Voltage Stability Assessment and Enhancement in Power Systems

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Abstract

Voltage stability is a long standing issue in power systems and also is critical in the power system. This thesis aims to address the voltage stability problems. When wind generators reach maximum reactive power output, the bus voltage will operate near its steady-state stability limit. In order to avoid voltage instability, a dynamic L-index minimization approach is proposed by incorporating both wind generators and other reactive power resources. It then verifies the proposed voltage stability enhancement method using real data from load and wind generation in the IEEE 14 bus system.

Additionally, power system is not necessary to always operate at the most voltage stable point as it requires high control efforts. Thus, we propose a novel L-index sensitivity based control algorithm using full Phasor measurement unit measurements for voltage stability enhancement. The proposed method uses both outputs of wind generators and additional reactive power compensators as control variables. The L-index sensitivity with respect to control variables is introduced. Based on these sensitivities, the control algorithm can minimise all the control efforts, while satisfying the predetermined L-index value. Additionally, a subsection control scheme is applied where both normal condition and weak condition are taken into account. It consists of the proposed L-index sensitivities based control algorithm and an overall L-index minimisation method. Threshold selection for the subsection control scheme is discussed and extreme learning machine is introduced for status fast classification to choose the method which has less power cost on the transmission line.

Due to the high cost of PMUs, a voltage stability assessment method using partial Phasor measurement unit (PMU) measurements is proposed. Firstly, a new optimisation formulation is proposed that minimizes the number of PMUs considering the most sensitive buses. Then, extreme learning machine (ELM) is used for fast voltage estimation. In this way, the voltages at buses without PMUs can be rapidly obtained based on the PMUs measurements. Finally, voltage stability can be assessed by using L-index.

Declaration

This thesis is based on the works carried out by Qitao Liu, under the Supervision of Dr. Hongjian Sun and Dr. Peter Matthews within the School of Engineering at Durham University in the United Kingdom. No part of this thesis has been submitted elsewhere for any other degree or qualification and it is all my own work unless referenced to the contrary in the text.

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Publication List

Journal Paper

– **Qitao Liu** ; Hongjian Sun ; Peter Matthews, “ *A Novel Control Strategy Based on L-index for Voltage Stability Enhancement”*, submitted to IEEE Transaction of Smart Grid, Oct 2018

– Minglei You ; **Qitao Liu** ; Hongjian Sun, “ *New communication strategy for spectrum sharing enabled smart grid cyber-physical system”* IET Cyber-Physical Systems: Theory & Applications, 2017

Conference Paper

– **Qitao Liu** ; Hongjian Sun ; Peter Matthews, “ *Enhancing dynamic voltage stability in power systems with distributed generations”*, 2017 IEEE International Conference on Smart Grid Communications (SmartGridComm), 2017, 218 - 222

– **Qitao Liu** ; Minglei You ; Hongjian Sun ; Peter Matthews, “ *L-Index Sensitivity Based Voltage Stability Enhancement”*, 2017 IEEE 85th Vehicular Technology Conference (VTC Spring), 2017, 1-5

– Minglei You ; **Qitao Liu** ; Jing Jiang ; Hongjian Sun, “ *Power grid observability redundancy analysis under communication constraints”*, 2017 IEEE/CIC International Conference on Communications in China (ICCC), 2017, 1-5

– Minglei You ; **Qitao Liu** ; Hongjian Sun, " *A Cognitive Radio Enabled Smart Grid Testbed Based on Software Defined Radio and Real Time Digital Simulator* ", 2018 IEEE International Conference on Communications Workshops (ICC Workshops), 2018, 1 - 6

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List of Abbreviations

ANN	Artificial Neural Network
AVR	Automatic Voltage Regulator
CAMC	Autonomous Management Controllers
CAN	Controller Area Network
CPF	Continuation Power Flow
CSC	Centralized Secondary Control
DER	Distributed Energy Resources
DFIG	Doubly Fed Induction Generators
DG	Distributed Generations
DMS	Distribution Management System
DSC	Distributed Secondary Control
FACTS	Flexible AC Transmission System
GA	Genetic Algorithm
GPS	Global Positioning System
HB	Hopf Bifurcation
HVDC	High Voltage Direct Current
ILP	Integer Linear Programming
IQP	Integer Quadratic Programming

ISO	Independent System Operator
LTC	Load Tap Changer
MAS	Multi Agent System
MGCC	Micro Grid Central Controller
MTU	Master Terminal Unit
OLTC	On-load Tap Changing
PMU	Phasor Measurement Unit
PV	Power-Voltage
PSO	Particle Swarm Optimization
RTU	Remote Terminal Units
SCADA	Supervisory Control and Data Acquisition
SVC	Static VAR Compensators
VCPI	Voltage Collapse Proximity Indicators
WAMS	Wide Area Monitoring Systems

Chapter 1

Introduction

1.1 Background

An electric power system is a network of electrical components deployed to supply, transfer, and use electric power. Exponential growth of loads due to the advancement of technology is one of the main factors for voltage stability problems. Also, The integration of renewable energy is another challenge for power system operations. The U.S. Energy Information Administration's latest International Energy Outlook 2017 (IEO2017) stuided the worlds power generations and consumptions as well as difference energy sources between 2015 and 2040 [1]. It is reported that world energy consumption will keep increasing, the percentage of increase between 2015 and 2040 will reach 28%, which is shown in Fig 1.1. The main driven force is the growth of economic, which makes demand higher and higher, Asia has the largest growth speed where has more than 60% of the world's total increase in energy consumption. Fig 1.2 shows the tendency that renewable energies will grow the fastest which is account for 2.3% of growth rate each year. Following the renewable energies, nuclear is the world's second fastest growing power source, which is 1.5% each year.

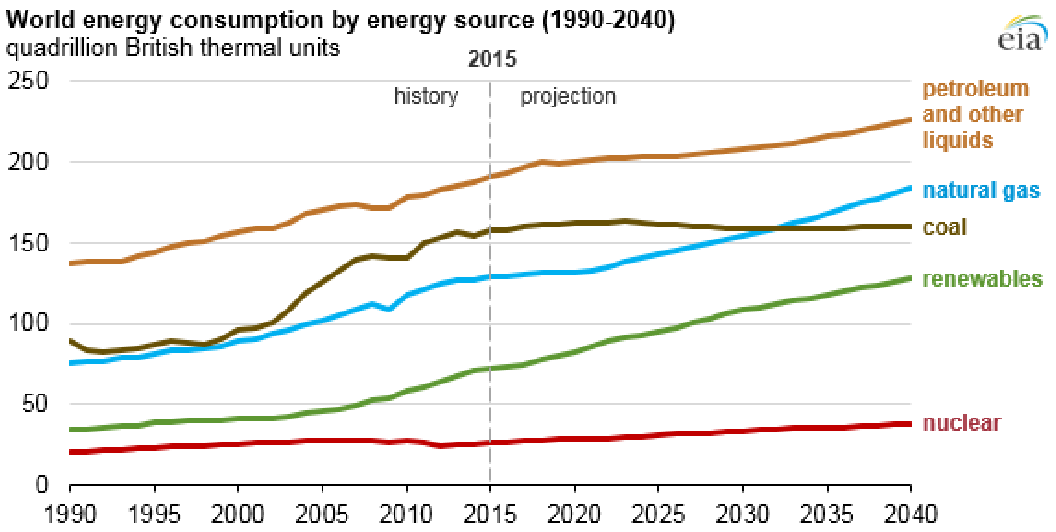

Figure 1.1: world energy consumption [1]

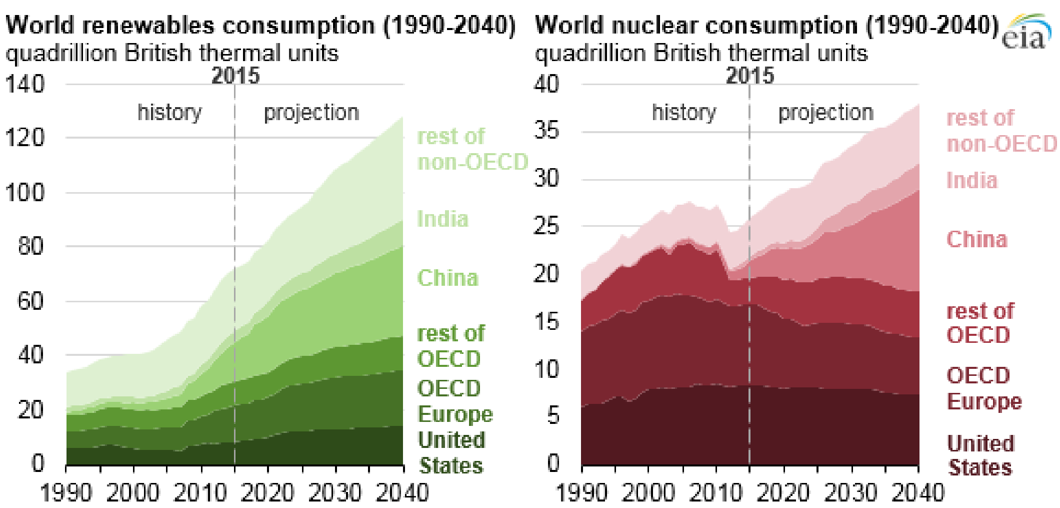

Figure 1.2: world renewable energy consumption [1]

1.2 Research Objectives and Solutions

In this thesis, the stability classification, voltage stability analysis tools and PMU implementation are firstly reviewed. Then, voltage stability assessment and enhancement are studied. There are three research objectives in this thesis.

- A dynamic voltage enhancement approach incorporating both wind generators and other reactive power resources.
- A control strategy considering operating conditions using full PMU measurements
- Voltage stability assessment using partial PMU measurements

1.2.1 Dynamic voltage stability enhancement

Due to the importance of the voltage stability on power systems, several methodologies for voltage stability analysis are proposed. These metrics can reflect the voltage stability condition if the voltage is stable for a given operating condition. Besides, PV curves also show the distance for the system between its current operating point and voltage stability limit. The impacts of variations in reactive power output of Doubly Fed Induction Generators (DFIGs) on the voltage stability of systems were studied in many papers. Some control techniques for active and reactive power of DFIGs and they are widely used in the control design of wind generators with DFIGs. It is suggested that system dynamics could be dramatically improved through an appropriate control strategy with reactive power compensators.

Besides, the impacts of Distributed Generations(DG) units on the voltage stability are studied in many researches. Their impacts on the voltage stability are studied by considering the variations in reactive power output of variable-speed wind generators and reactive power compensators. It is shown that significant improvement in the voltage stability margin could be obtained with proper coordination controls. Moreover, some dynamic loads models and wind generations models are taken into account for dynamic voltage stability analysis. However, little work has been done on the voltage stability enhancement using dynamic load data and dynamic wind generation data. Different from existing works, the objective of this section is to study the dynamic voltage stability enhancement problem with dynamic loads and wind generations.

The main contributions of this section are:

- It presents a dynamic voltage stability enhancement method by coordinating the reactive power sources. Both wind generators and additional installed static VAR compensators (SVCs) are taken into account based on IEEE 14 bus system.
- Real data (from both wind generations and loads) for 24 hours and 1 year are applied in the proposed method for time-series simulations.
- Benefits on enhancing system loadability are analysed. The effect of variations in the wind generation and demand on the loadability is investigated.

This will be detailed in Chapter 3.

1.2.2 Voltage Stability Enhancement Considering Weak Buses with Full PMU Measurements

The voltage stability issues have been investigated by many researchers in a large body of literature. Monitoring is the first step to enhance voltage stability regarding the current operating status. A powerful analysis method for evaluating voltage stability is to estimate the distance of load flow Jacobian to singularity. Thevenin's Theorem based metric is a powerfull method that is widely used for voltage stability assessment by using local measurements. Continuation power flow is an alternative approach. Power-Voltage (PV) curve is plotted from continuation power flow that makes collapse point visible and shows the maximum loadability of the power system. Several studies are proposed for voltage stability enhancement by coordinating reactive power sources. They aim to enhance voltage stability margin by enlarging loadability margin.

On the other hand, there is a trend of high penetration of renewable energy in the traditional grid. Therefore, distributed generations (DGs) should be taken into account when voltage stability problems are considered. The impacts of integrating renewable energy into distribution network are investigated, such as Doubly Fed Induction Generators (DFIGs). They are widely used in variable speed wind power plants. DFIGs offer many merits, such as low cost, high efficiency with the available wind resource and reactive power control capabilities. Particularly, the flexibility of reactive power output of DFIGs was utilized to reduce system losses.

Several considerations are emerged from the previous discussion that motivate the work in this section:

- Several voltage stability identification and enhancement approaches may have computation burden which are suitable for long-time planning. However, they cannot meet the requirements of real-time operation.
- Always maximisation the voltage stability margin may not be the most suitable and economical way to keep power system away from collapse point.
- Weak condition of power system is a crucial consideration. However, it always be considered independently in voltage stability identification.

A subsection control scheme approach is proposed to enhance voltage stability. The approach utilizes L-index, which is a voltage stability metric. The method is expected to be implemented in situations where real data of wind generations and demands are introduced. Additionally, both normal and weak condition are taken into account. A L-index sensitivities based control method is proposed to determine the most effective control actions under normal condition. While, an overall L-index minimisation method is introduced under weak condition. This chapter is directly targeted at utilizing reactive power output of all reactive sources for voltage stability enhancement. The only data and parameters needed to implement the approach are the nodal voltages which can be collected from PMUs. The control problem is linearized by using L-index sensitivities, so that it can be solved in a reasonable time frame, so that control actions can be taken in a short time. This will be detailed in Chapter 4.

1.2.3 Fast Voltage Stability Asscessment Using Partial PMU Measurements

Stability monitoring and assessment are the important applications of PMUs. Although, different types of system stabilities using PMUs data were studied, lack proper optimal PMU placement algorithm for stability assessment. Moreover, it is assumed that voltage phasor and current phasor in the power system are available for stability assessment which is not always the case, especially following disturbances, contingencies or communication failure.

The main idea of the proposed method is, voltage stability assessment method using partial PMU measurements. Eigenvalue or singular value analysis of Jacobian matrix has long been utilized to studied long-term voltage stability in the past research. However, such indices have traditionally disadvantages such as time consuming and dependent on the accuracy of system parameters as well as topology. Therefore, L-index is introduced for voltage stability assessment.

Chapter 5 presents a voltage stability assessment method using partial PMU measurements. Firstly, a new optimisation formulation, which minimize the number of PMUs considering the most sensitive buses, is proposed. Next, extreme learning machine (ELM) is used for fast state estimation. In this way, the states at buses without PMUs can be rapidly obtained based on the PMUs measurements. After that, voltage stability can be assessed by using L-index. The full set of measurements is not required. L-index is firstly calculated under the idealized assumption of PMU measurements assumed available at every bus. Then, L-index with full set of measurements is used to verify the effectiveness of the proposed voltage stability assessment method using PMU measurements which are available from a limit subset of buses. The proposed voltage stability assessment method is tested on the IEEE 118 bus test system and the results are presented. The results show that the error of voltage and L-index between method using partial PMU measurements and full PMU measurements. The effectiveness of fast assessment method using partial PMU measurements is verified. The contribution of this chapter can be seen as follows:

- A PMU placement method for voltage stability considering the most sensitive buses is proposed.
- The voltage stability assessment method can be implemented with limited subsets of PMU measurements.

This will be detailed in Chapter 5.

1.3 Contribution of This Thesis

The main contributions of this thesis are:

- A dynamic voltage stability enhancement method by coordinating the reactive power sources is studied in IEEE 14 bus system. Both wind generators and additional installed static VAR compensators (SVCs) are taken into account.
- A subsection control scheme approach is proposed to enhance voltage stability. Both normal and weak condition are considered.
- A voltage stability assessment method is proposed which can be implemented with limited subsets of PMU measurements from selected buses. The selected buses can be obtained from the proposed PMU placement method while considering the most sensitive buses.

1.4 Outline

The thesis is organised as follows.

In Chapter 2, a review of voltage stability analysis and control is performed. We focus on three main points: control strategies, voltage stability analysis methods and optimal PMU placement method.

Chapter 3 introduces a dynamic voltage stability enhancement method. Case studies are given on the performance comparison between using two optimisation algorithm. Besides, the method is tested using real time-series wind generation and load data.

In Chapter 4, an L-index based control strategy is proposed for voltage stability enhancement. Besides, a subsection control scheme is applied. It consists of the proposed L-index sensitivities based control algorithm and an overall L-index minimisation method.

Chapter 5 presents a voltage stability assessment method using partial Phasor measurement unit measurements. A voltage stability assessment method is proposed which optimize PMU placement while considering the most sensitive buses.

At the end of the thesis, conclusions are presented in Chapter 6, where contributions and results are summarized, and some topics are illustrated for future research.

Chapter 2

Voltage Stability Analysis and Control in Power system

2.1 Overview of Power Systems

In the past two decades, power systems were operated under much more stressed conditions than was usual in the past. There are some factors which can be classified into three reasons:

- environmental pressures on transmission expansion,
- increased electricity consumption in heavy load areas (where it is not feasible or economical to install new generating plants),
- new system loading patterns due to the opening up of the electricity market, etc.

A power system under these stressed conditions, a new type of unstable behaviour can exhibit, which is characterized by slow (or sudden) voltage drops, sometimes may results the form of a collapse.

2.1.1 Stability Problems in Power Systems

Power system stability became a critical consideration in secure operation since the 1920s. Power system instability caused several major blackouts which illustrated the importance to avoid power system unstable.

The definition of power system stability was proposed as

- Power system stability is the ability to regain to normal or stable operation, for a given initial operating condition, after being subjected to some form of disturbance. [2]

Conversely, unstable of a power system means loss of synchronism or falling out of step. A modern power system operation is a high-order multi-variable process. Several devices have different characteristics and response rates in power system that influence the dynamic behaviours. Stability is a equilibrium condition with opposing forces. It depends on network topology, system operation conditions and disturbance. Sustained imbalance caused by different sets of opposing forces that leads to different instability of the power system.

Power system stability is essentially a single problem. However, it may undergo understanding improperly or handling ineffectively due to the various forms of instabilities that a power system may have. Due to the high dimensionality and complexity of power system stability problems, it is important to simplify the assumptions that can help to use an appropriate system representation model and appropriate analytical methods in analysis of specific stability problems . Different system instability caused by different key factors that requires different methods for stable operation. Therefore, classification of stability problems into appropriate types is critical in stability analysis and control.

Fig 2.1 gives a overall picture of the power system stability problem [3], identifying its categories and subcategories.

There are three main categories in power system stability problems, which are stated as follows,

- Rotor angle stability refers to the ability of synchronous machines running in an interconnected power system to remain in the state of synchronism after being subjected to a disturbance. It depends on the electrical torque (power) output of the generator, as there is an angular separation between electromagnetic torque and mechanical torque of each synchronous machine. The Rotor

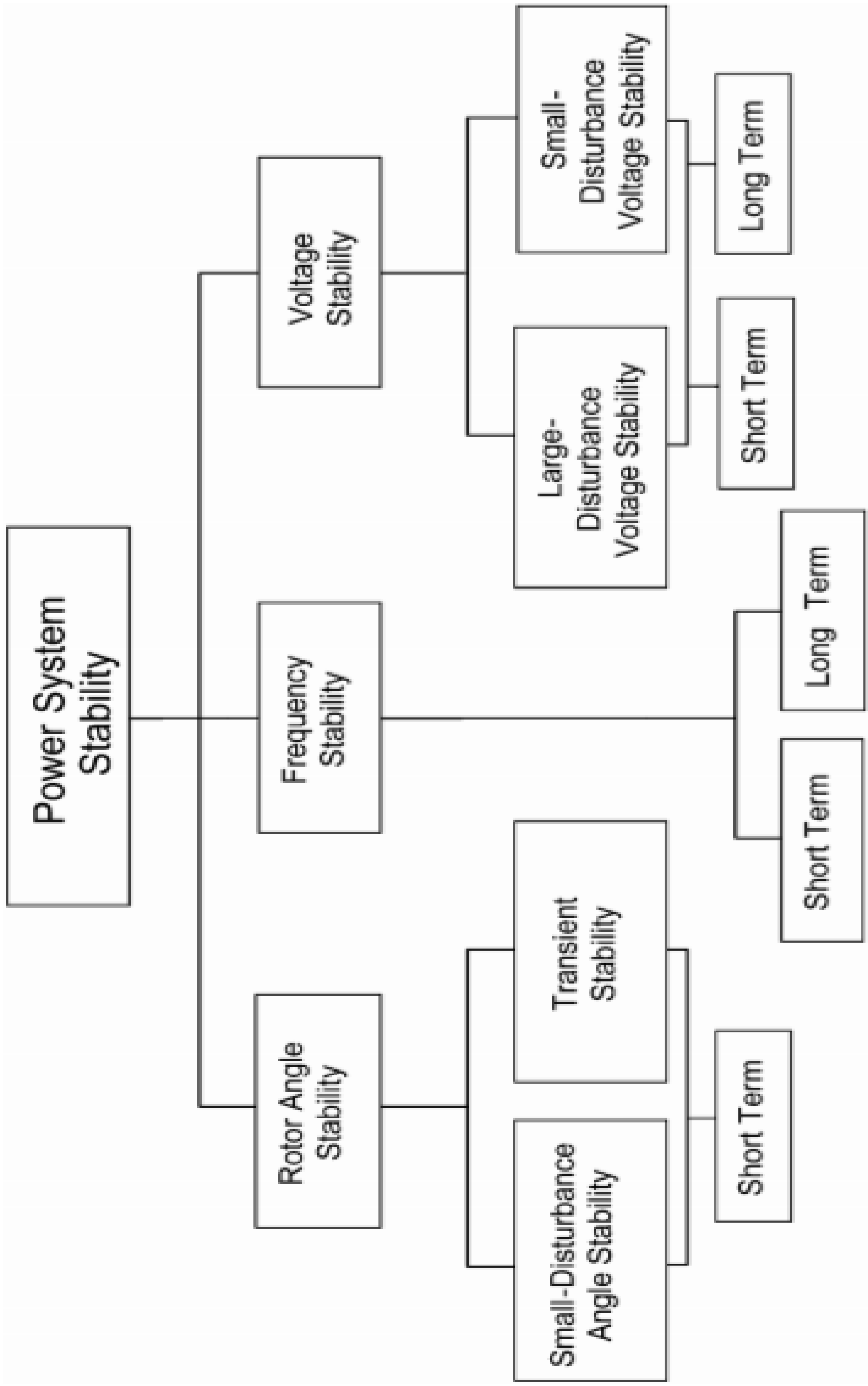

Figure 2.1: Classification of Power System Stability [2]

angle instability will result the increasing angular swings of some generators, which may leads to their loss of synchronism.

- Frequency stability refers to the allowable deviation from the specified Frequency. It depends on the ability to maintain equilibrium between generation and consumption in a power system. Frequency instability may results sustained frequency swings which will lead to tripping of generating units and loads.
- Voltage stability refers to the ability of a power system to maintain to normal or stable operation in the system after being subjected to a disturbance. Voltage instability may result voltages fall or rise on some buses. Its concept and research methods will be detailed in the following chapters.

2.1.2 Control Strategies in Power Systems

With the introduction of distributed power generation, operation of modern power system is becoming extremely complex, especially in control and coordination of multiple distributed. Some of control strategies have been proposed in this section, and divided into three categories which are centralized control, decentralized control and multi agent system.

Centralized control scheme is a feasible approach for distributed network with limited numbers of monitoring and control equipment.Even though the delay of communication has been solved by predictors or compensators. Due to the quantity of distributed networks grows rapidly, the data concentrator should be stronger, more complicate and expensive.

Meanwhile, decentralized control has been widely used in distributed network, such as droop control. So far, there is no exact answer showing which is better. However, it has shown that decentralized control strategy is a better fit for DG networks.It also has several limitations, such as poor transient performance and a lack of robustness. However, distributed network can be controlled autonomously and operated continuously with limited communication. In other words, the distributed networks are controlled independently that avoid a central controller.

- Centralized control

  A new methodology is proposed for coordinated voltage control in distributed generation networks with high penetration of renewable energy [4]. Fig 2.2 shows the architecture of the proposed system. The distribution management system (DMS) operates as supervisory center to control and manage the distributed systems. The central autonomous management controllers (CAMC) are performed as interfaces to the DMS. The micro grid central controllers (MGCC), which are installed in MV/LV substations, manage and control the micro sources and loads while voltage in each LV grid can be monitored by using the communication infrastructure.

