2014-10-02

Sensitivity and Bias Based Receding Horizon Multi Step Optimization (RHMSO) Controller for Real Time Voltage Control

KULOTHUNGAN, MADHUMATHI

KULOTHUNGAN, MADHUMATHI. (2014). Sensitivity and Bias Based Receding Horizon Multi Step Optimization (RHMSO) Controller for Real Time Voltage Control (Master's thesis, University of Calgary, Calgary, Canada). Retrieved from https://prism.ucalgary.ca. doi:10.11575/PRISM/27751

http://hdl.handle.net/11023/1903

UNIVERSITY OF CALGARY

Sensitivity And Bias Based
Receding Horizon Multi Step Optimization (RHMSO) Controller
For Real Time Voltage Control

by

Madhumathi Kulothungan

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

CALGARY, ALBERTA
SEPTEMBER, 2014

Abstract

A simplified multi-step optimization approach for the correction of violating transmission voltages is developed and analyzed in this thesis. The contribution of this thesis are two fold.

A receding horizon multi-step optimization (RHMSO) controller which utilizes a linearized system model is developed. This linear system model is derived from the non-linear steady state power flow equations based on sensitivity analysis. A comparison is made with single step optimization based on Model Predictive Control (MPC) to test the performance of the proposed multi step approach. Results show significant reduction in load shedding with a smoother system response.

In addition, the concept of bias based error correction is introduced in the linear system model mentioned above. A comparison is made between the bias and non-bias based controllers. The results show that the bias based RHMSO with linear system model provides decrease in settling time and significant reduction in load curtailment, thus achieving better system performance.

Acknowledgements

I would like to take this opportunity to express my sincere gratitude to everyone who helped and guided me throughtout the course of my program without which this thesis would not have been possible.

I thank my supervisor, Dr. William.D.Rosehart for taking me under his wing. His encouragement, patience and constructive criticism helped me to overcome all obstacles and to complete my thesis. I would also like to thank Dr. Mevludin Glavic for introducing me to the research topic and for giving his time for all the long discussions which helped me expand my knowledge and develop my thesis. I would like to extend my gratitude to Dr. Hamid Zariepour, Dr. Laleh Behjat, Dr. David Westwick and Dr. Rassouli, all of whose courses helped me to widen my knowledge in the respective areas.

I would like to thank Mr. Mahdi Hajian for his valuable technical discussions during the course of my research work.

I thank Monishaa, my first research partner who have been like my family during my stay here at Calgary. I would like to thank all my lab mates especially Ehsan and Babatunde for their timely help in reviewing my thesis work. I would like to appreciate the support of my friends in Calgary especially, Anand, Suhas, Siva and Poornima who have been like my family.

I would like to acknowledge my husband, Vivek Pandurangan without whose support, love and encouragement, I would not have completed my thesis smoothly.

Finally, a huge thanks to my parents, my sister and friends Aurelia, Gayathri, Aishwarya and Abhilasha in India. I am grateful for their continued love and support without which I would have never made it this far.

To my family, friends

and to my beloved husband

Table of Contents

List of Tables

List of Figures and Illustrations

List of Symbols, Abbreviations and Nomenclature

Symbols	Definition
Abbreviations:	
AVR	Automatic Voltage Regulator
FACTS	Flexible AC Transmission
GAMS	General Algebraic Modelling System
HVDC	High Voltage Direct Current
IPOPT	Interior Point Optimizer
LTC	Load Tap Changer
MPC	Model Predictive Control
OPF	Optimal Power Flow
OXL	Over Excitation Limiter
PMU	Phasor Measurement Unit
PV	Power Voltage
RHC	Receding Horizon Control
RHMSO	Receding Horizon Multi Step Optimization
SCADA	Supervisory Control And Data Acquisition
SSO	Single Step Optimization
WAM	Wide Area Monitoring

Indices:

i	index for control variables
j	index for time horizon
k	initial time step

Sets, Parameters and Variables:

λ	variable of interest
$\triangle$	limit for rate of change of controls
$\triangle F$	deviation in frequency
a	vector of algebraic variables
$bias_v$	bias term for voltage sensitivity constraints
$bias_{qg}$	bias term for reactive power sensitivity constraints
gb	number of generator buses
K	control and prediction horizon
lc	number of load buses allocated for load curtailment
n	number of control variables
$n1$	number of generator voltage set points
$n2$	number of load shedding
nb	number of all the buses
P_{pf}	generators active power involved in primary frquency control
P_{pf}^0	initial or base active power generation
Q	vector of reactive power of generators
R	generators speed droop involve in primary frequency control
S	Sensitivity matrix
$u(0^-)$	pre-disturbance control values
u	vector of control variables
$u1$	vector of generator voltage set points
$u2$	vector of load shedding
V	vector of system voltage magnitudes
w_i	costs corresponding to controls
x	vector of state variables

Chapter 1

Introduction

1.1. Overview

Increased complexities in nature, size and operation of modern power system has thrown up numerous technical challenges. Of this, voltage stability and control has gained prominence during the last decade. Voltage stability is defined as the ability of the system to restore the voltages back to the acceptable range after the occurrence of any kind of disturbance [1] [2] [3] . The recent blackouts experienced across the world has alarmed power system operators and has necessitated the need for providing faster control actions to maintain the system under stable operating condition [4] [5] [6]. This has kindled the interest in academia to develop and implement new and fast techniques of emergency controllers for voltage control.

Voltage stability analysis based on time span can be classified as short term and long term stability. Short term voltage stability focuses on the first few seconds after the occurance of a disturbance whereas long term voltage stability deals with the next few minutes. Long term voltage stability analysis can further be classified based on control approaches as off-line and on-line voltage control schemes. This thesis focuses on on-line voltage control which provides corrective control actions for violating voltages in real time. Here, an on-line voltage control is implemented using a simplified Receding Horizon Multi-Step Optimization (RHMSO) controller. The two major simplifications made in the development of simplified RHMSO controller are as follows:

- Transforming the non-linear steady state system model into linear system model based on sensitivity analysis.

- Addition of bias based error corrector in the system constraints for enhanced control performance.

The ability of the proposed controller to provide satisfactory control measures is studied in this thesis. To be best of the author's knowledge, the concept of bias based error correction control has not been utilized in the application of power system stability and control.

1.2. Literature Review

In this section, a brief review of voltage stability, sensitivity analysis and Model Predictive Control (MPC) based optimization approaches for on-line voltage control is provided.

1.2.1. Review on voltage stability and control

During emergency conditions, the power system may experience wide disparities between available and required reactive power to maintain adequate system voltages [1] [2] [3]. This eventually leads to voltage instability problems and its severity has lead to blackouts around the world. Prime examples would be the August 14, 2003 blackout which affected various parts of the US and Canada [4], September 28, 2003 in Italy [5] and November 4, 2006 blackout in parts of Europe [6]. All three blackouts experienced significant voltage instability problems. In [7], primary causes of outage and recommendations for future protection of power system is explained in detail.

In [8], explanation and illustration of problems; research challenges regarding voltage and reactive power control is explained. An analysis on the design and implementation emergency voltage stability controls in power systems is examined in [9]. A detailed review of the theory and practice tools available for voltage stability assessment is discussed in [10]. Simple and effective ways of identifying voltage collapse point by accounting for real time measurements under various system specifications has been demonstrated in [11]. A brief explanation on voltage management, voltage stability assessment and real-time voltage control is also presented. In [12] the system voltage oscillations are examined and new control scheme for voltage stability is proposed. Secondary voltage control schemes are discussed and a novel scheme for local secondary voltage control is presented [13].

1.2.2. Review on sensitivity analysis for voltage control

In sensitivity analysis [3], the sensitivity of a system variable is measured based on the influence of changes in control variable to that of the system variable. In power system analysis, the system model is represented as non-linear steady state power flow equations. Sensitivity analysis is used to transform these non-linear system equations to linear equations based on sensitivity matrices of state and control variables as illustrated in [3].

Usage of sensitivities in voltage control applications is not new. A voltage control algorithm is presented in [14] that involves calculating the sensitivities of reactive power generation with respect to active and reactive loads at various locations. An analysis of voltage collapse due to large disturbance is studied and corrective voltage control measures are implemented based on sensitivity analysis in [15]. In [16] and [17] sensitivity analysis based co-ordinated control schemes are presented and explained in detail. Sensitivity based analysis to overcome the occurrence of unstable or low voltages caused by disturbances such as load increase or line outage is dealt in [18]. In [19] sensitivity based control approach for voltage stability margins is presented where sensitivity analysis is involved in a time-domain simulation. Sensitivity analysis for voltage stability assessment and control is addressed in detail in [20]. A method that involves trajectory sensitivity approach in [21] [22] is used for emergency voltage control. Sensitivities between the reactive power generation and reactive power loads are calculated in [23]. The paper also analyses the characteristic of maximum loadability point and uses voltage phasors from PMUs for voltage instability detection. In

[24] a sensitivity based decentralized voltage control method is proposed where sensitivities of voltages with changes on injected active and reactive power is calculated. In [25] reactive power sensitivity index is applied to obtain the weakest bus in the system for voltage stability analysis of a real system. In [26] and [27] load control scheme involving sensitivity analysis for voltage stability and control are presented.

1.2.3. Review on MPC based optimization approaches for on-line voltage control

Model Predictive Control (MPC) is a real-time control method which has found recent interest in power system control applications. It involves obtaining chain of future control actions based on the present measurements and system model over a time horizon. The controller implements only the first sequence of control actions and repeats the same procedure in the next time step with new measurements.

The MPC controller often uses the differential algebraic equations for modelling the dynamic system responses. In [21] and [22] MPC based on trajectory sensitivity analysis is used for voltage stability assessment and emergency controls. A coordinated control approach based on MPC is presented in [22] for protection from voltage collapse. MPC and tree search optimization approach for co-ordinated voltage control is represented in [28] and [29]. Voltage stability based on control of load shedding that involves the MPC mechanism is addressed in [30]. A centralized MPC control scheme using lagrangian decomposition method is adopted for emergency voltage control in [31]. A comprehensive study on model predictive control with constraints is provided in [32] and [33]. In [34] an optimal coordination voltage controller involving MPC scheme is presented. Secondary voltage control based MPC for large power systems is presented in [35]. In [36] MPC based control algorithms for optimal control of transmission voltages are demonstrated. A two-stage MPC algorithm for overcoming voltage collapse is addressed in [37]. The first stage is prediction stage where a static load shedding algorithm is applied and the second stage is correction stage where based on predictions and trajectory sensitivities a linear program is applied to obtain optimal controls. In [38] capacitance control strategy that involves MPC based trajectory sensitivity approach to prevent voltage collapse situation is presented. A multi-step receding horizon controller based on MPC approach is applied to reduce long-term voltage instability and provide corrective control actions for voltage control in [39]. A quadratic optimization approach involving MPC based centralized control routine is applied to regulate the distributed network voltages in [40].

1.3. Research motivation & contributions

Voltage stability analysis is of great importance for proper planning and operation of power system. It is necessary to preserve the bus voltages within the specified limits for stable and reliable operations. This thesis focuses on the performance of a simplified multi step MPC based optimization approach with linearized system model for the application of on-line voltage control. In addition a bias term is introduced in the linearized system model which serves as an error controller. The motivation of the research work is to utilize the above mentioned concepts to develop a voltage controller which can achieve the following objectives:

- Minimize the total amount of load curtailment
- Provide faster system and control response
- Minimize control effort

The controller is based on Receding-Horizon Multi-Step Optimization (RHMSO); an expansion of single step optimization (SSO) controller explained in [39].The problem formulation of the simplified RHMSO varies from [39] as follows:

- Reduction in problem formulation complexity: The non-linear steady-state system constraints are replaced by the linear sensitivity based system constraints. By this replacement, all the constraints in the problem formulation are linear thereby reducing the computational complexity of the problem.
- Incorporation of bias term: A bias error corrector is included in the above transformed linearized system constraints. The bias term is a form of feedback based on the difference between the measured value of the parameter at the present step and the predicted value of the parameter obtained from previous step. Chapters 3 and 4 provides a detailed explanation about the sensitivity constraints and bias term.

The linearization of the system constraints is based on the sensitivity analysis between the state and control variables. The state variables are the bus voltages and generator reactive power and the control variables are the generator voltage set points and load shed. The two linearized system constraints are the voltage sensitivity constraint and the generator reactive power constraint which are similar to the equation in [41]. However, the voltage sensitivity constraints considered in the present formulation accommodates all the bus voltages instead of just the load bus voltages as in [41]. Thus, complete information of the system measurement is taken into account.

The simplified on-line voltage control scheme is verified through case studies in which long term voltage instability is investigated. Initially a disturbance is introduced in the form of line outage in the central area of the Nordic-32 test system which eventually makes the system unstable. The system being unstable is indicated by voltage collapse thereby pointing out the necessity for voltage control. So the required control actions are performed upon the detection of the disturbance in order to bring the bus voltages back to the specified limits and maintaining system stability. In addition, different contingencies such as increment in load demand, stable but low voltage conditions and partial control failure are considered for analysis.

The contributions of the research work can be pointed out as follows:

- To demonstrate a simplified Receding-Horizon Multi-Step Optimization (RHMSO) approach with sensitivity based system model.
- To introduce and highlight the significance of incorporating bias based error corrector in the linearized system model.

1.4. Organization of the thesis

Chapter 2: A detailed description on the concept of voltage stability and control is provided. An illustration of PV curve and brief description of control components is explained. Sensitivity analysis which is of key interest is explained and its formulation derived in this chapter. A general introduction to Optimal Power Flow (OPF) for real time voltage control along with a brief discussion on Single Step Optimization (SSO) approach is also presented.

Chapter 3: This chapter explains in detail about the simplified Receding Horizon Multi Step Optimization (RHMSO) controller with the sensitivity based system model. MPC method is briefly illustrated with an example. A comprehensive explanation of the RHMSO approach that forms the basis of the proposed controller is presented. The problem formulations and solution approaches for the proposed simplified RHMSO sensitivity based controller is explained in detail. Simulation results are analysed and discussed for different scenarios. A comparison with single step MPC based controller is made to discuss the effectiveness of the proposed controller.

Chapter 4: This chapter explains in detail about the addition of a bias term to the simplified RHMSO sensitivity based controller that is applied for real time voltage control. The formulation of the bias term along with its implementation in the optimization routine is presented. Simulation results are presented along with the comparisons made with other controllers in order to highlight the effectiveness of using the proposed bias based scheme.

Chapter 5: A summary of the major research contributions of the thesis along with scope of future works is listed out in this chapter.

Chapter 2

Background review

2.1. Introduction

A stable power system aims to maintain system equilibrium during normal operating conditions and under the influence of a disturbance. Stability analysis involves identification of factors that contribute to instability problem and also development of methods to overcome it. The following are some factors that are to be accounted for stability analysis [2]:

- The physical nature of instability.
- Size of the disturbance.
- The equipments, processes and time span considered for assessing stability.
- The appropriate methods for calculation and prediction of stability.

Based on time span, stability analysis can be classified into short term (first few seconds) and long term (last few minutes). Short term analysis comprises of angle stability and short term voltage stability. Short term stability analysis focuses on fast acting system components such as induction machines, HVDC converters etc which can bring the system back to stable condition within a few seconds. Long term analysis comprises of frequency stability and long term voltage stability. Long term stability focuses on slower control devices such as Load Tap Changers (LTCs), generation excitation limiters and system wide controllers.

2.2. Voltage stability and control

2.2.1. Voltage instability

Voltage instability is usually caused by the inability of the system to meet the required reactive power demand. Such condition can arise during system disturbances such as,

- Line/generator outages
- Increase in demand beyond the power transfer capability

Long term voltage instability manifests itself as a small voltage drop across the system which eventually progresses to voltage collapse contributing to a system wide blackout [4] [5] [6].

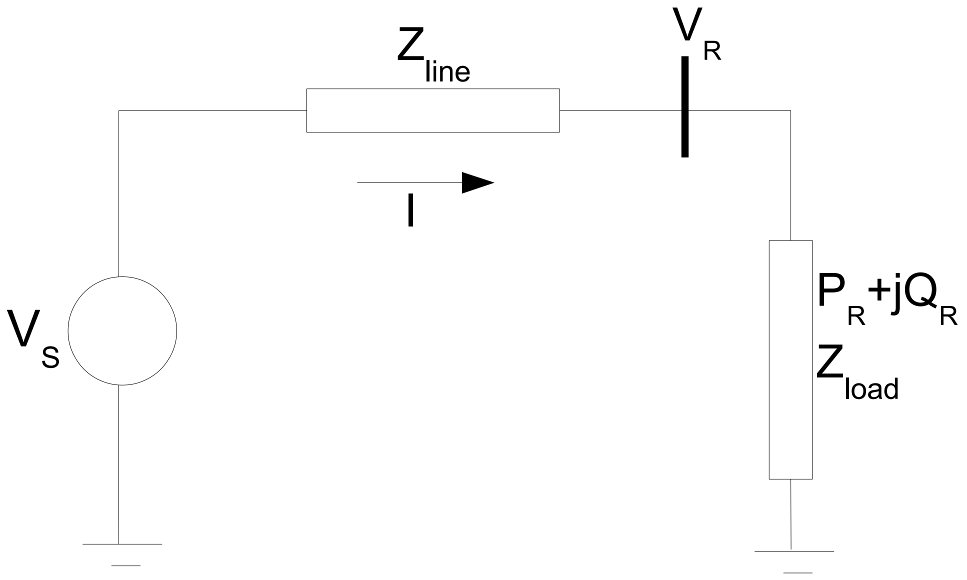

Figure 2.1: A 2 bus system used for demonstrating the concept of voltage stability (adapted from [3])

Voltage instability can be demonstrated using a two-bus system shown in Figure 2.1 [2]. The two bus network consists of a constant voltage source V_s supplying load Z_{load} through a series line impedance Z_{line} with the respective phasor angles ϕ and θ. $P_R + jQ_R$ are the active and reactive power loads respectively.

The magnitude of I is given as,

$$I = \frac{V_s}{\sqrt{(Z_{line}cos\theta + Z_{load}cos\phi)^2 + (Z_{line}sin\theta + Z_{load}sin\phi)^2}} \tag{2.1}$$

The above expression can be simplified as,

$$I = \frac{1}{\sqrt{F}}\frac{V_s}{Z_{line}} \tag{2.2}$$

where

$$F = 1 + \left(\frac{Z_{load}}{Z_{line}}\right)^2 + 2\left(\frac{Z_{load}}{Z_{line}}\right)cos(\theta - \phi) \tag{2.3}$$

The expression for I can also be written with respect to load as,

$$I = \frac{V_R}{Z_{load}} \tag{2.4}$$

From the equations (2.2) and (2.4), we get the magnitude of voltage at the receiving end to be,

$$V_R = \frac{1}{\sqrt{F}}\frac{Z_{load}}{Z_{line}}V_s \tag{2.5}$$

The active and reactive power supplied to the load is expressed as,

$$P_R + jQ_R = I(V_Rcos\phi + jV_Rsin\phi) \tag{2.6}$$

$$P_R = I(V_Rcos\phi) = \frac{Z_{load}}{F}\left(\frac{V_s}{Z_{line}}\right)^2 cos\phi \tag{2.7}$$

From the above expressions, let us consider V_R,I and P_R as a function of load demand $\frac{Z_{line}}{Z_{load}}$ with $tan\theta = 10.0$ and $cos\phi = 0.95$.

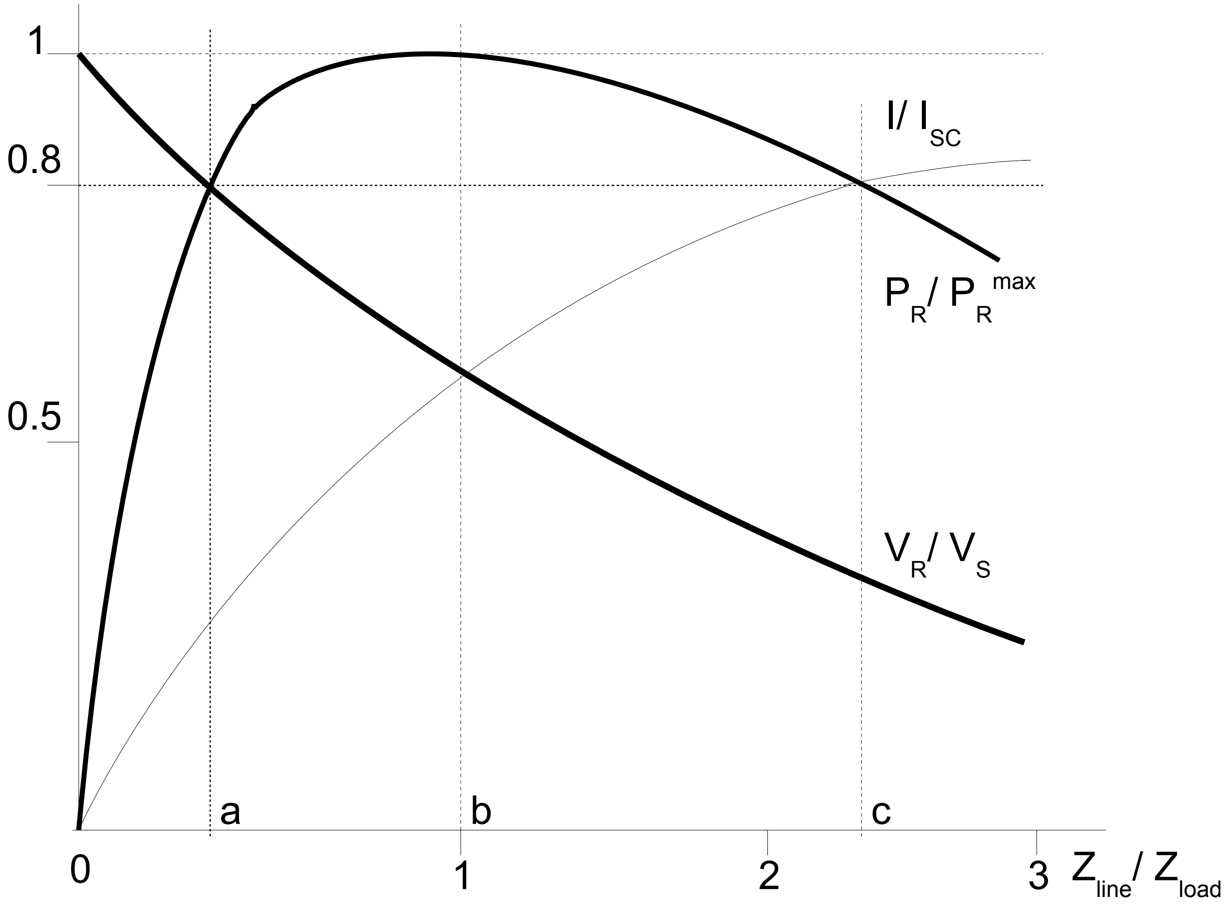

Figure 2.2: Evolution of V_R,I and P_R as a function of $\frac{Z_{line}}{Z_{load}}$ with $tan\theta = 10.0$ and $cos\phi = 0.95$ for the two bus system considered (adapted from [2])

In Figure 2.2, a, b, c indicates the normal operating region, the critical region and the abnormal operating region respectively.

When the load demand gets increased

- The receiving end voltage V_R gets decreased and the current I gets increased
- The active power supply P_R gets increased initially and decreases gradually

There is an initial increase in active power P_R as the load demand gets increased with reduction in Z_{load}. When $\frac{Z_{line}}{Z_{load}} = 1$ the active power reaches the point where it is maximum P_R^{max}

with decreasing V_R. The maximum power point represents the limit at which satisfactory operating condition is possible. Load characteristics play an important role in determining the voltage stability. With constant impedance load, the system is stable with lower levels of power and voltage whereas for a constant power load, the system becomes unstable through voltage collapse.

The relationship between P_R and V_R is of key interest for voltage stability analysis. The PV characteristics is influenced by the load power factor as evident from equation (2.7). Figure 2.3 represents the PV curve that can be divided into two parts as,

- Stable operating condition denoted by the curve above point P_R^{max}
- Unstable operating condition denoted by the curve below the maximum point.

