to the critical bus have smaller load variation in relation to the busses weakly connected to the critical bus. The proposed method has been tested using the IEEE 24-bus and 300-bus systems.

T. Van Cutsen dealt with the diagnosis of voltage collapse situations, following large disturbances and/or load increases [1.29]. A method had been proposed to identify the set of buses where load restoration is responsible for the collapse and to determine the corresponding corrective actions. It was implemented in a fast voltage stability simulator, using sensitivity techniques. Tap changer blocking and load shedding were illustrated on a real-life 410-bus system.

T. L. Le et al [1.43] proposed a comparatively newer approach of network equivalence technique to assess voltage stability. Their paper presented an application of the steady state network equivalents and expert system for voltage and reactive power (VAR) control in large-scale power systems. A steady state network equivalencing technique was used to construct the ‘three-tier’ subsystem, which is adequate to solve voltage violation problems. The expert system utilized the sensitivity tree method to select the optimal set of control actions to alleviate the voltage problem.

M. H. Haque proposed a simple and direct method of determining the steady state voltage stability limit of a power system when equipped with a Static Var Compensator (SVC) [1.50]. The maximum permissible loading of a particular bus in a power system was determined through a simplified equivalent model of the original system. The method was very efficient and does not require repetitive load flow simulations to generate the system $P-V$ or $Q-V$ curve. The effectiveness of the proposed method was then tested on a simple 2-bus system and the IEEE 14-bus
system. The effects of load power factor and SVC rating on voltage stability limit were also studied. The maximum permissible bus loading obtained by the proposed method in the IEEE system was also verified through recurring load flow simulations and were found to be in excellent agreement.

I. Musirin and T. K. Abdul Rahman [1.52] demonstrated the use of line stability index termed as fast voltage stability index (FVSI) in order to determine the maximum loadability in a power system. The bus that is ranked highest in this method was identified as the weakest bus since it can withstand a small amount of load before causing voltage collapse. The point at which FVSI close to unity was taken as indicator of the maximum possible connected load and has been termed as maximum loadability at the point of bifurcation. This technique was tested on the IEEE system and results proved the applicability of the proposed technique to estimate the maximum loadability in a system.

$P-V$ and $Q-V$ curves are commonly used to determine the steady state voltage stability limit of a power system. M. H. Haque presented a new method [1.51] of determining the voltage stability limit using the $P-Q$ curve. The boundary of the voltage stability region had been first determined and then presented in the $P-Q$ plane. For a given operating point, the voltage stability margin can easily be determined from the stability boundary in the $P-Q$ plane. The proposed method of determining the voltage stability limit was tested on a simple system and very interesting results were found. $P-V$ or $Q-V$ curves are also commonly used to determine the maximum permissible load (or static voltage stability limit) of a power system. M. H. Haque also presented [1.54] voltage versus current curve or $V-I$ characteristic as a tool to assess the voltage stability limit. It requires only bus voltage and current data at present, and some immediate past, operating points. The above data were processed through the least squares method to establish the $V-I$ characteristic. The extrapolated part of the characteristic was then used to estimate the critical load at the verge of voltage collapse. The proposed method does not require the knowledge of other system parameters or system-wide information. Any change in system condition usually modifies the $V-I$ characteristic and thus the effect of the change was indirectly incorporated in finding the critical load through the $V-I$ characteristic. The effectiveness of the proposed method was vigorously tested on the IEEE 30-bus system. Some of the results obtained by the proposed method were also
compared with the corresponding actual values found through repetitive power flow simulations and were observed to be in excellent agreement.

It has been observed from literature survey that most of the authors used the Jacobian of the load flow equations as the ‘workhorse’ for calculation of voltage stability; Kundur et al [1.8] probably had given more weightage in using reduced Jacobian matrix as well as modal form of analysis for assessing voltage stability. Kundur et al had analysed the voltage stability of large power systems using a modal analysis technique. The method computes a specified number of the smallest eigenvalues and the associated eigenvectors of a reduced Jacobian matrix using a steady state system model. A relative measure of proximity to voltage instability was provided from the eigenvalues each of which is associated with a mode of voltage/reactive power variation. The eigenvectors were used to describe the mode shape and to provide information about the network elements and generators, which participate in each mode. A simultaneous iterative method, which is well suited to applications involving large power systems, was used for selective calculation of appropriate eigenvalues. Results’ obtained using 3700-bus test system was presented illustrating the applicability of the approach.