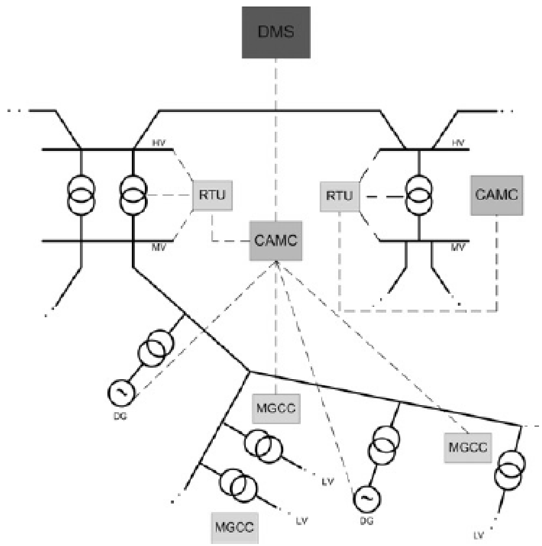

Figure 2.2: Coordinated Voltage Control [3]

A general hierarchical multilevel control scheme is reported [5]. There are three levels in this hierarchy. The primary control is completely local and operates with the inner voltage and current control loops and based on the droop control of individual DGs so that adjust the frequency and voltage amplitude depend on the demand of active and reactive power of the MG. When either load variations or mode transfer between grid connected and islanding perturbs MG, the primary level is unable to regulate the frequency and voltage of the system. Then, secondary control is employed to eliminate the frequency and voltage deviations in steady state or produced by the primary control;

and the tertiary control manages and optimizes the power flow between the MGs and other electrical distribution networks. Generally, the primary and tertiary control levels are performed as decentralized and centralized, respectively, while secondary control cooperates with the other control levels and can be operated in both centralized and decentralized control level. In centralized secondary control (CSC), a MG central controller (MGCC) receives all DGs measured data and then produces control signals bases on the received data. Finally these control signals are forwarded to the local primary control of the DGs. The exchange of measurements and control signals requires reliable communication network. However, all units of the secondary control would not response because of the MGCC failure.

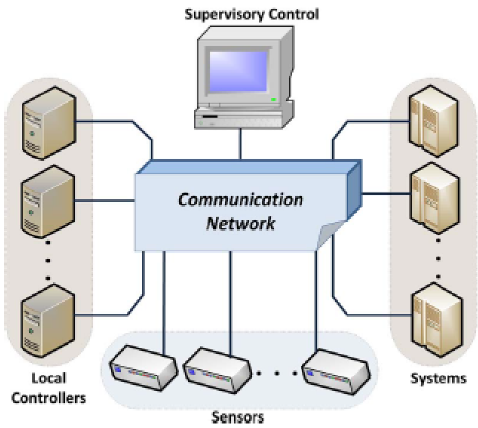

Figure 2.3: Centralized Secondary Control [5]

A distributed secondary control (DSC) scheme is proposed in [6] that avoids only using single centralized controller at the secondary level. In this architecture as shown in Fig 2.3, both of the primary and the secondary controllers are installed locally in each DG which means the communications and control layers are not separated. The controllers of the secondary control level receive all measured data and produce appropriate control signal for the primary controllers and the control signal is locally updated after each data exchange. Data exchange for DSC can be implemented based on distributed consensus algorithms. This scheme provides high reliability of DSC and robustness against delays and packet losses in wide area communication.

- Decentralized control

  There are two types of decentralized control, which are master slave control [7] and autonomous droop control [8] [9] [10] [11]. Master-slave In [7], parallel inverter based micro grid is considered, and master-slave framework is applied. The proposed system, as shown in Fig 2.4, including an upper level controller that assigns each inverter to different roles. One of converters in this system is assigned as the master which performs as a voltage stiff converter while the others in this system operate as current sources converter. Additionally, controller area network (CAN) communication is implemented with the voltage control loop and current sharing control loop.

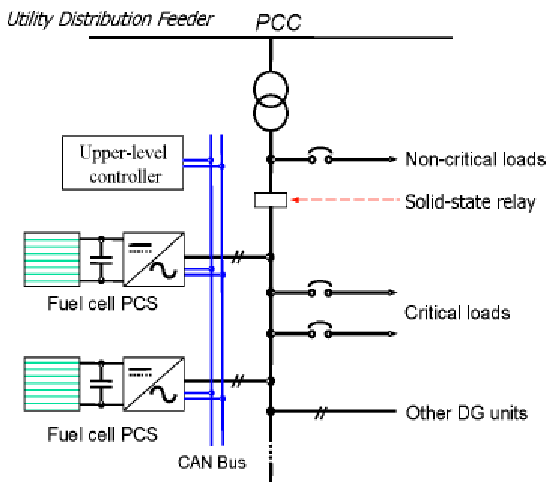

Figure 2.4: Master-slave [6]

Droop Control

Controlling Distributed energy Resources (DER) units based on droop characteristics has been proposed in several papers [8] [9] [10] [11] . In droop control, the relationship between real power/frequency and reactive power/voltage can be expressed as:

$$\omega_0 = \omega^* + K_P(P_0 - P^*) \tag{2.1.1}$$

$$V_0 = V^* + K_Q(Q_0 - Q^*) \tag{2.1.2}$$

where the values ω^* and V^* correspond to the reference values for angular frequency and voltage, respectively, ω_0 and V_0 correspond to the measured output frequency and voltage of the DG system, respectively. The droop coefficients K_P and K_Q are determined based on steady-state performance criteria.

The significant advantage of droop control is that the control action is merely based on local measurements without any communication. This feature provide flexibility that maintain the balance between supply side and demand side. Additionally, the action of controllers is result from the local measurements and droop characteristics . However, the conventional droop control method has several disadvantages which are detailed below : (1) Poor transient performance or instability issues because of using average values of active and reactive power over a cycle, (2) Ignoring load dynamics that once a large or fast load change failure may occur, (3)Unable to black-start-up after system collapse, requiring special provisions for system restoration, (4) Inability to provide accurate power sharing among the DER units due to output impedance uncertainties, (5)Inability to impose a fixed system frequency independent of system loading conditions. [12]

- Multi Agent System (MAS)

  In the decentralized approach, the multi agent system is a promising approach that has potential of autonomous decision making in solving complex problems. Fig 2.5 shows a multi agent system [13], where each agent provide a communication interface to connect other agents and control the operations of related distributed generation networks, such as the power exchange between micro grid and utility. In addition, every agent is an independent decision maker, this means that the connection of agents can be refigured by adding or removing agents. Hence multi agent system is robust. On the other hand, each agent is able to communicate with other agents. The responsibility of an agent is to collect data from all the devices of the micro grid and exchange information, which involves the intended actions, with the neighbouring agents.

Finally, the control signals of agents are adjusted based on the exchanged information. An overview of the MAS has shown in [14] and [15]. And it has shown that MAS embedded in future smart grid is inevitable. A centralized MAS is described in [16]. It has the same with conventional centralized control and subject to communication and significant data manipulation.

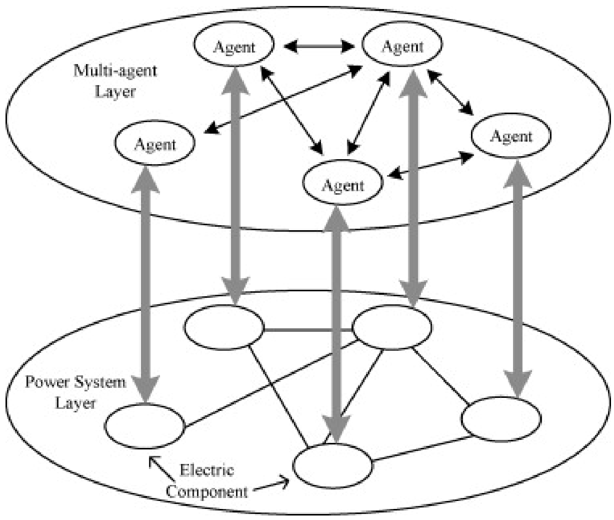

Figure 2.5: Multi Agent System [12]

In [17], a multi agent system for real-time operation of a micro grid is proposed. Agents interact cooperatively to optimize the control and management of the micro grid and two functions of demand side management (equation 2.1.3) and generation scheduling (equation 2.1.4) are shown in this paper. Demand side management plays an important role in smart grid operation that reduces the peak demand and optimizes the load profile. And generation scheduling determines the schedule of generation units in 5 min intervals that provides continuous and real-time matching of supply and demand of the micro grid.

$$\begin{gathered} Minimize \sum_{t=1}^{N} (PLoad(t) - Objective(t))^2 \\ \text{s.t. } Objective(t) + \sum_{i=1}^{N} P_i(t) \geq PLoad(t) \end{gathered} \tag{2.1.3}$$

where $Objective(t)$ is the value of the objective curve at time t, and $PLoad(t)$ is the actual consumption at time t, P_i is the power from i source.

The adjustment in power setting ΔP_i for source is given by the following equation:

$$\Delta P_i^{Assig} = \frac{(P_i^{max} - P_i^{sch})}{\sum(P_i^{max} - P_i^{sch})} \times \sum(P_i^{sch} - P_i^{meas}) \tag{2.1.4}$$

where P_i^{sch} is the scheduled power, P_i^{max} is the maximum power limit for the current market price, and P_i^{meas} is the measured power from the simulation.

In [18], each micro grid is modelled as an inventory system where energy is produced by wind or solar sources. Every smart micro grid has an agent which exchange data and information of demand. Moreover, it is completely autonomous to decide the smart micro grid whether or not to exchange power with others. The main objective is to provide the required power to local load and minimize the cost of energy storage and power exchange among smart micro grids.

A novel fully distributed multi agent based load restoration algorithm is presented in [19]. It is essential that once a fault in micro grids has been cleared, the unfaulted but stopped loads should be timely restored as much as possible. Each agent only communicates with their direct neighbours and exchange the discovered information which based on the Average-Consensus Theorem.

Several applications based on MAS are investigated and have described above, which involves distributed networks operation, power flow optimization and power system restoration. Comparing with the conventional centralized and decentralized control strategy, the main advantage of using Multi Agent System approach is to avoid to manipulate large quantities of data related to the complex network of micro grids and loads can be locally controlled and monitored with a wide range of actions, respectively.

Several schemes, which are based on centralized and decentralized control, are presented above. Both centralized control and decentralized control have advantages and their limitations, which are shown in Table 2.1. Due to the increasing penetration of renewable energy, the shortcomings of these control strategies have become increasing prominent. Therefore, it is particularly urgent to develop a new technique to control of multi distributed networks.

Table 2.1: Comparison of Centralized Control and Decentralized Control

Control Strategies	Centralized Control	Decentralized Control
Advantages	(1)coordinated control (2)wide range of control actions	(1)autonomous control (2)without communication
Disadvantages	(1)control for limited number of equipment (2)subject to the communication delay (3)need a strong concentrator to operate large number of data (4)poor robustness	(1)poor transient performance (2)ignoring large and fast load dynamics (3)unable to black-start-up (4)limited range of control actions

Compared to the traditional centralized and decentralized control, multi agent system is a promising control strategy in power system control. However, multi agent system is a prototype at present, some challenges are summarised in [20] [19] and include the following

- There are a number of multi-agent system platforms. However, long-term compatibility and the robustness acquirements for online applications are required to justification in platform selection.
- Agent communication languages and ontologies are still need to be developed that define how agents exchange information, communicate, and negotiate.
- Agents seamlessly join an agent community, such peer-to-peer nature of agent systems, security is a key consideration. A level of trust is required that evaluate agents and messages security.

Beyond these challenges, the lack of experience in the use of multi-agent system technology in industry is an another concern of both utilities and manufacturers considering MAS solutions. Moreover, with the implementation of PMUs in the power system, it is able to overcomes some drawbacks of the traditional control strategies. The traditional mature control strategies will still play an important role in power system control.

2.1.3 Voltage Stability in Power Systems

The load is usually the reason that leads in voltage unstable. In case of the occurrence of disturbance, power consumption of loads tends to be restored by several control actions, such as motor slip adjustment, distribution voltage regulators and tap-changing transformers. Restored loads may result in raise of reactive power consumption and voltage reduction that increase the stress on the power system, especially the high voltage network. Due to the load dynamics attempt to restore load whose consumption goes beyond the capability of the transmission network and the connected generation, the voltage drop in this situation causes voltage instability [2] [21].

At present, voltage stability has more attention due to voltage collapses and have caused several blackouts in the past decades. For example, the Swedish/Danish system had a blackout on 23rd September 2003 [22], a cascade blackout occurred in the United States and Canada on August 13th 2003, a blackout occurred on the Greek island of Kefallonia on January 24th 2006, one of the most severe fault failures in Vietnam happened on May 22nd 2013 [23].

Voltage stability is related to the ability to maintain the voltage at a certain level in the given nodes of the system during normal operation of the power system, even after a failure. Voltage is a parameter on a certain bus. However, voltage drop at a node may cause a serious impact on the whole system under certain circumstances.

Wu *et al*. [24] presented a decoupled control technique for active and reactive power of DFIGs and it was widely used in the control design of wind generators with DFIGs. The DFIG model is given by the following equations.

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s \varphi_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} - \omega_s \varphi_{ds} \\ v_{dr} = R_r i_{dr} + \frac{d\varphi_{dr}}{dt} - (\omega - \omega_s)\varphi_{qr} \\ v_{qr} = R_r i_{qr} + \frac{d\varphi_{qr}}{dt} + (\omega - \omega_s)\varphi_{dr} \end{cases} \tag{2.1.5}$$

$$\begin{cases} \varphi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \varphi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \varphi_{dr} = L_r i_{dr} + L_m i_{ds} \\ \varphi_{dr} = L_r i_{qr} + L_m i_{qs} \end{cases} \tag{2.1.6}$$

where: i_d, i_q are current components, φ_d, φ_q are the flux components. φ_d, φ_q are the voltage components. The superscripts s and r indicate that space vectors are referred to stator and rotor reference frames, respectively. R_r, R_s are the rotor and stator resistance, respectively. L_r, L_s, L_m are the rotor, stator and mutual inductances, respectively. ω, ω_s are the rotor rotating and stator pulsations, respectively.

Due to the advantage of DFIG for providing reactive power, it can be used in improving voltage stability. It consist of two back to back converters, which are Grid Side Converter (GSC) and Rotor Side Converter (RSC). The GSC is used to maintain DC link voltage constant while the RSC regulates rotor's current and power to control the active and reactive power output.

Voltage drop is the major issue which may cause voltage instability. On the one hand, in case of both high active and reactive power flow through the transmission network, this will cause voltage drop and limits the power transfer. On the other hand, the power transfer and voltage support also limited by field or armature current capability of some generators. Voltage stability is threatened, in case of disturbances or dynamic loads have higher reactive power demand than the available reactive power capacity. Furthermore, even the progressive voltages drop is a common form in voltage instability, but the risk of voltage instability is still available. An event caused by the sensitivity to over voltage of heavily loaded conditions are studied in [25]. Two factors caused the event which are the capacitive behaviour of the network and the excess reactive power due to the generators. In this case, the instability is associated with the inability of the both generation and transmission system [26].

2.1.4 Voltage Control Levels in Power Systems

Generally speaking, there are three hierarchical levels in the voltage control. Fig 2.6 show a schematic diagram of the hierarchical 3-level control scheme for a power system [27]. The lowest level is the primary voltage control and Secondary Voltage Control or the Coordinated Secondary Voltage Control is the middle control level while the Tertiary Voltage Control is the highest level [28].

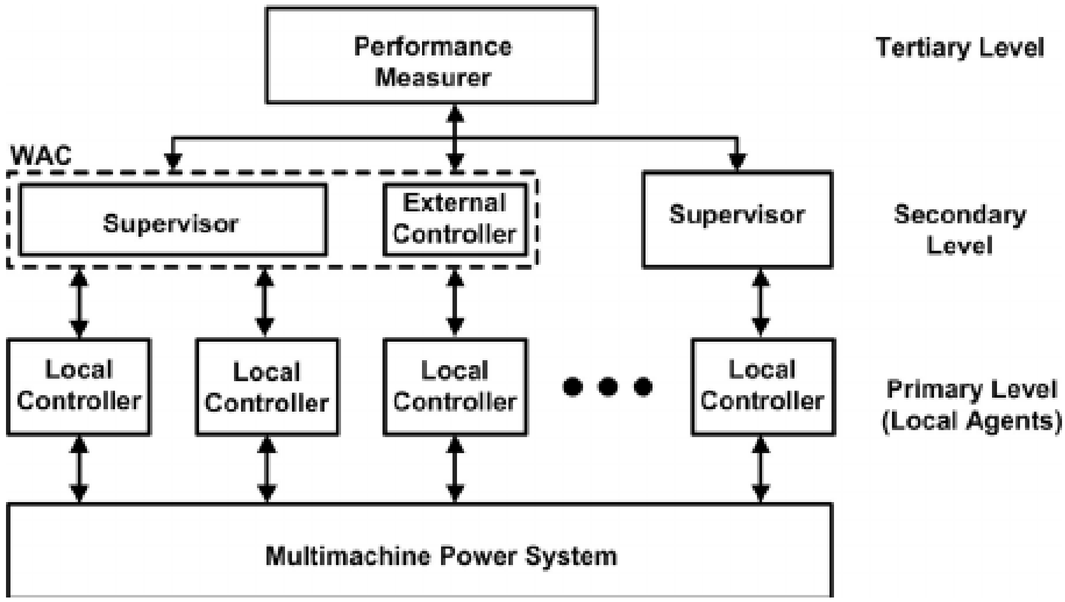

Figure 2.6: Schematic Diagram of The Hierarchical 3-level Control Scheme for Power Systems [23]

- Primary Voltage Control

  The primary voltage control is always to control the Automatic Voltage Regulator (AVR) of generators or the Load Tap Changer (LTC) of transformers that maintain its own bus at a certain voltage level [29]. The Primary Voltage Control levels are controlled by the system operators or higher control levels, such as Secondary Voltage Control or Coordinated Secondary Voltage Control. Compared to the other control levels, the response for Primary Voltage Control is faster and within a few seconds [30].

- Secondary Voltage Control

  As mentioned above, primary voltage control control of one reactive power resource to maintain a set of voltages. Secondary Voltage Control will control multiple reactive power resources based on measurements of one or multiple buses. Voltages will be altered by Secondary Voltage Control for AVRs, LTCs or synchronous capacitors [28].

- Coordinated Secondary Voltage Control Compared to the Secondary Voltage Control, Coordinated Secondary Voltage Control covers a wider area, where a larger number of target buses and control actions are involved.

  [31] shows the simulation for the French system considered both Coordinated Secondary Voltage Control and Secondary Voltage Control which indicates that the Coordinated Secondary Voltage Control is more effective in improving the system voltage profile.

- Tertiary Voltage Control

  Tertiary Voltage Control will play a higher role than the Secondary Voltage Control and Coordinated Secondary Voltage Control. Compared to the lower control level, Tertiary Voltage Control doesn't only provide a improved voltage profile but also an optimal voltage profile for the whole power system [32]. It provides optimal voltage set points for the target buses controlled by Secondary Voltage Control or Coordinated Secondary Voltage Control.

2.2 Mechanism of Voltage Instability

Voltage instability is a major problem of power systems. It has caused several incidences in different countries, for example, the blackouts in Ohio, Michigan, New York and Ontario on August 14, 2003 [33]. These contingencies and voltage collapses have prompted that a significant effort should be made towards the study and prevention of voltage instabilities. The circumstances of voltage instability and voltage collapse phenomenon are considered steady and dynamic instability [34]. In order to understand and resolve the voltage instability issues, it is important to investigate the mechanism of voltage instability, such as the reason of instability and the key contributing factors.

From figure 2.1, it can be seen that voltage stability has been further classified into four categories: Large disturbance voltage stability, small disturbance voltage stability, short term voltage satiability and long term voltage stability. A summary of these classifications is as follows:

- Large disturbance voltage stability: The large disturbances includes system faults, loss of generation or circuit contingencies [35] [36]. If following a large disturbance and subsequent system control actions, voltages at all the buses in the system settle down at acceptable levels, the system is said to be large disturbance voltage stable. Mixed potential function is introduced in [37] to model the large disturbance, which has the following standard form,

$$P_{i,v} = -A(i) + B(v) + (i, \gamma v - \alpha) \tag{2.2.7}$$

  where $-A(i)$ is current potential and $B(v)$ is voltage potential; i is the current through the inductors, and v is the voltage on the capacitor; γ and α are constant vectors.

- Small-disturbance voltage stability: It is concerned with the ability of the system to maintain acceptable level of steady voltages, when subjected to small perturbations such as increase in system load [38]. This form of stability is also influenced by the characteristics

- Short term voltage stability: It involves dynamics of fast acting load components such as induction motors, electronically controlled loads and HVDC converters [42] [43] [44]. The study period of interest is in the order of several seconds and the analysis requires solution of appropriate system differential equations.

- Long term voltage stability: The study of long term voltage stability involves the dynamics of slower acting equipment such as tap changing transformers, thermostatically controlled loads

Voltage instability caused by several reasons [2], the main contributors can be summarized as follows:

- Increasing in load demand
- Reactive power outputs of generators, synchronous condensers, or SVC reaching their limits
- Action of tap changing transformers
- Load recovery dynamics
- Line tripping or generator outages

Most of these changes have significant impacts on the reactive power production, consumption and transmission in the power system. Several control actions to overcome these problems and prevent voltage collapse are studied in [46] [47] [48] [49] and can be summarized as follows:

- Switching of shunt capacitors
- Blocking of tap-changing transformers
- Re-dispatch of generation
- Load shedding
- Temporary reactive power overloading of generators

2.3 Voltage Stability Analysis Methods

Voltage instability problems is a very important problem in power system secure operation, it has attracted loads of researchers. In order to analysis voltage stability problem, a lot of variety of methods and techniques for the voltage stability are proposed. They aim to predict if voltage is stable or unstable and maintain the voltage away from collapse. Among the exist methods, they can be mainly divided into two categories based on the different models be used, which are static methods using power flow calculation and dynamic methods using differential equations.

2.3.1 Static Voltage Stability Analysis Method

Most of the current voltage stability analysis tools are based on the power flow equations or its modification. Researches have verified that they are feasible solution for voltage stability analysis and also have some benefits, such as simple, fast, and convenient to use [50] . It is the fact that voltage collapse point is the solution of a critical power flow. On the other hand, both voltage stability margin and the state sensitivity can be obtained for power system monitoring as well as power system operation by using the exist methods. However, the apparent disadvantages are limited their usage. For example, the static voltage stability analysis methods requires further verification by using time-domain simulation, it is time consuming for some methods [51]. The static voltage stability analysis methods include sensitivity based method, power flow based method, and so on.

- Sensitivity Based Method: The sensitivity matrix in sensitivity based method is derived from the power flow equation. The element in the matrix are calculated by the relative relationship between the state variables. For example, the sensitivity of voltage at a load bus to active and reactive power ($\partial U_L/\partial P_L$, $\partial U_L/\partial Q_L$); sensitivity of reactive power output of a generator to active or reactive power of load ($\partial Q_g/\partial P_L$, $\partial Q_g/\partial Q_L$); sensitivity of voltage at a load bus to voltage at generator bus ($\partial U_L/\partial U_g$). When the sensitivity goes out of the range, it means the voltage tends to be unstable. A voltage stability margin sensitivity analysis method for local voltage stability index is presented in [52]. The margin with respect to voltage profile and reactive power compensation is proposed. Based on the sensitivity of the system, reactive power compensation can be implemented to enhance voltage stability margin. A similar sensitivity based method for selecting the most effective preventive controls is proposed in [53]. Load impedance modulus margin is applied as voltage stability index, it can be deduced from the local voltages and currents. The sensitivity ranking is introduced to eliminate small sensitivities and only those effective and sensitive variables are considered. So that, it helps to improve the efficiency of control actions.

- Continuation Power flow Method: Due to the multiple solutions of the power flow equation and convergence problems of power flow, when the power system operates near the voltage stable point, the continuation Power flow is proposed to overcome the problem using continuously updated power flow equation. It is an effective method to find out the voltage collapse point. In the continuation power flow method [54], there are four steps, prediction, correction, parameterization and step control. [55] presents a on-line voltage stability assessment method. Continuation power flow algorithm is implemented, along with Artificial Neural Network(ANN). The continuation power flow algorithm is used to find the distance between voltage collapse point and the current operating point, which can be used as data base for training ANN. The output of well trained ANN is the Voltage Collapse Proximity Indicators (VCPI). Reactive power is the major consideration in voltage instability. Improving the reactive power capacity of the power system is a solution which use flexible AC transmission system (FACTS) devices to prevent voltage unstable and voltage collapse. A effect comparison of four FACTS controllers controllers for Static Voltage Stability is studied in [56], where continuation power flow method is applied. An improved continuation power flow method is proposed in [57]. It aims to calculate the static voltage stability critical point. Compared to the traditional method, the least square method is used for prediction. Fit a quadratic curve combined with all the power flow solutions known in the calculation process. Through the curve we can get the nonlinear prediction of the critical point of voltage stability. And then by using the local parameters method, construct the parameters equation to obtain the actual power flow solution. The paper also proves the validity and rapidity of the improved method.