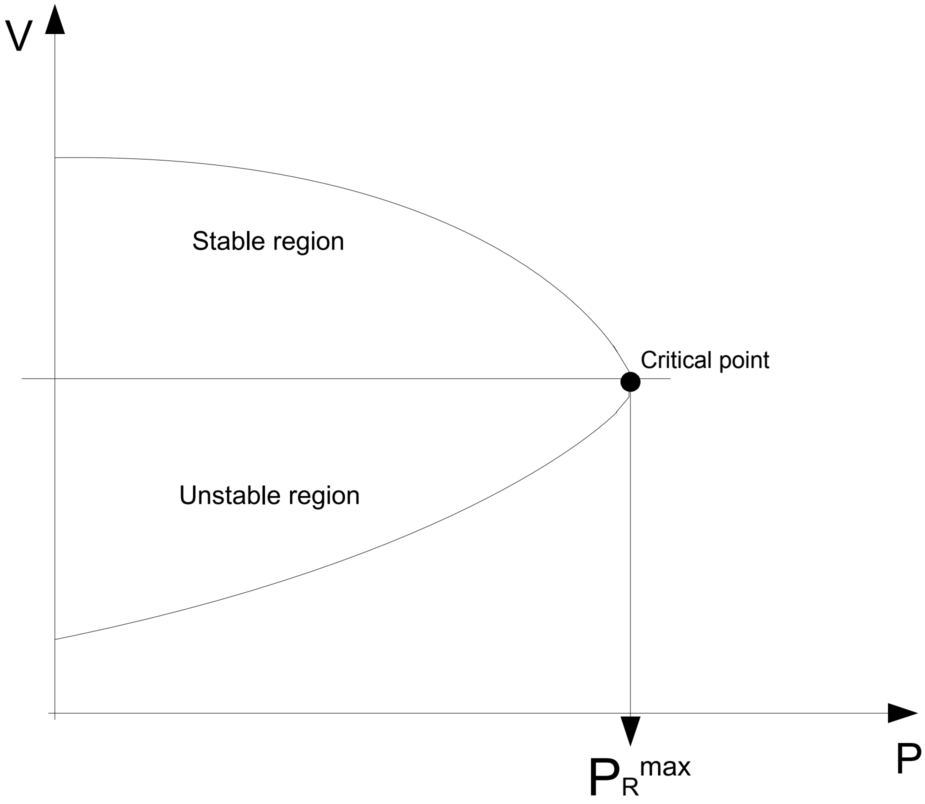

Figure 2.3: PV curve

The PV curve can be described as follows. When the power P_R is increased initially, the voltage drops gradually with increase in load current. Further increase in P_R, which is beyond the maximum P_R^{max} point, the voltage decreases drastically dominating the increase of I leading to degradation in the power to be delivered.

2.2.2. Control components

For long-term voltage stability analysis, Load Tap Changers (LTCs) and Over Excitation Limiters (OXLs) play an important role in maintaining system stability. The LTCs alter the tap ratio which raises the voltages in order to revive the distribution voltages within the desired range. The OXLs help in maintaining the reactive power generation by limiting the exceeding generators field current.

2.2.2.1 Load Tap Changers (LTC)

On - load tap changers provide restoration of distribution voltages within limits by altering their tap ratios that eventually restores load [3] [1]. The tap change in LTCs is based on the difference between the measured and specified voltages in the distribution side. If this difference exists over a particular period the tap change takes place one at a time where a minimum of 5 seconds is considered for realizing the tap change process. When the system experiences a disturbance, the voltage levels drop thereby decreasing the load powers which is a function of voltages. The LTCs immediately come into play to restore the voltage levels to the pre - disturbance values.

2.2.2.2 Over Excitation Limiters (OXL)

The purpose of OXLs or field current limiters is to provide protection from overheating of field windings of generators caused by increase in field current [42]. The field current is allowed to increase initially post disturbance, reaching a maximum level and then gets limited to avoid overheating of generators. When the system is subjected to disturbance, there is an increase in reactive power losses due to imbalance in network power flow. This increases the requirement of reactive power support which leads to increase in field current. The OXLs detect the increment in field current and tries to limit it where the reactive power support is also limited finally reaching voltage collapse condition [42] [43].

2.2.3. Voltage collapse and control

When the system is not able to maintain its reactive power demand, it experiences a combination of events that progressively leads to voltage collapse. Voltage collapse can be prevented by accounting for proper system design and operating measures pertaining to system control and compensation devices. Different control approaches are developed for both short term and long term voltage stability. Emergency controllers are designed for providing faster control measures during short term instability scenarios where the time interval between the initial disturbance and final collapse point is in seconds [9]. Coordinated and cost effective controllers are designed for long term instability which provides longer time to react [44] [16].

The thesis assumes the short term dynamics to be stable and focuses on transmission voltage control for long term stability analysis. The control approaches involved in long term instability prevention can be characterized as off-line or on-line.

- The off-line control approach pertains to obtaining optimal control actions with new stable operating point for a given anticipated load and generation.
- The on-line control approach is a real time control scheme where corrective control measures (emergency controls) are obtained when severe disturbance

affects the system stability.

The on-line control approach is studied and analyzed in this thesis. The general framework and constraints over which the on-line control approach is formulated and simulated is addressed below.

The system measurements such as voltages and generator power output snapshots are assumed to be collected at a sampling period of 10 s. This is accomplished by Supervisory Control And Data Acquisition systems (SCADA) or through Wide Area Monitoring (WAM) where the measurements are enhanced by the Phasor measurement units (PMUs) [24] [11].

In general, the transmission voltages are supposed to be maintained within a specified interval [39],

$$V_{min} \leq V \leq V_{max}$$

where V is the vector of voltage magnitudes and the upper and lower limits of voltages are denoted by V_{max} and V_{min} respectively. The main goal of the problem is to correct the voltages that deviates this specified limit.

Generator voltage set points and load shedding are the control variables chosen for correcting the unsatisfactory voltage condition. The problem formulation can also be extended to include other controls such as shunt capacitance, transmission line tap changers and Flexible AC transmission systems (FACTS). Each controller is associated with cost where the generator voltage set point cost is less than load shedding based on the priority of preferences.

The limits on the reactive power generation must also be satisfied when the transmission voltages are being corrected,

$$Q_{min} \leq Q \leq Q_{max}$$

where Q is the vector of reactive power of generators and the upper and lower limits of generator reactive power are denoted by Q_{max} and Q_{min} respectively. Based on the generator capability curves, the reactive power of generators is dependant upon active power of generators and terminal voltages where the limits on Q gets updated.

To analyse the performance of the controller, a severe disturbance condition such as transmission line outages is considered for the evolution of long term instability problem in the system. In addition, contingencies such as gradual increment in demand and depressed voltages at certain load buses (under stable condition) are also examined.

2.2.4. Sensitivity analysis

One of the important aspect of power system analysis is the identification of the operating point of the system that approaches the loadability limit. In sensitivity analysis, eigenvalue techniques are used for identification of critical operation point beyond which the system becomes unstable [3]

In power systems, any change in the output of control devices can provide considerable impact on the network power flows and voltages. These impacts can be measured by utilizing sensitivity analysis. The measure on the influence of any change in control variable u to the variable of concern p determines the sensitivity of p with respect to u. The mathematical representation of this sensitivity denoted as $S_{p,u}$ can be defined as,

$$S_{p,u} = \frac{dp(x,u)}{du}$$

This formulation holds for the system under equilibrium condition i.e $x = x_0$ and $u = u_0$.

2.2.4.1 Derivation of sensitivity equations

In this thesis, sensitivity analysis is utilized to obtain a linear system model. Based on sensitivity analysis explained in [3], the power flow equations can be represented as,

$$f(a, u) = 0 \tag{2.8}$$

where a and u represents the vectors of algebraic and control variables. A variable of interest say λ is considered where $\lambda(a, u)$. The sensitivity of λ with respect to control variable u can be obtained by the following derivation:

The equation $\lambda(a, u)$ is differentiated by chain rule method,

$$d\lambda = \frac{\partial \lambda}{\partial a} da^T + \frac{\partial \lambda}{\partial u} du^T \tag{2.9}$$

The differentiation of (2.8) yields,

$$\frac{\partial f}{\partial a} da + \frac{\partial f}{\partial u} du = 0 \tag{2.10}$$

$$da = - \quad \frac{\partial f}{\partial a}^{\ -1} \frac{\partial f}{\partial u} du \tag{2.11}$$

where $\frac{\partial f}{\partial u}$ is non-singular. Substituting equations (2.11) in (2.9) provides, (assuming $\frac{\partial \lambda}{\partial u} = 0$)

$$d\lambda = \frac{\partial \lambda}{\partial a} \left[- \quad \frac{\partial f}{\partial a}^{\ -1} \frac{\partial f}{\partial u} du \right]^T \tag{2.12}$$

$$d\lambda = - \left[\quad \frac{\partial f}{\partial a}^{\ T} \right]^{-1} \quad \frac{\partial f}{\partial u}^{\ T} \frac{\partial \lambda}{\partial a} du^T \tag{2.13}$$

Thus the sensitivity $S_{\lambda,u}$ is obtained as,

$$S_{\lambda,u} = \frac{d\lambda}{du^T} = - \left[\quad \frac{\partial f}{\partial a}^{\ T} \right]^{-1} \quad \frac{\partial f}{\partial u}^{\ T} \frac{\partial \lambda}{\partial a} \tag{2.14}$$

where $\frac{\partial f}{\partial a}$ and $\frac{\partial f}{\partial u}$ denotes the Jacobian or the partial derivatives of f with respect to a and u respectively.$\frac{\partial \lambda}{\partial a}$ denotes the gradient of λ with respect to a. It is to be noted that sensitivities depend on inverse of $\frac{\partial f}{\partial a}$.

The condition for loadability limit is that the Jacobian $\frac{\partial f}{\partial a}$ should be singular given as,

$$|\frac{\partial f}{\partial a}| = 0 \tag{2.15}$$

The sensitivities become larger and tends to infinity as the loadability limit is approached.

The sensitivity matrices are obtained from the steady state non-linear active and reactive power flow equations. Considering the system to be in equilibrium condition, the power flow equations can be represented as follows:

$$P_i = |V_i| \sum_{j=i}^{n} |V_j| \quad G_{ij}cos\theta_{ij} + B_{ij}sin\theta_{ij} \tag{2.16}$$

$$Q_i = |V_i| \sum_{j=i}^{n} |V_j| \quad G_{ij}cos\theta_{ij} - B_{ij}sin\theta_{ij} \tag{2.17}$$

where P_i and Q_i are the active and reactive power injections; the bus voltage magnitudes of node i and j are denoted as V_i and V_j; the bus conductance and susceptance are G and B respectively and the difference in phase angles denoted by θ_{ij}.

The above equation is non-linear in nature, however it can be linearized with the help of Jacobian matrices as follows,

$$[\triangle P \quad \triangle Q]^T = [J][\triangle\theta \quad \triangle V]^T \tag{2.18}$$

The mismatch vectors are $\triangle P$ and $\triangle Q$ representing the incremental change in active and reactive power injection. The incremental change in bus phase angles and voltage magnitudes are indicated by $\triangle\theta$ and $\triangle V$ respectively. The Jacobian matrix J comprises of the partial derivatives of P and Q with respect to θ and V.

The sensitivities of changes in voltages and reactive power of generators with respect to the changes in the control variable such as generator voltage set points and load shedding are considered in the proposed optimization problem. These equations form the replacement for the non-linear power flow equations. The explanation of the considered sensitivity equations is provided in the next chapter.

2.3. Optimal Power Flow (OPF) for real time voltage control

Optimal power flow (OPF) technique proposed by Carpentier proves to be a powerful optimization tool that is useful in solving a well-defined problem. In general, an OPF problem is non-linear which provides solutions to minimize a power system based objective function for a given set of equality and inequality constraints (network power flow equations, system and equipment operating limits) [45] [46].

The OPF technique tends to be the gateway to a wide range of optimization approaches for applications pertaining to power system planning and operation. A survey on optimization approaches for wide range of power system applications involving different objective functions (cost and loss minimization problems) is discussed in [45]. As stated earlier, this thesis focuses on optimization approach for real time voltage control application. In general, the mathematical formulation of OPF for real time voltage control can be formulated as follows:

$$min \qquad F(x,u) \tag{2.19}$$

$$s.t \qquad G(x,u) = 0 \tag{2.20}$$

$$H^{min} \leq H(x,u) \leq H^{max} \tag{2.21}$$

$$x^{min} \leq x \leq x^{max} \tag{2.22}$$

$$u^{min} \leq u \leq u^{max} \tag{2.23}$$

x corresponds to the state variables (voltage magnitude and angles, non-controlled active and reactive power of generators and loads) and u corresponds to the control variables (generator voltage set points, load shedding). The objective function is represented by (2.19) where $F(x, u)$ denotes the cost function that include the deviations in the considered control variables. The equality constraint is represented by (2.20) where $G(x, u)$ denotes the steady state system model which are the non-linear active and reactive power flow equations (supply demand balance). The equations (2.21)-(2.23) represents the inequality constraints which includes the upper and lower bounds for transmission lines, bus voltages, generator reactive power and control variables. The methods available to solve an OPF problem can be grouped into conventional and intelligent methods [47] [48]. The gradient base, newton method, linear and quadratic programming and interior point method form the conventional methods. Artificial neural networks, Genetic Algorithm, Partical swarm and ant colony algorithms form the intelligent methods.

2.4. Single Step Optimization (SSO)

Several optimization approaches have been developed and implemented for the application of power system planning and operations over the years [48]. There is a growing interest in handling and overcoming voltage instability problems through implementation of optimal control actions. There are many voltage controllers which are bend on OPF techniques described in section 2.3 [48]. Single step optimization (SSO) approach is one among them. SSO approach can be regarded as an open-loop controller that computes optimal control actions for only one time step. The following sections give a brief review about SSO, its formulation and drawbacks.

2.4.1. Problem formulation

The mathematical formulation of SSO approach is similar to OPF where the objective is to minimize the deviation in the control effort and provide optimal control actions. The mathematical formulation is as follows:

$$\min_{u} \sum_{i=1}^{n} w_i(u_i - u_i^{0-})^2 \tag{2.24}$$

$$s.t \quad g(x, u, s^{0^-}) = 0 \tag{2.25}$$

$$u^{min} \leq u \leq u^{max} \tag{2.26}$$

$$V^{min} \leq V(x, u) \leq V^{max} \tag{2.27}$$

$$Q^{min} \leq Q(x, u) \leq Q^{max} \tag{2.28}$$

$$P_{pf}^{max} \leq P_{pf}(x, u) \leq P_{pf}^{max} \tag{2.29}$$

$$P_{pf}^{j}(x, u) = P_{pf}^{o} + \frac{\triangle F}{R} \tag{2.30}$$

Here x is the state variable and u is the control variable. The state variable comprises of load bus voltage magnitudes and phase angles whereas the control variables comprises of generator voltage set points and load shedding. The number of available controls are denoted by n. w_i represents the cost associated to each control action. u^{0-} represents the pre-disturbance value. Also s^{0^-} is the pre-disturbance load values considered for load power restoration. V denotes the bus voltage magnitudes and Q denotes the reactive power of the generators. An addition to the SSO formulation presented in [39] would be the distributed slack bus which provides proper distribution of active power of generators that are active in the primary frequency control. P_{pf}^{0} is the base case generator active power and P_{pf} is the active power of generators in primary frequency control. The generators speed droop and the frequency deviation are denoted by R and $\triangle F$ respectively.

The objective of the optimization problem is to minimize the difference in control effort along with its associated cost. Thus, the controller provides optimal control actions to correct the undesired voltages causing system collapse. The objective function (2.24) is a quadratic non-linear formulation.

The system model is represented by (2.25) which is a steady state power flow equation of the system, expressed below:

$$P_g - P_l - P_{br} = 0 \tag{2.31}$$

$$Q_g - Q_l - Q_{br} = 0 \tag{2.32}$$

(2.31) and (2.32) are the active and reactive power flow equations respectively where P_g,P_l and P_{br} indicates the active power generation,load demand and the line flows respectively. In the same manner the reactive power generation,load demand and the line flows are indicated as Q_g,Q_l and Q_{br} respectively. The active power branch/line flow equation denoted by P_{br} can be expressed as,

$$P_{br} = \sum_{j=1}^{n} |V_i||V_j|(G_{ij}cos(\delta i - \delta j) + B_{ij}sin(\delta i - \delta j)) \tag{2.33}$$

The voltages of i^{th} and j^{th} buses are denoted as V_i and V_j respectively. The bus conductance and susceptance are G and B and the difference the bus angles are denoted by δ. The reactive power flow equations are modelled in a similar manner. The obtained system model is a non-linear constraint.

The upper and lower bounds are provided for the control variables, bus voltages and reactive power of generators that are denoted by constraints (2.26), (2.27) and (2.28) respectively. The constraint (2.29) and (2.30) are related to the distributed slack bus where the limits on active power of generators in primary frequency control are provided in (2.29).

2.4.2. Drawbacks of SSO

The following are few disadvantages of SSO when applied to real time voltage control :

- Inability to handle model inaccuracies and measurement errors
- Unaccountability of new events and control changes

SSO does not handle any model inaccuracies imposed on the final system settings and operation point. As it is an open loop control scheme, there is no way to provide corrections for the outcome due to single step evaluation. It does not compensate for changes reflected in the controls due to some failures or uncertainty in system behaviour. A transition that is required for the obtained target state is not given by SSO. This leads to unsatisfactory transients due to implementation of only optimal controls obtained in one time step.

In order to overcome the drawbacks of SSO, a multi-step optimization approach based on model predictive control (MPC) mechanism is explained in detail in chapter 3.

2.5. Summary

In this chapter, a general explanation with mathematical background for voltage stability and control is presented. The relationship between power and voltage is demonstrated using a PV curve denoting the stable and unstable regions. A framework for the voltage control problem that aims at providing corrective control measures to overcome the long-term instability problem is examined. A mathematical background on sensitivity analysis which is necessary to formulate a linear approximation of power flow equations utilized in the proposed problem formulation is presented. An introduction to OPF related to real time voltage control problem and a detailed description on SSO applied to on-line voltage control scheme is discussed.

Chapter 3

Simplified RHMSO controller for on-line voltage control

3.1. Introduction

In this chapter, an RHMSO approach that utilizes sensitivity based linear system model for on-line voltage control application is proposed. The proposed controller is an extension of SSO approach such that the optimization routine is distributed in multiple steps instead of single step [39] [41]. The RHMSO controller addresses the drawbacks of SSO approach thereby resulting in better performance.

The goal of the proposed RHMSO controller scheme based on model predictive control (MPC) is to provide corrective control measures for alleviating long-term voltage instability. Generator voltage set points and load shedding are the control outputs considered in this problem. Instead of using the steady state non-linear power flow equations, the RHMSO controller uses a linearized system model based on sensitivity analysis.

The proposed sensitivity based RHMSO controller is different from [41] in the following aspects:

- The proposed controller computes control actions in multiple steps instead of single step. The objective function considered in the proposed method is a quadratic non-linear cost function which minimizes control deviations.

- The voltage sensitivity constraint includes the sensitivities of all bus voltages to controls instead of just the load bus voltages.

3.2. Model Predictive Control (MPC)

Model predictive control is a real time control technique widely used in many control applications. The MPC mechanism comprises of both simultaneous prediction of future system behaviour and computation of optimal control signals for the system. MPC basically solves an open loop control problem that optimizes the objective function subjected to equality and inequality constraints over a finite time horizon [32] [33]. MPC algorithms vary based on the objective function, type of system model and constraints considered. MPC finds its application in various fields such as process industries, aerospace, oil and gas, power system utilities and robotics [49].

An example of MPC in real life can be related to driving a car (i.e) the person driving the car knows the route (which is the reference trajectory) to reach the destination. The driver is able to predict and determine the driving actions necessary to reach the destination (following the trajectory). The driving actions refer to the steering, acceleration and brakes involved.

The advantage of using MPC lies in the fact that it lends itself well to multivariable problems. It is easy to implement and can be used to provide control from simple applications to complex, dynamic and unstable systems. And most importantly, it helps the system to be operated quite close to its operation limits which is of key importance in voltage control. On the contrary, MPC models are often complex as it requires a large number of coefficients to define a response. In addition, many process have wide range of operating conditions and necessitates a need for non-linear model to provide better control performance. Both the above factors increase the computational complexity of MPC. In addition, for adequate control performance, an appropriate problem formulation should be chosen, which may not be easily available for many control applications.

MPC solves an optimization problem providing optimal control actions over a finite time horizon. It can also be referred as Receding Horizon Control (RHC) as the time horizon gets shifted forward. The operating principle of MPC is as follows:

- At time step k, the MPC predicts the future evolution of the system over the prediction horizon T_p.
- Simultaneously, MPC also computes a sequence of optimal control actions ($U1$,$U2$, etc) over the control horizon T_c.
- At the next time step $k+1$, the first sequence of control actions computed in the previous step is implemented. Simultaneously, new measurements are taken and the control and prediction horizon are updated thereby repeating the optimization routine.

A pictorial demonstration of the basic procedure of model predictive control is depicted in Figure 3.1

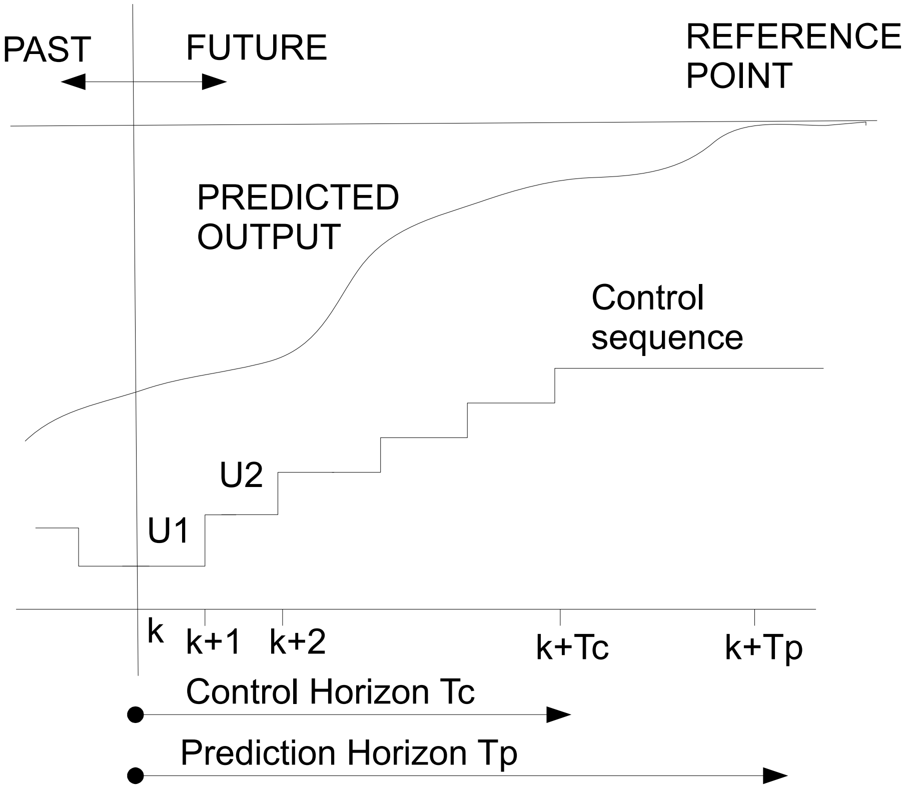

Figure 3.1: Model predictive control mechanism [41]

3.3. Receding Horizon Multi Step Optimization (RHMSO)

To overcome the disadvantages of SSO, an MPC based multi step control approach (RHMSO) is considered for controlling the transmission voltages. In general, non linear power flow equations are used as system constraints. However, the proposed RHMSO controller uses a linearized steady state model based on sensitivity analysis. Description of the sensitivity based linear system constraints, its usage in the problem formulation and the solution approach is described below:

3.3.1. Sensitivity based linear system constraints

Usually, the steady state power flow equations used are non-linear [39]. However, in the proposed controller, the non-linear power flow equations are linearized using the concept of sensitivity analysis. This transformation is similar to the one proposed in [41].

Under equilibrium conditions, the steady state power flow equations are represented as:

$$\phi(u, a) = 0$$

where u and a represents the vector of control and algebraic variables respectively. A variable of interest η which is a function of u and a is considered. The sensitivity of the variable of interest η with respect to the control variable u is formulated as stated in [3] as:

$$S_{\eta,u} = -\phi_u^T (\phi_a^T)^{-1} \bigtriangledown_a \eta \tag{3.1}$$

Here $S_{\eta,u}$ is the sensitivity matrix that corresponds to the sensitivity/impact of the change in control variable to η. The Jacobian of ϕ with respect to u(a) is denoted as $\phi_u(\phi_a)$. $\bigtriangledown_a \eta$

represents the partial derivative of η with respect to a.