Optimal Power Flow (OPF) techniques have also been used to assess voltage stability [1.4, 1.5, 1.20, 1.42, 1.55, 1.56]. Some researchers have incorporated contingency constraint in optimal power flow for proper voltage control in a power system [1.30].

T. Van Cutsen [1.4] proposed a method to compute the reactive power margin i.e., the difference between the maximum reactive load and the corresponding base case value at a given set of load buses of a power system. This margin was aimed at assessing the system robustness with respect to voltage collapse. The corresponding collapse point was directly obtained as the solution of an optimisation problem with the load increase as the objective, the non-optimised loads as equality constraints and the generator reactive limits as inequality constraints. The CRIC electrical decoupling yields a ‘voltage-only’ problem. The latter was solved using the Newton approach and a procedure was given to efficiently deal with the inequality constraints. A simple illustrative example is given as well as simulation results obtained on the Belgian 520-bus 41-generator system.

Y. Y. Hong and C.H. Gau [1.20] applied Newton optimal power flow technique (OPF) to identify the weakest bus/area, which is one of the most likely to
causes of voltage collapse. The $S$-$V$ curve (complex power to voltage) was examined via Newton OPF. Marginal costs (Lagrange multipliers) regarding power flow equations, VAR generations, voltages and taps, etc., to the system MW losses were obtained from Newton OPF. The weakest bus/area in the system was identified by an indicator achieved with these marginal costs via the Kuhn-Tucker theorem. This indicator helps users know which bus/area is most likely to cause voltage collapse. The IEEE 30-bus and a practical 251-bus systems were used to show the capability and feasibility of the proposed approach.

B. Cova et al [1,30] presented a preventive secure contingency constrained approach to the voltage profile optimisation suitable both for VAR planning and for short term reactive scheduling. The solution of the problems was based upon the implementation of two Optimal Reactive Power Flow (ORPF) programs: the first relevant to determining a workable state (security aspect), the second relevant to attaining the optimal and secure point (global target). The first ORPF was solved by recursively employing a linear programming algorithm, whilst the second one is based on the Han-Powell algorithm. Emphasis was given to the introduction of the contingency constraints in the ORPF models. The security constraints were explicitly introduced in the programs in order to obtain an operating point preventive-secure with respect to a selected contingency set. The performances of the procedures were shown by presenting the numerical results obtained from their applications to a small test network and to a large transmission system.

J. Y. Wen et al [1,55] developed an optimal coordinated voltage controller (OCVC) based on the spirit of model predictive control (MPC) method. The OCVC consists of three components, namely a predictor, a control candidate pool, and a selector. It had been used in secondary voltage control to coordinate dissimilar control actions at different geographical locations in order to maintain desired voltage profiles in a global sense in emergencies. A single-stage Euler state predictor (SESP) was utilised, based on the system model, to predict voltage performance under selected control actions; the selection of the optimum control action from the pool was a complex optimisation problem that was achieved by a Pseudogradient Evolutionary Programming (PGEP) technique. Simulation results on a six-bus benchmark system and the New England 10-generator-39-bus system were given to show the potential of this method for online usage.
C. M. Affonso et al [1.56] proposed a methodology to improve the power system economic dispatch from a voltage stability margin perspective. The time horizon under discussion was the short-term operation planning. The proposed method was based on active/reactive power re-dispatch for normal operation, and also minimum load shedding strategies in case of critical contingencies. The actions were taken in the direction provided by modal participation factors computed for generator and load buses. The generators with negative impact on system margin, which were indicated by the modal index, were penalized with high costs on the objective function of the optimal power flow program used to run the re-dispatch process. Results of this work demonstrated decrease on system losses and significant increase on voltage stability margin as well as on system reactive reserves. This work also presented a study considering critical contingencies, for which an optimal load shedding strategy was proposed based on modal participation factors to identify the most adequate buses for load shedding purposes. Finally, the proposed methodology was applied considering a typical hour-to-hour daily load curve, and the method presented very good performance since it considerably increases voltage stability margin for the insecure intervals.

S. Aboreshaid and R. Billinton [1.44] proposed probabilistic evaluation of voltage stability. They presented a contingency enumeration based approach to evaluate the voltage stability of a power system. The proposed approach includes the selection and evaluation of contingencies, the classification of contingency according to selected failure criteria and the accumulation of voltage stability indices. Voltage stability was quantified in the form of indices such as the probability and frequency of voltage instability and the expected voltage stability margin. Investigations using this approach had been conducted on a small test system and on the IEEE reliability test system.