- Singular Value Decomposition Method: Considering the physical point of view, when the power system reaches its maximum power transfer capability, the current operating point is the critical point of voltage stability. From a mathematical point of view, the singular point of the Jacobi matrix, which is derived from power flow equation, is the critical point. In case of the power system operates near the collapse point, Jacobi matrix tend to be singular. It is the fact that, the minimum singular value shows the singular degree of Jacobian matrix. Thus, the minimum singular value is able to used as a index to reflect the current working state. A voltage stability analysis method using selected smallest eigenvalues to provide a proximity measure for voltage stability [58]. [59] proposes a novel control algorithm for improving steady-state voltage stability where high voltage direct current (HVDC) system is embedded. The sensitivity between reactive power injection and the voltage stability margin is introduced based on singular Value. It aims to firstly enhance voltage stability margin for the entire power system and then to satisfies pre-defined requirements of voltage magnitudes. A singular value decomposition based voltage stability assessment using PMU measurements is proposed in [60]. Firstly, full measurement data is assumed available at all buses. Then, only subset of measurement data is considered. It shows the efficient computation of singular values and singular value decomposition method incorporating PMU measurements can be used in near-real-time in a power system.

2.3.2 Dynamic Voltage Stability Analysis Method

Apart from the static method which is reviewed above, the dynamic nature of voltage stability is also should be considered. In order to explore the characteristic of dynamic voltage stability, the dynamic models, for example system models, generator models and load models, should be taken into account. Studying on the dynamic voltage instability mechanism and mastering analysis methods is able to avoid the occurrence of voltage collapse accidents. Currently, there are some dynamic voltage stability analysis methods, which can mainly divided into small signal analysis methods, bifurcation analysis methods and time domain simulation methods, etc.

- Small Signal Analysis Method: The analysis method aims to study the behaviours of electronic circuits which contain non-linear devices. It can be modelled as linear differential equations and only suitable for small disturbance. Currently, some power system are considered the influence of the voltage stability in small signal analysis, such as on-load tap changing (OLTC) transformer , generator and its excitation control system and load model, etc. The differential algebraic equation of the system can be formulated as

$$\begin{aligned} \dot{x} &= F(x, y, p) \\ 0 &= G(x, y, p) \end{aligned} \tag{2.3.8}$$

where x is a system state variable; y is an algebraic variable; p is a parameter variable. The formula (2.3.8) is linearized at the equilibrium point.

$$\begin{aligned} \Delta\dot{x} &= A\Delta x + B\Delta y \\ 0 &= C\Delta x + D\Delta y \end{aligned} \tag{2.3.9}$$

The algebraic variable Δ of the formula (2.3.9) is eliminated,and the standard state equation can be obtained as follows:

$$\begin{aligned} \Delta\dot{x} &= J\Delta x \\ J &= A - BD^{-1}C \end{aligned} \tag{2.3.10}$$

The eigenvalues of the coefficient matrix J can be used to analysis and judge the voltage stability of the system with small disturbance. The effects of flexible AC transmission system (FACTS) controllers are studied when considering the small signal voltage stability. In [61], both static load and dynamic load are taken into account in the power system. The small signal stability region can be enlarged by using FACTS controllers. [62] uses small-sign analysis method to study voltage stability in a multi-infeed HVDC which has two HVDC infeeds and dynamic models. A voltage stability correlation ratio relating to voltage stability is introduced. While, a DC control model, a generator model and a induction motor based load model are implemented in a power system. The ratio is able to identify the critical elements which is strongly related to voltage stability in a such system. [63] investigates the eigenvalue-based small signal stability method frequency domain. It is the fact that it can judge the stability of the entire system globally. However, there are two main disadvantages. Firstly, the detailed modelling of the whole system is required. Secondly, pulse-width modulation (PWM) is neglected in modelling the VSC systems, it causes sustained harmonic oscillations in the VSC-based HVdc system. To solve the limitations, the system should be discretized and requires high computational effort.

- Time Domain Simulation Method: So far, time domain simulation analysis is the most powerful method to study the dynamic mechanism [21].It is suitable for any power system dynamic model. At present, real time monitoring and control of the power system are required, because of the load is creasing and the intermittent renewable energy are integrated into power system. [64] presents a on-line monitoring method for risk voltage collapse. This method combine off-line computation and on-line monitoring to overcome the time-consuming in computation problem. During the off-line computation, high-risk situations following a pre-defined voltage stability criterion is obtained by using basic statistics analyses. During on-line operation, the voltage magnitudes at critical buses which are obtained from PMU are monitored according to the statistics analyses. The method is tested in time series and shows it able to avoid voltage collapse incidences.

- Bifurcation Analysis Method: Bifurcation theory is widely used in description of the properties and changes of the trajectory structure . The bifurcation theory are nonlinear dynamic analysis for voltage stability. It is related to both static stability and dynamic stability to a certain extent. Hopf bifurcation is proposed [65] which is the most basic and the most representative form of bifurcation . Based on the basic concepts and the main methods of bifurcation theory, [66] introduce the dynamic bifurcation Phenomenon in the power system voltage stability analysis and the relationship between them, making a more comprehensive summary and comment about dynamic bifurcation which used in the power system voltage stability analysis currently. Different methods are discussed, such as the Hopf bifurcation (HB), period-doubling bifurcation, torus bifurcation and homoclinic (heteroclinic) bifurcation. However, there are still some limitations and need further exploration. The authors suggest that modern mathematical analysis can be used to reduce the dimension of high-dimensional equations, besides complicated calculation and transformation process of bifurcation analysis methods should be simplified for practical implementation. Moreover, it is possible to develop a unified voltage stability analysis method which is suitable for both static and dynamic bifurcation.

- Energy function Method: The energy function method is using the Lyapunov direct method to evaluate the stability of the system, which is based on the non-linear differential equations. A extended energy function is proposed in [67], where loads modelled as voltage dependent. The method is implemented in a IEEE 3-bus system and the results show that accurate estimation of the critical clearing time can be achieved.Considering renewable energy are connected to the distribution network, a voltage stability assessment method is required. [68] proposes a energy function based method. The Newton-Raphson power flow is applied to find the voltages and angles of the stable and unstable solutions based on load variations, then the energy function is obtained. Due to the complicate convergence process in Newton-Raphson method, when distribution systems has high R/X ratio. Hence, axis rotation method is introduced. In case of the energy function equal to zero, it means that the system is operated towards the voltage collapse point.

The voltage stability analysis are summarized as follows,

Table 2.2: Summary of Voltage Stability Analysis Methods

	method	description
Static Voltage Stability Analysis Method	Sensitivity Analysis Method	good in judging weak point, can not reflect the critical state of the system
	Continuation Power flow Method	calculate the critical voltage stability point, however it has large amount of calculation, high time consuming.
	Singular Value Decomposition Method	based on the linearized power flow equation, but the Jacobian matrix of the power flow equation has a high degree of nonlinearity.
Dynamic Voltage Stability Analysis Method	Small Signal Analysis Method	only suitable for the case of small disturbance.
	Time Domain Simulation Method	powerful method and suitable for any power system dynamic model
	Bifurcation Analysis Method	describes the properties and changes of the trajectory structure of a dynamic system with parameter variations.
	Energy function Method	provides a quantitative measure, however requires detailed dynamic load models

2.4 Voltage Stability Monitoring

Due to large inertia of a large interconnected stable power system, the voltage and frequency at a node remains constant at a fixed value for a short time, in case of the irrespective sudden change of load or irrespective sudden outage of generators. However, some sudden transients or some faults may occurring in the system, the system tends to become unstable that cause some deviation of voltage and frequency from the standard value [69]. Hence, the nodes voltage and frequency should be monitored continuously in the whole network. Control actions can be taken when received any preventive measurements which show change tendency, so that prevent loss of synchronism.

2.4.1 Supervisory Control and Data Acquisition (SCADA)

SCADA system is a critical application in a power grid for monitoring. Nowadays, most critical nodes are monitored in static or quasi static methods and measurements. These methods are based on the cyclic non synchronized acquisition of root mean square measurements from remote terminal units (RTUs) of a SCADA (Supervisory Control and Data Acquisition) system. However, one of the disadvantages of SCADA is that very few transients information can be achieved from the traditional SCADA systems.

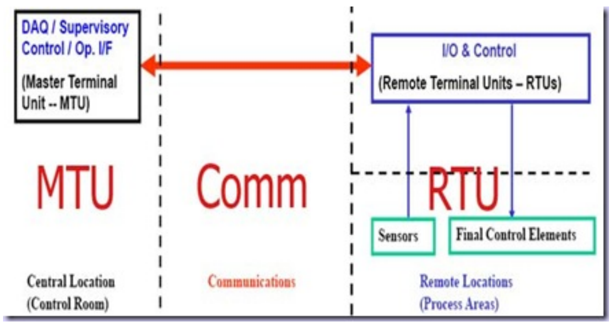

Figure 2.7: Supervisory Control and Data Acquisition System [65]

SCADA system provides snapshots of the system condition periodically, which include relevant system state measurements. These measurements forms data sets that build the primary data sources for the power system monitoring. The typical

SCADA structure shows in fig 2.7 [70] and it comprises :

- a central host (Master Terminal Unit, MTU),
- field data gathering and control units or Remote Terminal Units (RTUs),
- a communication system
- a software application to control the RTUs.

SCADA systems capture and deliver the power system performances in every 5 to 20 second. The steady state snapshot covers the complete national transmission area and eventually partial sections of the neighbouring systems [71].

Apart from the actual value or status of the point or group of points transmitted from RTUs. Another option is referred to as reporting by exception [72]. The data requested from those points or groups of points where changes of state have occurred or where changes has exceeded a predefined value. This option has a advantage that it helps to reduce data processing at the master station. Besides, there is a reduction in average loading on the communication circuits. However, in order to accommodate the worst condition of the power system, due to a large percentage of the points are rapidly changing or a large disturbance occurs, sufficient communication bandwidth is required as well as timely and high accurate data.

2.4.2 PMU Implementations in Power System

Dur to the high penertration of renewable enegy in power system and more complex electrical networks, which makes the power system planning, operation, and protection more complicated. In this way, the performance of the SCADA system cannot meet the requirements.

- Introduction of PMUs

  PMU was first developed in early 1990s [73]. It started deployment in the wide area monitoring systems (WAMS) which can provide time-synchronized data which includes bus voltages as well as currents [72]. Moreover, the sampling of SCADA system is normally at 50/60 Hz, conversely PMU has higher sampling rate. Hence, PMUs is much suitable in implemntation of voltage controls as it much faster [74]. Therefore, PMUs are the promising solutions and will be widely installed across the network with high penertration of renewable energy in the future.

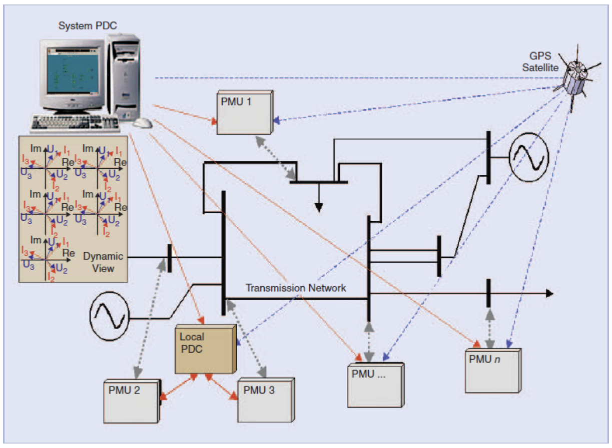

Figure 2.8: PMU Based Wide Area Measurement System [70]

Fig 2.8 shows that Phasor measurement units (PMU) measure dynamic data of the power system, such as magnitude, phase angle and frequency of the voltage and current. Then, the full observability of the power system can be achieved from the installed PMUs. And measurements are used to monitor the stability of the power system and help to operate securely. PMU is the latest technology to achieve the dynamic data from the power system. In the past, it has been used in conventional power system to damp out the inter area oscillations [75]. In the recent years, it plays an important role in control of distributed generation networks. However, its disadvantages, which has been shown in conventional power system, also occurs in control of distributed generation networks. The disadvantage and its affects will be presented in the following discussion.

In order to improve the performances of the wide-area control and protection system in the power grid with the increasing demand of consumers and complexity of the network, synchronous phasor measurement technology and modern communication technology have been combined into smart grid and called wide-area measurement system (WAM) which employs the PMU. PMU measure dynamic data of the power system, such as magnitude, phase angle and frequency of the voltage and current.

These data are synchronized by global positioning system (GPS) satellites and sampled as regularly as once per cycle of power frequency. In other words, time stamps are added to the data packages by the GPS satellites before send to the system phasor data concentrator (PDC). Once PDC receives the data from all the PMUs, the dynamic performance of the entire network can be achieved in real time, which means the data of the entire power system can be clearly monitored at the same time point and the changes in the same time interval.

In addition, the core of WAM is to explore how to guarantee the reliability and real-time information transmission. Inter-area oscillations are typically inherent in large inter-connected power systems on the order of 0.1-1.0Hz [76]. The amount of power transfers on the tie-lines between the different regions, usually with inherent generators, are limited by the inter-area oscillation. Nowadays, due to the increase of energy exchanges among the large power systems, it is essential to damp out theses low-frequency oscillations, which means wide-area damping control is becoming more important.

- Measurements of PMUs

  IEEE defined phasor is a complex equivalent which is a sinusoidal wave. The complex modulus is the cosine wave amplitude, and the complex angle is the phase angle of the cosine wave. An AC waveform ia formulated in equation 2.4.8

$$A\left(t\right) = A_m cos(\omega t + \phi) \tag{2.4.11}$$

  is commonly represented as the Phasor as shown in equation 2.4.9

$$\overrightarrow{A} = \frac{A_m}{\sqrt{2}} e^{j\phi} = \frac{A_m}{\sqrt{2}}\left(cos\phi + jsin\phi\right) = A_r + jA_i \tag{2.4.12}$$

  where the magnitude $\frac{A_m}{\sqrt{2}}$ is the root-mean-square (RMS) value of the waveform, and the subscripts r and i are the real and imaginary parts of the complex value, respectively. The value of ϕ is the angular frequency ω, which is depends on the time scale, especially $t = 0$.

- Applications of PMUs

  It is the fact that PMU is one of the most crucial measuring devices that can provide synchronized voltages and currents in real time. Due to PMUs are equipped global positioning system (GPS), they are able to provide timestamped synchronized signal [77]. Also, PMUs can support two-way flows of system status in an electric network, where PMUs are widely installed [78].

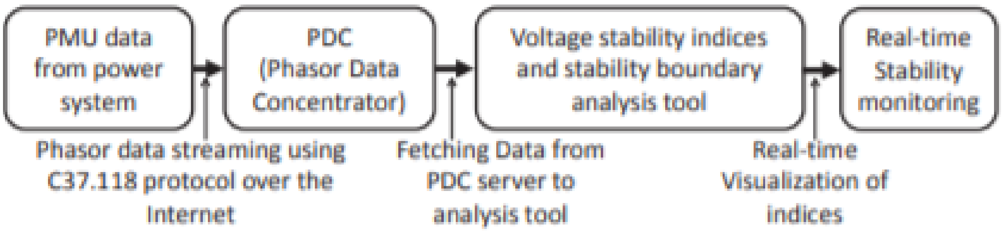

Figure 2.9: Real-time Implementation of PMU based Stability Monitoring Tool [74]

Fig 2.9 shows a general progress of PMU implementation in real time stability monitoring. The utilizations of PMU measurements for improved monitoring and control power networks are discussed in [79]. The authors point out, the PMU data can be applied in the procedures of system state estimation, linear state estimation and dynamic phenomena tracking would be possible with sufficient PMU quantity. [80] proposes a new voltage instability risk indicator using local phasor measurements. A modification of the Thevenin equivalent impedance equation is used as the risk criterion in real time. The equation is formulated as an equivalent generator and an equivalent load impedance are connected through an equivalent connecting impedance. Another Thevenin equivalent impedance based method is proposed in [81]. Starting with devising a new on-line voltage stability index. Then, a simplification method for a large network is developed that the index can be applied using PMU measurements and network parameters. The index combined with the simplification method is able to shows the voltage stability limits for each load buses. In [82], applications of PMU measurements for voltage stability are reviewed. A hybrid state estimator models is introduced in on-line voltage stability analysis. While the PMUs integration architecture are addressed considering some power system component, such as substations, concentrators and control centers. [83] proposes a new method for tracking Thevenin equivalent parameters for a power system at a node using local phasor measurement unit (PMU) measurements. Three consecutive phasor measurements for voltage and current, recorded at one location, are used. The phase drifts caused by the measurement slip frequency are first determined and phase angles of the measured phasors are corrected so that the corrected phasors are synchronized to the same reference. The synchronized phasors are then used to determine the equivalent Thevenin parameters of the system.

[84] proposes an application artificial neural network (ANN) based method for voltage stability. The developed neural network is trained by using real power P_L, reactive power Q_L at load buses as input and voltage stability index as output, which shows voltage stability at individual load buses. An ANN based method is proposed for fast estimation of long-term voltage stability margin under contingencies [85]. It shows that voltage magnitudes and phase angles have good performance in voltage stability margin estimation. The method has ability to estimate the voltage stability margin under both normal operations and N-1 contingency conditions in real time. A voltage stability assessment method using voltage phase angles is proposed in [86], it aims to visualize the difference of voltage angles using PMUs. The stress level and the proximity of voltage stability limit can be obtained by using the method. The stress level is defined as the change of frequency. It helps to monitor the loss of generators and also transmission line outages. [87] proposes a neural network based voltage instability detector based on bus voltage angles from Phasor Measurement Units (PMUs). An enhanced Feed-Forward Neural Network is developed and trained as the voltage instability detector, it monitors the voltage angles from PMU installed buses. In [88], an long-term on line voltage instability monitoring is proposed using Hybrid Artificial Neural Network and Genetic Algorithm (ANN-GA) technique. The accuracy of ANN is improved by tuning the parameters of the genetic algorithm (GA). In this approach,

PMUs are utilized to obtain voltage magnitude and phase angle which are used as the input vectors and voltage stability margin index vector used as the input vectors in training ANN.

With the implementation of PMUs in recent years, another method is proposed to guarantee the voltage stability level of power systems using a concept of generator volt-ampere reactive (var) reserves. [89] studies the impact of var reserves in power system and it shows that the var reserves is area-dependent in the view of voltage stability. Bonneville Power Administration (BPA) proposes a voltage stability monitoring and control system that the key generators can be monitored using PMU [90]. The total var reserve level is firstly used as a voltage stability measure of the system. A power system has a small value of the value means the var reserve level is low. It is noted that the var reserves of generators can also shows the degree of controllability of voltages at generator buses. From this point of view, [91] and [92] use the corrective relationship between generator var reserves and system voltage stability margins for online voltage stability monitoring. [93] studies the calculation of voltage stability margin by using a indicator based on var reserve. Statistical multi regression model is applied to express the variations relationship between var reserve and voltage stability margin. However, the methodology proposed in [93] has not focused on finding a pattern recognition tool. Considering the online environment, [94] proposed a pattern recognition tool, which can help system operators to identify the appropriate multi linear regression model. [95] proposes a voltage stability indicator based on Wide Area Measurement System (WAMS), operating limits like reactive power reserve, voltage limits are taken into account. Additionally, the indicator is a combination of reactive power resources and actual load demand at each buses. Several control methods are proposed to access and control the voltage stability of the system, which are generally based on voltage stability indices. All of these have diverse physical interpretations [96]. Considering the computational simplicity, some of these methods are suitable for real time applications, however, accuracy is another consideration. Some methods are restricted by the information, which are obtained from a single location [80] [97].

2.4.3 Comparisons between PMUs and SCADA system

In the recent years, the implementation of PMUs are superior to the SCADA system. The reasons are summarized as follows:

– PMUs produce more accurate measurements of voltage and current magnitude and also phasor angles. The same as the time stamped measurements, the status of breakers with timestamps can also be provided and synchronized to those measurements. Due to the synchrophasors with respect to a global angle reference, the number of critical measurements can be reduced and less than the state estimator when uses SCADA measurements.

– The angle measurements are made directly by using PMUs, the errors can be reduced. Conversely, voltage angles can only be calculated by the SCADA system measurements which includes voltage, active power, reactive power, as well as network parameters. Due to the PMU measurements do not need network parameters, therefore it is able to provides more direct and more precise measurements [98].

– One of the major advantages of PMUs is the ability to provide coherent data from different areas of the network. The trends of voltage phase angle differences is required by system operators, thus the stability of the system can be monitored in a large interconnection power system. However, precise voltage phase angle differences can not be obtained using SCADA based measurements [99].

– PMUs are able to provide solutions to a number of protection problems, which includes series compensated lines, multi-terminal lines, and relays. The reliable measurements in a power system has made a great contribution in protection improvement. The communication of measurements across a large distances is necessary in a complicated power system. [100].

On the other hand, SCADA systems can only able to capture steady state operation and unable to monitor fast transient phenomena. Additionally, low sampling density and their asynchronous characters are the disadvantages of SCADA systems. Thus, it is hard to operate the power system in real time by using SCADA data.

2.4.4 Optimal Placement of PMUs For Online Voltage Stability Monitoring and Control of Real Time Systems

The increasing penetration of renewable energy in power system makes the power systems more complex, which cause the power system planning, operation, and protection be more complicated. The comparisons between PMUs and SCADA system have been discussed. As previously stated, the performance of SCADA system cannot meet the requirements. In order to obtain better measurement of the power system, the PMUs are introduced in monitoring system. PMUa are tend to be installed widely. In this way, the full observability of the power system can be achieved from the installed PMUs. So that, the voltage stability can be monitored by using the dynamic PMU measurements, which includes magnitude, phase angle as well as frequency of the voltage and current. These data are firstly measured and stamped by global positioning system (GPS).

The median cost for installing a single PMU at a new substation was approximately USD 43400 [101]. This cost is comprised of the cost of the device itself as well as design and engineering costs, labor and material costs for installation and construction.

Due to its high cost, it is practically not feasible to install PMUs at all the buses of the system [102]. So, a reduction of PMU installation quantities is required. Depending upon the conditions of the system, PMUs are to be optimally placed in a power system network. Optimal PMU placement has became a popular research topic since the widely implementation of PMUs in practical systems.

Three different methods for optimal placement of PMUs were explained and compared [103] [104]. The methods available in the literature can be divided into two types, which are Conventional Methods and Heuristic Methods.

A. Deterministic Methods Deterministic techniques mainly includes integer programming and numerical based methods

- Integer Quadratic Programming (IQP): OPP problem is generally formulated by using the connectivity matrix which represents network topology. A quadratic objective function is introduced in the optimisation which considers the linear constrains and integer variables. By using this optimisation process, the number of PMUs can be dramatically reduced, while achieve a full system observability.

Integer quadratic programming and genetic algorithm for optimal PMU placement considering the measurement redundancy is studied in [105] [106]

- Integer Linear Programming (ILP): Integer Linear Programming techniques, it is also known as Binary integer programming. The ILP is formulated by eigenvectors which are obtained from the spanning tree adjacency matrix.

  [107] [108] [109] [110] studied integer linear programming techniques. while, binary search algorithm is implemented to ensure full observability of the entire system.

  The depth of unobservability and critical buses has been studied in [101], while considering the real-time monitoring of the power system network. In this work, the buses with high voltage and high connectivity buses are defined as critical buses. D. Dua et al [111] proposed a two indices approach which are the bus observability index and the system observability redundancy index. While, observability factor analysis, sequential orthogonalization algorithm, combination of coherency identification technique as well as the observability factor analysis are considered.

B. Heuristic Methods

Heuristic methods involve intelligent search processes considering discrete variables and non-continuous cost functions. These methods can be summarized as genetic algorithms, particle swarm optimization, topology and tree search, which shows as following.

- Genetic Algorithms Based Method

  Marin et al. studied a GA-based method to solve the OPP problem in [112], which is based on the process of genetic breeding.

- Particle Swarm Optimization (PSO) Based Method

Table 2.3: Optimal PMU Placement Methods

	Method	Description
Deterministic Methods	Integer Quadratic Programming	Computationally fast method, adaptable.
	Integer Linear Programming	Exhaustive search
Heuristic Methods	GA Based Method	Robust, adaptable, but long execution time
	BPSO Based Method	Offers multiple solution
	Topology And Tree search Based Method	Simple logic, but some results not optimal.

[113] used Particle swarm optimization (PSO) based method in optimal PMU placement. It is a population based stochastic optimization technique. With the benefit of the method, it is able to map the configuration criteria while considering data loss modelling.

