Chapter 1

Introduction

1.1 General

Voltage stability is one of the key concerns for power system researchers and utilities. Several incidences of voltage collapse caused as a result of voltage instability have been observed in different parts of the world [1-3]. Significant contributions have been made in estimation of voltage stability and planning remedial measures to prevent system failures initiated by voltage instability phenomenon. However, most of the research has concentrated on offline estimation of voltage stability margin. Online monitoring of voltage stability margin and its real time control at regular intervals is still a challenge. It seems feasible with the help of synchrophasor technology [4] to monitor voltage stability margin of online systems. Phasor Measurement Units (PMUs) placed at few selected locations may be able to monitor voltage stability margin of the system through its phasor measurements. Controllers may be tuned to PMU measurements to adjust their parameters based on voltage stability requirements. Thus, security of the power system networks may be enhanced through online monitoring and control of its voltage stability margin. In this thesis, attempt has been made to monitor voltage stability of the system through PMU measurements. Optimally placed Static Synchronous Compensator (STATCOM) has been considered in this work to control voltage stability margin in real time. Reactive power injection through STATCOM has been regularly varied depending upon the need to maintain voltage stability of the online system.

1.2 Literature Survey

Lot of research has been made in last few decades on voltage stability estimation of offline systems. Many researchers have worked in the area of static and dynamic voltage stability studies [5]. The minimum singular value of the power flow

Jacobian matrix was utilized as a static voltage stability index representing the distance between the current operating point and static voltage stability limit [6]. Parameter sensitivities of the Hopf and saddle node bifurcations were developed. It was observed that Hopf bifurcation depends on dynamic aspects of the load models [7-9]. The continuation power flow has been widely used in voltage stability estimation of offline systems [10]. Unlike Newton Raphson load flow, continuation power flow converges at and near the nose point. Using continuation power flow, it is possible to obtain static and modal indices for operation and planning of the system [11-12]. Continuation power flows though accurately estimates voltage stability margin, is not suitable for online studies due to its computational involvement.

With advancement in Wide Area Measurement System (WAMS), it seems possible to monitor voltage stability of online systems. D. Arias et. al. [13] proposed WAMS based voltage stability indicator that considers operating limits such as reactive power reserves, voltage limits. In Wide Area Measurement System, Phasor Measurement Units (PMUs) play an important role. PMU has become more attractive to power system engineers as it can provide time synchronized measurements of voltage and current phasors. Time synchronization is achieved through same time sampling of voltage and current waveforms using timing signals obtained from Global Positioning Systems (GPS) [4], [14-15]. PMUs may play an important role in online monitoring of voltage stability margin. However, due to high cost, it is practically not feasible to install PMUs at all the buses of the system. So, an attempt is required to be made to reduce the number of PMUs to be installed. The concept of optimal PMU placement has been a highly researched topic since the deployment of PMUs in practical systems [16]. Literature available on optimal PMU placement has considered methods based on (a) topological aspects and (b) system aspects [17]. References [18-21] used integer linear programming techniques based on binary search algorithm for optimal placement of PMUs to ensure complete observability of the system. D. Dua et. al. [22] proposed a two indices approach having the bus observability index and the system observability index. References [23-24] used integer quadratic programming and genetic algorithm for minimizing the number of PMUs maximizing the measurement redundancy. Optimal placement of PMUs based on observability factor analysis, sequential orthogonalization algorithm and coherency identification technique has been considered [25-26]. Optimal placement of PMUs utilizing the concept of depth of unobservability to ensure real time monitoring of critical buses has been proposed [27]. Antonio C. Zambroni de Souza et. al. proposed a new methodology for online voltage stability assessment based on time evolution of the power system operating state with the help of forecasting-aided state estimator [28]. Voltage collapse point was determined through an extrapolation technique using tangent vector behaviour. This method considers only local load monitoring [29]. M. Zhou et. al. gave the concept of state estimation using phasor measurement units [30]. The Tellegen's Theorem and adjoint networks were used to derive a new local voltage stability index [31]. Sandro Corsi et. al. proposed the voltage stability risk indicator based on local phasor measurements [32]. The risk indicator was based on the computation of Thevenin equivalent of the power system network in real time. Online voltage stability monitoring and control using PMUs considering Thevenin's model has been considered [33-38]. However, Thevenin's model is valid for linear approximation of power system networks.