The sensitivity based system constraints are the voltage sensitivity constraint (3.2) and the generator reactive power constraint (3.3)

$$V_{nb}^{j} - V_{nb}^{j-1} - S_{nb,gb} \sum_{i=1}^{n_1} (u_{1,i}^{j} - u_{1,i}^{j-1}) - S_{nb,lc} \sum_{i=1}^{n_2} (u_{2,i}^{j} - u_{2,i}^{j-1}) = 0 \tag{3.2}$$

$$Q_{gb}^{j} - Q_{gb}^{j-1} - S_{gb,gb} \sum_{i=1}^{n_1} (u_{1,i}^{j} - u_{1,i}^{j-1}) - S_{gb,lc} \sum_{i=1}^{n_2} (u_{2,i}^{j} - u_{2,i}^{j-1}) = 0 \tag{3.3}$$

Each of the sensitivity constraints consists of the sensitivity matrices denoted by S. S gives the measure for the change in state variables (voltages and reactive power generators) to the change in control variables (generator voltage set points and load shedding). The notations nb, gb and lc indicates the number of buses, generator buses and load curtailable buses respectively. $S_{nb,gb}$, $S_{nb,lc}$ denotes the sensitivity matrices used in voltage sensitivity constraint where nb, gb and nb, lc indicates the size of the sensitivity matrices. Specifically in (3.2) voltage sensitivity constraint represents the changes in voltage magnitudes on all buses $(V_{nb}^{j} - V_{nb}^{j-1})$ as a function of change in controls such as generator voltage set points $(u_{1,i}^{j} - u_{1,i}^{j-1})$ and load shedding $(u_{2,i}^{j} - u_{2,i}^{j-1})$. Similarly in (3.3) generator reactive power constraint represents the changes in reactive power on generator buses $(Q_{gb}^{j} - Q_{gb}^{j-1})$ as a function of change in generator voltage set points $(u_{1,i}^{j} - u_{1,i}^{j-1})$ and load shedding $(u_{2,i}^{j} - u_{2,i}^{j-1})$.

3.3.2. Proposed problem formulation

The mathematical formulation of RHMSO is an extension of SSO control scheme explained in previous chapter. The problem formulation is given below:

$$\min_{u^{k+1},...,u^{k+K}} \sum_{j=k+1}^{k+K} \sum_{i=1}^{n} w_i(u_i^j - u_i^{j-1})^2 \tag{3.4}$$

$$\forall j = k+1...k+K$$

$$s.t \quad g(x^j, u^j) = 0 \tag{3.5}$$

$$u^{min} \leq u^j \leq u^{max} \tag{3.6}$$

$$|u^j - u^{j-1}| \leq \triangle \tag{3.7}$$

$$V^{min} \leq V^{k+K}(x,u) \leq V^{max} \tag{3.8}$$

$$Q^{min} \leq Q^{k+K}(x,u) \leq Q^{max} \tag{3.9}$$

$$Q_i^{min} \leq Q(x^j, u^j) \leq Q_i^{max} \qquad i \epsilon G(k) \tag{3.10}$$

$$P_{pf}^{max} \leq P_{pf}^j \leq P_{pf}^{max} \tag{3.11}$$

$$P_{pf}^j(x,u) = P_{pf}^o + \frac{\triangle F}{R} \tag{3.12}$$

The objective of the optimization problem is to minimize the deviation in control variables which is distributed over the specified time steps $j = k+1, ..., k+K$ where K is the control/prediction horizon. The objective function (3.4) is a quadratic non-linear formulation. The explanation for each term used in the problem formulation is provided in detail under the section (2.4.2) of SSO.

In the proposed RHMSO controller, the constraint (3.5) represents the linearized steady state system model derived from the non-linear power flow equation based on sensitivity analysis denoted by (3.2) and (3.3). The constraints (3.5) is distributed over j time steps (

consists of one set of (2.2) per time step). The remaining constraints represent the upper and lower bounds provided for each parameters considered. Constraint (3.6),(3.7),(3.8),(3.9) and (3.10) represents the limits on the controls, bus voltages and reactive power production respectively. The constraint (3.10) is related to the intermediate time steps that applies to few $G(k)$ generators that are explained later in this chapter. The limits are imposed only to the final step (the end of control horizon) bus voltages and reactive power of generators. $\triangle$ that represents the limits on the rate of change of control variables is provided denoted by constraint (3.7). The constraints (3.11) and (3.12) represents the distributed slack bus which is considered in all the future time steps.

3.3.3. Solution approach

The solution approach of RHMSO approach is similar to MPC control scheme explained as follows [33] [39]:

1. At time k which is considered as initial step, all the necessary measurements are collected and sensitivities are calculated.
2. Optimization routine is executed for the specified time horizon and a sequence of control actions $u^j(\forall j = k+1, ..., k+K)$ is obtained.
3. At next time step $k+1$, the optimization routine is repeated with new measurements and by applying only the first step control actions u^{k+1} computed at k. Also, sensitivities are updated for every time step.

In this scheme, the prediction and control horizon are considered to be same K. Generally, the control horizon is taken to be less than or equal to the prediction horizon. Due to simplified dynamics considered in this scheme, the control and prediction horizon is same as there was no difference is choosing prediction horizon greater than control horizon [39].

3.4. Controller scheme description

A brief description of the control schemes are provided under this section.

3.4.1. Load power restoration

Dynamic load models used in [38] do not account for all uncertainties involved in the load parameters like variation of power consumption with voltages and behaviour of operational delays in LTCs. In addition, these load models increase the computational complexities of the controller. As using these models do not bring any added benefit, the controller uses post-disturbance load power restoration effect produced by LTCs [39] to achieve satisfactory voltage control. The actions of LTCs used for voltage control are modelled by setting the loads to pre-disturbance values. This not only reduces the computational complexity but also uses minimal information about the load behaviour to achieve satisfactory voltage control.

3.4.2. Generator voltage set points

In the optimization model only the terminal voltages of the generators are used. Usually, it is known that a small change in AVR set points impacts an equal amount of change in the generator terminal voltages. By incorporating the change of n-th generator terminal voltages $(V_n^{k+1} - V_n^k)$ as a change in the AVR set points, the controller provides set point corrections rather than set point values.

3.4.3. Generator reactive power limits

Limitations on generator reactive powers can lead to unacceptable voltages. From the generator capability curve, the maximum limit of the generator reactive power Q_{limit}^{max} which is a function of generators active power and terminal voltages can be obtained. It is calculated based on the formulation and equations Equ(3.32a, 3.32b and 3.49) in [3] neglecting saturation effect.

It is important to account for the actions of over excitation limiters OXLs which helps in maintaining the voltage within limits. It helps in limiting the field current when the synchronous generator operates with field current above the specified value. In usual practice, the information about the evolution of field current profile or the actions of OXLs are not known in control center.

The OXLs comes into play when the reactive power of generators are equal or higher than the Q_{limit}^{max}. So in the problem formulation of the controller, when the reactive power of generators violate this limit, OXLs are activated and stops the increase of the voltages which comes under AVR control. The constraints that handles the generator limits in the formulation can be explained from [39] as follows

- When the generator operates within the field current limits, that generator is included only in (3.9) and the same is applied to all the future time steps.
- When the generator operates below the field current limits, that generator is included in both (3.9) and (3.10) the same is applied to all future steps.
- When the generator operates above the limit, that generator is included only in (3.10). The OXLs are activated and the reactive power limits are provided only for the final step.

3.4.4. Test system and controller specifications

Nordic 32 , a Swedish test system which is developed for the analysis of voltage stability problem is used to test the proposed controller [50] [51]. It comprises of 74 buses and 102 branches of which 52 are generation and transmission buses and 22 are distribution buses. It has total active and reactive power demand of 11,060 MW and 3,695 MVAR respectively. The Nordic 32 system comprises of four areas namely:

- North region consisting of hydro generation units and few load centres.
- Central region with large number of load centres and thermal units.
- South region consisting of thermal generation units.
- Equiv region consisting of an equivalent external system along with few generators and loads, connected to the north.

The system comprises of 400 KV, 220 KV and 130 KV transmission lines. The main disturbances which causes voltage instability in the system are:

- Outage of transmission lines in the North - Central regions.
- Outage of generators in Central region.

Reactive power capabilities of the Central and some of the North generators have an impact on the maximum power transferred to the Central region. The OXLs impose limits on the reactive power of these generators. Also, the LTCs revive the voltages within the desired limits on the event of disturbances.

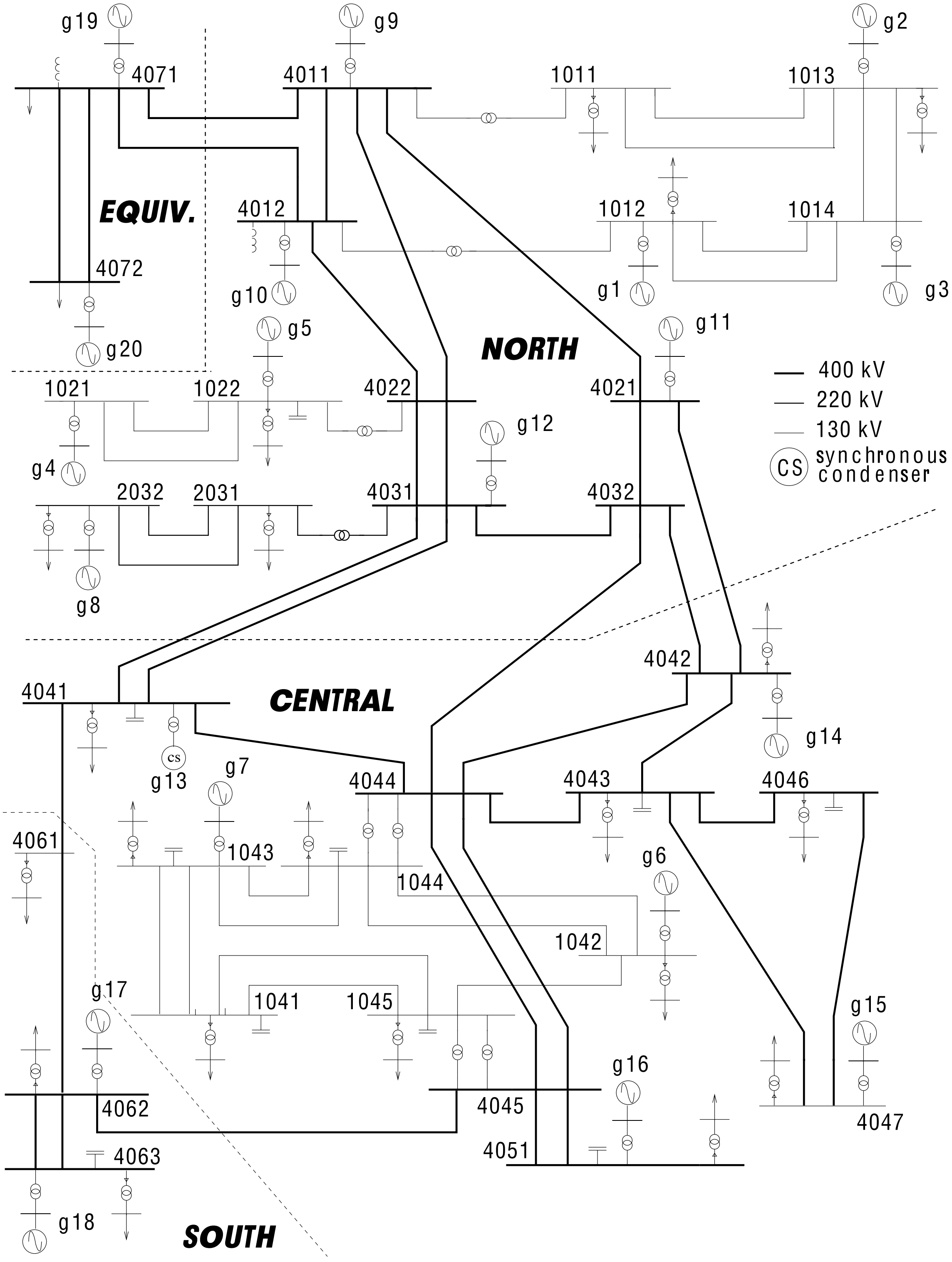

Figure 3.2: Single - line diagram of Nordic - 32 test system [50]

Figure 3.2 represents the single - line diagram of Nordic 32 test system. It has 20 synchronous machines which are represented by a standard model with three or four rotor windings. For the purpose of testing controller in real time, a detailed dynamic model of the generators, AVRs, speed governors and loads are considered. The generator that contributes the most to the primary frequency control is g20. The synchronous generators g1-g5, g8-g12 and g19-g20 form the hydro units with 0.08 p.u. of speed droop on machine basis of g19-g20 and 0.04 p.u for the remaining hydro units. The load is modelled as constant current for the active power and constant impedance for the reactive power and are fed through transformers equipped with load tap changers. A detailed description of each generator load models, their respective parameters can be referred from [51].

Matlab/Simulink based tool is used to build the model and simulate the test system. General Algebraic Modelling System (GAMS-IDE) is used to compute the optimal control actions for the optimization problem using the interior point primal-dual non-linear solver (IPOPT). Matlab and Gams are interfaced with MATGAMS.

3.4.5. Controller settings

The proposed controller can modify the 20 generator voltages in the range of 0.95 to 1.075 (p.u). There are 7 load buses which are considered for curtailment namely 1022, 1041, 1042, 1043, 1044, 1045 and 2031 and the total active and reactive power available for shedding are 3130 MW and 1025 MVAR respectively. The available controls and their respective cost are provided below:

- 1 for load shedding
- 0.001 for generator voltage setpoints

The load shedding is provided with higher cost when compared to generator voltage set points as it is considered as the last resort control action.

A 5% maximum rate of change of controls is provided to the generator voltages alone. A 10 second sample period is provided to the controller where it collects the measured voltages and bus power injections. The control as well prediction horizon K is taken to be 3 time steps.

The values considered for the controller settings are similar to [39] to facilitate comparison. The controller is initiated when it detects a disturbance and necessary changes occur in order to bring the voltages measurements to the desired range.

Table 3.1: Active and reactive power demand of the load buses

Load buses	**active power P(MW)**	**reactive power Q (MVAR)**
1022	280	95
1041	600	180
1042	330	90
1043	260	100
1044	840	300
1045	720	230
2031	100	30

3.4.6. Controller activation

The snapshots of bus voltage and power injection measurements are provided to the controller for a sample period of 10 s. The controller is inactive when the voltages and generator reactive powers are maintained within the specified limits. The controller gets activated immediately when the system encounters any violation in the values of voltages and reactive powers upon any disturbance. The necessary control actions are implemented at every time step to bring the voltages and reactive power within the specified intervals. Once the system gets controlled and stabilized, the controller stops issuing the control actions. The controller also provides 10 s delay to execute the control actions in order to accommodate for communication delays between the generators & the load centers and computation time.

3.5. Simulation Results

To test the effectiveness of the proposed sensitivity based RHMSO controller, the test system was subjected to various scenarios such as,

- Scenario 1 - Line outages
- Scenario 2 - Increment in load demand
- Scenario 3 - Stable but depressed voltages
- Scenario 4 - Impact of control failure

In addition, the simulation results are compared with single step MPC based controller to validate the performance of the proposed controller.

3.5.1. Scenario - 1: Stabilization of an unstable system (line outages)

Under this section, the impact of voltages, field currents and tap ratios of LTCs when subjected to line outage is examined. The Nordic 32 test system experiences a fault in the form of an outage of transmission line in the central region 4032-4044 (remains open) at t = 12 s. The voltage drops continuously inspite of the fact that LTCs and generators attempt to restore the distribution voltages. The over excitation limiter of the generator gets triggered one by one (g14 at t = 99.25, g12 at t = 103.6, g6 at t = 108.9, g15 at t = 117.1, g7 at t = 149.5, g16 at t = 152.4) and finally the voltage collapse takes place at t = 160 s once g16 gets limited. The post - disturbance plots for voltage, field current and transformer tap ratio are presented and explained as follows.

The evolution of voltages for four buses namely, 1044(central), 4042(central), 4062(south) and 1012(north) are depicted in Figure 3.3. Once the disturbance is initialized, for a short period of time till t = 48 s, the system is influenced by transients and settles to a short term equilibrium for few seconds. Later the evolution of the system voltage takes place due to the actions of LTCs and generators (starting from t = 49 s) which tries to bring back the voltages to the desired values. Finally system collapse takes place at t = 160 s. It is certain that the most affected area is the Central region of the test system.

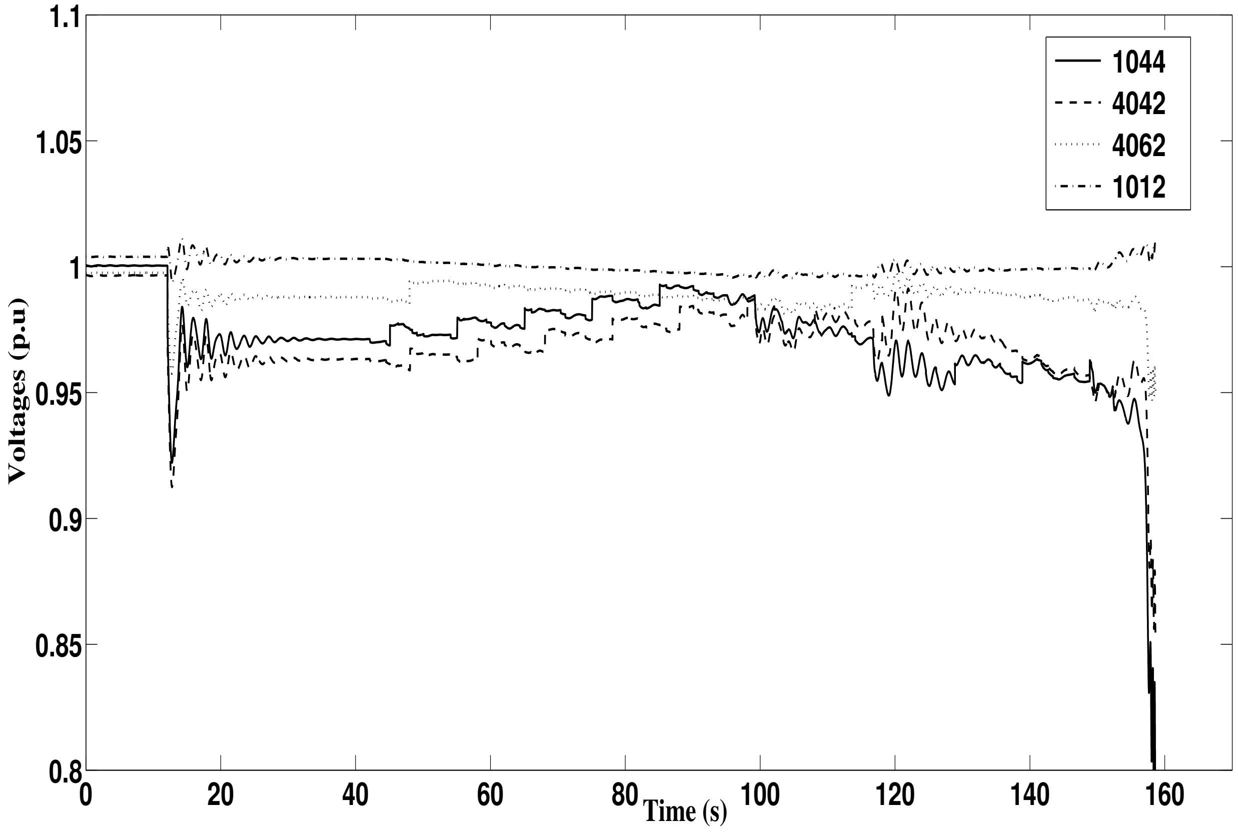

Figure 3.3: Evolution of unstable voltages of buses 1044, 4042, 4062, 1012

Figure 3.4 shows the evolution of field currents of generators with and without getting limited. As seen from the figure, it is to be noted that the field current starts to increase from t = 48 s post short term equilibrium upon the activation of LTCs. Figure 3.5 provides the evolution of generator voltage of bus 6 where the voltage is maintained almost constant and voltage drops once the field current gets limited.

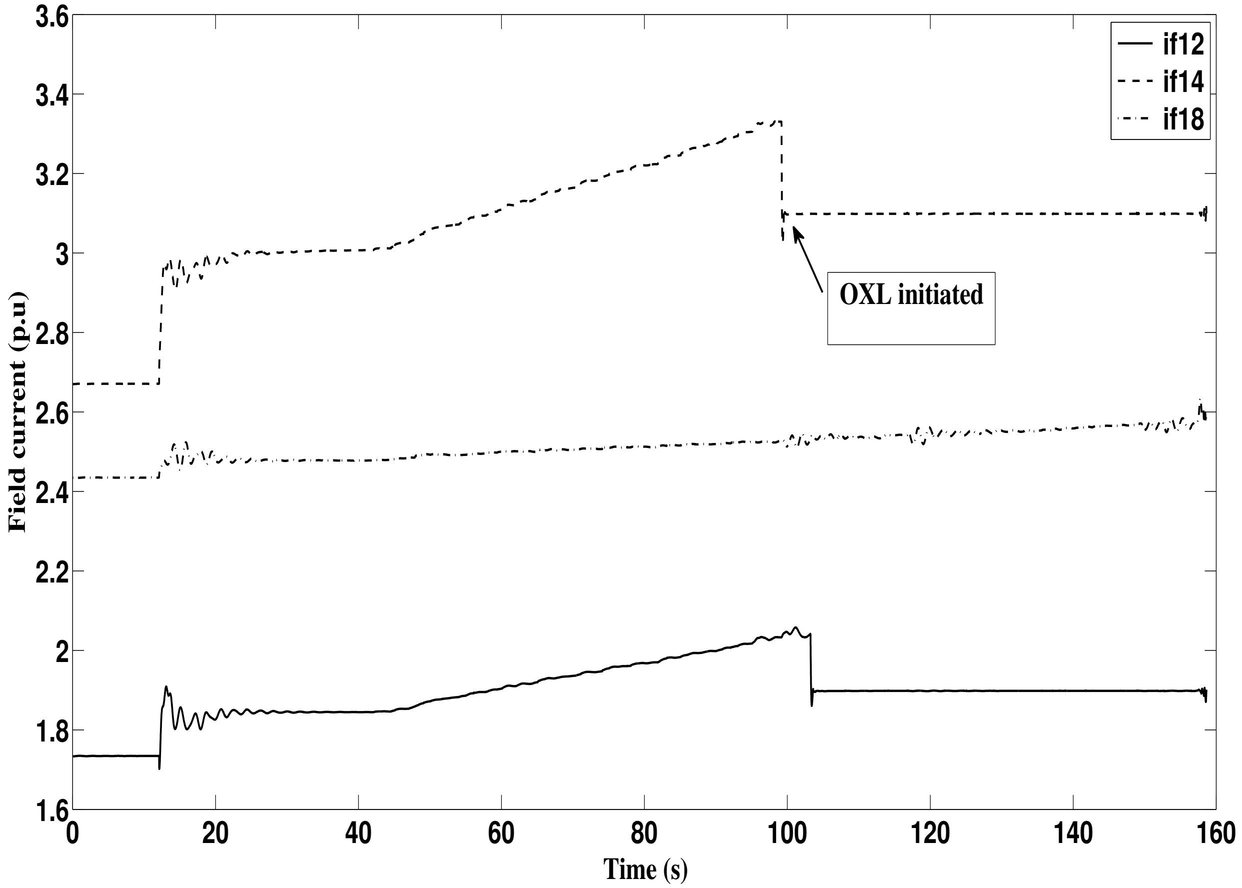

Figure 3.4: Evolution of field current of generators g12(limited) g14(limited) and g18(non-limited)

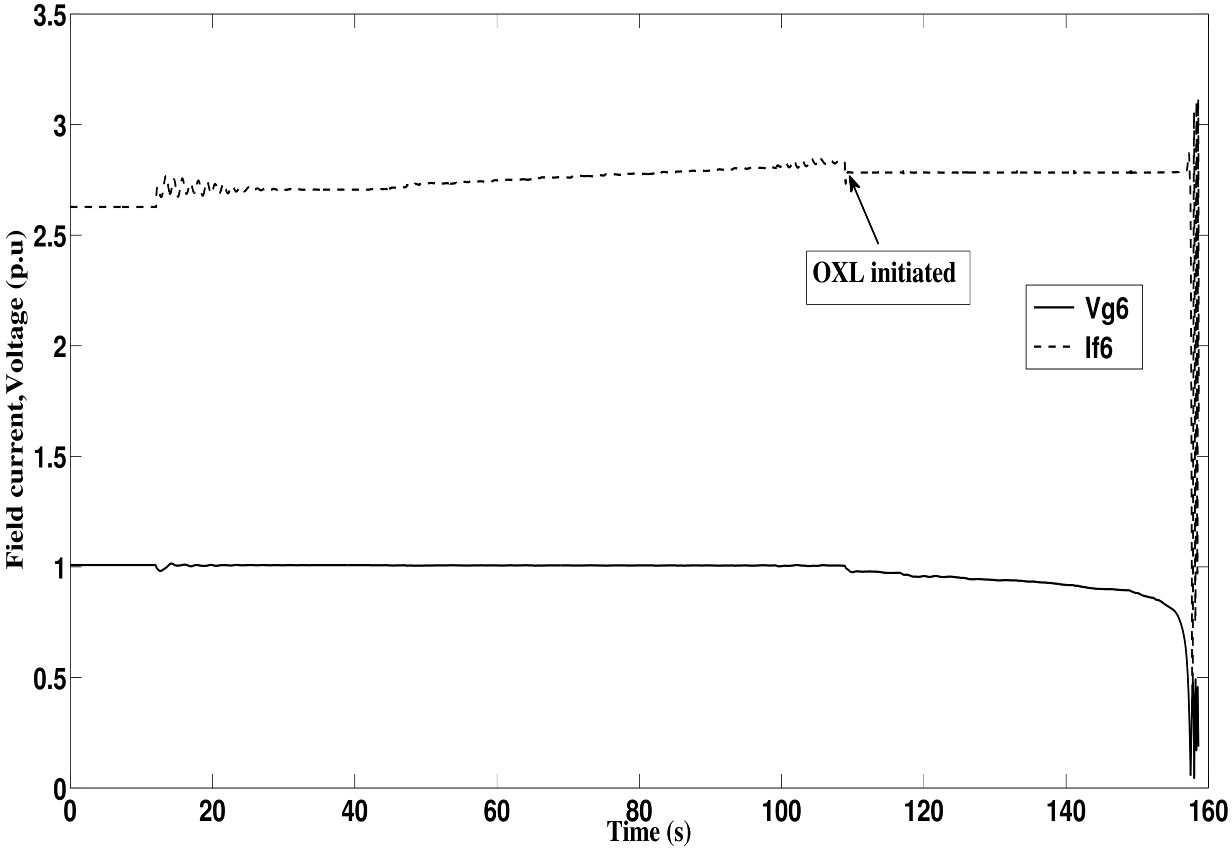

Figure 3.5: Evolution of generator voltage and field current of generator g6

Figure 3.6 shows transformer tap ratios to restore the distribution voltages. It can be observed that the LTCs start to function from t = 48 s by decreasing the tap ratios in an attempt to recover the distribution voltages. For each tap change, the distribution voltage is increased to reach within the desired level. Figure 3.7 depicts the evolution of both voltage and tap ratios of bus 1044 is presented. From this figure it is evident that the system collapse takes place even after the attempt of LTCs in restoring the voltage levels.