- Tree Search and Topology Based Method

  Spanning tree and tree search based method are used to obtain a certain depth of unobservability. The Depth of unobservability is defined in [114]. The algorithm search the PMU logical placement from bus to bus. Once every buses have been visited, the search will be terminated.

Table 2.3 gives a summary of optimal PMU placement methods. The size of the problem and type of application should be considered in the choice of techniques. And also, the status of the power system should be considered as well, for example, conventional measurements in the power system.

2.5 Chapter Summary

In this chapter, the stability of the power system is reviewed. There are three main stability research area, which are rotor angle stability, frequency stability and voltage stability. Voltage control method and stability problems are the focused concerns in this chapter as well as in this thesis. Three main control strategies, centralized control, decentralized control and multi agent system are reviewed. Several centralized and decentralized control schemes are presented and compared. Both centralized control and decentralized control have advantages and their drawbacks, respectively. It seems that multi agent system is a promising solution to overcome their drawback. However, multi agent system still has some challenges as it is still a prototype at present. Moreover, with the introduction of PMU, centralized control and decentralized control strategies have the capability to meet the requirements of the modern power system. Voltage stability is a major objective for control system, mature centralized control and decentralized control technique embedded PMUs will play an important role.

In order to understand and resolve the voltage instability issues, it is important to investigate the mechanism of voltage instability. Voltage instability mechanism are illustrated. While a lot of variety of methods and techniques for the voltage stability are presented based on static and dynamic as well. They aim to predict if voltage is stable or unstable and maintain the voltage away from collapse. Among the exist methods, they can be mainly divided into two categories based on the different models be used, which are static methods using power flow calculation and dynamic methods using differential equations. The static voltage stability analysis methods include sensitivity based method, power flow based method, and so on. And dynamic voltage stability analysis methods can mainly divided into small signal analysis methods, bifurcation analysis methods and time domain simulation methods, etc. It is noted that maintaining voltage at a certain level does not automatically guarantee the voltage stability. In other words, low voltage stability may not be related to low voltage profiles.

PMU is a promising tool to be integrated into power system. The utilization of PMU in monitoring system is able to overcomes the drawbacks of SCADA and meet the requirements of a modern power system. However, due to its high cost, it is not feasible and not economical to install PMUs at all buses of the power system. Therefore, a reduction of PMU installation quantities is required. The methods available in the literature can be divided into two types, which are conventional methods and heuristic methods.

Chapter 3

Enhancing Dynamic Voltage Stability in Power Systems with Distributed Generations

In recent years, there is a trend of high penetration of renewable energy in the traditional power grid. Meanwhile, load characteristics have a significant impact on power system behaviours [115]. Both load and distributed generations (DGs) should be taken into account when voltage stability problems are considered.

Several methodologies for voltage stability analysis are reviewed in chapter 2. These metrics can reflect the voltage stability condition if the voltage is stable for a given operating condition. Additionally, PV curves show the distance for the system between its current operating point and voltage stability limit. The impacts of variations in reactive power output of Doubly Fed Induction Generators (DFIGs) on the voltage stability of systems were studied in many papers. It is suggested that system dynamics could be dramatically improved through an appropriate control strategy with reactive power compensators [116].

The impacts of DG units on the voltage stability and their impacts on the voltage stability were studied by considering the variations in reactive power output of variable-speed wind generators and reactive power compensators. It is shown that significant improvement in the voltage stability margin could be obtained with proper coordination controls [117]. On the other hand, some dynamic loads models and wind generations models were taken into account for dynamic voltage stability analysis. As the time domain simulation analysis is the most powerful method to study the dynamic voltage stability problems, little work has been done on the voltage stability enhancement using dynamic load data and dynamic wind generation data. Besides, different from existing works, this chapter aims to study the dynamic voltage stability enhancement problem considering dynamic loads and wind generations.

The main contributions of this chapter are:

- It presents a dynamic voltage stability enhancement method by coordinating the reactive power sources. Both wind generators and additional installed static VAR compensators (SVCs) are taken into account based on IEEE 14 bus system.
- Real data (from both wind generations and loads) for 24 hours and 1 year are applied in the proposed method for time-series simulations.
- Benefits on enhancing system loadability are analysed. The effect of variations in the wind generation and demand on the loadability is investigated.

This chapter is organized as follows. Section 3.1 illustrates the relationship between voltage and power. In Section 3.2, system model and analysis tool are presented. Section 3.3 shows the proposed methodology for voltage stability enhancement. Section 3.4 verifies the proposed method. Trust region and genetic algorithm are used as optimisation algorithm and their performance comparison is discussed. Besides, the proposed method is implemented in IEEE 14 bus systems together with real dynamic load and wind generation data to demonstrate the benefits in loadability. Conclusions are given in Section 3.6.

3.1 Relationship Between Voltage and Power

Voltage stability is an important measure in power system operations. It depends on the system status, such as the load bus voltage magnitude, the power transmission, the reactive power injection and absorption. In this section, both mathematical expression and figures are used to illustrate the relationship between voltage and power.

3.1.1 Mathematical Expression

Newton Raphson method has been widely used in power-flow study [118], which can be given by

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = J \begin{bmatrix} \Delta \theta \\ \Delta \left| V \right| \end{bmatrix}. \tag{3.1.1}$$

where ΔP and ΔQ are the mismatch equations, and are given in (3.1.2) and (3.1.3) below

$$\Delta P = -P_e + \sum_{f=1}^{N} \left| V_e \right| \left| V_f \right| (G_{ef} \cos \theta_{ef} + B_{ef} \sin \theta_{ef}). \tag{3.1.2}$$

$$\Delta Q = -Q_e + \sum_{f=1}^{N} \left| V_e \right| \left| V_f \right| (G_{ef} \sin \theta_{ef} - B_{ef} \cos \theta_{ef}). \tag{3.1.3}$$

where P_e is the net power injected at the bus e, Q_e is the net reactive power injected at the bus e. V_e and V_f are the voltage at bus e and f, respectively. G_{ef} is the real part of the element in Y_{bus} corresponding to the eth row and fth column, B_{ef} is the imaginary part of the element in Y_{bus} corresponding to the eth row and fth column and θ_{ef} is the difference in voltage angle between the eth and fth buses ($\theta_{ef} = \delta_e - \delta_f$). J is a matrix of partial derivatives, called as Jacobian matrix as below

$$J = \begin{bmatrix} \frac{\partial \Delta P}{\partial \theta} & \frac{\partial \Delta P}{\partial |V|} \\ \frac{\partial \Delta Q}{\partial \theta} & \frac{\partial \Delta Q}{\partial |V|} \end{bmatrix}. \tag{3.1.4}$$

Once the computation of Newton Raphson method is completed, the voltages of both load and generator bus can be determined by using (3.1.1) and expressed as V_j and V_i, respectively.

3.1.2 PV Curves

P-V curve analysis is used to show the voltage stability of power system and determine the voltage collapse point. For this analysis, active power of the load at a particular bus is increased in steps and voltage is then observed. Curves for those particular buses will be plotted based on the continuous power flow (CPF) to determine the voltage stability of a system.

CPF can be used to trace the power flow solution, begins with a base load and obtains the maximum transfer power by increasing load. Thus the loadability margin can be obtained which is the maximum active load at the critical bus in the power system.

Loadability limits can be defined as the operating points, where the load demand reaches a maximum value that can be served subject to system and operational constraints. Any attempt to increase load consumption beyond system constraints by means of either a gradual increase of demand, or a load restoration processes, will result in instability and collapse. [119]

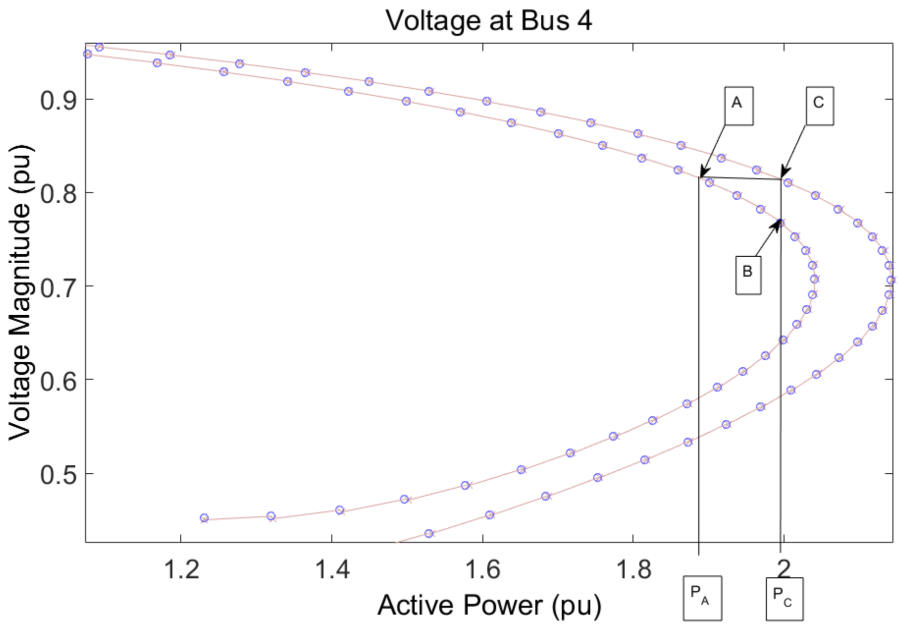

Figure 3.1: PV Curves in The Presence of A SVC

Fig. 3.1 shows the PV characteristic when the network has a SVC. It is assumed that the system is operating at the base point A. Meanwhile the load power is increased from P_A to P_C. Without controlling SVC, the new operating point would be at B. This causes a voltage drop which indicates the power cost on the transmission line. From point A to point C, it can be seen that voltage falls slightly with controlling SVC.

Although there are some other indicators can show the distance between operating point and collapse point, PV curves is used in this study as it also shows the exact distance and the relationship between voltage and power.

3.2 Voltage Stability Identification

As voltage stability is a long standing power system issue, lots of voltage stability identification methods have been proposed. Their different features make the control performance different. In order to enhance system efficiency and maintain reliability, control actions will need to be quick and effectively decided against rapidly changing of operation status. Therefore, fast computation of methodologies for voltage control will play a crucial role in maintaining safe operation. The comparison of these methods is discussed as follows.

3.2.1 Jacobian Matrix-Based Method:

Jacobian matrix is obtained from power-flow computation using Newton-Raphson method [120]. It is introduced for voltage stability identification in diverse ways. In this approach, the voltage stability α_{ij} is calculated as the attenuation of voltage variations between two nodes i and j given by

$$\alpha_{ij} = \partial V_i / \partial V_j = \frac{\partial V_i}{\partial Q_j} / \frac{\partial V_j}{\partial Q_j} \tag{3.2.5}$$

where the sensitivity matrix $\partial V/\partial Q$ is the inverse of the matrix $\partial Q/\partial V$, which is the part of the Jacobian matrix. In [39], singular value of a matrix J_R, which is transformed from Jacobian matrix, is proposed. It can be formulated as follows:

$$J_R = \frac{\partial Q}{\partial V} - \frac{\partial Q}{\partial \theta} \frac{\partial P}{\partial \theta}^{-1} \frac{\partial P}{\partial V} \tag{3.2.6}$$

where $\frac{\partial Q}{\partial V}, \frac{\partial Q}{\partial \theta}, \frac{\partial P}{\partial \theta}, \frac{\partial P}{\partial V}$ are the elements in Jacobian matrix.

3.2.2 Bus Admittance Matrix-Based Method:

In [121], a control approach against power system voltage instability is proposed. It is building on an admittance matrix-based method called electric distance, which can be easily derived from the absolute value of the inverse of the system admittance matrix. The metric is formulated as:

$$[D] = \left| [Y_{\text{bus}}]^{-1} \right| \tag{3.2.7}$$

where Y_{bus} is the admittance matrix of the power system. The elements d_{ij} in the distance matrix $[D]$ indicate active and reactive power sensitivities with voltage changes between buses i and j. It is worth highlighting that the smaller electrical distance means the higher impacts on the voltage change as a result of the change in active and reactive powers.

3.2.3 Continuation Power Flow (CPF):

CPF is used to determine voltage stability of a network. The curve plotted by using CPF shows the distance between current operating point and collapse point. The CPF is based on a simple principle which employs a predictor-corrector scheme. A set of power flow equations are reformulated to find a system operating path where includes a load parameter. As shown in Fig. 3.2, it starts from a known solution and uses a tangent predictor to estimate a subsequent solution corresponding to a different value of the load parameter. This estimate is then corrected using the same Newton-Raphson technique employed by a conventional power flow. The local parameterization mentioned earlier provides a means of identifying each point along the solution path and plays an integral part in avoiding singularity in the Jacobian.

For this analysis, power of the load at a particular bus is increased in steps and voltage is observed. Then curves for those particular buses will be plotted based on the continues power flow to determine the voltage stability of a system by static analysis approach. It is widely employed in power systems to determine steady state stability limits. The limit is determined from a nose curve where the nose represents the maximum power transfer that the system can handle given a power transfer schedule.

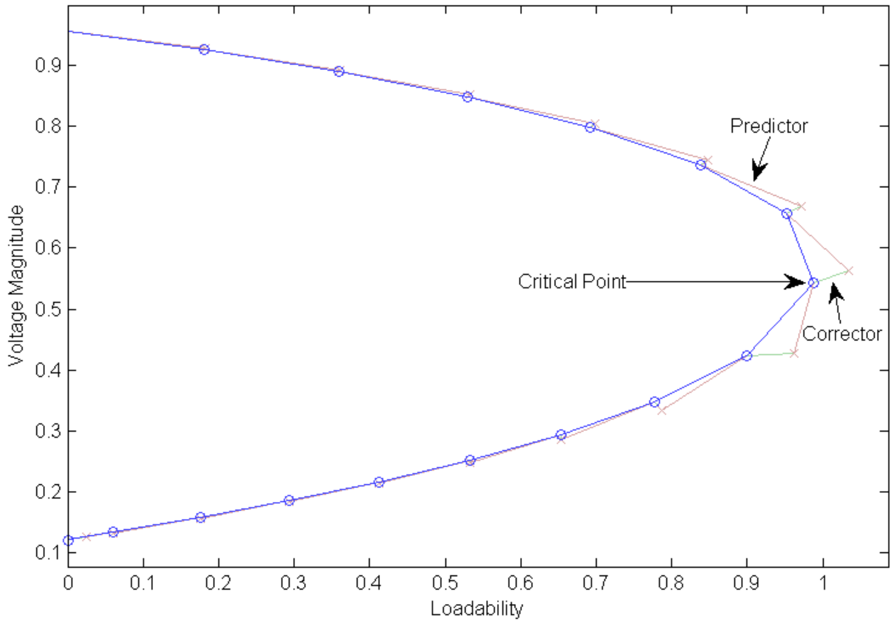

Figure 3.2: An Illustration of the Predictorand Corrector Scheme Used In Continuation Power Flow

3.2.4 Methods Comparison:

It is reported that voltage stability index based on the minimum singular value would probably be used for long-term planning and 'off line' operational planning studies [122]. By contrast, the elements of Y_{BUS} are usually readily available. They will not necessary to be updated until the change of network has been made. In this way, the voltage stability can be identified quickly from an earlier known admittance matrix. During the emergency condition, no global knowledge or the new Y_{BUS} of the system is required. Therefore, bus admittance matrix-Based method have better performance in computation speed that can meet the requirements of power system with rapid change in load.

3.3 L-index Based Minimisation Control Method

It is known that power demand and supply are affected by weather, season, hour of day, etc. Meanwhile, there is a trend of the high renewable energy penetration in the power system. These varying power demand and supply may worsen the imbalance between demand and supply, which may result in reduced loadability and reach the edge of the voltage stability limit, hence endanger the whole power system. The objective of chapter is to enhance the dynamic voltage stability of power system with distributed generations. L-index is adopted in this paper as an objective for dynamic voltage stability enhancement.

In case high reactive power is transferred through a transmission line, may cause a voltage drop. Meanwhile, it is easy to reach the capability limits of the transmission network and armature current boundaries of generators. This is the major factor results in voltage instability. It is noted that when the crucial generators are operating at their reactive power capability limits, the voltage instability contingencies. The increasing demand of reactive power may threaten the voltage stability without the available reactive power resources. Steady-state voltage stability enhancement can be achieved by maximizing the loadability margin.

3.3.1 L-index

Loadability margins is used to describe how much the maximum power can be dispatched through the transmission line based on the stability limits and device constraint. The loadability margin indicator employed in this paper is the L-index. The L-index is computed as

$$L_j = \left| 1 - \sum_{i=1}^{g} F_{ji} \frac{V_i}{V_j} \right| \tag{3.3.8}$$

where V and I indicate the voltages and currents, respectively, at the bus and subscripts and are used to differentiate between load and generator bus values. $1, ..., g$ are the generators and n is the total number of buses in the system. $[F_{ji}]$ in (3.3.8) is the element of the $[F_{lg}]$ matrix which is obtained by rearranging the elements of the admittance matrix as

$$\begin{bmatrix} V_l \\ I_g \end{bmatrix} = \begin{bmatrix} Z_{ll} & F_{lg} \\ K_{gl} & Y_{gg} \end{bmatrix} \begin{bmatrix} I_l \\ V_g \end{bmatrix} \tag{3.3.9}$$

$[F_{lg}]$ is computed $[F_{lg}] = -\left[Y_{ll}\right]^{-1}\left[Y_{lg}\right]$

The derivation process is shown below. Based on the circuit theory, current can be calculate as follows,

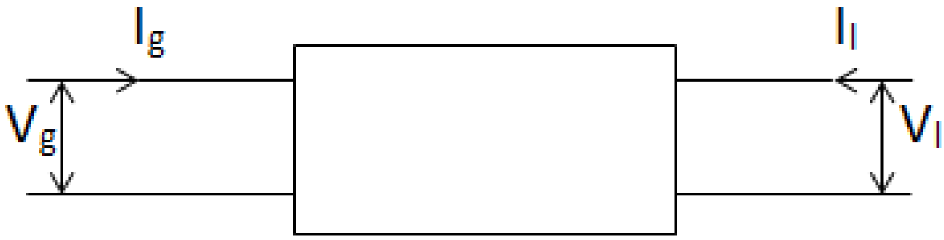

Figure 3.3: General Two-port Network

A general two-port network is shown in Fig.3.3. I_g and V_g are input current and voltage, respectively. Also, I_l and V_l are output current and voltage, respectively. Based on the circuit superposition principle, current can be calculate as follows,

$$\begin{bmatrix} I_g \\ I_l \end{bmatrix} = \begin{bmatrix} Y_{gg} & Y_{gl} \\ Y_{lg} & Y_{ll} \end{bmatrix} \begin{bmatrix} V_g \\ V_l \end{bmatrix} \tag{3.3.10}$$

from (3.3.10)

$$I_l = Y_{lg} V_g + Y_{ll} V_l \tag{3.3.11}$$

thus

$$V_l = Y_{ll}^{-1} I_{ll} - Y_{ll}^{-1} Y_{lg} V_g \tag{3.3.12}$$

can be written as

$$V_l = Z_{ll} I_{ll} + F_{lg} V_g \tag{3.3.13}$$

where $Z_{ll} = Y_{ll}^{-1}$ and $[F_{lg}] = -[Y_{ll}]^{-1}[Y_{lg}]$

i and j substitute for g and l, respectively. We get

$$V_j = Z_{jj} I_{jj} + F_{ji} V_i \tag{3.3.14}$$

It is noted that voltage of load bus has two parts which are the voltage can be supplied from all the generators and the voltage drop on the transmission line based on the loads. Compare to (3.3.8), it can be observed that L-index is firstly to calculate the ratio for a particular load bus between the voltage can be supplied from the generators and real voltage of the bus, then the distance between 1 and the ratio can be achieved. Therefore, a larger ratio or a smaller value of L_j indicates that the voltage is more stable.

It has shown that L_j is a function depends on V_i and V_j, which can be computed from (3.3.10)-(3.3.14).

L-index has several benefits which are reported as following points,

- the L-index has a very simple structure and can be handled easily
- the L-index can be used in large systems
- accurate predictions of instabilities caused by a uniform increase of the load
- the accuracies in voltage stability identification are very satisfactory

3.3.2 Objective Function

The relationship between L-index and loadability is proposed in [123] and verified in [117]. The L-index is a simple and effective loadability margin indicator though its validity as a voltage collapse indicator is debatable. Fig. 3.4 shows the plot between the index and loadability margin at a particular bus.

It indicates that a smaller value of L-index can achieve a larger loadability margin. Therefore, L-index is employed in voltage stability enhancement as a measure of loadability. Compared to Jacobian matrix based lowest singular value method, the elements of F_{ji} in the formulation of L-index are usually readily available. Besides, the value of L-index is determined only from voltages at generator and load buses, thus no power flow calculation is required.

To improve the steady-state voltage stability of the power system, the loadability margin at all nodes should be maximized, which in turn minimize the value of L-index for each bus. The objective function thus can be written by

$$T(Q) = \sum_{j=g+1}^{n} L_j^2 \tag{3.3.15}$$

where n is the total number of buses in the system.

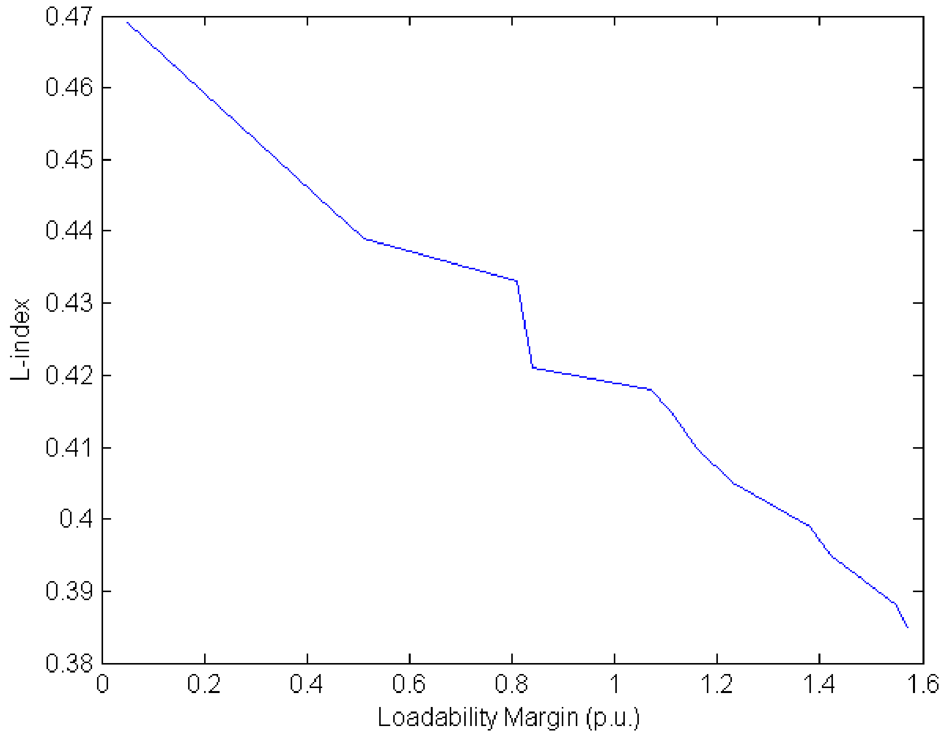

Figure 3.4: L-index Versus Loadability Margin at A Bus

Reactive power compensation, which is injecting reactive power into the power system, helps to reduce line currents and network losses, so that voltages can be kept close to the nominal values and stability enhanced. Therefore, voltage stability margins can be significantly improved by appropriate reactive power compensation. It is assumed that SVC has been installed on each load bus. Due to the rotor current injection schemes, the reactive power output can also be controlled. Controlling wind generators as the sources of reactive power is feasible. Therefore, the control variables are Q_{svc} and Q_{wg}, which represent the reactive power output of SVCs and wind generators, respectively.