Artificial Neural Network (ANN) based methods for online voltage stability monitoring and control have been proposed [39-42]. Debbie Q. Zhou et. al. reported an ANN based method for quickly estimating the long term voltage stability margin under contingencies [43]. The ANN based method proposed in [43] may not be suitable for online voltage stability estimation under varying load conditions [44]. ANN based voltage stability assessment utilizing PMU measurements has been reported [45]. However, this method has not been tested under dynamically changing loads. Hybrid Artificial Neural Network and Genetic Algorithm (ANN-GA) technique for online monitoring of long-term voltage stability utilized the genetic algorithm (GA) to improve the accuracy of ANN by tuning its meta-parameters such as number of nodes in hidden layer, input and output activation function and learning role [46-48]. In this approach, voltage magnitude and phase angle are obtained from PMUs and these are used as input vectors that gives outputs in form of voltage stability margin index vector.

Over the years, researchers have relied on generator var reserves to guarantee the voltage stability level of a power system network. In [49], it has been shown that impact of var reserves on voltage stability is area-dependent. L. Sandberg et. al. [50] suggested utilization of switched capacitors to maintain var reserves in a system. Bonneville Power Administration (BPA) developed a system that can monitor key generators for voltage stability monitoring and control [51]. In this work, an index was introduced that measures the total var reserve level and the voltage stability level in a system. A small value of index indicates the shortage of var reserve level. However, this method did not quantify the relationship between the var reserve level and voltage stability in a system. It has been noticed that the var reserves of key generators can indicate the degree of controllability of key bus voltages in a power system. This observation leads to development of few var reserve monitoring systems. With the use of corrective relationship between generator var reserves and system voltage stability margin, practical and systematic method for online voltage stability monitoring has been addressed [52-55]. However, a need for alternative methods was realized that can capture the correlation between the system margin and var reserves to provide better system margin information. Bruno Leonardi et. al. [56] have reported the use of reactive power reserve as an indicator to determine voltage stability margin in an online environment. The methodology depends upon the relationship between system reactive power reserve and voltage stability margin. In this case, statistical multi regression models are utilized to express variations in reactive power reserve transformed to provide information about voltage stability margin. The methodology proposed in [56] has not concentrated on finding a pattern recognition tool that enables operations to identify the approximate multi linear regression model to be used at each instant in the online environment [57].

A number of voltage stability indices based on PMU measurements have been proposed [58-65]. All such indices have diverse interpretations. The computational simplicity of these methods makes them suitable for real time applications, but the accuracy of these methods is restricted by the information obtained from a single location [66-75].

Lack of reactive support at weak buses has been identified as one of major causes for voltage instability. Unlike real power, transmission of reactive power becomes difficult in heavily loaded networks. Therefore, installation of local var sources at critical buses seems a viable solution for maintaining voltage stability. With advancement in power electronics technology, new controllers known as Flexible AC Transmission Systems (FACTS) have emerged [76] that can control reactive power injection to critical buses and lines. These controllers include series controllers such as Thyristor Controlled Series Capacitor (TCSC), and Static Synchronous Series Compensator (SSSC), shunt controllers such as Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM), series-shunt controllers such as Unified Power Flow Controller (UPFC), and series-series controllers such as Interline Power Flow Controller (IPFC). Though all such controllers may be effectively utilized in control of voltage stability margin, shunt controller can directly control reactive power injection to critical buses. STATCOM seems to be more effective in control of voltage stability margin compared to SVC as its reactive power injection/absorption is independent of bus voltage, whereas, reactive power injection/absorption by SVC is proportional to square of the voltage. Therefore, SVC provides less reactive support near nose point compared to STATCOM. Considering cost of the device and for maximizing benefit, STATCOM is to be optimally placed at critical buses. Many strategies have been suggested in literature for optimal placement of STATCOM. Such strategies include determination of critical bus based on L-index [77], P-V and Q-V curves based techniques [1], [78]. Particle Swarm optimization based approach for optimal placement of STATCOM has also been suggested [79-80].

1.3 Motivation

From the limited literature survey carried out in this thesis, it is observed that lot of contributions have been made in voltage stability estimation of offline systems. However, very limited effort seems to be made in voltage stability monitoring of online systems. Online monitoring of voltage stability margin seems possible through placement of PMUs at selected locations. Considerable research has been made in optimal placement of PMUs to ensure complete network observability. However, no effort seems to be made in optimal placement of PMUs based on voltage stability criterion. Significant research is available in literature on optimal placement of STATCOM to enhance voltage stability margin. However, studies have been mainly carried out on seeing impact of STATCOM placement in voltage stability enhancement of offline systems. Voltage stability control of real time systems through reactive power injections/absorption by STATCOM is still a challenge. Therefore, motivations behind work carried out in this thesis are:

- To develop a methodology for optimal placement of PMUs based on voltage stability criterion to ensure full network observability even in case of loss of few PMUs.
- To develop an approach that accurately determines voltage stability margin of online systems through PMU measurements.
- To develop an online voltage stability monitoring scheme based on PMU measurements.
- To develop a strategy for online control of voltage stability margin through optimally placed STATCOM in the system.