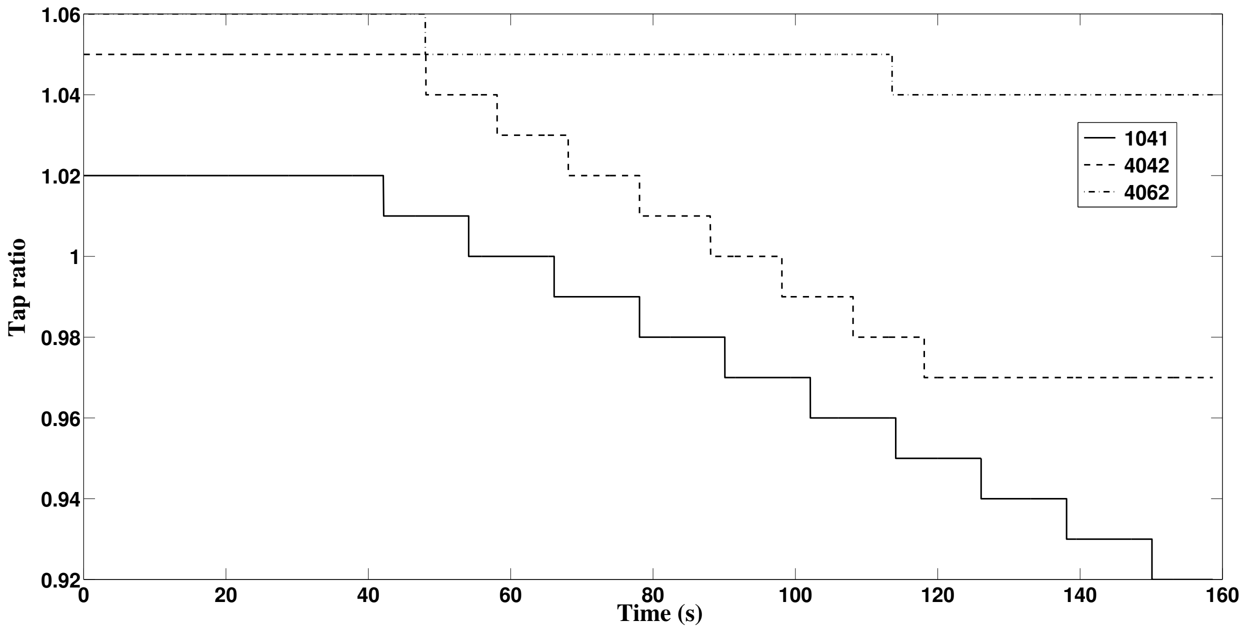

Figure 3.6: Evolution of Transformer tap ratios

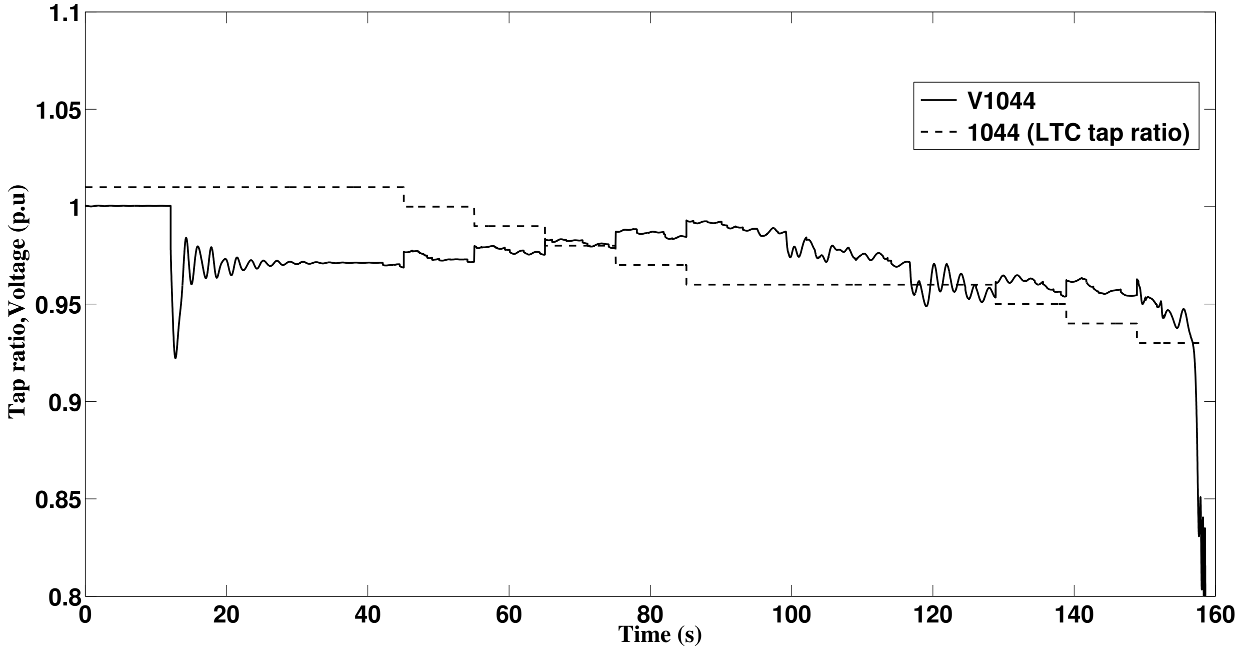

Figure 3.7: Evolution of voltage and tap ratio of bus 1044

The test system becomes unstable inspite of the control actions provided by the primary controllable devices like the LTCs and generators to restore the voltages and load powers. Inorder to stabilize the system, the proposed controller is introduced which provides secondary control actions such as changes in generator voltage set points and load shedding.

Figure 3.8 illustrates the stabilized voltage at bus 1044 by the proposed controller. It can be observed that, the controller gets activated at t = 20 s and starts computing the control actions by solving the optimization problem for every 10 s from then, based on the new measurements and previous step solutions. The proposed controller implements the control actions only when the primary controllable devices fail to provide the control actions. From the figure it can be noted that from t = 40 to t = 80 s the response is influenced by the LTCs and generators trying to increase the voltage levels. Then from t = 80 s, the response is under the control of the secondary controllers which gets initiated upon the detection of low voltages at bus 1044 and also the reactive power violations of generators g14 and g12. The controller issues the necessary control actions with changes in generator voltage set points and load shedding after which the system becomes completely stabilized before the point of collapse. Thus the controller is capable of predicting the requirement of the control actions necessary in future step which the available primary controllable devices in the test system were not able to do so.

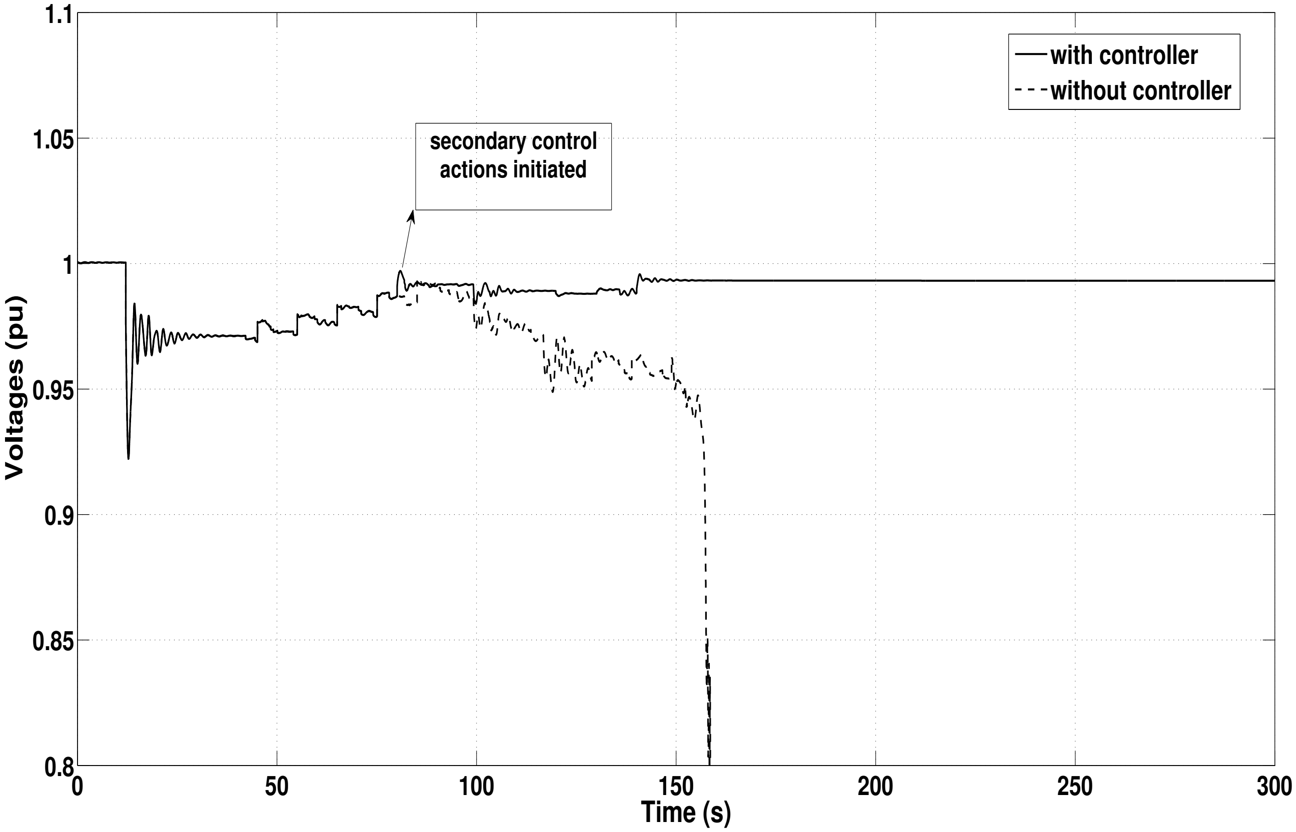

Figure 3.8: Stabilized voltage of bus 1044 by the proposed RHMSO sensitivity based controller for Scenario - 1 (line outage)

In addition, the controller was tested for different line outages in order to test its ability to handle it. It was found that the controller was able to stabilize the system with the secondary controllers.

Table 3.2: Various line outages and corresponding active load curtailment by the proposed controller

Line outages	Without controller	With proposed controller (Load shed)
4032-4042	system collapse at t = 526.9 s	84 MW
4032-4044	system collapse at t = 160 s	131 MW
4041-4044	system collapse at t = 238.6 s	114 MW
4042-4044	stable	no load shed
1043-1044	stable	no load shed

Table 3.2 summarizes the outages and amount of active load shed in MW accounted by the proposed controller.

3.5.2. Scenario - 2: Increase in load demand

In this case, the increase in load demand of the system leads to unstable condition. Load increment is provided for five load buses namely, 1041, 1042, 1043, 1044, 1045. The increment is introduced linearly until t = 530 s at the rate of 7.2 MW per minute with time. The system became unstable due to the fact that the point of collapse or the loadability limit was reached before t = 530 s. The LTCs attempted in restoring the voltage, however, the system became unstable once the g6 field current gets limited at t = 516.7 s.

When the proposed controller was introduced, the controller started to issue the control actions from t = 442 and 451 s after which the system attained complete stability at t = 520 s. Figure 3.9 illustrates the stabilization of bus 1044 for load increase scenario.

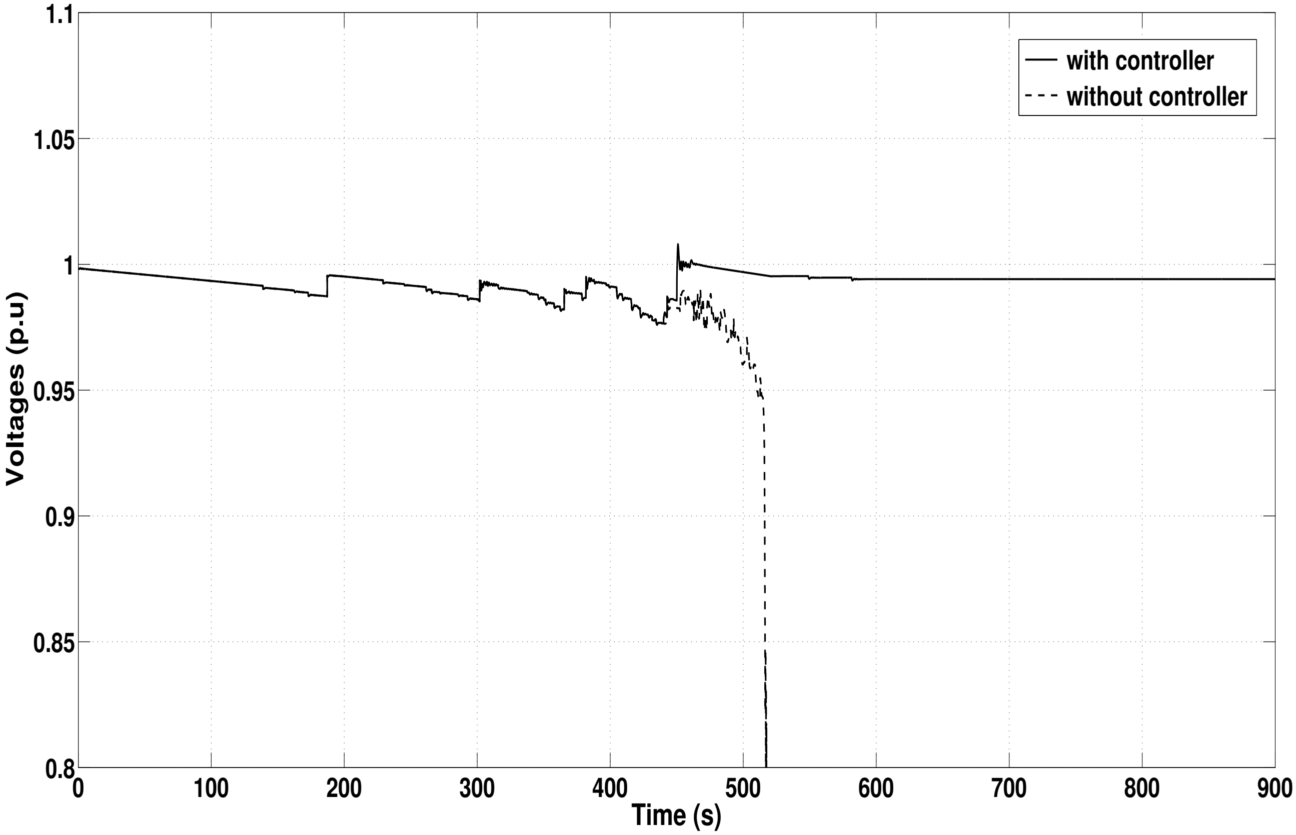

Figure 3.9: Evolution of voltage at bus 1044 with and without the RHMSO sensitivity based controller for Scenario - 2 (load increase)

3.5.3. Scenario - 3: Stable but depressed voltages

In this scenario, the line outage of scenario 1 is considered with lower initial load values on certain load buses in the central region of the test system. This scenario provides a stable operating system, however, certain load buses experiences voltages that are below the specified limits (low/depressed voltages). For instance, the voltage at bus 1041 is about 0.94 p.u which is below the desired range of 0.95 to 1.075 p.u.

When the proposed controller is introduced, it was able to correct the lower voltage levels at the respective buses. The Figure 3.10 illustrates the evolution of the voltages with and without the controller. Thus the controller was able to stabilize the system with the voltages maintained within the specified range. It shows that the controller is able to accomodate to sudden changes that occur in a stable operating system and provides necessary control actions as required.

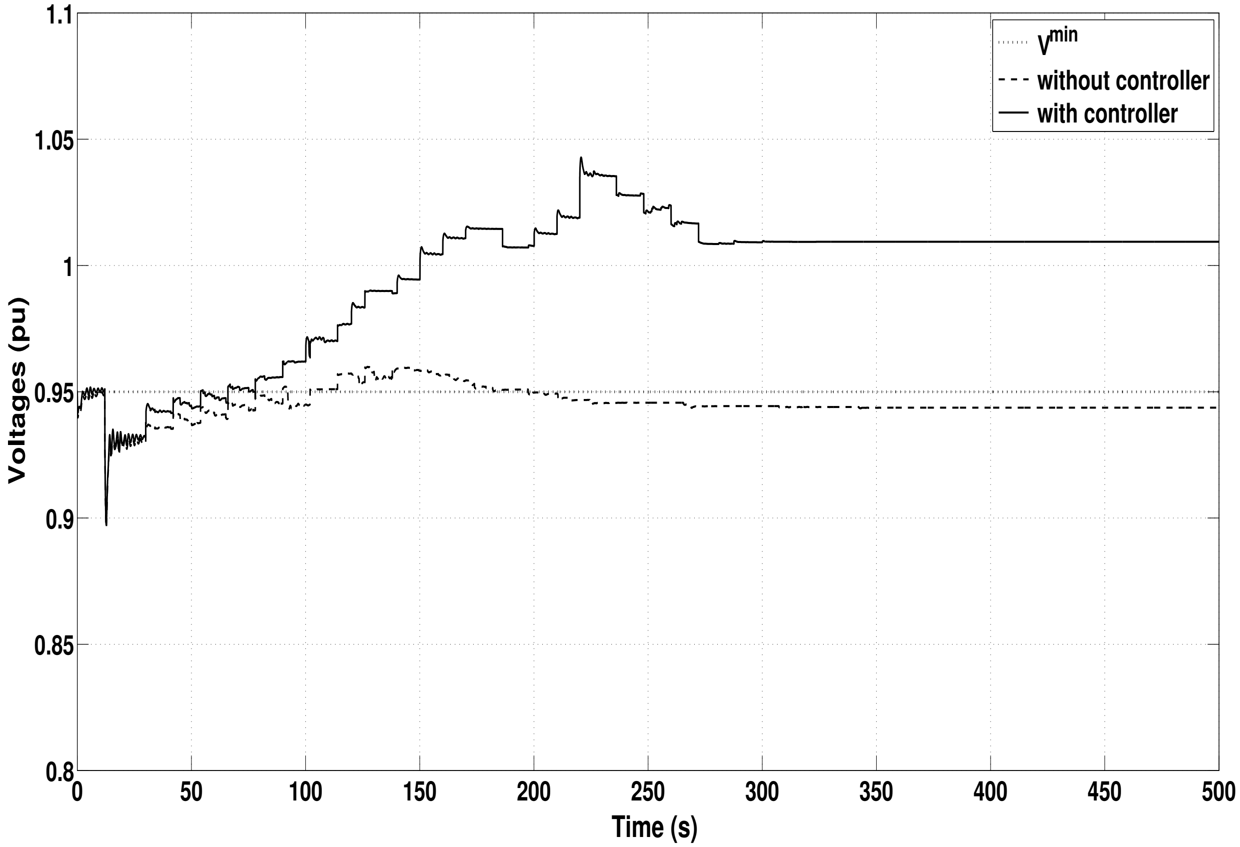

Figure 3.10: Corrected voltage at bus 1041 by the proposed controller for Scenario - 3 (Stable but low voltage)

3.5.4. Scenario - 4: Impact of control failure

A multi step controller is capable of handling control component failures. The control failure scenario is simulated by restricting few generators from not implementing their computed control actions. For this scenario, similar settings of a line outage scenario is considered with the control failure of **g1 to g5 (not issuing control actions)**

Figure 3.11 shows the evolution of voltages with and without the control failure. It is observed that the controller stabilizes the system which starts to compensate for the failure from t = 100 s. Though the generators g1 to g5 were not able to issue the computed control actions, the remaining available generators were able to compensate for the failure by increasing their control effort and also resorts to load shedding on few buses.

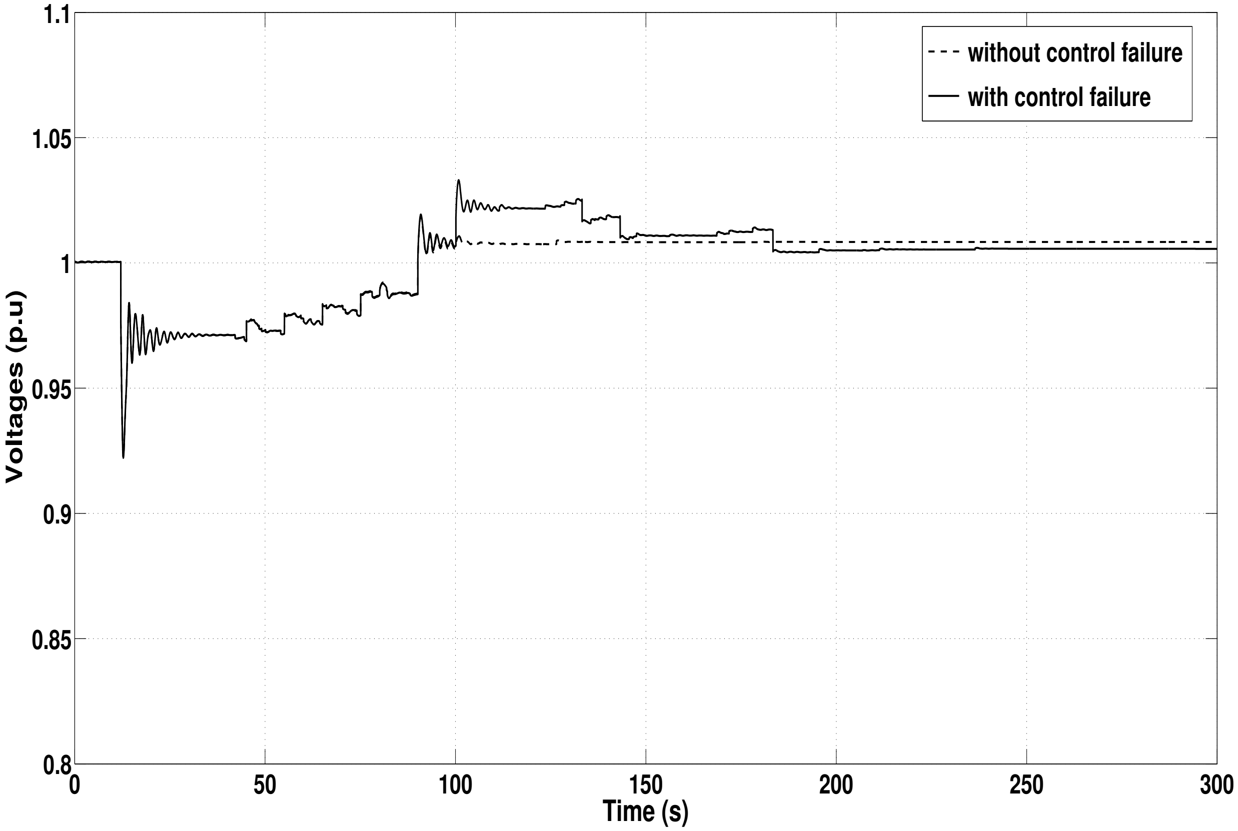

Figure 3.11: Evolution of voltage at bus 1044 with and without the control failure

3.6. Analysis of sensitivity based system model (only voltage (V) and combined (V,Q) sensitivity constraints)

In this scenario, the proposed controller is tested for line outage scenario - 1 by considering only the voltage sensitivity constraint to be the system constraint in the problem formulation. From the simulation results it was found that, the stabilization of an unstable scenario can be achieved successfully by just utilizing only the voltage sensitivity constraints. However, addition of reactive power sensitivities along with voltage sensitivities do stabilize the system with better performance.