Fig. 3.5 shows the typical reactive power capability characteristic of a variable-speed wind generator [124]. For a given active power output, it is possible to control the reactive power output to the desired level (within the capability limits). Further, modeling a variable-speed wind generator as a PQ bus with negative load is valid as long as the variable speed wind generator is operated at constant power factor. However, when the output of the wind generator is allowed to vary, it becomes

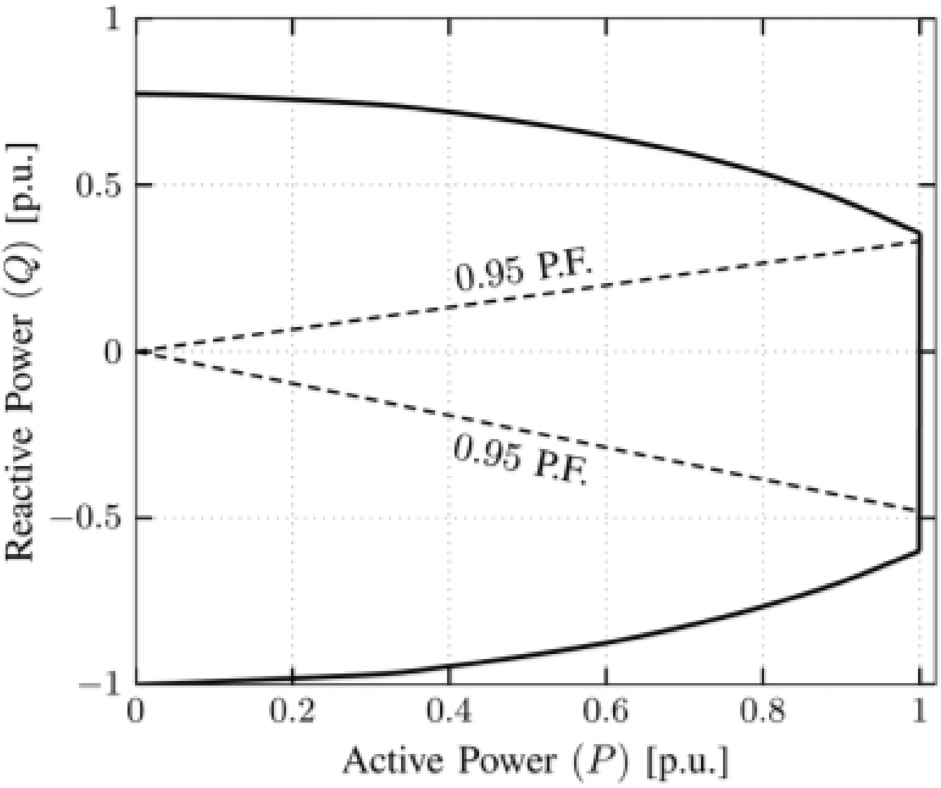

Figure 3.5: Typical Power Capability Curve of Variable-speed Wind Generator (DFIG) [118]

necessary to model them as accurately as possible. we employ the power flow model of variable speed wind generators presented in [125] which takes into account the current and reactive limits of the machine.

Due to trust region requires gradient of the objective function, in order to make the first and subsequent differentials simple, the optimization formulation can be defined by combining the objective function and the associated constraints, as follows:

$$\begin{aligned} &\min T(Q) = \sum_{j=g+1}^{n} L_j^2 \\ &\text{s.t. } Q_{wg}^{min} \leq Q_{wg} \leq Q_{wg}^{max} \\ &\qquad Q_{svc}^{min} \leq Q_{svc} \leq Q_{svc}^{max} \end{aligned} \tag{3.3.16}$$

where Q is the control variable including: Q_{svc} and Q_{wg}.

Solution of the minimisation control problem shown in 3.3.16 will determine the control necessary to obtain the lowest L-index. With the implementation of the control actions, the power system will operates at the most stable point.

3.3.3 Optimisation Algorithm

Trust region algorithm [117] is applied to find the minimum value of the objective function. The limits of control variables are also considered. To implement the trust region, the gradient of the objective function is provided. The derivation process of gradient is shown below:

$$\frac{\partial T(Q)}{\partial V_i} = \frac{\partial}{\partial V_i}\left(\sum_{j=g+1}^{n} L_j^2\right) \tag{3.3.17}$$

where the term L_j^2 can be rewritten as

$$L_j^2 = \left[1 - \sum_{i=1}^{g} C_{ji}\frac{V_i}{V_j}\right]^2 + \left[\sum_{i=1}^{g} D_{ji}\frac{V_i}{V_j}\right]^2 \tag{3.3.18}$$

in which

$$C_{ji} = F_{ji}\cos(\theta_{ji} + \delta_i - \delta_j) \tag{3.3.19}$$

$$D_{ji} = F_{ji}\sin(\theta_{ji} + \delta_i - \delta_j). \tag{3.3.20}$$

The partial derivative for $T(Q)$ with respect to V_i and V_j can be given as

$$\frac{\partial L_j^2}{\partial V_i} = 2\left[1-\sum_{i=1}^{g} C_{ji}\frac{V_i}{V_j}\right]\left[\frac{-C_{ji}}{V_j}\right] + 2\left[\sum_{i=1}^{g} D_{ji}\frac{V_i}{V_j}\right]\left[\frac{D_{ji}}{V_j}\right] \tag{3.3.21}$$

$$\begin{aligned}\frac{\partial L_j^2}{\partial V_j} = 2\left[1-\sum_{i=1}^{g} C_{ji}\frac{V_i}{V_j}\right]\left[\sum_{i=1}^{g} C_{ji}\frac{V_i}{V_j^2}\right] + \\ 2\left[\sum_{i=1}^{g} D_{ji}\frac{V_i}{V_j}\right]\left[-\sum_{i=1}^{g} D_{ji}\frac{V_i}{V_j^2}\right].\end{aligned} \tag{3.3.22}$$

Finally, the partial derivative for $T(Q)$ with respect to reactive power output of various reactive source can be computed as

$$\begin{bmatrix} \frac{\partial T(Q)}{\partial Q_2} \\ \vdots \\ \frac{\partial T(Q)}{\partial Q_n} \end{bmatrix} = \begin{bmatrix} \frac{\partial Q_2}{\partial V_2} & \cdots & \frac{\partial Q_2}{\partial V_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_2}{\partial V_2} & \cdots & \frac{\partial Q_n}{\partial V_n} \end{bmatrix}^{-1} \begin{bmatrix} \frac{\partial T(Q)}{\partial V_2} \\ \vdots \\ \frac{\partial T(Q)}{\partial V_n} \end{bmatrix}. \tag{3.3.23}$$

In the optimization, trust region is a local search method that begin with a given solution. In each iteration, a new solution will be created. Trust region determines whether to keep the old solution, or to drop the old one and keep the new one for the next iteration, which means the better of the two will be kept.

Another optimisation algorithm genetic algorithm is introduced. A genetic algorithm is a search heuristic that is inspired by Charles Darwin's theory of natural evolution. This algorithm reflects the process of natural selection where the fittest individuals are selected for reproduction in order to produce offspring of the next generation.

Genetic algorithm begin with a large set of randomly generated individuals, μ solutions. In each iteration, λ new generation are created. These μ parents and together with these λ generations will be modified to form the next μ parents. This approach hopefully shields against the so-called premature convergence to local optima, if the population is sufficiently diverse [126].

3.4 Simulation Results

Simulation results are presented in two aspects: performance analysis and time domain simulation. Performance analysis is given by comparison between using trust region and genetic algorithm. The proposed method is implemented in Matlab using the IEEE 14 bus system by using real wind generation and load data. Matpower [127] is used to solve power flow and optimal power flow problems and the tool to draw the PV curves. The base bus system parameters are from case14.m produced by Matpower.

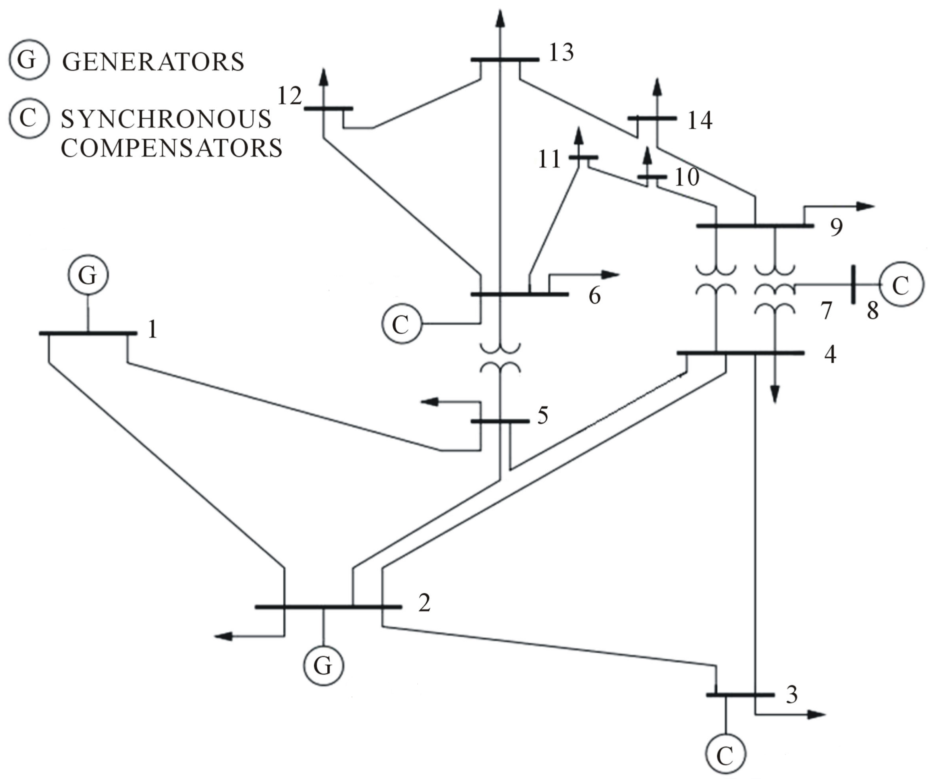

Figure 3.6: IEEE 14 Bus System [122]

Fig.3.6 shows the IEEE 14 bus system [128]. It is assumed that generators installed on bus 2 are DFIGs. The wind farm consists of 100 generators, each rated at 2 MW. SVC has been installed on each load bus, each rated at 50 MVAR. This IEEE 14 bus system contains one wind farm on bus 2.

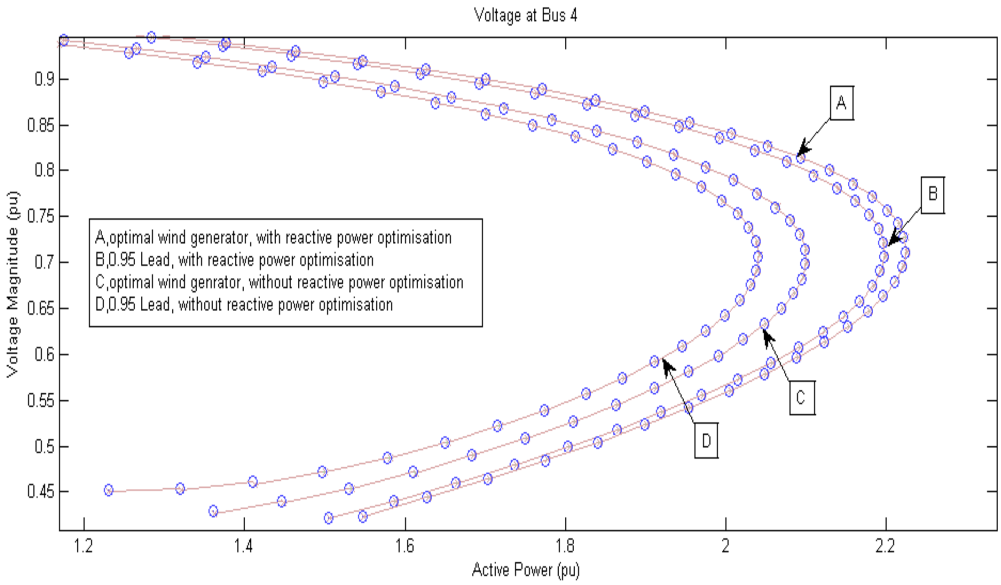

Figure 3.7: PV Curves at bus 4 for the IEE 14 bus system.

3.4.1 Performance Analysis

The PV curves for the two scenarios are indicated in Fig. 3.7. It is assumed that wind generators are operated at 100% rating. Curve A in Fig.3.7 indicates the PV curve at bus 4 when all of the wind machines are operated at optimal power factor and all of the reactive sources and wind farms coordinated. Comparison of curves A and C in Fig. 3.7 indicates a higher loadability margin when all of the reactive sources are properly coordinated. Curves B and D in Fig. 3.7 indicate the wind machines are operated at optimal power factor. It can be observed that proper coordination of various reactive sources results in larger loadability margin and better voltage profile.

In Fig.3.8, it is observed that bus 4 has the least loadability margin without wind generation. Hence PV curves at bus 4 are presented as a performance measure. It is noted that loadability is larger when wind energy is integrated in power system. Therefore, integration of wind energy has positive affect on power system.

The performance of the approach with varying wind penetration ratios is indicated using the convergence characteristics. Fig.3.9 indicates the convergence characteristics of the proposed approach for different wind farm outputs. The value of the objective function following each successful iteration in trust region algorithm

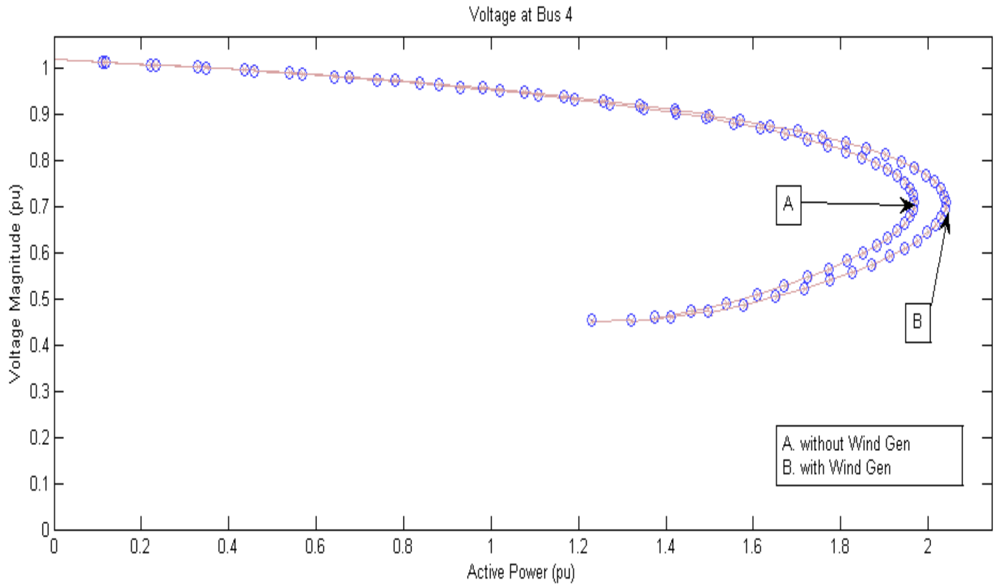

Figure 3.8: PV Curves At Bus 4 With and Without Wind Generation

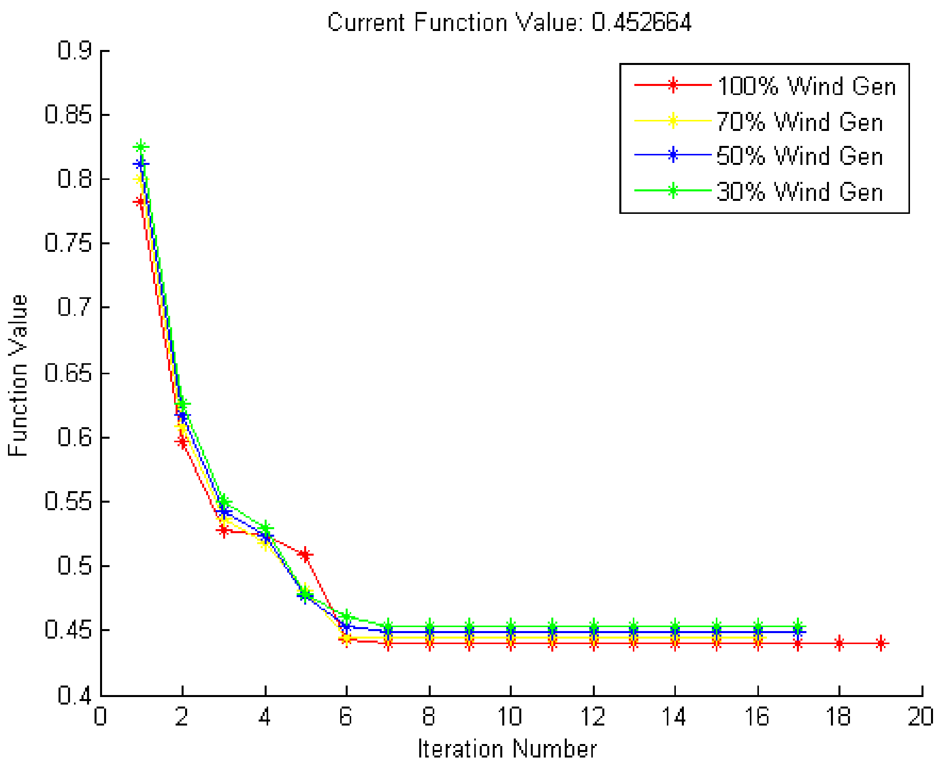

Figure 3.9: Convergence Characteristics of Trust Region With Different Ratios of Wind Penetration.

is plotted. Plots indicate smooth convergence of the algorithm.

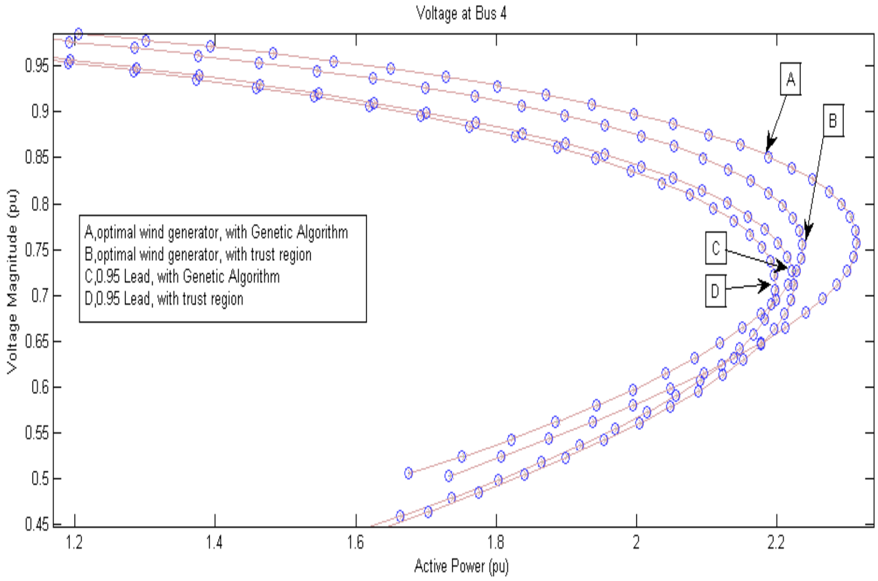

Figure 3.10: Comparison of PV Curves at Bus 4 with Trust Region and Genetic Algorithm.

The PV curves in the Fig. 3.10 show the comparison of PV curves at bus 4 with trust region and genetic algorithm. Curve A in Fig.3.10 indicates the PV curve at bus 4 when all of the wind machines are operated at optimal power factor and all of the reactive sources and wind farms coordinated by using genetic algorithm. By comparison, Curve C in Fig. 3.10 is obtained by using trust region under same conditions. Curves C and D indicates the wind machines are operated at normal power factor, the optimisation algorithm are genetic algorithm and trust region, respectively. It can be seen that using genetic algorithm can achieve a larger loadability and shows a better performance.

Fig. 3.11 indicates the convergence characteristics of genetic algorithm. It show that the minimum value of 0.419 is reached at the generation of 58.

Fig. 3.12 shows the comparison of convergence characteristics between genetic algorithm and trust region. It can be seen that trust region and genetic algorithm achieves 0.453 and 0.419 for the minimum value. It has proved that a larger loadablity can be obtained by using genetic algorithm as shown in Fig.3.12. On the other hand, the voltage stability study in this report is based on the steady state

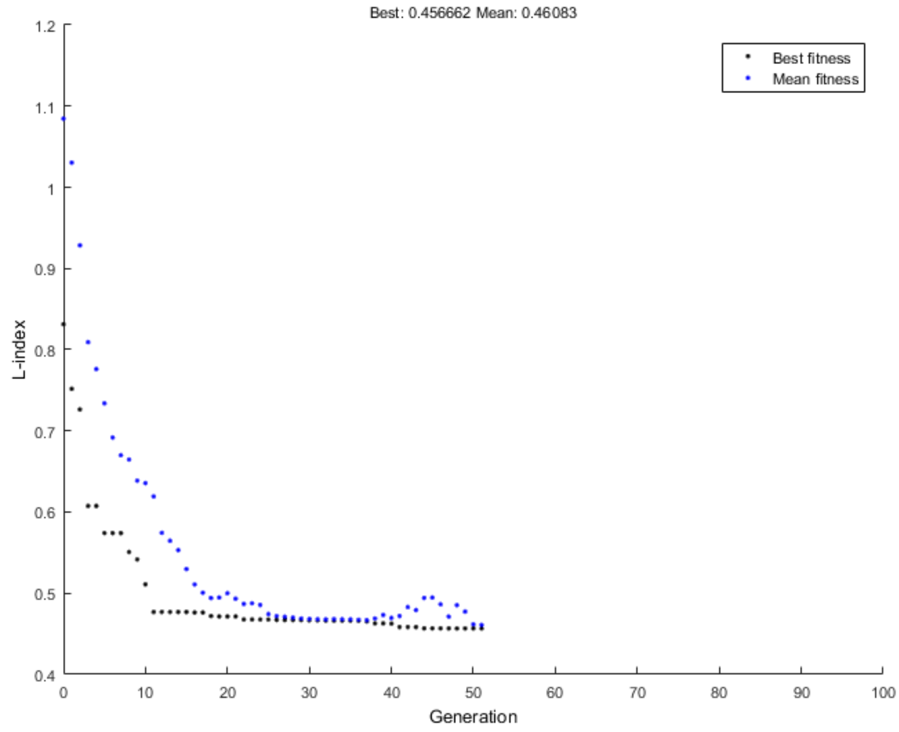

Figure 3.11: Convergence Characteristics of GA.

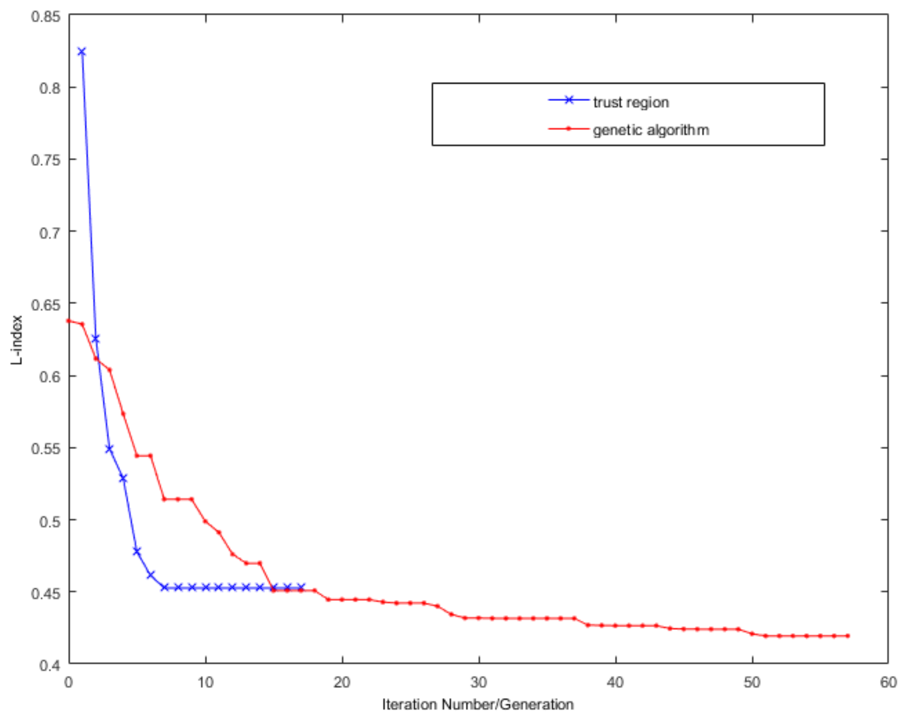

Figure 3.12: Convergence Characteristics of Genetic Algorithm and Trust Region.

of the power grid. Thus, the iteration number is not a crucial consideration, even genetic needs about 60 generations to achieve the lowest function value, while trust region needs 17 iterations. Additionally, trust region can easily be trapped in a local optimum. To the contrary, genetic algorithm has global convergence characteristic. Therefore, genetic algorithm has better performance in this steady state voltage stability study.

3.4.2 Time Domain Simulation

For the comparison purpose, there is no control actions in the base condition. Dynamic optimisation means the power of supply and demand vary with time. The control algorithm is implemented in an iterative manner. Once an optimisation is finished with a set of data, the next cycle will start. During each cycle, loadability margin can be achieved at the normal operating condition. With the coordination control of reactive power output of wind generators and other reactive power sources, larger loadability can be achieved. Thus, the voltage stability can be enhanced based on dynamic data.