1.4 The Main Objectives of the Thesis

The following are the main objectives of the thesis:

- An effective strategy is to be developed for optimal placement of PMUs based on voltage stability criterion.
- A methodology is to be developed for voltage stability estimation using optimally placed PMUs.
- An algorithm is to be developed for real time monitoring and control of voltage stability margin using PMU measurements.
- A scheme is to be developed for real time enhancement of voltage stability margin with the help of optimally placed STATCOM.

1.5 Thesis Organization

The thesis has been organized in following six chapters:

The **Chapter 1** introduces the general introduction on impact of voltage instability in power networks around the world and the role of PMUs in monitoring voltage stability of real time systems, presents a brief literature survey on voltage stability estimation, monitoring and control, and sets motivation behind the work carried out in this thesis.

In **Chapter 2** optimal placement of PMUs considering impact of voltage stability based critical contingencies has been proposed. Contingencies have been ranked based on voltage stability margin (the distance between the base case operating point and nose point). Variations in voltage stability margin caused by changing load patterns have also been considered while deciding critical contingencies. PMUs have been placed in the system based on results of binary integer linear programming run under system intact case and voltage stability based critical contingency cases. Effectiveness of proposed PMUs placement approach has been established by comparing nose curves obtained using PMUs measurements and pseudo-measurements under increased demands, with offline estimation of nose curves based on the results of continuation power flow. Case studies have been performed on a standard IEEE 14-bus system, New England 39-bus system, and practical 246-bus Northern Regional Power Grid (NRPG) system representing power network of nine states (including two union territories) of India, with the help of Power System Analysis Toolbox (PSAT) software.

Online estimation of voltage stability margin must be fast. Therefore, in **Chapter 3** quadratic fitting of nose curves (loading factor versus bus voltage magnitude curves) based on measurements obtained from PMUs at only three operating points has been proposed. Proposed estimation of nose curves have been compared with nose curves estimated by continuation power flow method. Case studies have been performed on IEEE 14-bus system, New England 39-bus system and 246-bus Northern Regional Power Grid (NRPG) using Power System Analysis Toolbox (PSAT) software. Simulation results show that proposed approach of quadratic fitting of nose curves using PMU measurements quite matches with nose curves obtained by continuation power flow method. Therefore, proposed approach seems to be more effective in voltage stability assessment of real time systems.

In **Chapter 4,** voltage stability monitoring in real time framework using synchrophasor measurements obtained by PMUs has been carried out. Proposed approach estimates maximum real power as well as reactive power loadability of most critical bus using PMU data. As system operating conditions keep on changing, maximum loadability as well as critical bus information is updated at regular intervals using fresh PMU measurements. Simulations have been carried out using Power System Analysis Toolbox (PSAT) software. Accuracy of proposed Wide Area Monitoring System (WAMS) based estimation of voltage stability margin has been tested by comparing results with maximum loadability obtained by continuation power flow method (an offline approach for accurate estimation of voltage stability margin) under same set of operating conditions. Case studies performed on IEEE 14-bus system, New England 39-bus system and a practical 246-bus Indian power system validate effectiveness of proposed approach of online monitoring of maximum loadability.

In **Chapter 5,** online control of voltage stability margin through optimally placed STATCOM is suggested. STATCOM has been placed at the most critical bus based on lowest real power and reactive power loadability of the system under critical contingencies for different patterns of load increase. Considering STATCOM placement to be an offline strategy, its optimal location has been obtained based on simulations carried out for offline system. However, control of voltage stability margin through optimally placed STATCOM has been considered for online system. Reactive power injection/absorption by STATCOM has been adjusted based on voltage stability margin estimated by proposed approach using real time phasor measurements obtained by PMUs. Thus, STATCOM is capable to enhance voltage stability margin in real time. Case studies have been performed on IEEE 14-bus system, New England 39-bus system and NRPG 246-bus system.

Chapter 6 presents the main contributions of research work carried out in this thesis and provides some suggestions for future research work in this direction.