A. B. Marques [1.58] presented a knowledge-based system for supervision and control of regional voltage profile and security using fuzzy logic. The control strategies were defined by system operators based on their experience and on off-line studies, which were translated into rules of a hierarchical fuzzy inference system (FIS). Two hierarchical levels, namely, task-oriented control level (high level) and set-point control level (low level) compose the control structure. The high-level control was comprised of a continuous FIS that updates high-side voltage set points at power plants, and a discrete FIS that switches capacitor/reactor banks at the transmission
network. The low level control was comprised of automatic voltage regulators and joint VAR controllers at the power plants. It was presented a simulation study in the Rio de Janeiro (Rio) Area, an energy importing region part of the South/Southeastern Brazilian system.

M.V.Suganyadevi and C.K.Babulal [1.65] estimated the margin in the loadability of the power system. Voltage Stability Indices can be useful for estimating the distance from the current operating point to voltage collapse point. The indices can either reveal the critical bus of a power system or the stability of each line connected between two buses in an interconnected network or evaluate the voltage stability margins of a system. The comparison of the performances of different indices presented and the effectiveness of the analyzed methods demonstrated through simulation studies in IEEE 14 bus reliability test systems.

1.5 MITIGATION OF VOLTAGE STABILITY PROBLEM

Power system performance basically depends on stability margin, system efficiency and loadability. Though these factors are inter-related, individually they can predict the performance of a power system network. Larger stability margin instigates formidable insulation against sudden and steady state disturbances. It also increases the loadability of a network, which is an essential requirement of modern power systems. This stability margin can be achieved by the improvement of voltage profile of a system. On the other hand the efficiency of a power system can be improved by reducing the power losses in the network. Hence both voltage profile improvement and loss minimization are quite imperative in power system networks. Without disturbing the generation and load conditions, external devices can be incorporated in predetermined locations to achieve better control over the power network. Flexible AC Transmission System (FACTS) controllers narrow the gap between the non-controlled and the controlled power system mode of operation, by providing additional degrees of freedom to control power flows and voltages at key locations of the network. The primary limitations of the transmission of power are high reactive power loss on heavily loaded conditions and line outages. As proclaimed earlier power system network can be modified to alleviate voltage instability or collapse by adding reactive power sources i.e. shunt capacitors and/or FACTS devices. Unlike shunt capacitor FACTS controllers can be connected as series or shunt compensator depending upon the topology of the network. FACTS
controllers such as STATCOM, SVC, TCSC, SSSC and UPFC are able to change the network parameters in a fast and effective way in order to achieve better system performance.

Adequate reactive power support at appropriate locations in order to improve the voltage profile is well understood and reported in literatures [1.11, 1.19, 1.25]. Voltage stability improvement by installation of static VAR compensator (SVC) in longitudinal or weak power system is not new and references [1.31, 1.47] suggested its applicability and utility in improving voltage stability and overall performance of LPS load buses.

R. R. Zalapa et al [1.25] has proposed a methodology in steady state to determine the output or setting of existing VAR/voltage control devices so that the allocation of reactive reserves guarantees that the system does not move towards voltage collapse as demand changes and that it will cope under credible contingency conditions.

M. Parniani and M. R. Iravani [1.31] made a comprehensive investigation on small-signal dynamic interactions of voltage control loops of multiple static VAR compensators (SVCs), the phenomena of SVC-network interactions, and torsional interactions with SVCs. Traditionally in optimal VAR planning, the feasible operation has been translated as observing voltage profile criteria ensuring that the system voltage profile is acceptable for system normal and post contingency conditions. This feasibility definition is not sufficient when considering the VAR planning practice of the utilities concerned with voltage stability problems. Presently, these utilities use two reinforcement criteria for VAR additions. While for VAR design in the regions the voltage profile criteria is considered, for bulk transmission system VAR resources are designed to guard against voltage instability. E. Vaahedi et al [1.45] reports on the findings of a completed EPRI project evaluating the existing Optimal VAR planning/OPF tools for voltage stability constrained VAR planning and voltage stability applications.

M. A. Kashem et al [1.46] performed network reconfiguration by altering the topological structure of distribution feeders. They proved that reconfiguring the network; voltage stability can be maximized for a particular set of loads in distribution systems. A new algorithm had been formulated for enhancement of voltage stability by network reconfiguration. The enhancement of voltage stability can be achieved by the proposed method without any additional cost involved for
installation of capacitors, tap-changing transformers and the related switching equipment in the distribution systems. It had also been shown that power losses were reduced when voltage stability was improved by network reconfiguration.