Generation and load profiles are obtained from Gridwatch provided by BM reports [129]. The data are for the whole year of 2015. To simplify the calculations, hourly data are extracted from raw generation and load profiles. Then, they can be applied to the proposed method.

Fig 3.13 shows one day (24 hours on 1 May 2015) demand profile extracted from Gridwatch and Fig 3.14 shows one day wind generation profile. The peak demand occurs at around 7pm-8pm and the demands are relative lower between 0:00 and 4.30. It can be seen that there are some fluctuations in the wind generation profile. The amount of wind generation is the highest at 10:00 and lowest at 16:00. In Fig.3.15, 3D PV curves are given using one whole day around load and wind generation data. The PV curves are drawn each hour. Blue lines are normal conditions where no control action is considered. After optimisation by using coordination control, the new PV curves are drawn with red colour. It can be seen that the loadability is enlarged significantly when applied the proposed method. From 10am to 9pm, the loadability margins are relative higher, due to the heavier load compared

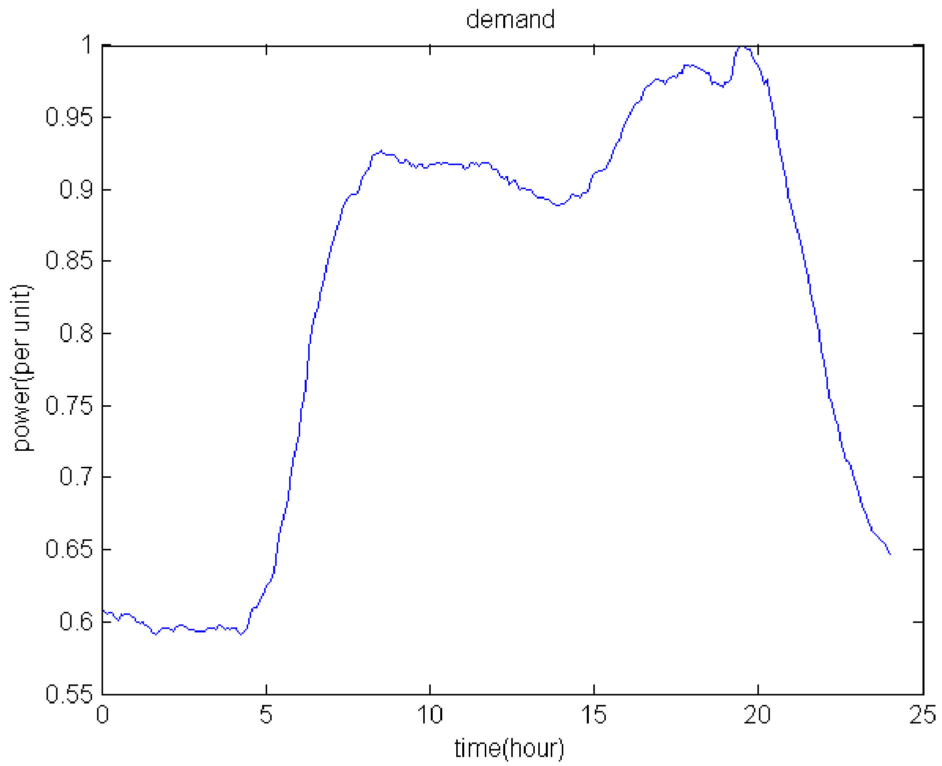

Figure 3.13: Demand Profile

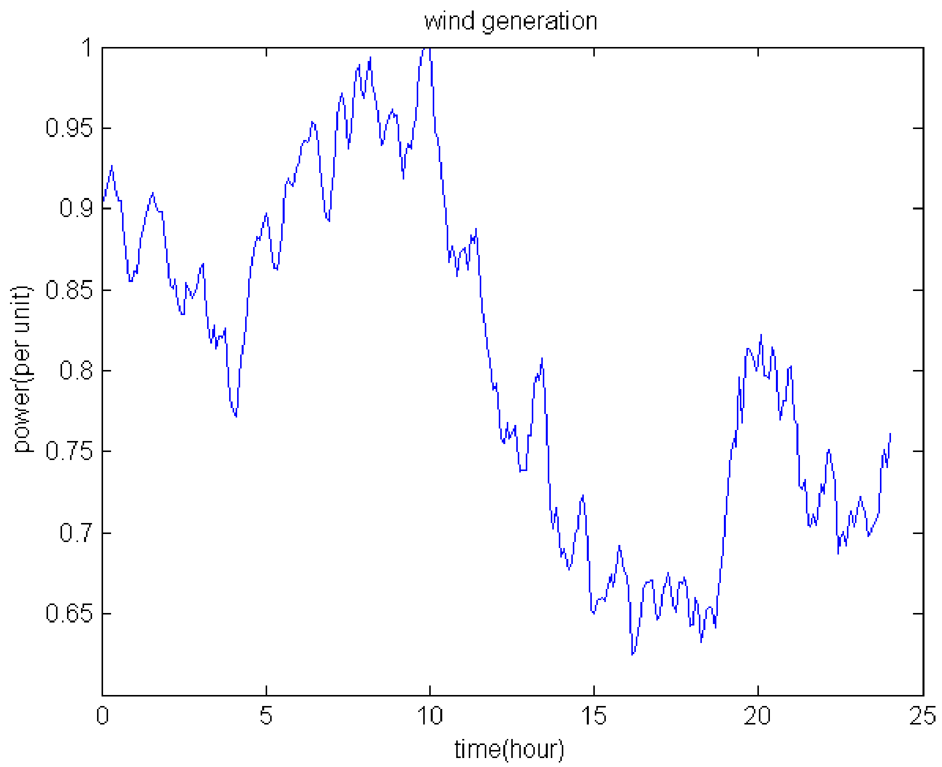

Figure 3.14: Wind Generation Profile

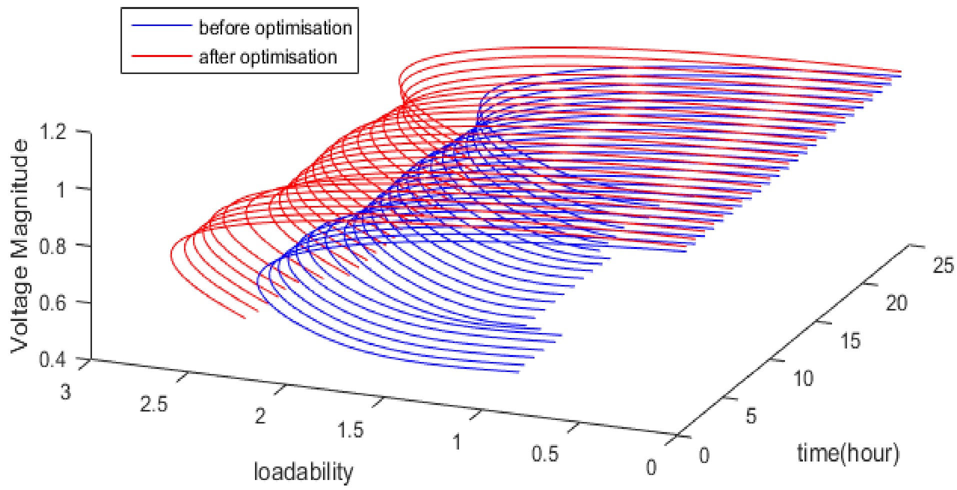

Figure 3.15: One Day Hourly PV Curves

to the sleeping time.

It is also important to know the growth rate of loadability between base condition and after optimisation. With one day real data of wind generation and load, the curve in Fig.3.16 indicates the one-day hourly benefit from using the proposed method. The benefit is calculated as

$$gain = \frac{P_2 - P_1}{P_1} \times 100\% \tag{3.4.24}$$

where P_1 is the loadability under normal condition and P_2 is the loadability after optimisation. The curve is plotted from 1am to midnight. It can be seen that there are some fluctuations. Higher benefits occur at 6am, 9am, 4pm and 8pm. The highest benefit value is 20.3% at 6 am and the lowest value is 17.3% at 1am. Due to the loads are at the same level in the night and in the early morning, wind generation determines benefits. Higher wind generation helps achieve higher benefit.

The benefits of different wind generation and demand are plotted in 3-dimension shown in Fig 3.17. It can be seen that with the increasing of demand, the benefit is decreased. On the other hand, it is noted that loadability is enlarged when wind energy is integrated into power system. Therefore, the integration of wind energy has a positive effect on the power system. Fig 3.17 also shows highest value of benefit, i.e. around 28%. In this case, it is caused by higher wind generation and lower

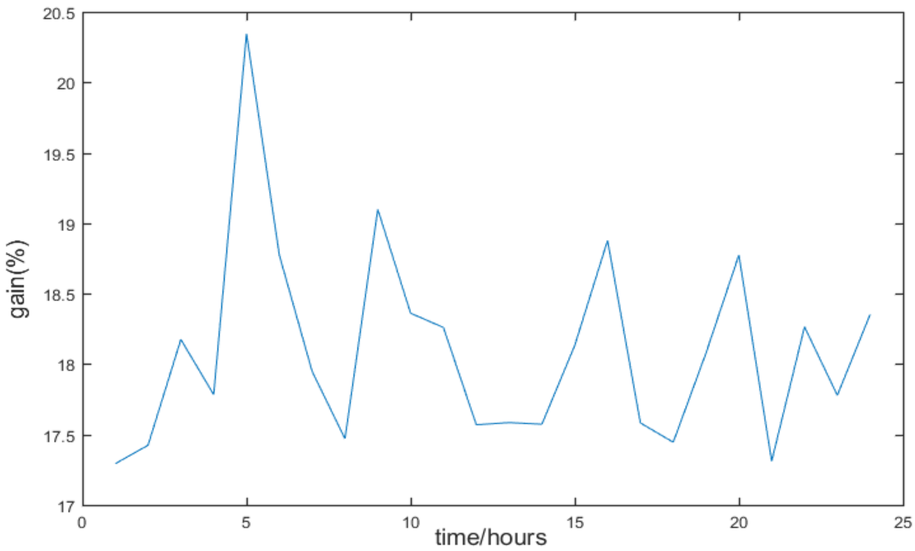

Figure 3.16: Hourly Loadability Benefit in Percentage

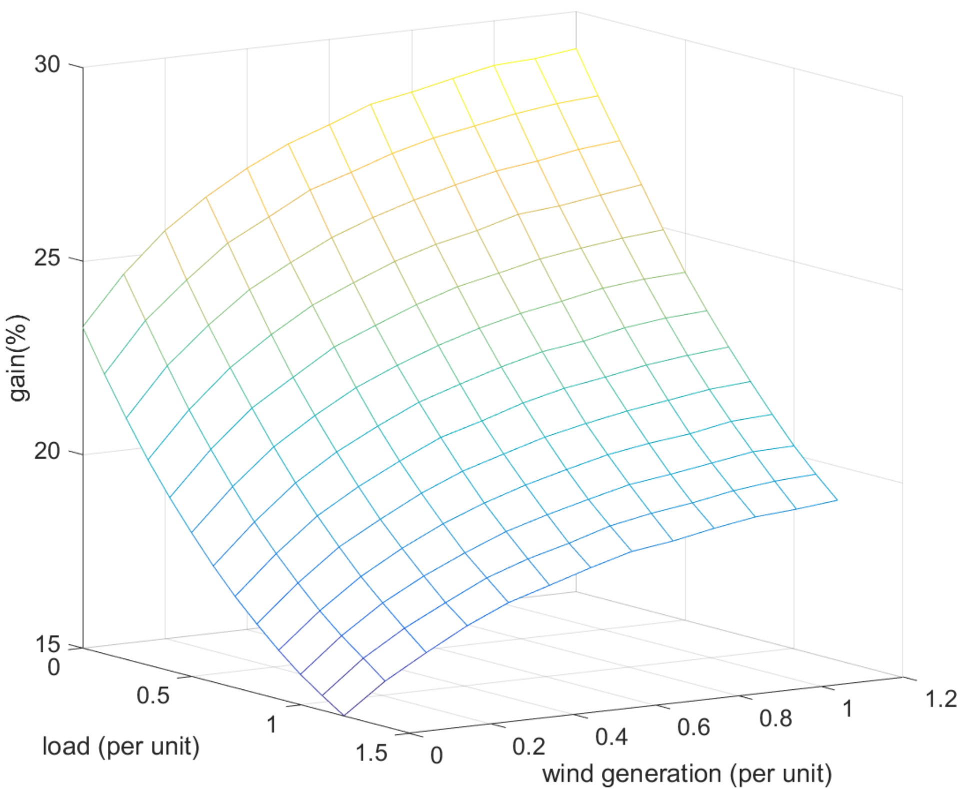

Figure 3.17: Loadability Benefit Based on Different Wind Generation and Demand.

demand. The lowest value (15%) of benefit occurs, when the system has heavier load and without wind generation.

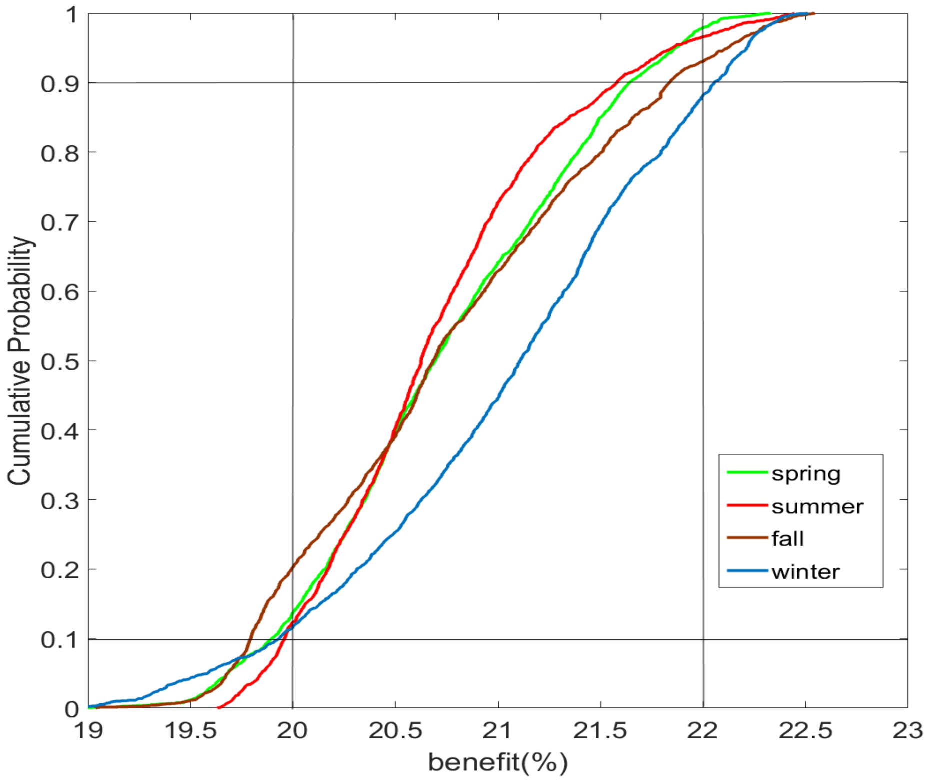

Figure 3.18: Comparison of Four Seasons Loadability Benefit Based on Cumulative Distribution Functions.

Fig 3.18 displays benefits analysis based on cumulative distribution functions for four seasons in one year based on UK annual data. The Cumulative Distribution Function indicates the probability of a random variate less than or equal to a certain value. It can be seen that the cumulative probability of red line is always larger than other lines', when the benefit is larger than 20.5%. Thus, the proposed method has the best performance in summer. The heaviest load and lower wind generation in winter, will caused the worst performance. It is observed that 80% of the data based on one year loadability benefit are distributed in the region of 20% to 22%. Hence the performance of proposed approach is stable.

3.5 Chapter Summary

In this chapter, we use both mathematical expression and PV curves to illustrate the relationship between voltage and power. Mathematical expression is based on Jacobian which is obtained from power flow calculation. PV curve is plotted by using continuation power flow. It shows the maximum power can be transferred through the transmission line. Different voltage stability analysis tools are discussed. Two main methods, Jocobian matrix based method and bus admittance matrix based, are compared. Due to the requirements of on-line monitoring and high computation efficiency, L-index is used as voltage stability metric in this study. It is based on impedance matrix and requires less computation time. Lower L-index value means higher voltage stability that more power can be transferred. The capability of power transfer is also called loadability.

In order to keep voltage away from collapse point, a dynamic voltage stability enhancement method is presented which is based on minimisation of L-index. The L-index based voltage stability control method is verified in the IEEE 14 bus system. Both trust region method and genetic algorithm are implemented and compared. It is proved that it is feasible to enhance the voltage stability with proper coordination control of reactive power output of wind generators and other reactive controllers under dynamic conditions. In addition, using genetic algorithm can achieve lower L-index value than using trust region. However, using genetic algorithm has much more iteration to reach the lowest L-index value that requires more time, this may not meet the requirement of real time operation. Therefore, trust region is used in time domain simulation. The benefits of optimisation based on different wind generation and demand are illustrated. Further, loadability benefits in four seasons are compared. This proposed method can be easily extended to other different power networks where the power system is integrated with wind farms.

Chapter 4

A Subsection Control Strategy Based on L-index for Voltage Stability Enhancement using Full PMU Measurement

Nowadays, the load demand is constantly increasing. This tendency coupled with the high penetration of renewable energy will not only significantly affect behaviours of power system, but also the way to control. Voltage stability is one of the most critical issues as it may cause power system collapse, e.g. the blackout in Italy 2003. In chapter 3, a voltage stability enhancement method based on L-index minimisation is implemented using real load and wind generation data. It can be seen that power systems can always operate at its the most stable point. However, power system is not necessary to always operate at the most voltage stable point as it requires high control efforts. It is possible to enhance voltage stability using the most sensitive control actions, when the voltage is relative stable. In case of voltage stability is weak or close to collapse point, the system is required to make every effort that keeps away from collapse point. The objective of this chapter is to enhance voltage stability considering power system conditions.

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Several considerations are emerged from the previous discussion that motivate the work in this chapter:

1. Traditional identification and enhancement approaches may have computation burden which are not suitable for real-time operation.

2. All time maximisation the voltage stability margin is not a economical way to maintain power system stable.

3. Weak condition always be considered independently in voltage stability identification.

In this chapter, a subsection control scheme approach is proposed to enhance voltage stability. The approach utilizes L-index, which is a voltage stability metric. The method is expected to be implemented in situations where real data of wind generations and demands are introduced. Additionally, both normal and weak condition are taken into account. A L-index sensitivities based control method is proposed to determine the most effective control actions under normal condition. While, an overall L-index minimisation method is introduced under weak condition. This chapter is directly targeted at utilizing reactive power output of all reactive sources for voltage stability enhancement. The only data and parameters needed to implement the approach are the nodal voltages which can be collected from PMUs. The control problem is linearized by using L-index sensitivities, so that it can be solved in a reasonable time frame, so that control actions can be taken in a short time. The main contributions of this chapter are:

- It proposed L-index sensitivities based method for voltage stability enhancement. The proposed method has two main features: fast computation and enhance voltage stability with the most sensitive control actions.

- A subsection control scheme approach is proposed to enhance voltage stability considering stable and weak conditions, as it requires high control efforts, when power system always operate at the most voltage stable point using L-index minimisation method.

The rest of the chapter is organized as follows.Section 4.1 illustrates PMU principles and wide area monitoring systems for voltage stability. In Section 4.2, L-index sensitivities are formulated. The control strategy for voltage stability enhancement is proposed. Case studies presented in Section 4.3 show results of the proposed control strategy in both IEEE-30 bus system and IEEE-118 bus system. Concluding remarks and future research questions are provided in Section 4.4.

4.1 L-index Sensitivity Based Control Method

The basic idea in this chapter is to maintain the voltage stability at a desired level with the most sensitive control actions. Both normal and stressed conditions are considered. A subsection control scheme is introduced to implement optimal control in an effectiveness way. Under normal conditions, the objective function is to determine the minimal compulsory control efforts to improve voltage stability, so that voltage stability can be enhanced directly. On the other hand, an overall L-index optimisation method is applied under stressed conditions. In this way, the lowest L-index value can always be found with proper control actions and the power system operates with the largest loadability, thus enhancing voltage stability. Moreover, computation speed is a critical aspect in real time voltage stability enhancement. Based on the comparison of different voltage stability identification methods in Section 3.2, L-index sensitivity based voltage control approach is proposed. Due to the rotor current injection schemes, the reactive power output can also be controlled. Controlling wind generators as the sources of reactive power is feasible. Therefore, two sets of control variables are considered: reactive power output of wind generators Q_{g} and compensators Q_{svc}. The L-index sensitivity formulations with respect to Static Var Compenators (SVCs) and wind generators are introduced.

4.1.1 L-index Sensitivities

L-index sensitivities based control depends on L-index value L_j which varies with the changing injection vectors Q_{svc} and Q_{g}. With the presence of SVCs and installed Doubly-Fed Induction Generators (DFIG) in the network, the reactive power outputs of SVCs Q_{svc} and wind generators Q_{g} are considered as control variables and can be controlled independently. The changing of these control variables will affect the L-index values at all load buses. The relationship between the control variables and the L-index value is highly non-linear and depends on the system operating point.

Small changes in the control variables are used to find the corresponding sensitivities. At operating point k, a small change $\overline{\delta}_{Q_{\text{svc}}}$ is applied in the injection vector Q_{svc} and the sensitivity to this small change is found via (4.1.1):

$$a^k_{\Delta Q_{\text{svc}}} = \frac{L^k_c(Q_{\text{svc}} + \overline{\delta}_{Q_{\text{svc}}}, Q_{\text{g}}) - L^k_c(Q_{\text{svc}}, Q_{\text{g}})}{\overline{\delta}_{Q_{\text{svc}}}} \tag{4.1.1}$$

where $a^k_{\Delta Q_{\text{svc}}}$ is the sensitivity with respect to Q_{svc} at operating k. In the same manner as (4.1.1), these resulting critical L-index values can then be utilized to find the corresponding sensitivities using (4.1.2):

$$a^k_{\Delta Q_{\text{g}}} = \frac{L^k_c(Q_{\text{svc}}, Q_{\text{g}} + \overline{\delta}_{Q_{\text{g}}}) - L^k_c(Q_{\text{svc}}, Q_{\text{g}})}{\overline{\delta}_{Q_{\text{g}}}} \tag{4.1.2}$$

where $a^k_{\Delta Q_{\text{g}}}$ is the sensitivity with respect to Q_{g} at operating k. It is the fact that the power system is non-linear as well as the relationship of dependent control variables and L-index value. However, the linear equation can be formulated at a system operating point. L-index sensitivities can be utilized with dependent control variables that will achieve the predetermined L-index step size, Λ_L:

$$\Lambda_L = \sum_{i \in T} a^k_{\Delta Q_{\text{svc}}} \Delta Q_{\text{svc}} + \sum_{i \in T} a^k_{\Delta Q_{\text{g}}} \Delta Q_{\text{g}} \tag{4.1.3}$$

L-index step size Λ_L is the desired reduction in L-index value. In other words, reducing L-index is utilized to enhance voltage stability. Large step size makes lower L-index value and voltage is more stable. It can be seen that, both the reactive power injections of L-index sensitivity control algorithm and wind generator contribute to reduce in L-index value. On the other hand, at an operating point, larger L-index step size requires more reactive power output of SVCs and wind generators.