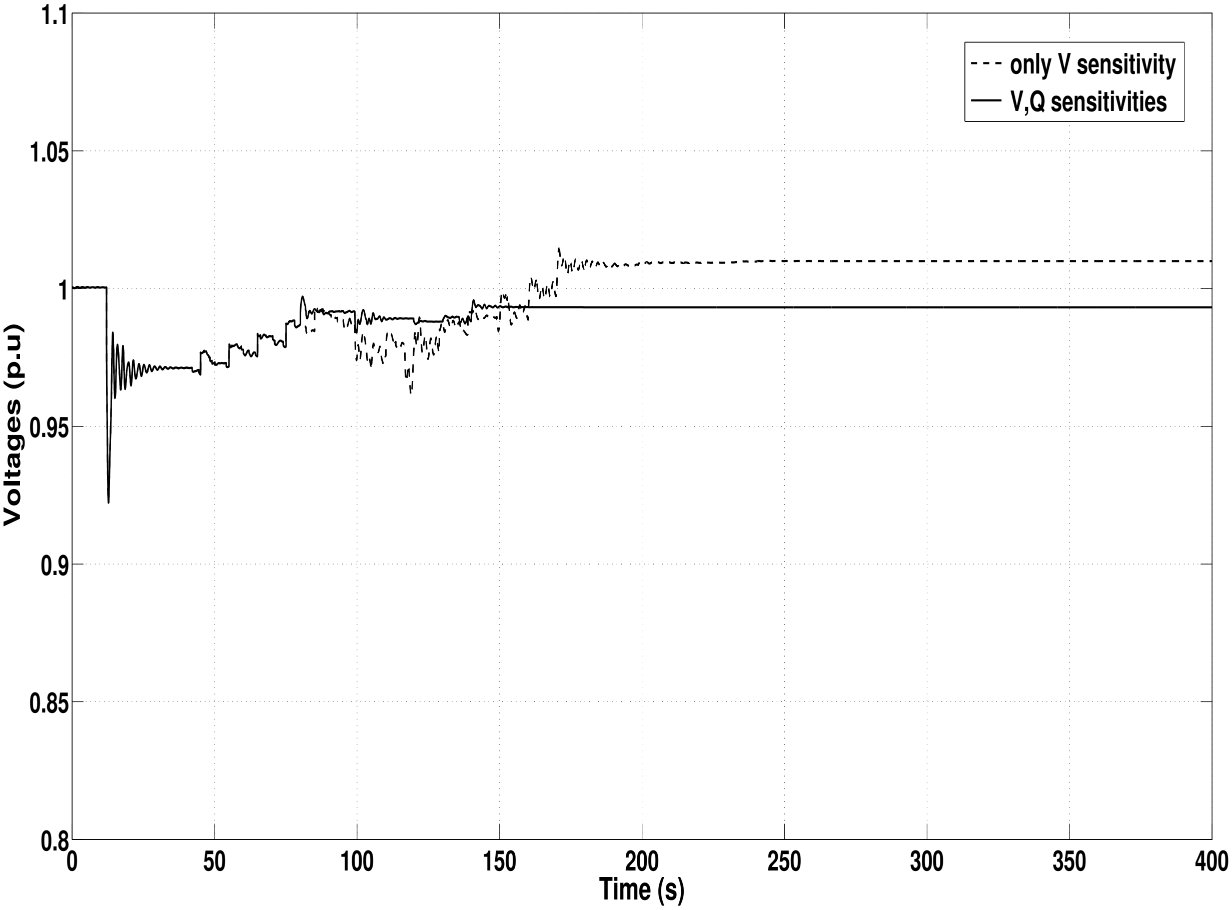

Figure 3.12: Stabilization of voltage by simplifies RHMSO based on only V sensitivity and combined V, Q sensitivities

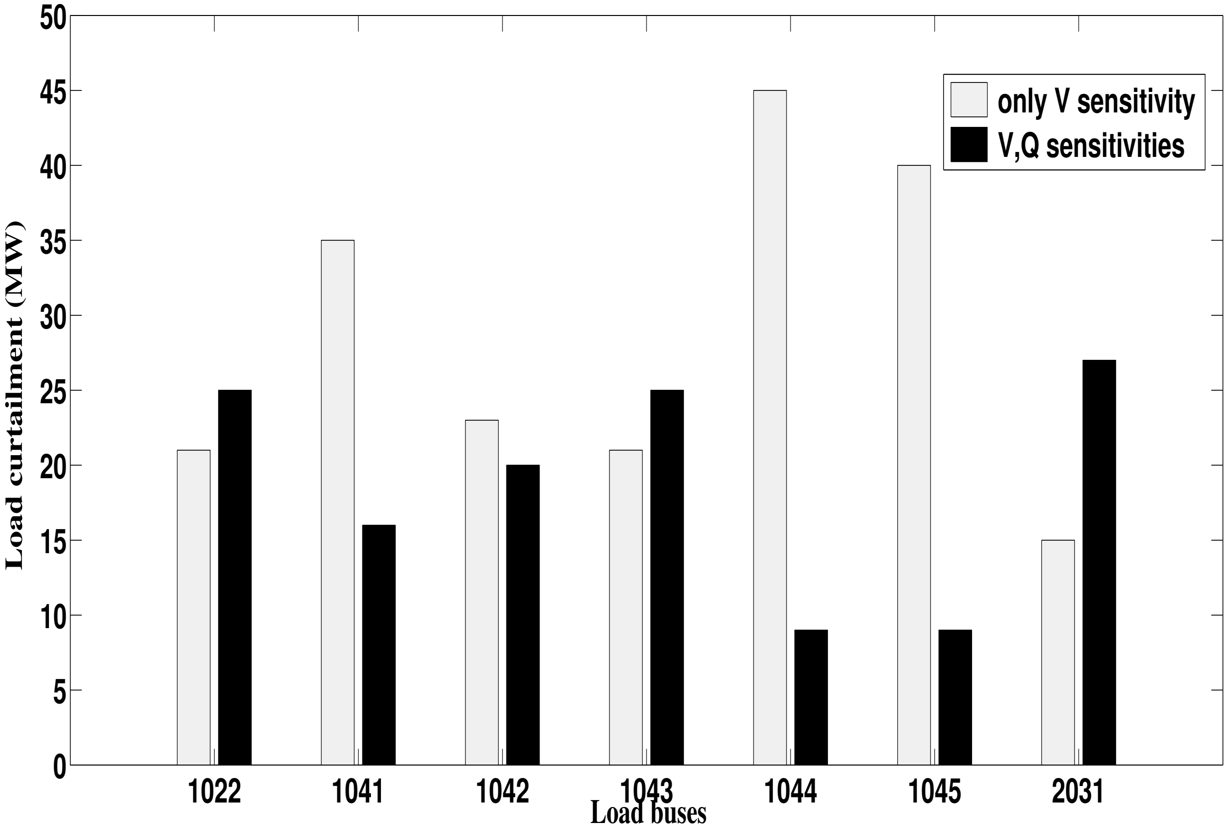

Figure 3.13: Total amount of load shedded on each load buses by both RHMSO based V sensitivity and combined V, Q sensitivities

Figure 3.12 depicts the evolution of stabilized voltage at bus 1044 by the controllers. Both the controllers is capable of providing a stable system. However, a better performance (in terms of amount of load shedding and settling time of the response) is provided by the controller which considers the combined V,Q sensitivity constraints as the system constraints.

The addition of reactive power sensitivity constraint makes the controller to act much earlier which is able to detect the violations in the reactive power limits of the generators after the disturbances. The total amount of load shed was found to be **131 MW** which is about 70 MW less than the controller with only V constraints providing a total load shed of **202 MW**. It is to be noted that when utilizing only V sensitivities, the upper and lower bounds on the voltages was assigned for all time steps instead of only for final step in order to provide stability.

3.7. Comparison with sensitivity based single step MPC and proposed simplified RHMSO controllers

Both the controllers utilize the sensitivity based linear steady state model in the problem formulation. The controllers are labelled as follows for the purpose of simplicity.

- controller 1 - Multi step MPC based controller (proposed simplified RHMSO controller)
- controller 2 - Single step MPC based controller

An accurate system model with similar control settings was selected for both the controllers in order to facilitate comparisons. The comparison was based on the amount of load shedding accounted by the respective controllers. It was found that the controller 1 provided lesser amount of load shed when compared to the controller 2. However, the settling time for response tends to be larger for controller 1.

As the single step MPC based controller has a control and prediction horizon of 1, it cannot see the future system behaviour as farther as the multi step MPC based controller which has a control and prediction horizon of 3 can do so. So wherever the system is at present, the single step controller computes the control actions only for one step. This leads to the disadvantage of providing larger control output. Table 3.3 addresses the types of scenarios, controllers and the total load curtailment (MW) provided by each controllers.

Table 3.3: Results for total amount of load curtailed by respective controllers for different scenarios

Scenarios	**Controller 1(multi step) Load shed (MW)**	**Controller 2 (single step) Load shed (MW)**
Stabilization of unstable system	Stable, 131	Stable, 177
Correction of low voltages	Stable, corrected	Stable, not corrected
Load increase	Stable, 143	Stable, 189
line outage of 4032-4042	Stable, 84	Stable, 144
line outage of 4041-4044	Stable, 104	Stable, 120

From the Table 3.3 it is evident that the controller 1 was able to stabilize the system with lesser amount of load shed when compared to controller 2. It is able to provide a significant amount of less load shed almost on an average of 40 MW less. Figure 3.14 depicts the stabilized voltage at bus 1044 by controller 1 and controller 2 for Scenario - 1.

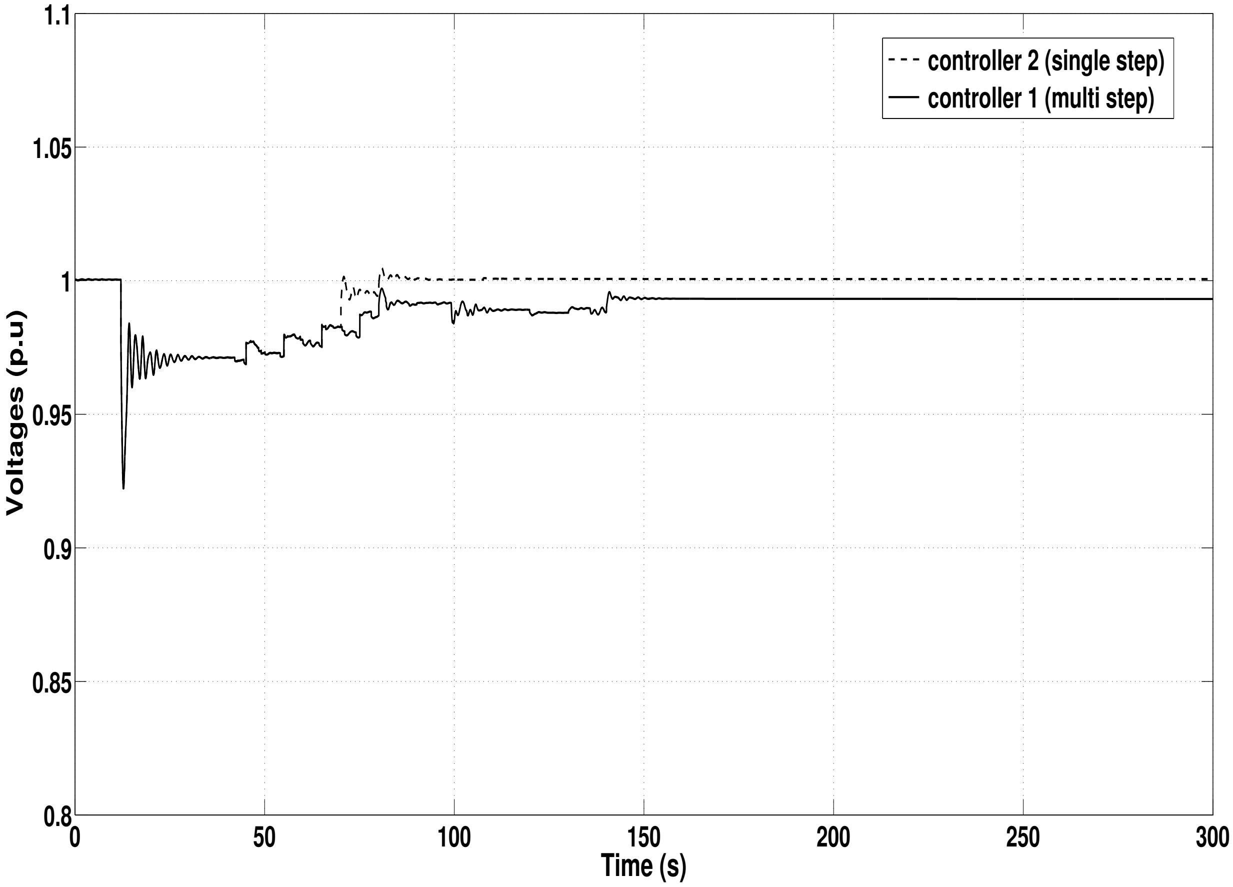

Figure 3.14: Stabilized voltage at bus 1044 for Scenario - 1 (line outage of 4032-4044)

From Table 3.2, it can be noticed that for scenario - 1 which is the line outage, the controller 1 provides 46 MW less load shedding than the controller 2. In terms of the system response, from Figures 3.14, the controller 2 tends to respond faster due to the reason that the control actions are enforced in single step leading to large control output. Though the response of the controller 2 is faster than the controller 1, the amount of load shedding tends to be much higher than controller 1.

Table 3.4 provides the total amount of load curtailed by each of the load buses for the respective controllers pertaining to scenario - 1.

Table 3.4: Total amount of load shedding on each load buses for Scenario - 1 by both the controllers

Load buses	Controller 1 (multi step) Load shed MW	Controller 2 (single step) Load shed MW
1022	25	24
1041	16	28
1042	20	25
1043	25	24
1044	9	29
1045	9	29
2031	27	18
Total load shed	**131**	**177**

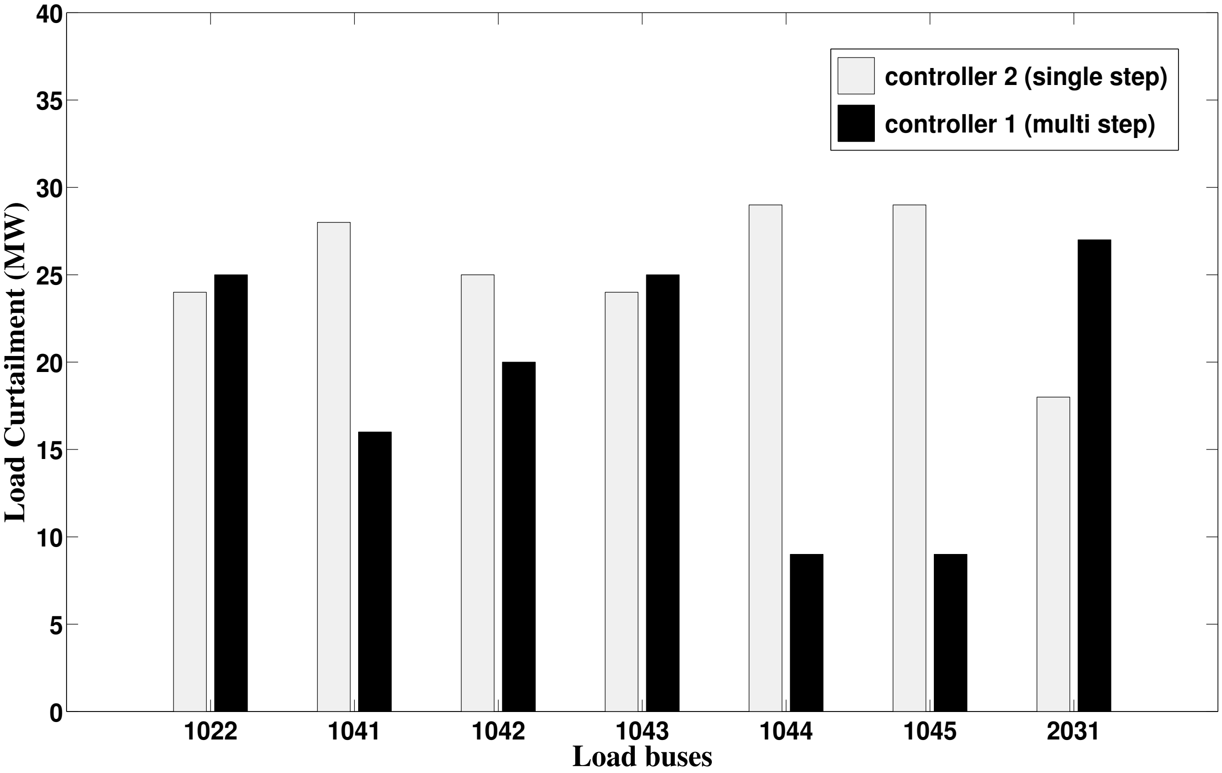

Figure 3.15: Scenario - 1: Total amount of load curtailed on each load buses for controllers 1 and 2 respectively

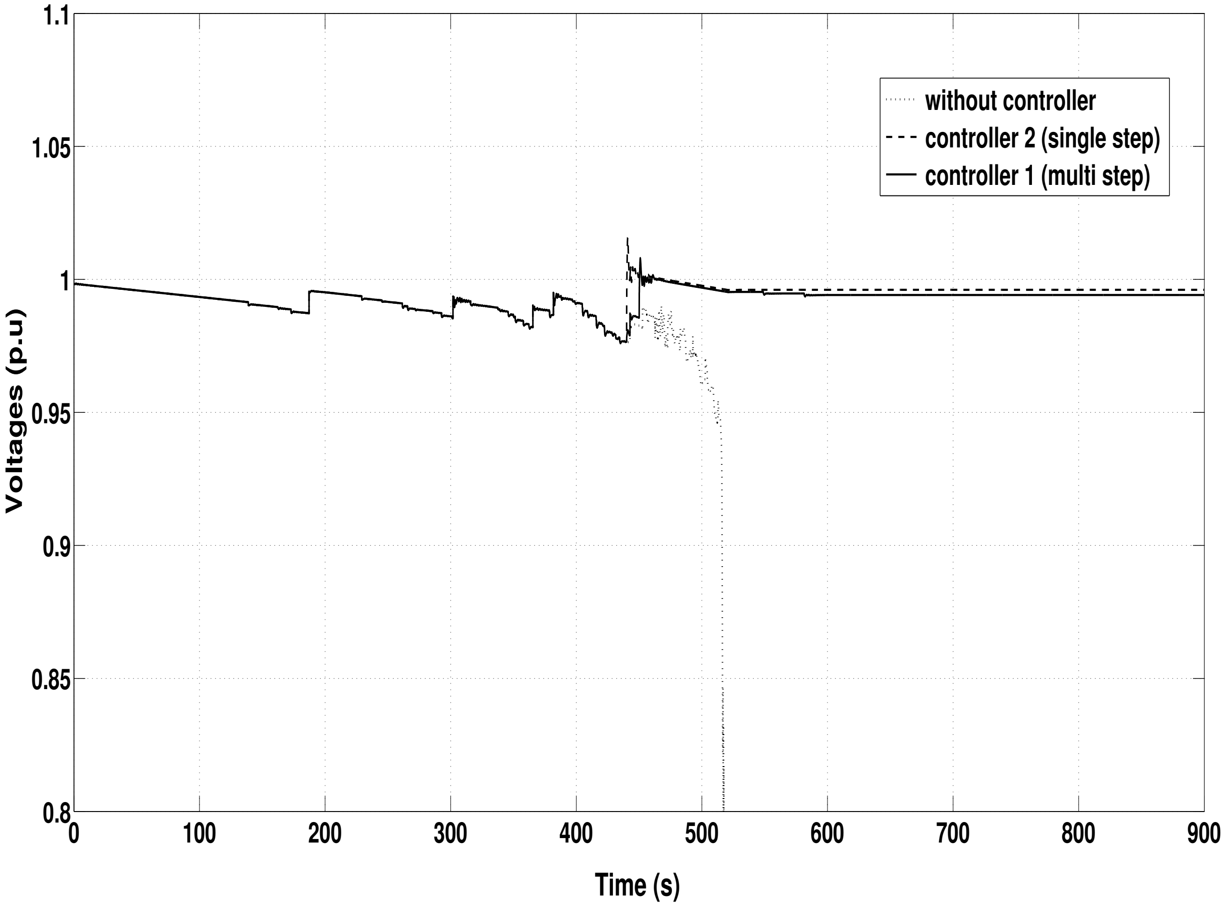

Figure 3.16: Stabilized voltage at bus 1044 for Scenario - 2 (load increase)

Figure 3.16 depicts the stabilized voltage at bus 1044 by controller 1 and controller 2 for Scenario - 2. With regards to Scenario - 2 which is the load increment, though both the controllers were able to provide a stable response, it can be observed from Figure 3.16 and Table 3.5 that, the controller 2 sheds more load when compared to controller 1. The controller 2 sheds more load at t = 440 s whereas the controller 1 gradually sheds load at t = 442 and 451 s which tends to be almost 46 MW less shedding.

Table 3.5: Total amount of load shedding on each load buses for Scenario - 2 (load increase) by both the controllers

Load buses	Controller 1 (multi step) Load shed (MW)	Controller 2 (single step) Load shed (MW)
1022	22	25
1041	24	32
1042	21	23
1043	18	21
1044	23	37
1045	20	35
2031	15	16
Total load shed	**143**	**189**

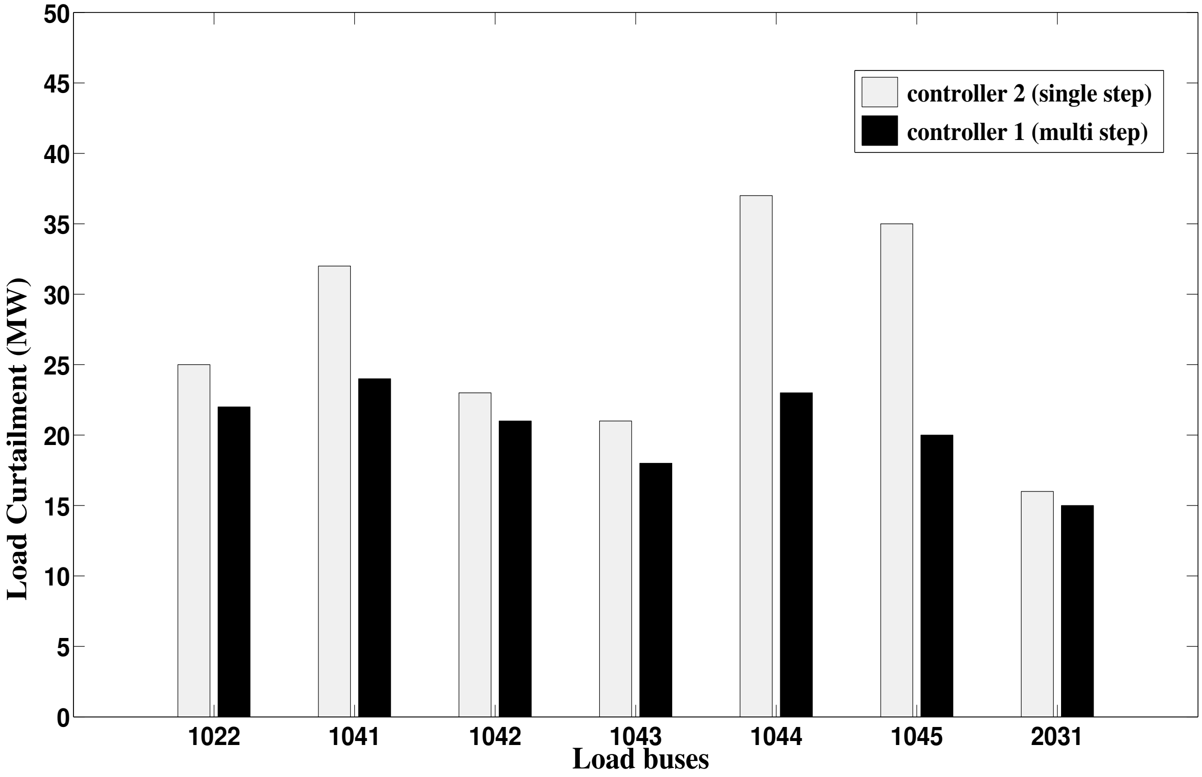

Figure 3.17: Scenario - 2: Total amount of load curtailed on each load buses for controllers 1 and 2 respectively

Based on the comparisons made between the single and multi step MPC based controllers, it is observed that the proposed controller (controller 1) is able to provide lesser amount of load shedding when compared to the controller 2. Table 3.4 and Figure 3.16 delivers the total amount of load shedding for the corresponding load buses for scenario - 1 by both controllers 1 and 2. Similarly Table 3.5 and Figure 3.17 delivers the total amount of load shedded on each of the load buses for load increase scenario by both the controllers.