The amount of reactive reserves at generating stations is a measure of the degree of voltage stability [1.37]. Chakrabarti et al [1.3, 1.47] developed unique microprocessor based thyristor controlled method of controlling the VAR supply at the load node of a typical distribution system. The developed model was a totally software dependent static VAR compensator (SVC) enhancing its reliability and flexibility of control.

The emergence of FACTS devices and in particular GTO thyristor-based STATCOM has enabled such technology to be proposed as serious competitive alternatives to conventional SVC [1.64]. From the power system dynamic stability viewpoint, the STATCOM provides better damping characteristics than the SVC as it is able to transiently exchange active power with the system. The effectiveness of the STATCOM to control the power system voltage was presented in [1.65]. Abido [1.66] presented a singular value decomposition (SVD) based approach to assess and measure the controllability of the poorly damped electromechanical modes by STATCOM different control channels. It was also concluded that the STATCOM-based damping stabilizers extend the critical clearing time and enhance greatly the power system transient stability.

Many different techniques have been reported in the literature pertaining to investigating the effect of TCSC on system stability [1.62, 1.63]. Several approaches based on modern control theory have been applied to TCSC controller design. Chen et al. [1.62] presented a state feedback controller for TCSC by using a pole placement technique. However, the controller requires all system states, which reduces its applicability. Chang and Chow [1.63] developed a time optimal control strategy for the TCSC where a performance index of time was minimized.

In this review, the current status of power system stability enhancement using FACTS controllers was discussed and scrutinized. The essential features of FACTS controllers and their potential to enhance system stability were addressed.
1.6 ORGANIZATION OF THE THESIS

Chapter 1: Presents a detailed literature review on basic concepts of voltage stability, static voltage security and its determination using different methods.

Chapter 2: Here brief discussions have been made on relevant voltage stability & security indices to predict the proximity to the voltage collapse. A comprehensive comparison of the indices is provided in this chapter.

Chapter 3: Presents the formulation of load flow problem using N-R method to calculate the system state variable for different operating conditions and also discussions on steady state modeling of the three important Facts controllers namely SVC, STATCOM & TCSC and then the incorporation of these modes into load flow formulation is described.

Chapter 4: This chapter presents methodologies to assess voltage security of a multi-bus power system using network equivalents. A global voltage security indicator (GVSI) with the help of series network equivalent has been used to assess overall voltage security of a multi-bus power system. A local voltage security indicator (LVSI) using the concept of Thevenin’s equivalent has been proposed to assess local voltage security with respect to a particular load bus of the system. SVC, STATCOM and TCSC have been included in the mathematical model of Newton Raphson load flow study and their effect have been observed in improvement of voltage security using a robust practical 203-bus Indian eastern power (WBSEB) grid.

Chapter 5: This chapter deals with the voltage stability analysis of power system network with the help of network equivalent. Two voltage stability indicators i.e., Direct Voltage Stability Indicator (DVSI) and Fast System Voltage Stability Index (FSVSI) have been applied to assess overall system voltage security with help of network equivalent. The Direct System Voltage Stability Index (DSVSI) has also been calculated to assess local as well as overall system voltage stability. Another index called System Transmission Quality Factor (STQF) has also been proposed to monitor overall transmission quality of the interconnected power system in the context of voltage stability. Two FACTS controllers, STATCOM and TCSC have also been incorporated in the proposed system to observe their effectiveness and to
ensure voltage security. STATCOM has been found to be better to improve voltage security of power system as compared to TCSC. A methodology to obtain global critical loadability and corresponding global critical voltage for a multi-bus power system has also been proposed.

Chapter 6: This chapter deals with the load and loss allocation problem of any interconnected power system. In this chapter, an attempt has been made to minimize the transmission line loss using FACTS controllers. Two most commonly used FACTS controllers; TCSC and STATCOM are employed here to observe the effect of FACTS device in reducing the loss of the lines and to relieve the reactive burden in the generators. The contribution of system generators at a particular operating load has been calculated using power tracing algorithm and STATCOM is found to be most effective in order to reduce system generation as well as line loss. The analysis has been presented here using a robust practical 203-bus (Indian Eastern Grid) system,

Chapter 7: Provides a conclusion of the work presented, highlighting the main contribution of the proposed research work and suggesting possible directives for the future work.

1.7 BIBLIOGRAPHY


1.18 CIGRE Taskforce 38.02.11, “Indices predicting voltage collapse including dynamic phenomena”, Final report, July’1994.


1.59 T. Van Cutsen, and C. Vournas, Voltage stability of electric power system, (Book), KAP, Power Electronics and Power System.