4.1.2 L-index Based Subsection Control Algorithm Diagram

In order to keep the voltage stability at an acceptable level with effective control actions, a subsection control scheme is introduced. Two operating scenarios are

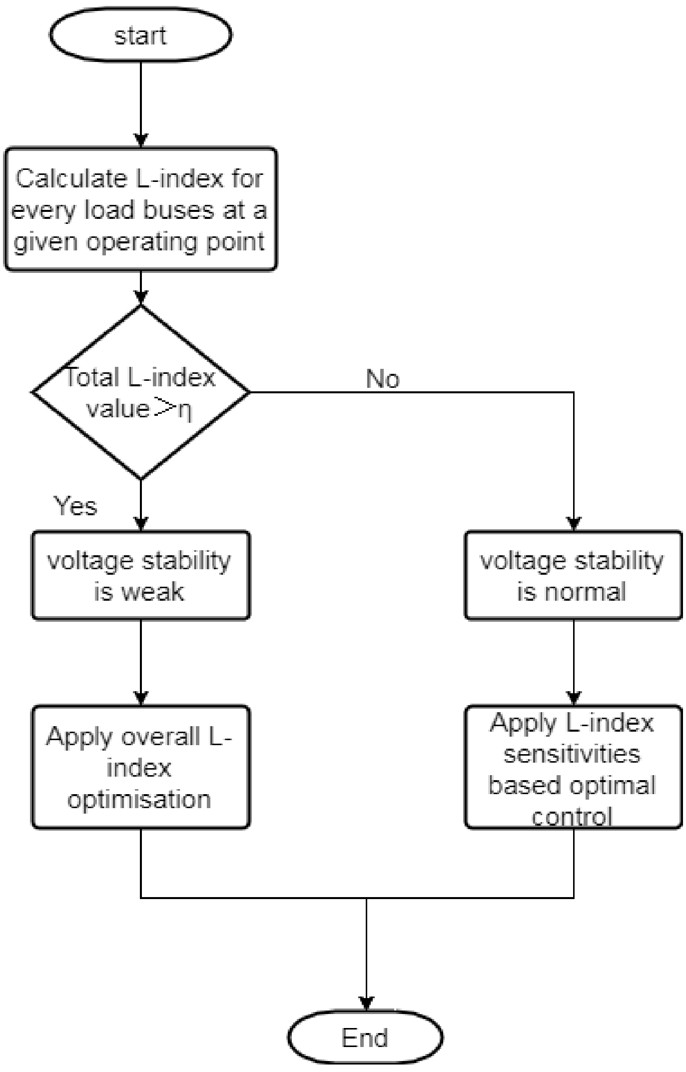

Figure 4.1: Subsection Control Scheme

considered which includes normal and stressed condition. These two corresponding control methods are applied in the subsection control scheme, which consists of the proposed L-index sensitivities based control algorithm for normal condition and an overall L-index minimisation method for stressed condition. A block diagram of the subsection control scheme is shown in Fig. 4.1. Firstly, the system data are sent to a concentrator from PMUs so that L-index on every load buses can be achieved. Then, two control options are available. The decisions will be made based on the L-index value threshold η which will be discussed in the following section. If the total L-index value is larger than the predefined value η , the L-index sensitivity control algorithm will utilize the control variables, Q_{svc} and Q_{g} in combination for voltage stability enhancement. Otherwise, overall L-index optimisation control is executed. The subsection control scheme attempts to provide a solution for Q_{svc} and Q_{g} that moves the L-index value away from 1, with the minimum amount of control actions. In order to achieve the best performance of the proposed method, threshold η should be set properly. Transmission cost is utilized as a measure in threshold selection. In this way, the control algorithm will be selected who has less total cost, in the case of overall L-index values are the same after optimisation.

4.1.3 L-index Sensitivities Based Optimal Control

If the total L-index value is smaller than the predefined threshold η, L-index sensitivities based Optimal control will be executed. L-index is identified and the sensitivities with respect to the control actions are found (4.1.1) and (4.1.2). These sensitivities are then utilized in the optimal control, with each step explained in depth as follows.

This control method is used in an iteration manner as shown in Fig. 4.2. L-index step size Λ_{L1} is firstly set at a relative small value. In L-index sensitivities based Optimal control cycle, the total L-index value will be checked if they are out of bounds, L_{r1}. L_{r1} is the total L-index requirement for global optimal control. If total L-index value is not within the predefined limitation, then the new step size will be set as $\Lambda_{L1} = \Lambda_{L1} + \Delta_1$, where Δ_1 is set at a fixed value, i.e.,$\Delta_1 = 0.1$. As L-index should be between 0 and 1, 0.1 is a reasonable increase in step size. This control loop will be ended once the total L-index value meet the requirement. Every cycle is independent and based on its operating point. The output will be set and implemented by all the reactive power output resources. Quadratic objective function is convex and smooth, which makes evaluation of derivatives easy. Therefore, the objective function is formulated as a minimization of the control efforts which include two independent control variables for each iteration as below:

$$\text{Min} \sum_{i \in T} (Q^2_{\text{svc,i}} + Q^2_{\text{g,i}}) \tag{4.1.4}$$

The most basic linear equality constraints are (4.1.5)-(4.1.6) which relate to the objective function:

$$Q^{k+1}_{\text{svc,i}} = Q^{k}_{\text{svc,i}} + \delta_{Q_{\text{svc}}}, \forall i \in T \tag{4.1.5}$$

$$Q^{k+1}_{\text{g,i}} = Q^{k}_{\text{g,i}} + \delta_{Q_{\text{g}}}, \forall i \in T \tag{4.1.6}$$

The linear inequality constraints (4.1.7)-(4.2.8) maintain the control variables within operating limits:

$$Q_{\text{svc,i,min}} \leq Q_{\text{svc,i}} \leq Q_{\text{svc,i,max}} \tag{4.1.7}$$

$$Q_{\text{g,i,min}} \leq Q_{\text{g,i}} \leq Q_{\text{g,i,max}} \tag{4.1.8}$$

L-index sensitivities with respect to the reactive power injection from SVCs and wind generators are introduced. Control constraints (4.1.5)-(4.1.8) are incorporated with L-index based linear sensitivities. The most sensitive control actions can be achieved by solving the optimisation problem (4.1.4)-(4.1.8). Solution of (4.1.4) will determine the minimal amount of control actions to enhance voltage stability. This makes the control action more effective.

There are two main tasks in the proposed method. Initially, we calculate L-index values for all load buses which shows the voltage stability level and the desire total L-index values can be set based on the power system requirement. Then the control efforts can be minimised by the objective function. Additionally, in order to reach higher voltage stability level, L-index value could approaches 0 by enlarging control

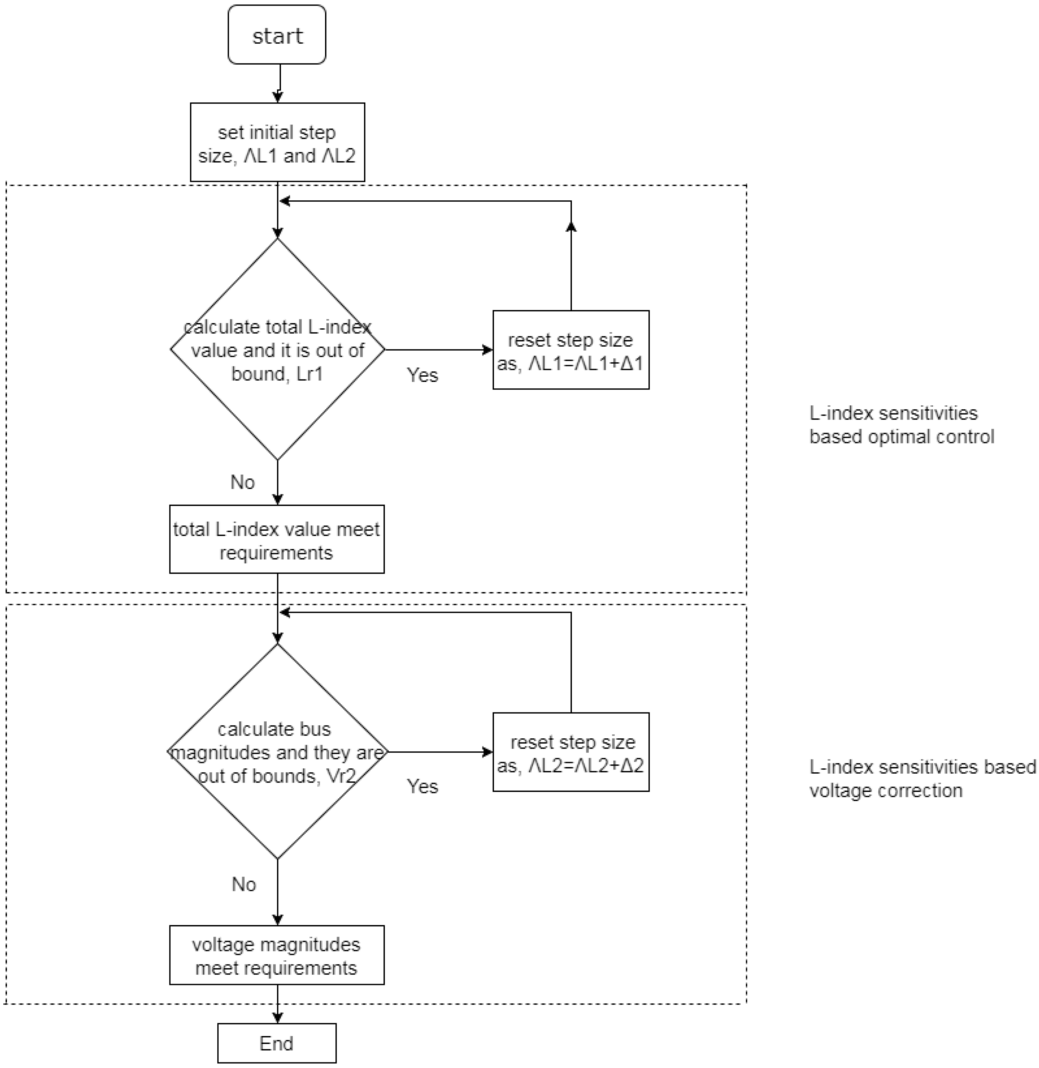

Figure 4.2: L-index Sensitivity Based Control Loop

step size.

4.1.4 L-index Sensitivities Based Optimal Control With Local Voltage Correction

The first loop of the control algorithm in Fig. 4.2 is the minimisation of L-index value. In the second loop, the algorithm not only obtains the global optimisation but also maintains the local voltage magnitude. When the local voltages of the network are within the predefined limits, control actions will be taken once this process is finishes. If any voltages is out of constrain, then the proposed algorithm will start another loop, which is called voltage correction loop. For the buses are out of limits, a separate control step Λ_{L2} by using their corresponding L-index sensitivities buses will be given in the voltage correction loop. Once the voltage magnitude reaches the predefined value, control actions will be applied and will start a new iteration.

4.1.5 Overall L-index Optimisation

Under stressed conditions, minimising the overall L-index is applied to maximise the steady-state voltage stability margin. The relationship between L-index and loadability was proposed in [123] and verified in [117]. They indicate that a smaller value of L-index can achieve a larger loadability margin. For a power system, the total L-index can be formulated as follows.

$$S = \sum_{j=g+1}^{n} L_j^2 \tag{4.1.9}$$

where S is defined as the voltage stability index for a power system. Once the calculations of L-index value for all load buses are completed, the total L-index can be obtained.

To improve the steady-state voltage stability of the power system, the loadability margin should be maximised, which in turn minimises the value of L-index for each bus. In order to maintain voltages close to the defined values, the power system requires reactive power compensation, which is injecting reactive power into the power system, it helps to reduce line currents and network losses, so that the stability is enhanced. Therefore, voltage stability margins can be improved by appropriate reactive power compensation. In this chapter, this method is adapted for real time implementation. The optimization formulation can be defined by combining the objective function and the associated constraints, as follows:

$$\begin{aligned} \text{Min } T(Q) &= \sum_{j=g+1}^{n} L_j^2 \\ \text{s.t. } Q_{\text{g}}^{min} &\leq Q_{\text{g}} \leq Q_{\text{g}}^{max} \\ Q_{\text{svc}}^{min} &\leq Q_{\text{svc}} \leq Q_{\text{svc}}^{max} \end{aligned} \tag{4.1.10}$$

where Q is the control variable including Q_{svc} and Q_{g}.

As studied in Chapter 3, compared to trust region, genetic algorithm has better performance in optimal results. While, calculation speed can be improved by using strong data concentrators, also genetic algorithm is easy to be applied. Therefore, Genetic algorithm is used for optimisation in this chapter.

Under normal conditions, only the most sensitive control actions for voltage stability enhancement are included in the optimization problem. This makes the control search very effective and reduces the dimension of the optimization problem. On the other hand, the minimisation of the overall L-index method can be used under stressed conditions, so that the voltage stability always keep away from the collapse point.

4.1.6 Intelligent System for Fast Voltage Stability Identification

Due to the continuous load growth, modern power systems operate near their limits. In the meantime, considered the carbon emission and the development of smart grid, renewable energy resources (such as wind power) are integrated into the traditional power systems. However, renewable energy are generally intermittent and difficult to predict and control. Thus, a fast tool which enable real-time monitoring and control of the power system is required. In the past decades, the intelligent system (IS) strategy has been introduced which is a promising method to meet these requirements [130]. It firstly learn from a dynamic voltage stability database.

Then, the non-linear relationship between the power system status (input) and the corresponding voltage stability index (output) can be extracted and reformulated in an IS. During the on-line application process, once the IS gets the input, the voltage stability will be assessed immediately. Apart from the high speed in on-line decision-making. The IS-based classifier requires less data. Therefore, IS is an ideal application in the near future.

Fig. 4.3 shows the control flow chart based on intelligent system. Extreme learning machine is introduced, which is a feed-forward neural network for classification. It is reported that they can outperform support vector machines (SVM) and SVM provides suboptimal solutions in classification [131]. ELM model should firstly be well trained. A database is required, which includes loads, voltage magnitudes on every buses, and also the classification results from calculation of the subsection control method. After the model training is complete, it can be applied on-line. This ELM model is intended to be implemented at a central location like a control centre. The voltage magnitudes are obtained from PMUs and send to the control centre, voltage stability will be classified rapidly. Thereafter, one of the control algorithm will be executed. The control actions will be taken once the computation process is complete.

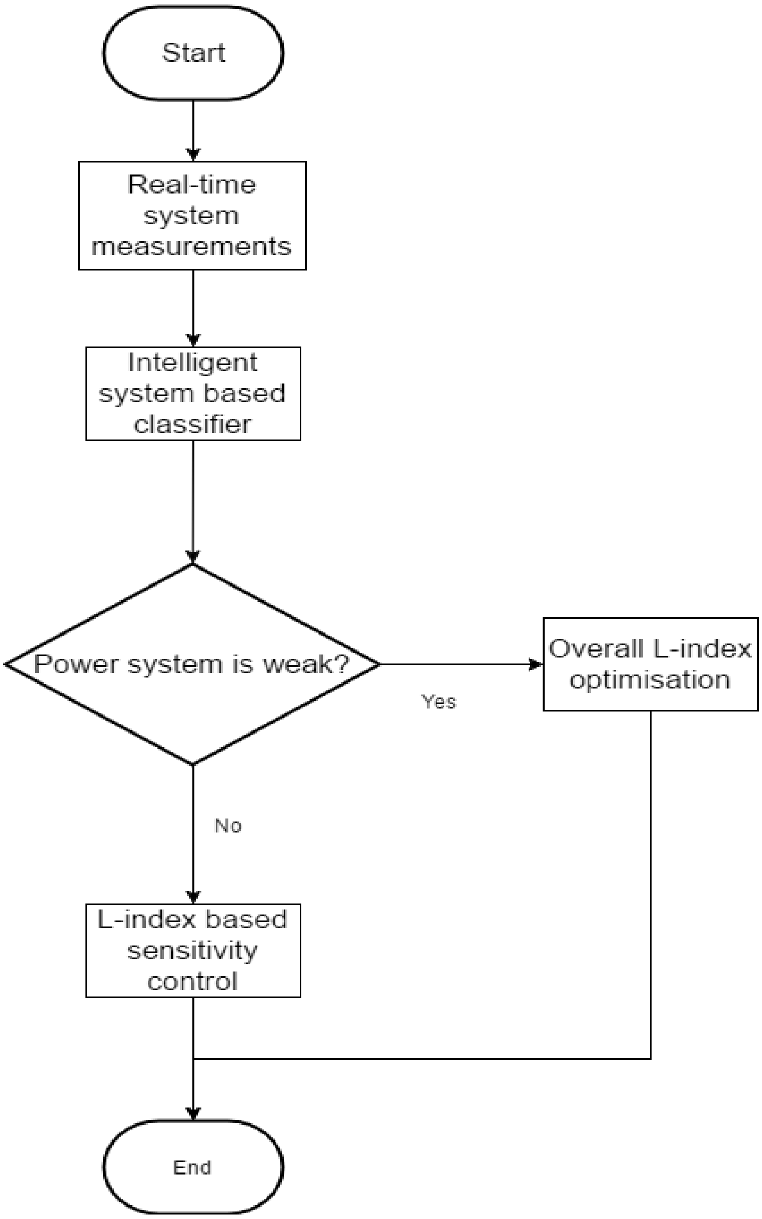

Figure 4.3: Control Flow Chart Based on Intelligent System

4.2 Simulation Results

In this section, we present case studies of the L-index sensitivities based voltage control performance analysis and the subsection control strategy performance analysis. Generation and load profiles are obtained from Gridwatch provided by BM reports [129]. The data are for the whole day on 1 Jan of 2015. To simplify the calculations, hourly data are extracted from raw generation and load profiles.

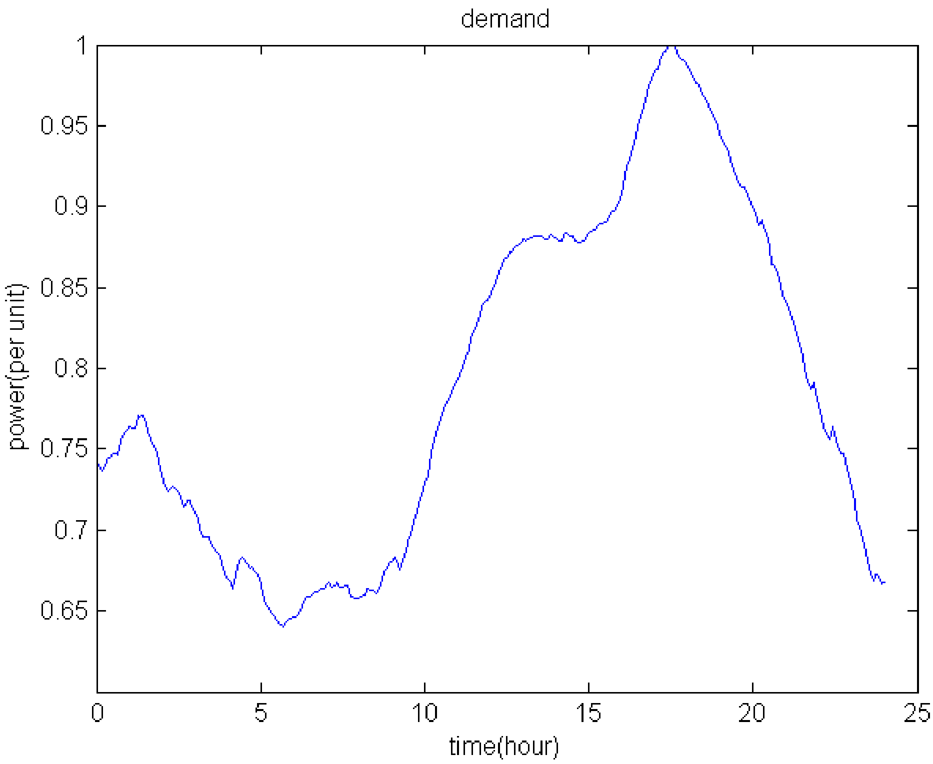

Figure 4.4: Demand Profile

Fig 4.4 shows one day (24 hours on 1 Jan 2015) demand profile extracted from Gridwatch and Fig 4.5 shows one day wind generation profile. The peak demand occurs at around 17pm-18pm and the demands are relative lower between 5:00 and 6:30. It can be seen that there are some fluctuations in the wind generation profile. The amount of wind generation is the highest at 14:00 and lowest at 24:00.

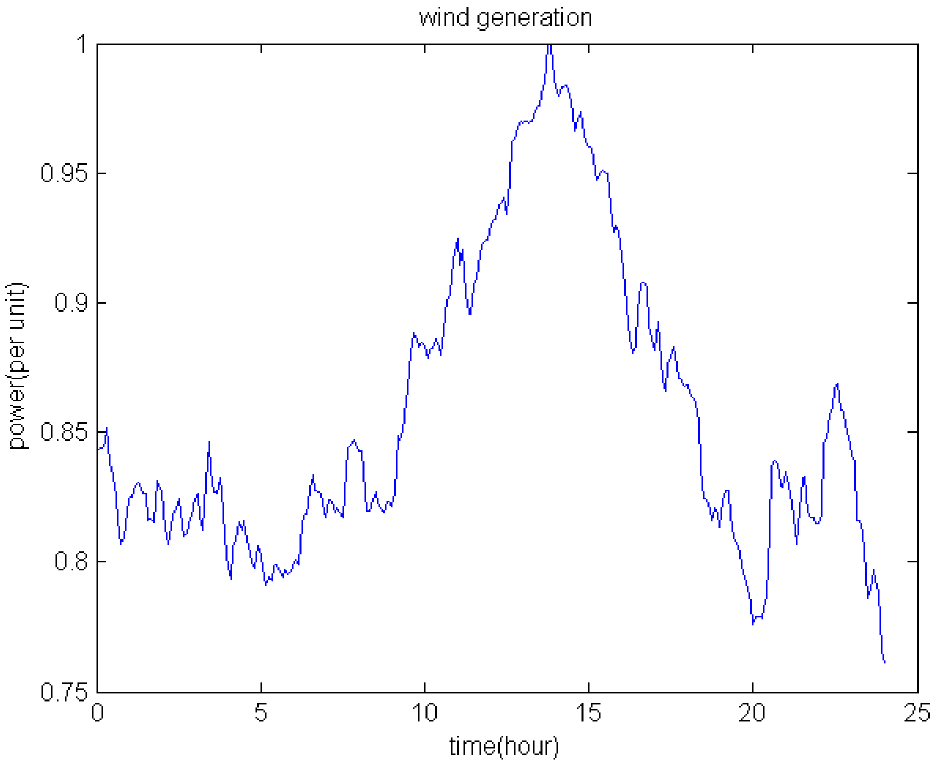

Figure 4.5: Wind Generation Profile

4.2.1 L-index Sensitivities Based Voltage Control Performance Analysis

The proposed control algorithm is implemented in Matlab. A modified IEEE 14 bus system and Matpower are utilized to verify the effectiveness of the proposed method.

Fig.4.6 shows the IEEE 14 bus system. It is assumed that the main power plant is installed on bus 1. It also contains one wind farm on bus 2, which consists of 100 DFIGs, each rated at 2 MW. Reactive power compensation is better if done locally, due to the fact that reactive power travel long distance may cause high consumption. Therefore, each load bus has a SVC.

In Fig.4.7, two fold lines are obtained by using a set of load and wind generation data at a time. Red line is drawn under normal condition. After optimisation by using coordination control, the new voltage profile is drawn with red colour. The main generators are installed on bus 1, hence its voltage magnitude maintains

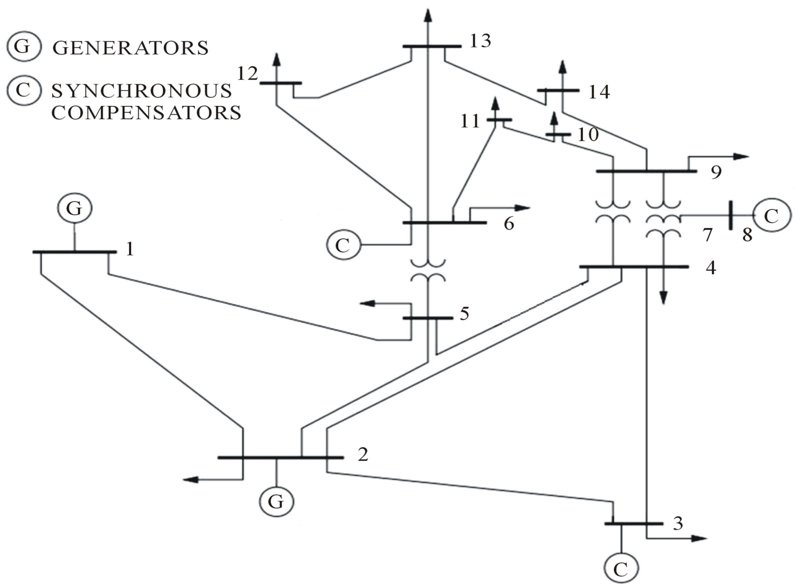

Figure 4.6: IEEE 14 Bus System

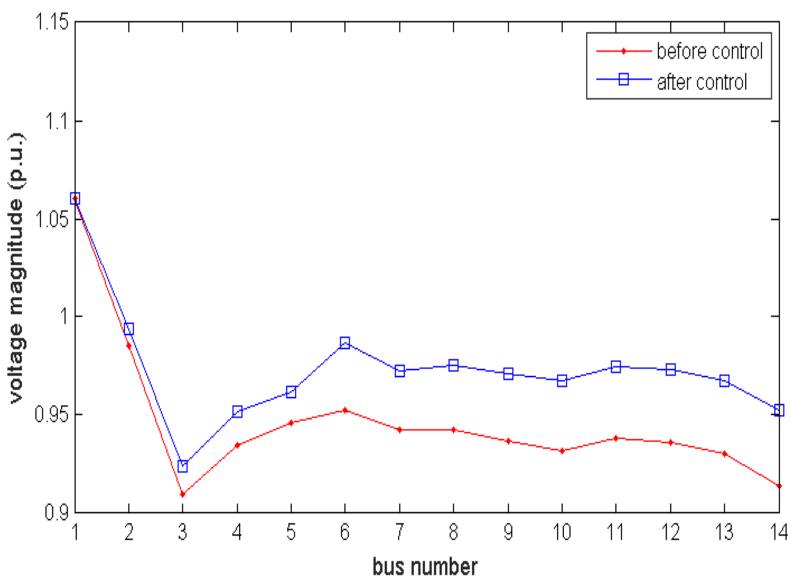

Figure 4.7: Voltage Profile Enhancement On Buses

at 1.06. It can be seen that the voltage level is improved significantly when the proposed method is applied. Due to the heavier load on bus 3 and 14, their voltage magnitudes are relative lower.