The conclusion that can be derived from the simulations results of the proposed simplified RHMSO controller is that,

- Smoother system response
- Reduced amount of load shed
- Increased settling time of the response

3.8. Summary

In this chapter, the proposed simplified RHMSO approach for on-line voltage control is presented. An introduction to the simplified RHMSO approach is given. A brief illustration on model predictive control (MPC) is addressed which forms the control mechanism for the simplified controller. The problem formulation and solution approach for the simplified RHMSO approach is explained in detail. Description on the test system, controller schemes and settings are presented. Simulation results of the proposed controller for different scenarios are analyzed and discussed. Comparisons with the single step MPC based approach is made to prove that the proposed simplified RHMSO approach renders better performances. The observations deliver that the multi-step approach, though the response faces larger settling time than single step approach, it provides significant reduction in load shedding.

Chapter 4

Simplified RHMSO with bias based system model for real time voltage control

4.1. Introduction

In chapter 3, simplified RHMSO approach was implemented and its results were compared with single step MPC based optimization approach. However, the approach had two major drawbacks namely,

- Response settling time: It can be seen from results under section (3.5.4) that the multi step controller significantly reduces the load shed amount, however, the settling time of the response is comparatively large.
- Computational burden: Even though multi step controller utilizes linear system constraints to reduce computational complexity in the problem formulation, the sensitivity matrix needs to be updated for every time step adding an additional computational burden.

In this chapter, we address the above drawbacks by introducing a bias term in the sensitivity constraints. The MPC control technique largely depends on the accuracy of the system model to provide adequate control response. A highly accurate model minimizes the error between the measured and predicted values thereby reducing the control actions required to meet the control objective. The bias term introduced aims at being an error control to improve system performance.

4.1.1. Bias based error control

Bias is a simple and effective method to correct modelling errors and to reduce discrepancies between the actual and predicted values. When a non linear model is converted to a linear model, the approximations induces some measurement errors in the linear system model. These errors should be corrected to provide better system performance. This error correction is handled by the bias term introduced in the system model of the proposed problem formulation.

Bias is a popular error corrector in MPC controllers and has been successfully used in industrial process control applications [49]. It is shown to reduce control action and provide a smoother system response. A similar concept has been applied to this voltage control problem.

The bias term is added to the linearized sensitivity constraints (4.2) and (4.3) which can be regarded as an error controller. It works on the principle of feedback control. The formulation of the bias term is as follows:

1. At the initial step of the optimization routine, the bias term is set to zero. (i.e) at k,

$$bias_v = 0 \tag{4.1}$$

$$bias_{qg} = 0 \tag{4.2}$$

2. From next time step $k + 1$, the bias term is calculated as (4.14), (4.15) and are updated for every time step. Here the bias term is formulated as the difference between the measured value at the current step and the predicted

value obtained from previous step.

$$bias_v = V^m - V^{k+1} \tag{4.3}$$

$$bias_{qg} = Q^m - Q^{k+1} \tag{4.4}$$

V^m, Q^m represents the present step measured values of the voltages and generator reactive powers respectively. V^{k+1}, Q^{k+1} represents the predicted values of voltage and generator reactive power at previous step respectively.

4.1.2. Problem formulation for the proposed bias based controller

In this section, the problem formulation for simplified RHMSO sensitivity and bias based controller is presented.

$$\min_{\substack{u_1^{k+1},\ldots,u_1^{k+K} \\ u_2^{k+1},\ldots,u_2^{k+K}}} \sum_{j=k+1}^{k+K} \left[\sum_{i=1}^{n_1} w_i (u_{1,i}^{j} - u_{1,i}^{j-1})^2 + \sum_{i=1}^{n_2} w_i (u_{2,i}^{j} - u_{2,i}^{j-1})^2 \right] \tag{4.5}$$

$$\forall j = k+1 \ldots k+K$$

$$s.t \;\; V_{nb}^{j} - V_{nb}^{j-1} - S_{nb,gb} \sum_{i=1}^{n_1} (u_{1,i}^{j} - u_{1,i}^{j-1}) - S_{nb,lc} \sum_{i=1}^{n_2} (u_{2,i}^{j} - u_{2,i}^{j-1}) + bias_v = 0 \tag{4.6}$$

$$Q_{gb}^{j} - Q_{gb}^{j-1} - S_{gb,gb} \sum_{i=1}^{n_1} (u_{1,i}^{j} - u_{1,i}^{j-1}) - S_{gb,lc} \sum_{i=1}^{n_2} (u_{2,i}^{j} - u_{2,i}^{j-1}) + bias_{qg} = 0 \tag{4.7}$$

$$u_1^{min} \le u_1^{j} \le u_1^{max} \tag{4.8}$$

$$u_2^{min} \leq u_2^j \leq u_2^{max} \tag{4.9}$$

$$|u^j - u^{j-1}| \leq \triangle \tag{4.10}$$

$$V^{min} \leq V^{k+K}(x,u) \leq V^{max} \tag{4.11}$$

$$Q^{min} \leq Q^{k+K}(x,u) \leq Q^{max} \tag{4.12}$$

$$Q_i^{min} \leq Q(x^j,u^j) \leq Q_i^{max} \qquad i\epsilon I(k) \tag{4.13}$$

$$P_{pf}^{max} \leq P_{pf}^j \leq P_{pf}^{max} \tag{4.14}$$

$$P_{pf}^j(x,u_1,u_2) = P_{pf}^o + \frac{\triangle F}{R} \tag{4.15}$$

The equations (4.1) - (4.11) represents the RHMSO approach with the sensitivity and bias based system model. The equation set is similar to the one explained in section (3.3.2). The main difference lies in the addition of bias terms which are denoted as $bias_v$ and $bias_{qg}$. $bias_v$ indicates the voltage bias vector added to (4.2) while $bias_{qg}$ is the generator reactive power vector added to (4.3). In this formulation the control variables are separated as $u1$ (generator voltage set points) and $u2$ (load shedding) for clear understanding.

4.1.3. Solution approach for the proposed method

The solution approach for simplified sensitivity and bias RHMSO controller is presented as follows:

1. At initial time step k, collect all the necessary measurements.
2. Then, the sensitivity matrices for the system constraints (4.2) and (4.3) are calculated and the bias terms ($bias_v, bias_{qg}$) are assumed to be zero. It is to be noted that sensitivity matrices are calculated only for k step and not updated in future steps.

3. Compute a chain of control actions for $k+1, ..., k+K$ steps $(u^{k+1}, .., u^{k+K})$ by solving the optimization routine.

4. Apply only the final step control actions (u^{k+1}) at the next time step k+1.

5. At k+1, calculation of sensitivities are stopped and the bias terms $bias_v, bias_{qg}$ are updated based on the formulation (4.14) and (4.15). The optimization routine is repeated with the updated bias terms and new measurements.

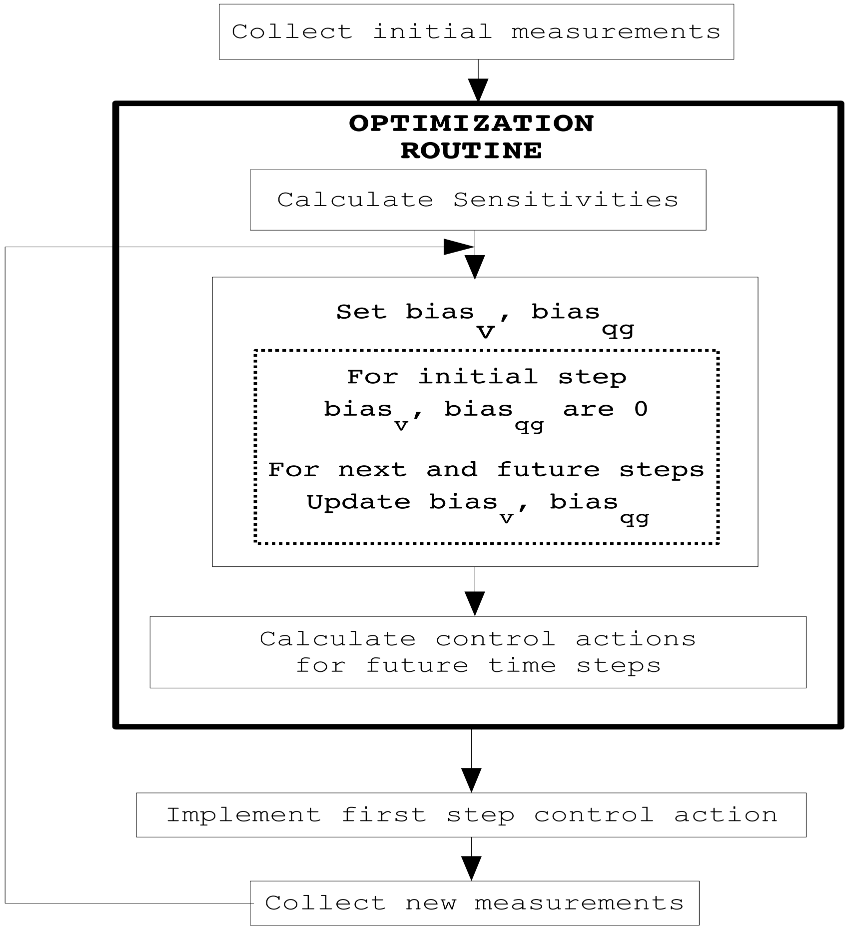

Figure 4.1: Block diagram for the solution approach of proposed bias and sensitivity based RHMSO controller

4.1.4. Test system and controller specifications

The test system considered for the analysis of the proposed bias based controller is the same Nordic - 32 test system which has been described in detail under Chapter 3. In addition, the controller setting is also the same as dealt in Chapter 3 under the sections 3.4.5 and 3.4.6

4.2. Simulation results

The test system is subjected to the same scenarios as considered for analysis in Chapter 3, with the following results considered:

- The simulation results for the proposed simplified RHMSO sensitivity and bias based controller are discussed which involves analysis under various scenarios.
- A discussion on the ability to provide stabilization by utilizing only the voltage (V) sensitivity and bias based system model is presented. A comparison between only V sensitivity and combined V,Q sensitivity based controllers (both non-bias and bias based) is presented for scenario - 1.
- Comparisons for the proposed RHMSO sensitivity bias and non-bias based controllers have been addressed. In terms of sensitivity based system model, the combined voltage and reactive power sensitivity constraints are considered in this discussion. Also a comparison with RHMSO sensitivity bias based and non-linear system model is addressed.

The following scenarios are tested for the proposed bias based controller and the results are being analyzed and discussed.

4.2.1. Scenario - 1: Stabilization of an unstable system (line outages)

The test system is affected by the outage of line 4032-4044 (central region). The system undergoes long-term voltage instability problem which can be observed in Figure 4.2, where the voltage collapse takes place at around t = 160 s even after the actions of automatic LTCs and generators.

The proposed bias based controller was able to stabilize the system with a load shedding of **104 MW**. Figure 4.2 shows the unstable and stabilized voltage of bus 1044 for the bias based controller. From this figure, it can be observed that the controller gets activated at t = 20 s upon the detection of violated voltages and reactive power limits. From t = 70 s onwards the controller implements the secondary control actions like modifications in generator voltage set points and load shedding when the primary controllers like LTCs where not able to provide the required controls. Thus the controller stabilizes the system before the collapse point which is t = 160 s. The Table 4.1 shows the amount of the active and reactive power values after the load curtailment. The amount of load shed at each buses were 13 MW on 1022; 17 MW on 1041; 14 MW 0n 1042; 13 MW on 1043; 19MW on 1044; 18 MW on 1045; 10 MW on 2031 corresponding to a total amount of 104 MW load shed.

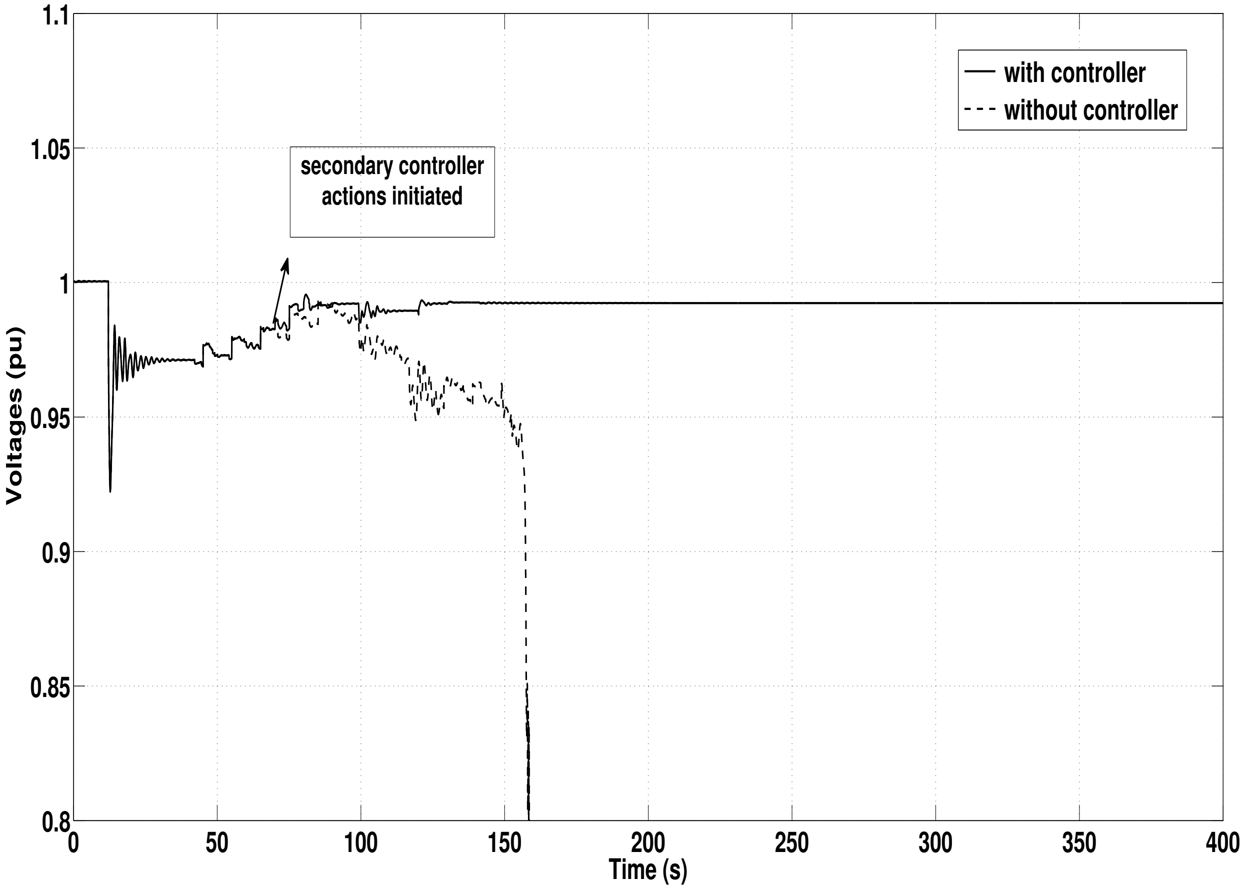

Figure 4.2: Stabilization of voltage at bus 1044 by RHMSO with voltage and reactive power sensitivity and bias based controller for Scenario - 1

Table 4.1: Total amount of active power shedded by each load buses for proposed bias based controller

Load buses	**Total amount of curtailed active power P(MW)**
1022	13
1041	17
1042	14
1043	13
1044	19
1045	18
2031	10
Total load shed	**104**

Apart from the outage of line 4032-4044, other line outages such as outage of line 4032-4042 were considered to test the controllers ability to handle any other type of disturbances that leads to system collapse. The same settings as considered for scenario 1 is chosen with different line outages. It was found that the controller was able to stabilize the system with load shedding. The Table 4.2 delivers the amount of load curtailed for the corresponding line outages.

Table 4.2: List of line outages and corresponding total amount of load shedding by the proposed bias based controller

line outages	without controller	with controller (Load shed (MW))
4032-4044	system collapse at t = 160s	stable, 104
4031-4041	system collapse at t=180.6s	stable, 101
4042-4044	stable	stable, no load shed
4032-4042	system collapse at t = 526.9s	stable, 57
4041-4044	system collapse at t = 238.6 s	stable, 89

For the same disturbance scenario, measurement errors on voltages were considered in order to test the effectiveness of the controller to account for it. A 10 % error on the values of voltages were considered in addition to the scenario - 1. It was found that the controller was able to stabilize the system which proves the robustness of the proposed controller. Figure 4.3 depicts the evolution of the stabilized voltage at bus 1044 with and without the voltage measurement errors.

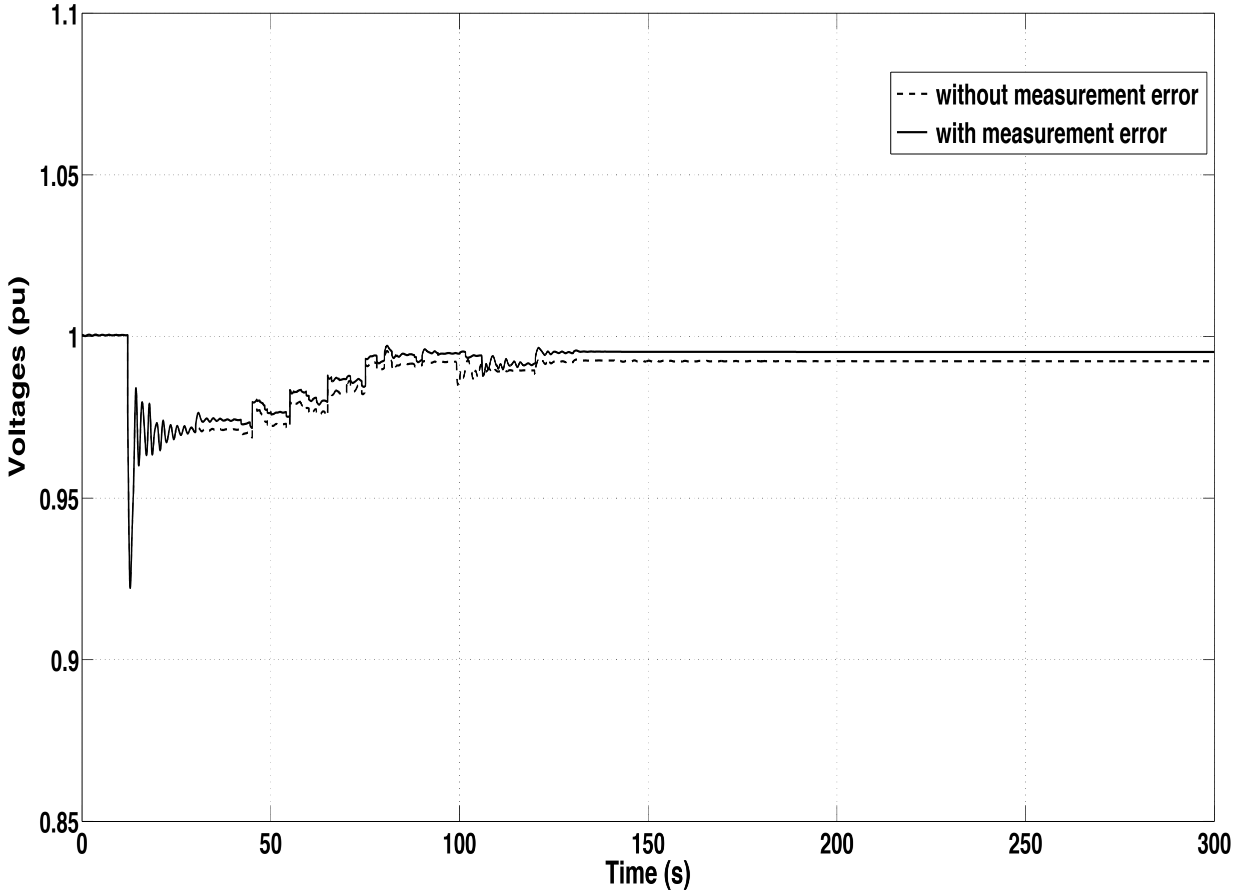

Figure 4.3: Stabilization of voltage at bus 1044 for voltage measurement errors

4.2.2. Scenario - 2: Increase in load demand

In this scenario, the loads on buses 1041, 1042, 1043, 1044 and 1045 were provided with an increase of 7.2 MW/min linearly with time until t = 530 s. The system reaches the point of collapse before this time contributing to long-term voltage instability. The system tries to restore the voltages with the help of LTCs and finally collapse takes place at around t = 513 s.

Upon the activation of the controller, the system was able to become stable after t = 600 s settling to a new long-term equilibrium point. Figure 4.4 shows the evolution of voltage at 1044 with and without the controller for the load increase scenario. The controller start to activate at t = 400 s before the collapse point by issuing control actions by the generator voltages and load shedding leading to a smooth stable response at t = 600 s. The controller issues the modifications in generator voltage set points and load shedding that starts at t = 400 s.

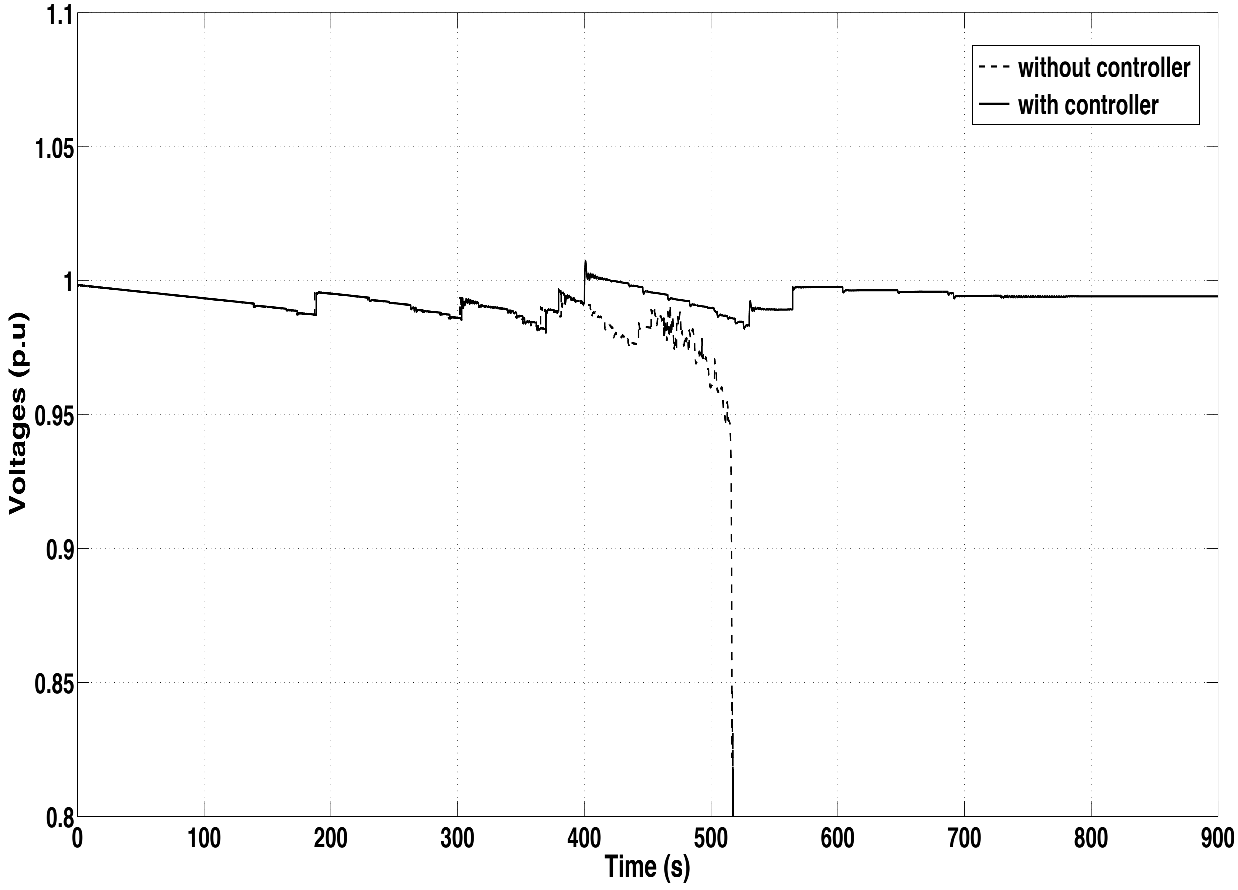

Figure 4.4: Stabilization of voltage at bus 1044 for Scenario - 2

4.2.3. Scenario - 3: Stable but depressed voltages

In this scenario, the controller is tested for a stable system in which voltages at certain buses say for instance the voltage at bus 1041 is 0.94 p.u which is below the desired range of 0.95 to 1.075 p.u. From Figure 4.5, it can be observed that the controller corrects the voltages by bringing back within the desired range.

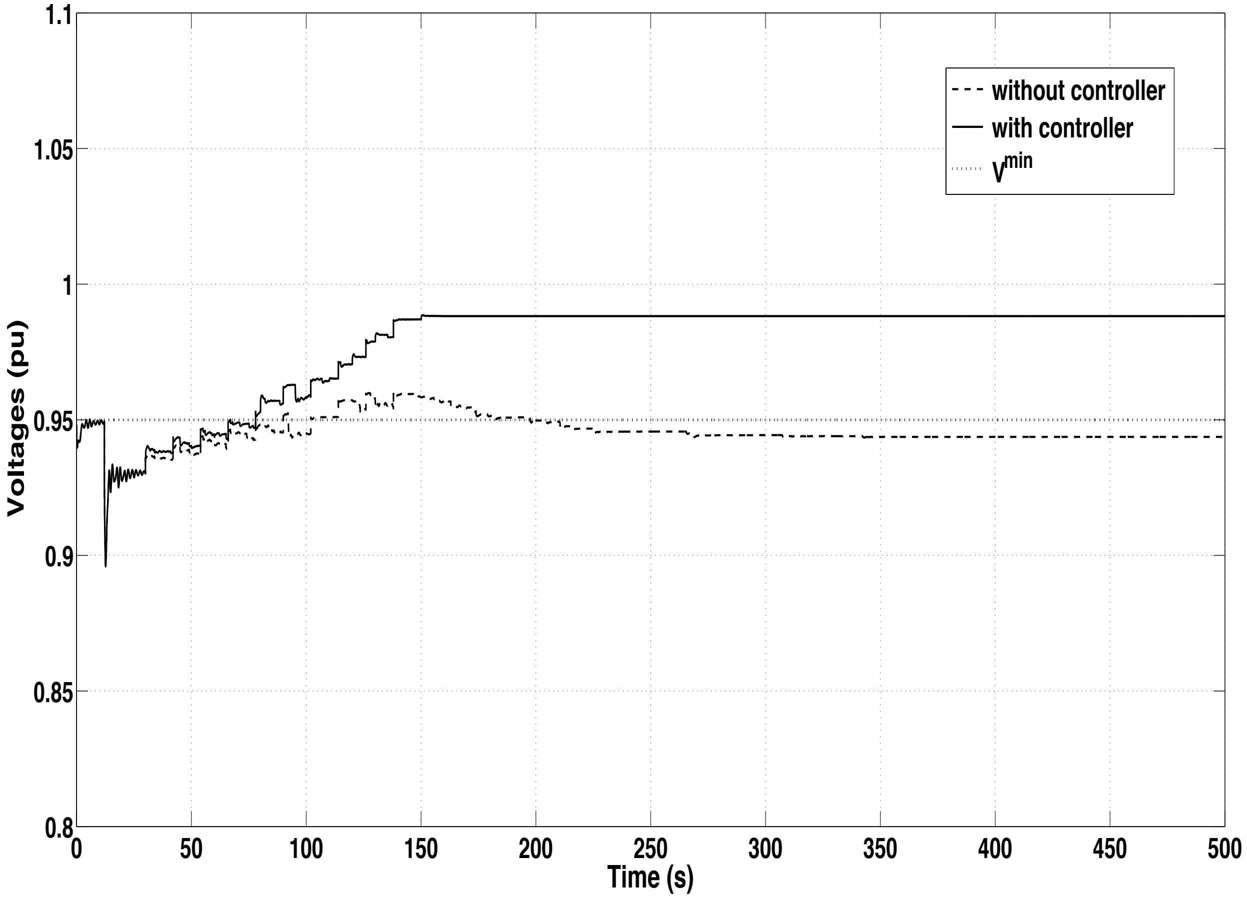

Figure 4.5: Correction of low voltage at bus 1041 by the proposed controller for Scenario - 3

4.2.4. Scenario - 4: Impact of control failure

Control equipment failures are known to be handled by the multi-step controller scheme. In this case, the controller was subjected to control equipment failures to test its ability in handling the failure and stabilizing the system with the rest of the available controls. For this scenario, the case 1 is repeated with the following control failure:

Failure of g1 to g5 (not providing the computed control actions)

Figure 4.6 shows the evolution of voltages with and without the control failure implementation. It is observed that the controller stabilizes the system which starts to compensate for the failure from t = 80 s. The compensation for the control failure was provided by increasing the control effort on the rest of the generators and load shedding.

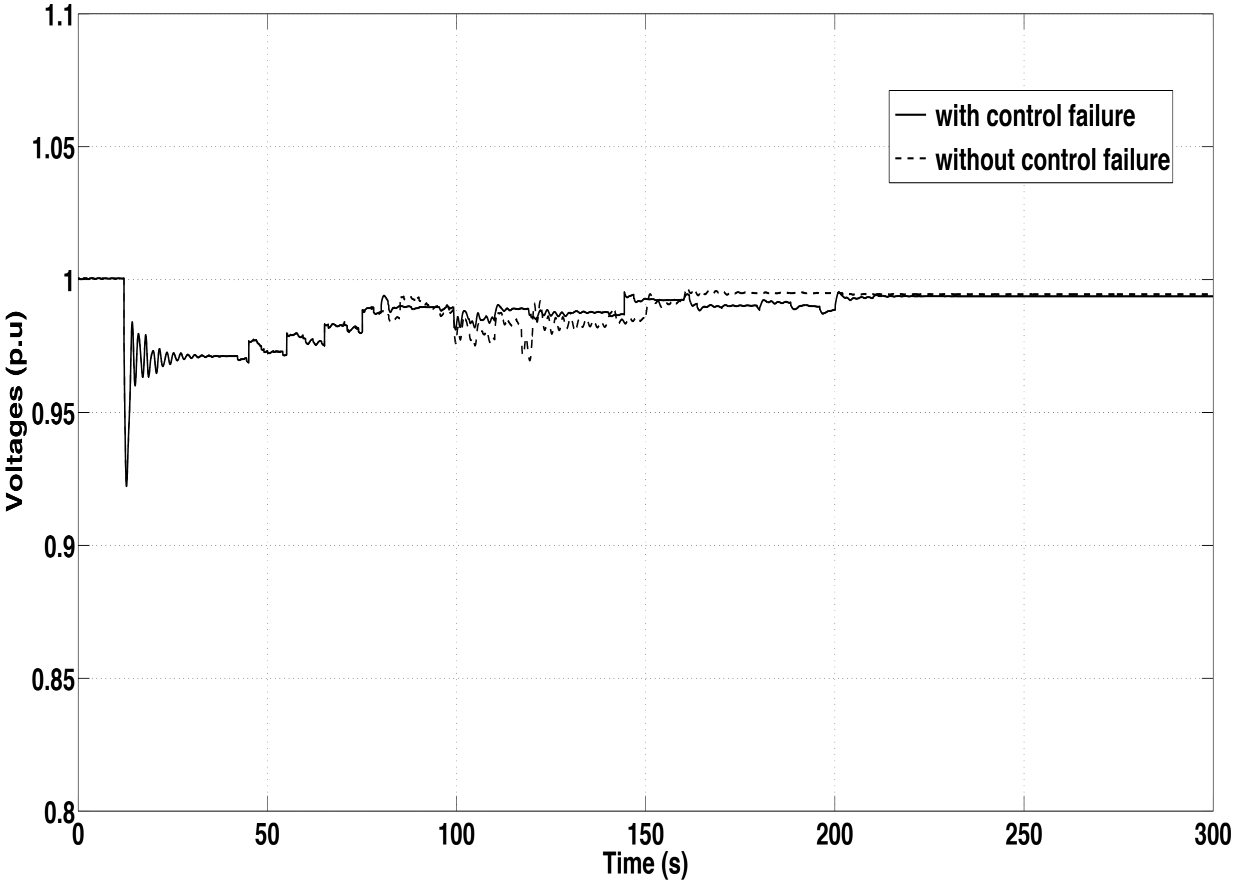

Figure 4.6: Stabilization of voltage at bus 1044 for control failure

The controller was able to stabilize the system with the available controls. Thus the controller offers robustness with respect to component failures.

4.3. Analysis of sensitivity and bias based system model (only V and combined V,Q sensitivities)

The central region line 4032-4044 outage (scenario - 1) is considered for comparisons. In this case, the system that becomes unstable is being stabilized by the load shedding. The stabilized voltage plots for the following simulations are presented:

- RHMSO with only voltage (V) sensitivity constraint (bias and non-bias based)
- RHMSO with both voltage (V) and generator reactive power (Q) sensitivity constraints (bias and non-bias based)

Both the sensitivity based RHMSO controllers were tested by adding the bias error corrector to the sensitivity constraints. It was observed that the usage of bias term which provides automatic correction of errors that had encountered at every time step was able to provide a significant amount of less load curtailment in comparison to the non-bias based controllers. Here non-bias controller refers to simplified RHMSO controller (Chapter 3).

The RHMSO controller with only V sensitivity is simulated with and without the bias. The system gets stabilized by both the controller however, the bias based controller provided better performance which is shown in Figure 4.7 portraying the stabilization of voltage at bus 1044 of the respective controllers.

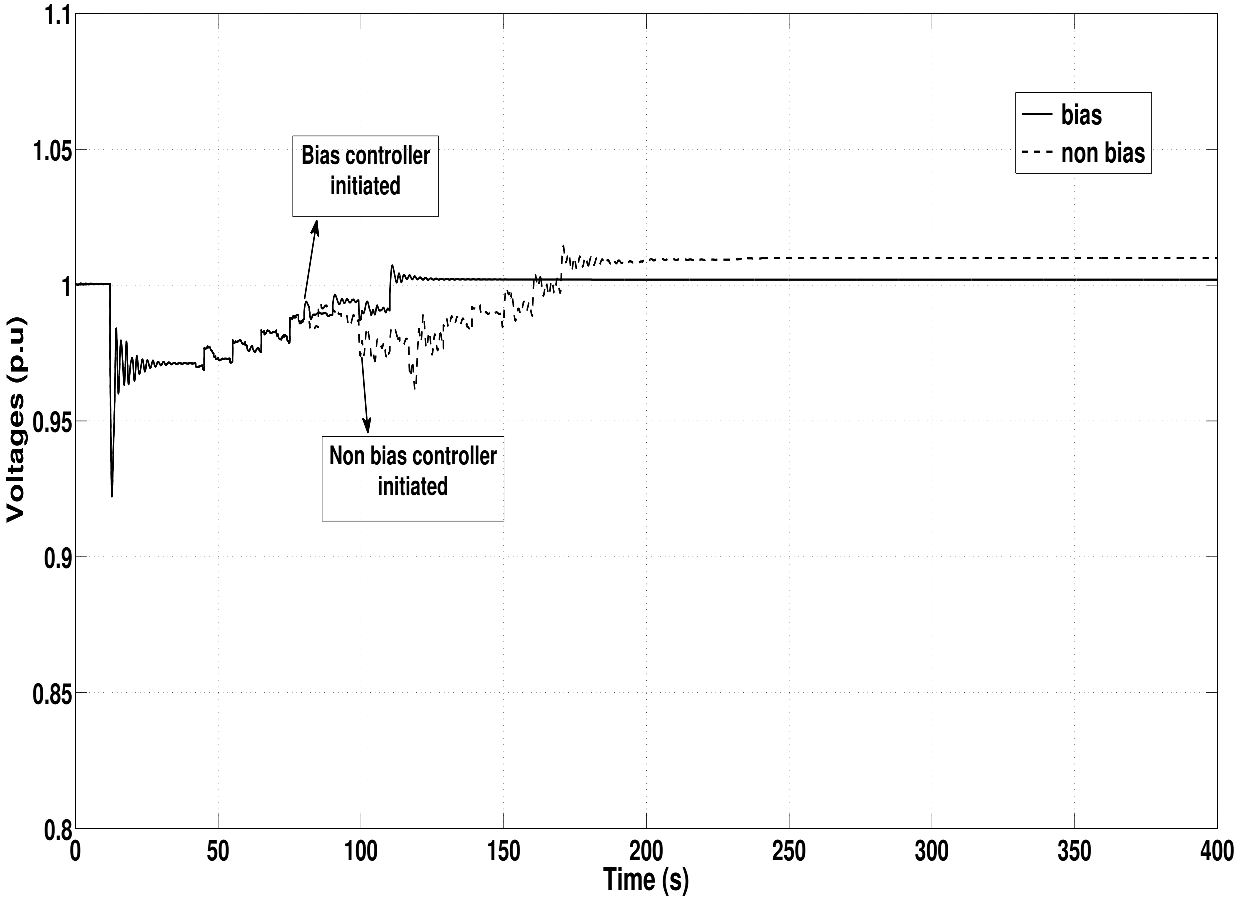

Figure 4.7: Stabilization of voltage at bus 1044 by RHMSO V sensitivity with and without bias based controller for Scenario - 1

It can be observed that the bias based controller was able to stabilize faster (decrease in settling time) and provide less load shedding when compared to the controller without bias. Both the controllers starts activates the controller at t = 20 s where the control actions get computed for every 10 s from then on. The bias based controller starts to implement the secondary control actions from t = 70 s while the non bias controller implements at t = 80 s. Both the controllers stabilizes the system however the control effort and the settling time of the response (t = 120 s) for the bias based controller is significantly less when compared to the non bias controller (settling time t = 215 s).

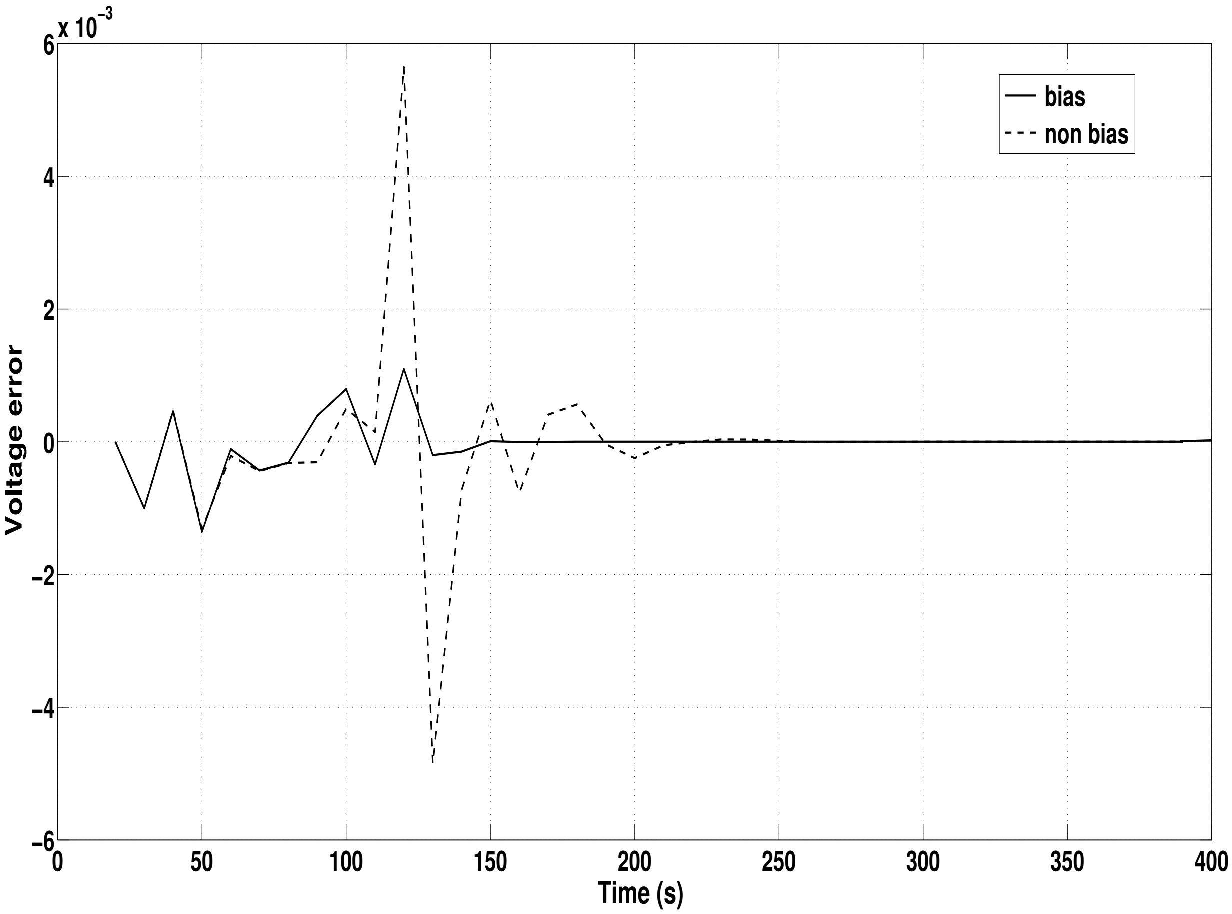

Figure 4.8: Voltage errors for bias and non bias controllers

Figure 4.8 provides the voltage error plots for both the bias and non bias based controllers. This plot supports the usage of the bias which acts as an error corrector. The bias controller is able to correct the errors in the system model which is not seen by the non bias controller at every time step and eventually reduces the errors to zero bringing it close to perfect system model. This error correction results in better performance of the system where the control actions and settling time of the response gets reduced with smoother system response. Figure 4.9 provides the total amount of load shed on each of the load buses for the bias and non bias controller.

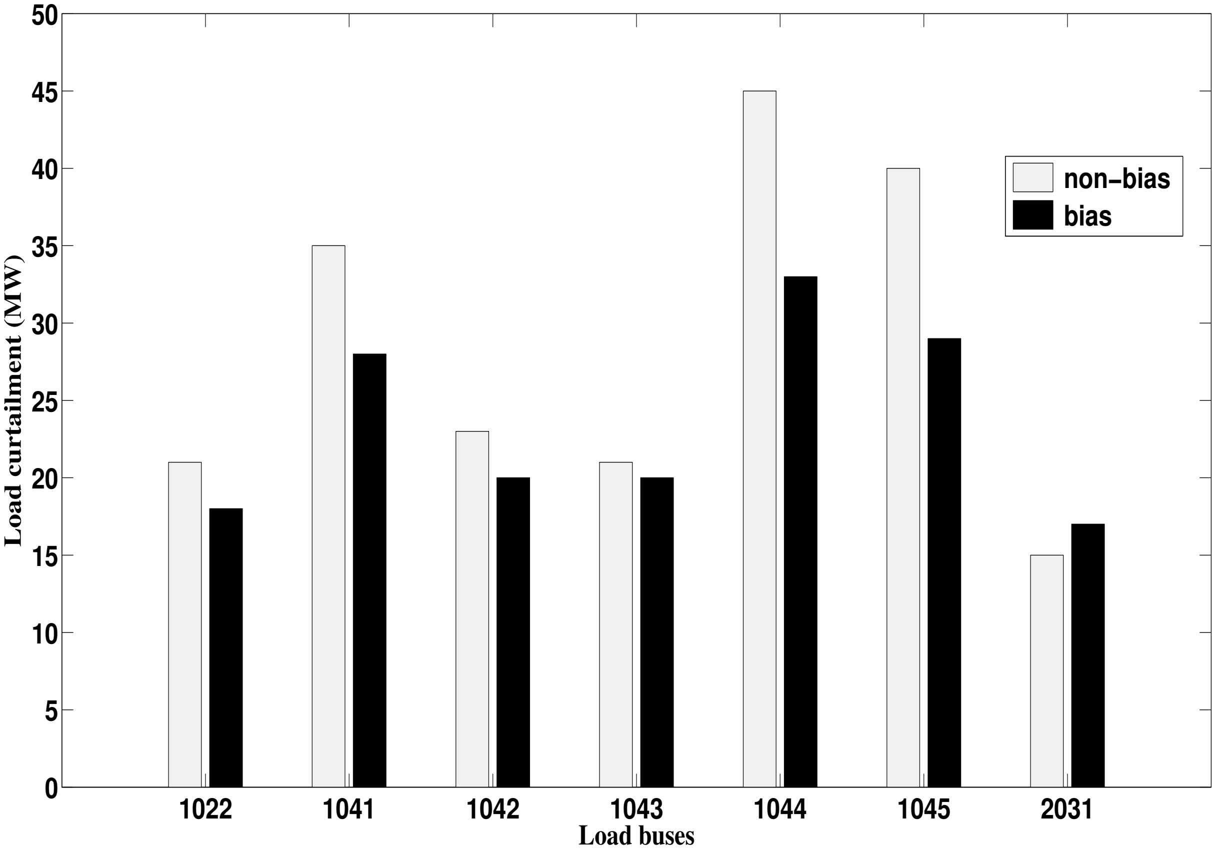

Figure 4.9: Total amount of load shedded on each load buses by RHMSO V sensitivity with and without bias based controller for Scenario - 1

Similarly, the RHMSO with V,Q sensitivities is simulated with and without the bias and the stabilization of the voltage at bus 1044 by both controllers is provided in Figure 4.10. The bias based controller provides better performance as seen in previous scenario when compared to the controller without bias.

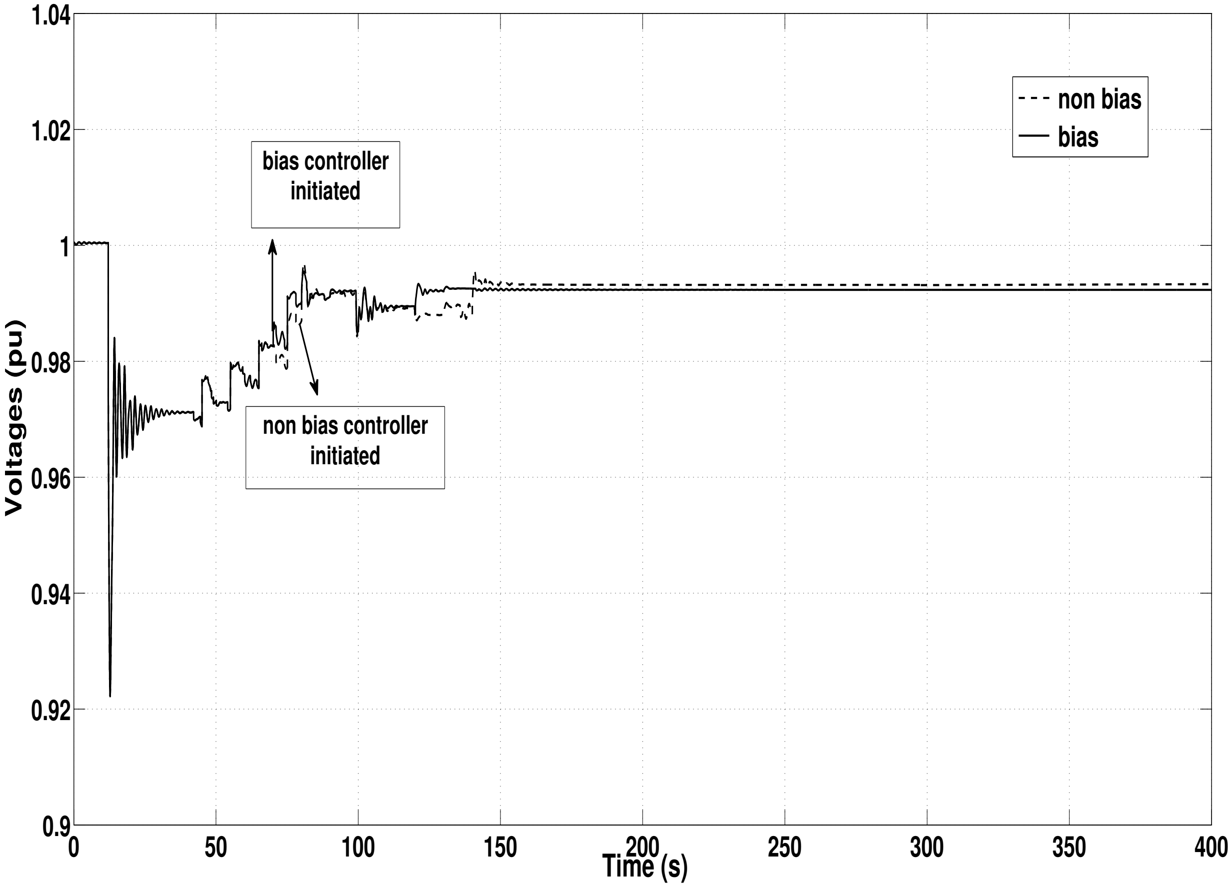

Figure 4.10: Stabilization of voltage at bus 1044 by RHMSO with V,Q sensitivities with and without bias based controller for Scenario - 1

From Figure 4.10, it is evident that both the bias and non bias controller stabilizes the system with smoother response. Both the controller gets activated at t= 20 s where, the bias controller implements the secondary controls at t = 70 s and settles much faster at t=120 s than the non bias controller which implements the control actions at t = 80 s and settles at t = 150 s. As mentioned in the previous scenario (only V sensitivity), the bias controller performs better as it is able to correct and reduce the errors to zero in less time step, thereby leading to effective control actions with less settling time.

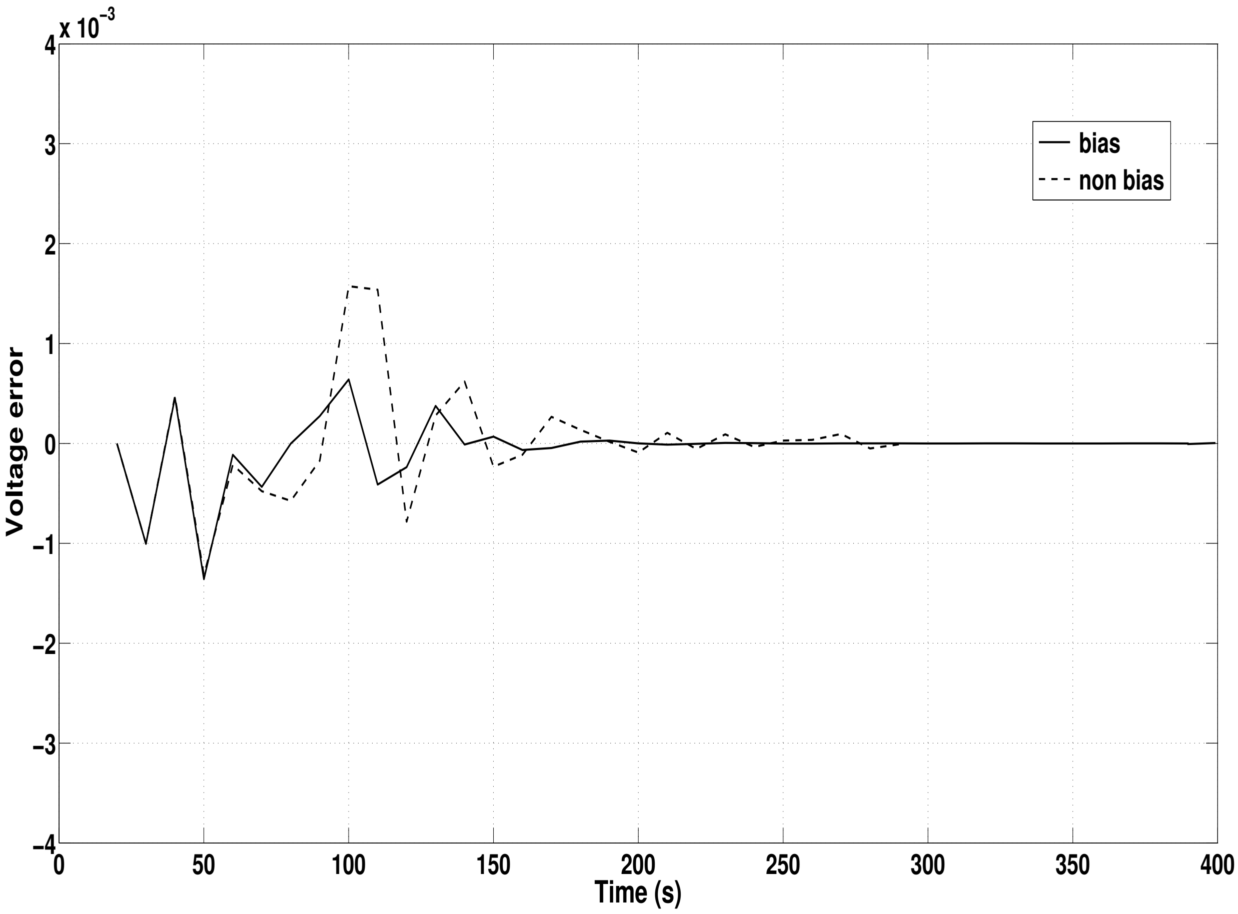

Figure 4.11: Voltage errors for bias and non bias controllers

Figure 4.11 delivers the voltage error plots for both the bias and non bias controller which verifies the usage of the bias error correction. Figure 4.12 provides the total amount of load shed on each load buses respectively for both the bias and non bias based controllers.

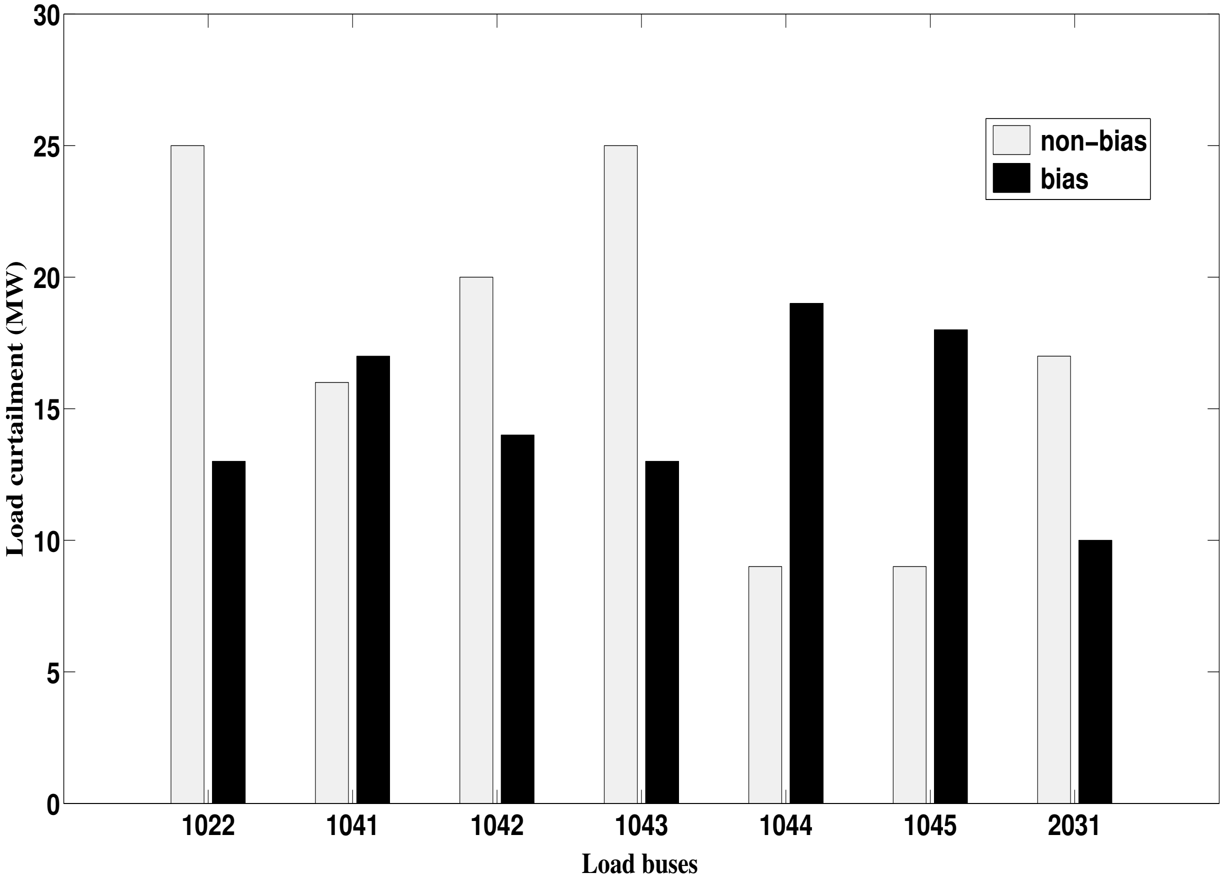

Figure 4.12: Total amount of load shedded on each load buses by RHMSO with V,Q sensitivities with and without bias based controller for Scenario - 1

It is evident from the Figure 4.7 and Figure 4.9 that the bias controller provides effective error correction that is done automatically at each time step and finally resulting in faster response (decrease in settling time) and lower load curtailment. The Table 4.3 provides a list of controllers considered for analysis with their respective total load shedding. The conclusion to be drawn from the observations is that,

- The system was able to attain stability when accounting for only voltage sensitivity constraint
- The combined V,Q sensitivity constraints performs better providing lesser load shedding

- The bias based controller performs much better than the non-bias based controller with decrease in settling time and load curtailment.

Table 4.3: List of controllers and corresponding total load curtailment

Controller Type	Total load curtailed P(MW)
RHMSO with V sensitivity	202
RHMSO with V sensitivity and bias	163
RHMSO with V and Q sensitivities	131
RHMSO with V Q sensitivities and bias	104

4.4. Comparisons with different controllers

4.4.1. Proposed bias Vs non-bias based RHMSO with V,Q sensitivities

From the observations, the bias based controller tends to be better than the non-bias based controller on the following basis:

- Faster system response (decrease in settling time)
- Reduced load shed

Table 4.4 delivers the list of scenarios tested for both the bias and non-bias based controllers along with the total amount of load shedding accounted by each controllers. The bias based controller was able to provide more than 20 MW lesser load shedding when compared to the non-bias based controller with respect to most of the scenarios. Both the controllers were able to handle control failures.

Table 4.4: Results for total amount of active power curtailed by bias and non-bias based RHMSO with V,Q sensitivities controller for different scenarios

Scenarios	Bias based V,Q sensitivities Load shed (MW)	non-bias based V,Q sensitivities Load shed (MW)
Stabilization of unstable system	Stable, 104	Stable, 131
Load increase	Stable, 130	Stable, 143
line outage of 4032-4042	Stable, 57	Stable, 84
line outage of 4041-4044	Stable, 88	Stable, 104
Correction of low voltages	Stable and corrected	Stable and corrected
Control failure	Compensates and stabilizes with decrease in settling time	Compensates and stabilizes with increase in settling time

4.4.2. Proposed bias and linear system based Vs non-linear system based RHMSO

The RHMSO sensitivity and bias based controller was compared with the RHMSO non-linear system based approach that utilizes non-linear power flow based equations for scenario 1. It was observed that, the RHMSO with non-linear system model provided a load shedding of **107 MW** (3 MW more than bias based). There is no significant reduction in terms of load shedding. However, the RHMSO non-linear model requires a predictive load model (based on load restoration effect) whereas it is not necessary for the RHMSO sensitivity and bias based model. The non-linear model does not stabilize the system when the actual values of the loads (without predictive load model) were considered whereas sensitivity and bias based model was able to stabilize the system. This can be regarded as an advantage of using sensitivity and bias based model.

4.5. Summary

In this chapter, the proposed simplified RHMSO sensitivity and bias based controller is addressed. The problem formulation and solution approaches are described in detail. The simulation results for the proposed method is analyzed and observations are discussed for various scenarios. An analysis is provided for the controller considering only V sensitivity and combined V,Q sensitivities (with and without bias based approach). Comparison for bias and non - bias based controllers with the combined V,Q sensitivities for different scenarios are addressed. Finally, a brief comparison for the the bias based controller and RHMSO non-linear system model is provided.

Chapter 5

Conclusions

5.1. Summary of contributions and conclusions

Over the years, power system has grown in complexity and so has the controls pertaining to them. Analysis of voltage instability is of vital importance for smooth and reliable operations of power systems. This thesis has focused predominantly on long term voltage instability problem; the corrective mechanism and controls for the same. An MPC based voltage control is formulated, the corrective measures and controls applied to alleviate it are analyzed through simulation results. Even though MPC based voltage control is not new, the research work stands apart on the merit of its original contributions listed below.

- The non linear power flow equations are substituted by linear sensitivity based system model, thereby reducing the computation complexity of the problem.
- A multi step optimization approach is adopted to alleviate the drawbacks of single step approach as seen in previous works.
- A bias based error corrector is included in the linear system model to correct and reduce the measurement errors thereby increasing system and control performance.

Over the course of the research, the effectiveness of the simplified RHMSO controller was tested on the Nordic - 32 test system. Contingency scenarios like line outages, gradual increase in loads, stable but depressed voltages, control failure were simulated. The results show that the bias based controller was able to stabilize unstable system and correct voltages as seen in line outages and load increase scenarios. It performs admirably well even during partial control failure by stabilizing the system and bringing back voltages to pre-defined levels. It is also seen that the controller is able to correct low voltage scenarios with minimal response time.

The conclusions for the above mentioned contributions are as follows:

- The transformation of non-linear to the linear system model based on sensitivity analysis simplifies the problem formulation such that all the constraints to be satisfied are linear.
- The load model does not require any predictive mechanism as required for non linear system model in [39] due to the usage of sensitivity based system model.
- Analysis on using only voltage sensitivity and combined voltage (V) and generator reactive power (Q) sensitivity constraints is presented and concluded that better performance is provided by the combined V, Q sensitivity constraints. Also it was observed that accounting for only voltage constraints were sufficient to stabilize an unstable system with considerable amount of load shedding.
- Inclusion of a bias error corrector provides effective control performance with minimal load shedding and decrease in settling time by the minimizing the errors at every time step. In addition, the need for updating the sensitivities is not required in bias based controller.
- The results were compared with previous works and it can be clearly seen that the proposed controller both bias and non - bias offers significant reduction in load curtailment during all contingency scenarios. However, the bias based controller tends to provide better performance.

5.2. Future works

The future works for the proposed controller can be summarized as follows:

- Testing the proposed controllers with different test systems and controller settings.
- Inclusion of uncertainty in on-line voltage control scheme such as the amount of load shedding, power factor can be implemented in the proposed controller.
- Stochastic optimization approaches such as Chance Constrained Optimization (CCO), capable of handling uncertainties can be applied to the proposed RHMSO non-bias and bias based controllers.

Bibliography

[1] C.W.Taylor. *Power system voltage stability.* McGraw-Hill,New York, 1994.

[2] P.Kundur. *Power system stability and control.* McGraw-Hill,New York, 1994.

[3] T.Van Custem and C.Vournas. *Voltage Stability of Electric Power Systems.* Boston,Kluwer, 1998.

[4] Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations. *U.S.-Canada Power System Outage Task Force*, 2004. [Online]. Available. `http://emp.lbl.gov/sites/all/files/2003-blackout-US-Canada.pdf`.

[5] A. Berizzi. The Italian 2003 blackout. *Power Engineering Society General Meeting, 2004. IEEE*, pages 1673–1679, 2004.

[6] Final report: System disturbance on 4 November, 2006, Union for the Co-ordination of Transmission of Electricity, 2007, accessed in june 2010. [Online] . Available. `http://www.entsoe.eu/fileadmin/userupload/library/publications/ce/otherreports`.

[7] G. Andersson, P. Donalek, R. Farmer, N. Hatziargyriou, I Kamwa, P. Kundur, N. Martins, J. Paserba, P. Pourbeik, J. Sanchez-Gasca, R. Schulz, A Stankovic, C. Taylor, and V. Vittal. Causes of the 2003 major grid blackouts in north america and europe, and recommended means to improve system dynamic performance. *Power Systems, IEEE Transactions on*, 20(4):1922–1928, Nov 2005.

[8] P.W. Sauer. Reactive power and voltage control issues in electric power systems. In *Applied Mathematics for Restructured Electric Power Systems*, Power Electronics and Power Systems, pages 11–24. Springer US, 2005.

[9] T. Van Cutsem and C.D. Vournas. Emergency voltage stability controls: an overview. In *Power Engineering Society General Meeting, 2007. IEEE*, pages 1–10, June 2007.

[10] C. Canizares. Voltage stability assessment : concepts, practices and tools. Technical report, Special Publication of IEEE Power System Stability Subcommittee, C. Canizares (editor/coordinator), 2002. [Online] . Available. `http://www.montefiore.ulg.ac.be/services/stochastic/pubs/2002/Can02`.

[11] M. Glavic, D. Novosel, E. Heredia, D. Kosterev, A. Salazar, F. Habibi-Ashrafi, and M. Donnelly. See it fast to keep calm: Real-time voltage control under stressed conditions. *Power and Energy Magazine, IEEE*, 10(4):43–55, July 2012.

[12] Y. Song and M. Begovic. Secondary voltage and stability control. In *Power Electronics and Motion Control Conference (EPE/PEMC), 2012 15th International*, pages LS2b.4–1–LS2b.4–7, Sept 2012.

[13] Y. Suzuki, R. Ogahara, and S. Iwamoto. Study on system voltage oscillation and voltage stability control. In *IPEC, 2012 Conference on Power Energy*, pages 172–177, Dec 2012.

[14] M. Begovic and A.G. Phadke. Control of voltage stability using sensitivity analysis. *Power Systems, IEEE Transactions on*, 7(1):114–123, Feb 1992.

[15] T. Van Cutsem. An approach to corrective control of voltage instability using simulation and sensitivity. *Power Systems, IEEE Transactions on*, 10(2):616–622, May 1995.

[16] H. Vu, P. Pruvot, C. Launay, and Y. Harmand. An improved voltage control on large-scale power system. *Power Systems, IEEE Transactions on*, 11(3):1295–1303, Aug 1996.

[17] D. S. Popovi, V. A. Levi, and Z. A. Gorean. Co-ordination of emergency secondary-voltage control and load shedding to prevent voltage instability. *IEE Proceedings - Generation, Transmission and Distribution*, 144:293–300(7), May 1997. [Online]. Available. `http://digital-library.theiet.org/content/journals/10.1049/ip-gtd_19970865`.

[18] F. Capitanescu and T. Van Cutsem. Unified sensitivity analysis of unstable or low voltages caused by load increases or contingencies. *Power Systems, IEEE Transactions on*, 20(1):321–329, Feb 2005.

[19] F. Capitanescu and T. Van Cutsem. Preventive control of voltage security margins: a multicontingency sensitivity-based approach. *Power Systems, IEEE Transactions on*, 17(2):358–364, May 2002.

[20] V. Ajjarapu. *Computational techniques for voltage stability assessment and control*. Springer, 2007.

[21] M. Zima and G. Andersson. Stability assessment and emergency control method using trajectory sensitivities. In *Power Tech Conference Proceedings, 2003 IEEE Bologna*, volume 2, pages 7 pp. Vol.2–, June 2003.

[22] M. Zima and G. Andersson. Model predictive control employing trajectory sensitivities for power systems applications. In *Decision and Control, 2005 and 2005 European Control Conference. CDC-ECC '05. 44th IEEE Conference on*, pages 4452–4456, Dec 2005.

[23] M. Glavic and T. Van Cutsem. Wide-area detection of voltage instability from synchronized phasor measurements. part i: Principle. *Power Systems, IEEE Transactions on*, 24(3):1408–1416, Aug 2009.

[24] V. Calderaro, V. Galdi, G. Massa, and A. Piccolo. Distributed generation and local voltage regulation: An approach based on sensitivity analysis. In *Innovative Smart Grid Technologies (ISGT Europe), 2011 2nd IEEE PES International Conference and Exhibition on*, pages 1–8, Dec 2011.

[25] P. Roy and P. K. Das. Reactive power sensitivity index based voltage stability analysis to a real system (400kv system of wbseb) 1. In *International Journal of Electronics and*

Communication Technology (IJECT), Jan 2013.

[26] P. Li, Y. Wang, Y. Yuan, and B. Zhang. Study on a novel load shedding strategy for voltage stability control. In *Power and Energy Society General Meeting (PES), 2013 IEEE*, pages 1–5, July 2013.

[27] Z. Zhang, Z. Wang, and P Fang. Study on emergency load shedding based on frequency and voltage stability. *International Journal of Control & Automation*, 7(2), 2014.

[28] M. Larsson, D. J. Hill, and G. Olsson. Emergency voltage control using search and predictive control. *International Journal of Electrical Power and Energy Systems*, 24(2):121 – 130, 2002.

[29] M. Larsson and D. Karlsson. Coordinated system protection scheme against voltage collapse using heuristic search and predictive control. *Power Systems, IEEE Transactions on*, 18(3):1001–1006, 2003.

[30] I.A. Hiskens and B. Gong. Voltage stability enhancement via model predictive control of load. *Intelligent Automation & Soft Computing*, 12(1):117–124, 2006.

[31] A. G. Beccuti, T. H. Demiray, G. Andersson, and M. Morari. A lagrangian decomposition algorithm for optimal emergency voltage control. *Power Systems, IEEE Transactions on*, 25(4):1769–1779, 2010.

[32] D. Q. Mayne, J. B. Rawlings, C. V. Rao, and P. O. M. Scokaert. Constrained model predictive control: Stability and optimality. *Automatica*, 36(6):789–814, 2000.

[33] J. M. Maciejowski. *Predictive control: with constraints*. Pearson education, 2002.

[34] J.Y. Wen, Q. H. Wu, D. R. Turner, S. J. Cheng, and J. Fitch. Optimal coordinated voltage control for power system voltage stability. *Power Systems, IEEE Transactions on*, 19(2):1115–1122, 2004.

[35] B. Marinescu and H. Bourles. Robust predictive control for the flexible coordinated secondary voltage control of large-scale power systems. *Power Systems, IEEE Transactions on*, 14(4):1262–1268, 1999.

[36] M. Glavic and T. Van Cutsem. Some reflections on model predictive control of transmission voltages. In *Power Symposium, 2006. NAPS 2006. 38th North American*, pages 625–632. IEEE, 2006.

[37] B. Gong and I. A. Hiskens. Two-stage model predictive control for voltage collapse prevention. In *Power Symposium, 2008. NAPS'08. 40th North American*, pages 1–7. IEEE, 2008.

[38] L. Jin, R. Kumar, and N. Elia. Model predictive control-based real-time power system protection schemes. *Power Systems, IEEE Transactions on*, 25(2):988–998, 2010.

[39] M. Glavic, M. Hajian, W. Rosehart, and T. Van Cutsem. Receding-horizon multi-step optimization to correct nonviable or unstable transmission voltages. *Power Systems, IEEE Transactions on*, 26(3):1641–1650, Aug 2011.

[40] G. Valverde and T. Van Cutsem. Model predictive control of voltages in active distribution networks. *Smart Grid, IEEE Transactions on*, 4(4):2152–2161, 2013.

[41] M. Hajian, W. Rosehart, M. Glavic, H. Zareipour, and T. Van Cutsem. Linearized power flow equations based predictive control of transmission voltages. *2014 47th Hawaii International Conference on System Sciences*, 0:2298–2304, 2013.

[42] C.D. Vournas, G.A Manos, P.W. Sauer, and M. A Pai. Effect of overexcitation limiters on power system long-term modeling. *Energy Conversion, IEEE Transactions on*, 14(4):1529–1536, Dec 1999.

[43] M. Glavic and T. Van Cutsem. Detecting with pmus the onset of voltage instability caused by a large disturbance. In *Power and Energy Society General Meeting - Con-*

version and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, pages 1–8, July 2008.

[44] M. Larsson. *Coordinated voltage control in electric power systems.* Lund University, 2001.

[45] M. Huneault, F. D. Galiana, and Q. St Bruno. A survey of the optimal power flow literature. *IEEE Transactions on Power Systems*, 6(2), 1991.

[46] M. E. El-Hawary et al. Ieee tutorial course, optimal power flow: Solution techniques, requirements and challenges. *IEEE*, 96:110–0, 1996.

[47] H. W. Dommel and W. F. Tinney. Optimal power flow solutions. *Power Apparatus and Systems, IEEE Transactions on*, PAS-87(10):1866–1876, Oct 1968.

[48] S. Frank, I. Steponavice, and S. Rebennack. Optimal power flow: a bibliographic survey ii. *Energy Systems*, 3(3):259–289, 2012.

[49] S. J. Qin and T. A. Badgwell. A survey of industrial model predictive control technology. *Control engineering practice*, 11(7):733–764, 2003.

[50] M. Stubbe. Long-term dynamics-phase ii. *Report of CIGRE Task Force*, 38(08), 1995.

[51] T. Van Cutsem. Description, modeling and simulation results of a test system for voltage stability analysis, Université de liège. February 2012.