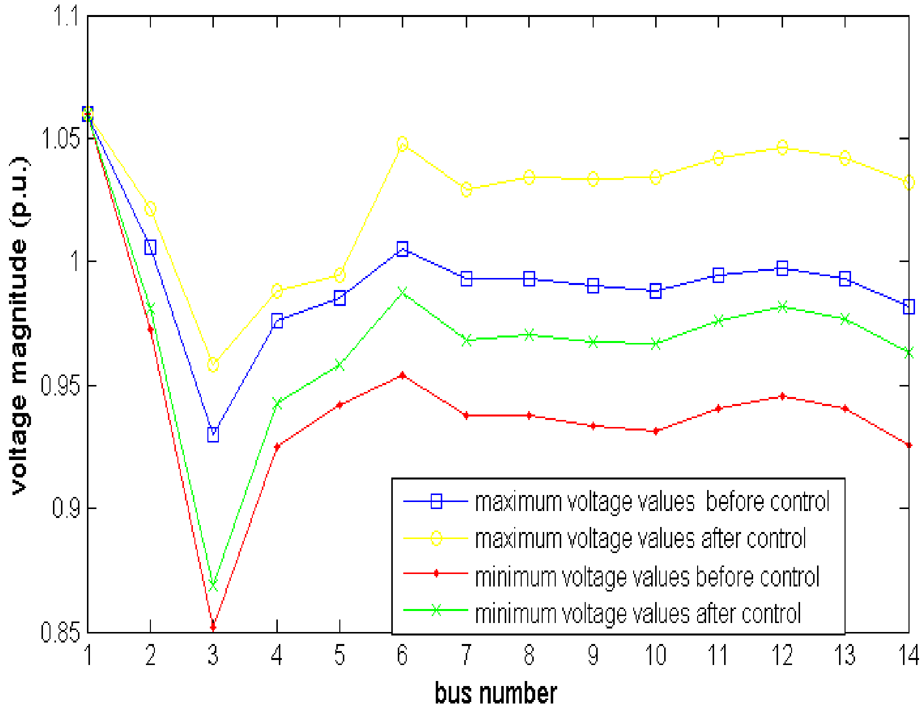

Figure 4.8: Maximum and Minimum Voltage Profiles

One hundred sets of real wind generations and loads data are utilized to verify the effectiveness of the proposed method. Under normal conditions, the voltage profiles are drawn with yellow and red for the highest and lowest values respectively in Fig 4.8. The yellow line shows the highest voltage profile when the proposed method is applied. While the green line indicates the lowest voltage profile after optimal control. It is noted that the voltage on bus 3 is much lower than others, because the load on bus 3 is much heavier.

The PV curves in Fig.4.9 indicate the loadability of normal condition and optimised performance as well as the benefit of the proposed method. It is also important to know the growth rate of loadability between normal condition and after optimisation, which reaches 37%. The red curve shows the largest loadability at around 1.75 without optimal control. In contrast, black curve shows that there is a significantly increasing in loadability which reaches 2.4.

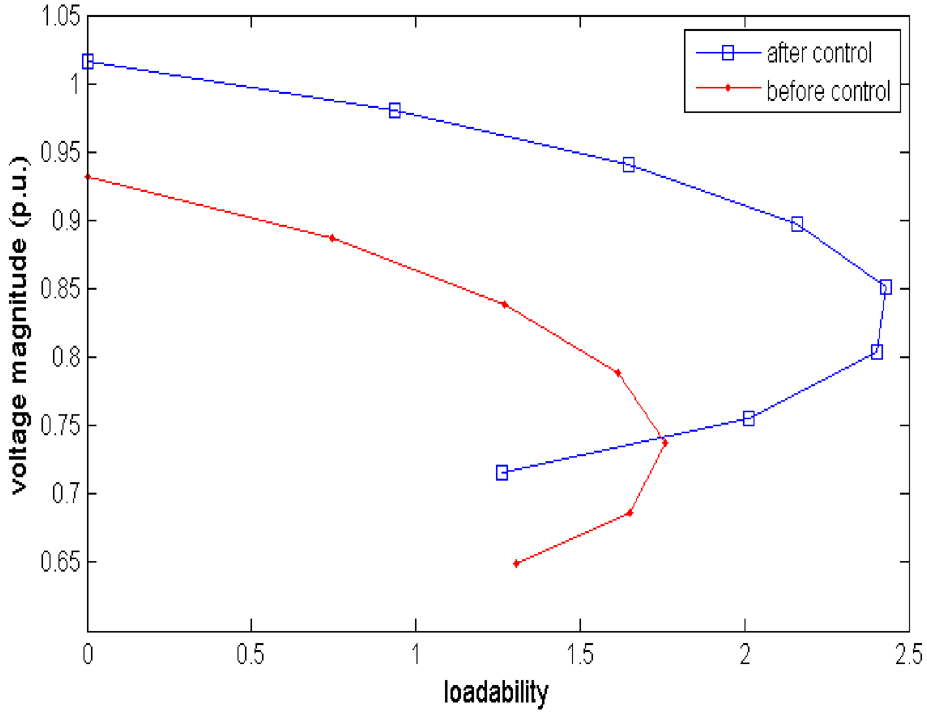

Figure 4.9: Loadability Enhancement

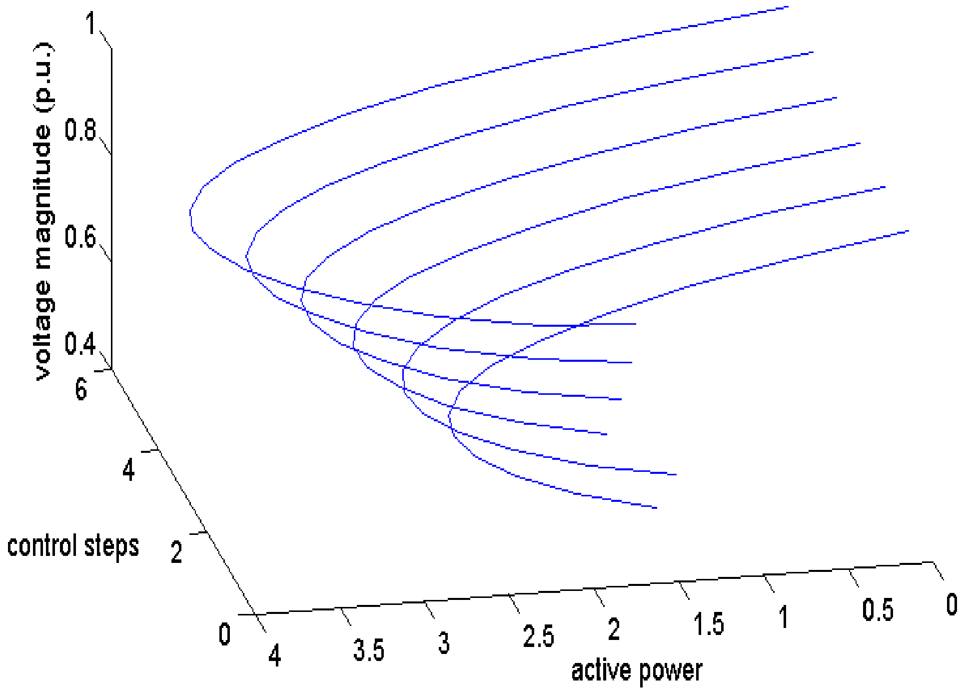

Figure 4.10: Loadability Enhancement With Different Control Steps

The optimised control performances are shown as PV curves in Fig. 4.10. The PV curves are plotted in 3-dimension with different control steps. Every control step interval means the pre-defined difference value of L-index need to be decreased. It can be seen that with lower L-index value, the loadability of power system is larger. It is easy to achieve target loadability based on the system requirement by setting a pre-determined L-index value. Moreover, voltage stability can reach the required level with the most sensitive control actions.

4.2.2 Subsection Control Strategy Performance Analysis

In this Section, we present two case studies of the subsection control algorithm in an IEEE 30-bus and an IEEE 118-bus systems, respectively. In actual implementation, two sets of control variables would be allowed to vary, which are the reactive power outputs of wind generators and SVCs. To complete each load flow calculation, Matpower [132] was used with MATLAB R2012b on a desktop running Windows 7 64-bit operating system with an Intel i5 3.20-GHz processor. Commercial load flow software running on dedicated computers would be used in a practical implementation which would greatly reduce the computation time. In the simulation, reactive power control is better if done locally due to the fact that reactive power cannot travel long distances without being consumed. Thus, it is assumed that compensators are installed on every load bus.

30 bus system

Firstly, as a part of proposed control strategy, L-index sensitivity based control algorithm is used as an independent control method in IEEE 30 Bus System. It is implemented with various control steps. It is assumed that a 30x1.5 MW wind farm is injected at bus 22 [133]. Fig. 4.11 shows the IEEE 30 Bus System. This system is composed of 5 generating units and a slack bus, 21 loads, and 4 transformers. For the stressed purpose, a total of 100 different operating states covering a variety of different load patterns ranging from 80% to 150% of the base loading level are generated and applied.

The optimised control performances are shown as PV curves in Fig. 4.12. The

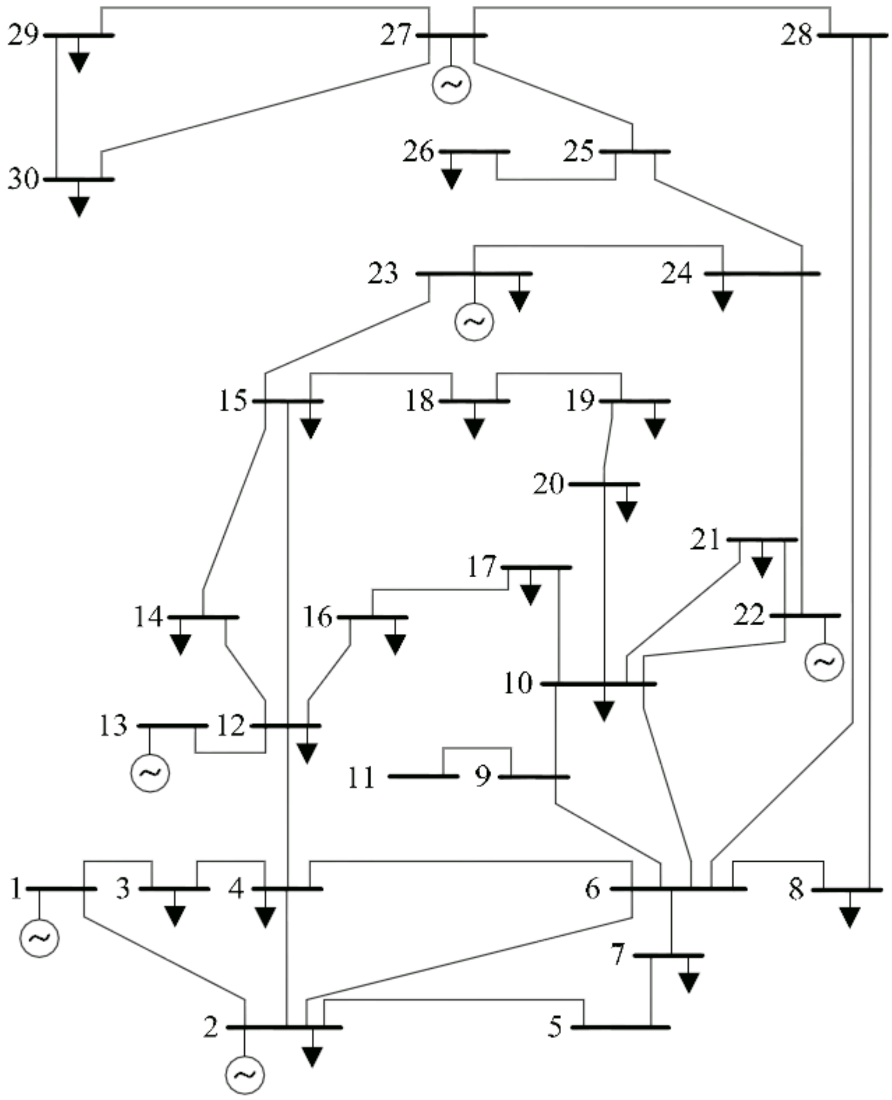

Figure 4.11: IEEE 30 Bus System

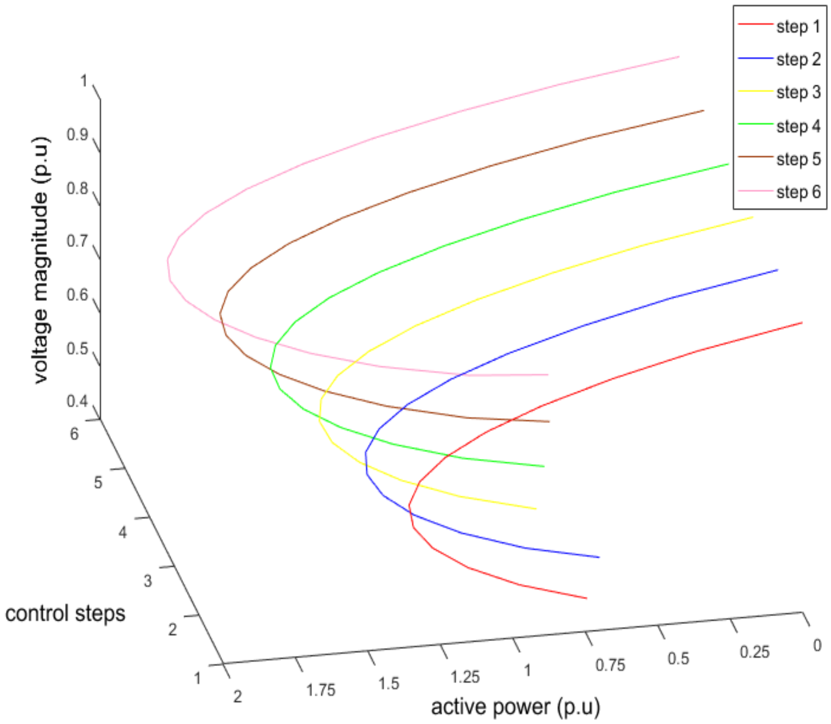

Figure 4.12: L-index Sensitivity Based Control with Various Control Steps

PV curves are plotted in 3-dimension with different control steps. Every control step interval means the pre-defined difference value of L-index need to be decreased. It can be seen that with lower L-index value, the loadability of power system is larger. It is easy to achieve target loadability based on the system requirement by setting a pre-determined L-index value. Moreover, voltage stability can reach the required level with the most sensitive control actions.

In a heavier load condition, where loads ranging from 100% to 150% of the base loading level. By using L-index sensitivity based control algorithm, the PV curves in Fig. 4.13 indicate the loadability of base condition and optimised performance as well as the benefit of the L-index sensitivity based control algorithm. It is worth to know the growth rate of loadability between normal condition and after optimisation, which reaches 5%. The red curve shows the largest loadability at around 2.1 without optimal control. In contrast, blue curve shows that there is a increasing in loadability which nearly reaches 2.3.

In normal load condition, the operation point is not close to the collapse point, so that it is not necessary to always keep the voltage stability at the lowest value.

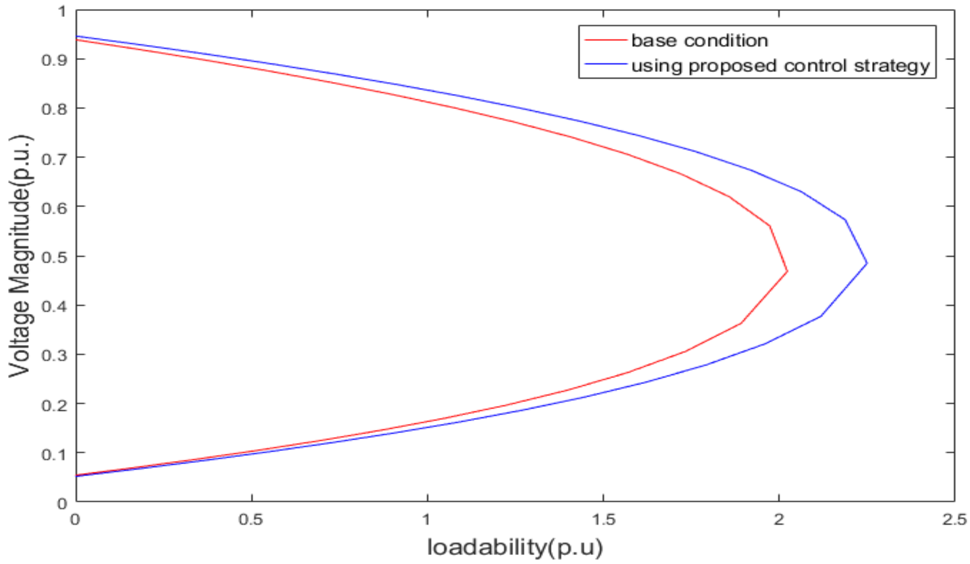

Figure 4.13: PV Curves with Loadability Enhancement

It is possible that voltage stability can be enhanced by using the most sensitive control actions. On the other hand, in a heavy load power system, the operation point is close to collapse point, the voltage stability should be as stable as possible. Hence, overall L-index optimisation is an effective method to keep the operation point away from collapse point. With the subsection control scheme voltage stability enhancement, the voltage stability can always keep safe, also directly control actions can be taken.

In Fig.4.14, three fold lines are obtained by using a set of load and wind generation data at a time. Red line is drawn under normal condition. After optimisation by using L-index sensitivities based control, the new voltage profile is drawn with blue colour. The generators are installed on some buses, hence their voltage magnitude maintains at 1. However, voltages at bus 9 and 30 are below 0.95, which do not reach the requirement in the voltage correction scheme. Hence, control actions should be taken to improve the voltages over 0.95. Compared to the blue line, green line shows that there are slightly improvements in voltages. It can be seen that the voltage level is improved significantly when L-index sensitivities based control with voltage correction method is applied. Due to the heavier load on bus 8, 19 and 30, their voltage magnitudes are relative lower.

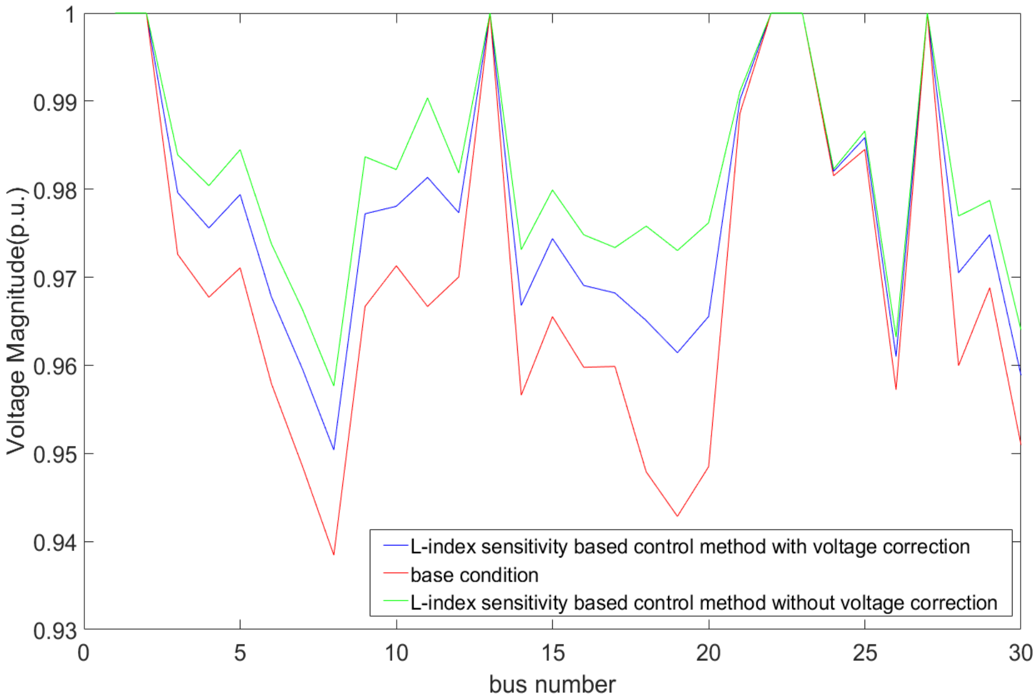

Figure 4.14: Voltages on Buses With Different Control Actions

Due to the selection of the most sensitive control actions on loadability, it can be noticed from Fig. 4.13 that there is a improvement of loadability. Moreover, voltage magnitude requirements are met after the voltage correction control as shown in Fig. 4.14.

80 sets of randomized load data are used in the proposed method to calculate the transmission cost for both approaches. It is assumed that load patterns rang from 100% to 150% of the base loading level. The transmission cost is formulated as

$$P_{loss} = \sum_{k=1}^{N} Resistance_k \cdot I_k^2 \tag{4.2.11}$$

Where N is the number of branches, P_{loss} is power loss, $Resistance_k$ is in $Ohms$ on branch k and I_k is the current on branch k. The cost comparison is shown in Fig. 4.15.

It can be seen that when overall L-index value smaller than 2.3, the total cost of L-index sensitivity based control algorithm is less than the total cost of overall

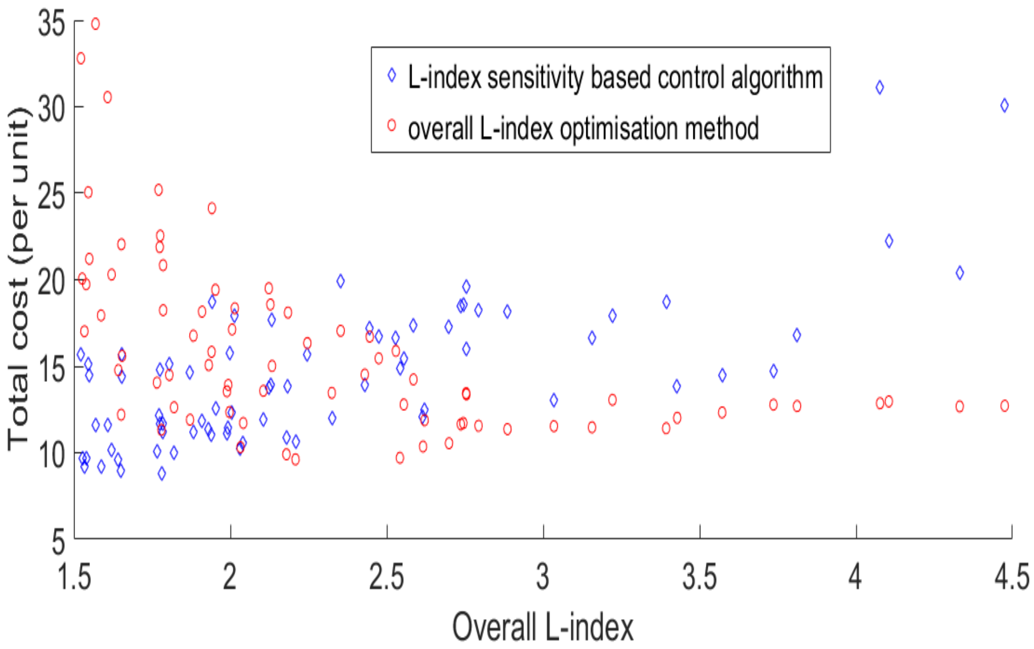

Figure 4.15: Transmission Cost Comparison under Different Load Scenarios

L-index optimisation algorithm. Besides, the total cost of L-index sensitivity based control algorithm is higher than the total cost of overall L-index optimisation algorithm when overall L-index value larger than 2.7. Therefore, 2.5 is a reasonable threshold value.

Real wind generations and loads data are utilized to verify the effectiveness of the proposed method. In Fig. 4.16, 3-Dimension PV curves are given using 10 rounds load and wind generation data. The PV curves are drawn every 10 minutes. Blue lines are normal conditions. After optimisation by using proposed control method, the new PV curves are drawn with red colour. It can be seen that the loadability is enlarged significantly when applied the proposed method.

118 bus system

In this part, ELM is introduced for fast voltage stability identification and implemented in a large power system. The proposed subsection control strategy is applied to a IEEE 118-bus system which is shown in fig 4.17. To produce a stressed system for the case studies, the system is augmented in the following way: The base bus system parameters are from case118.m produced by Matpower. It is assumed that

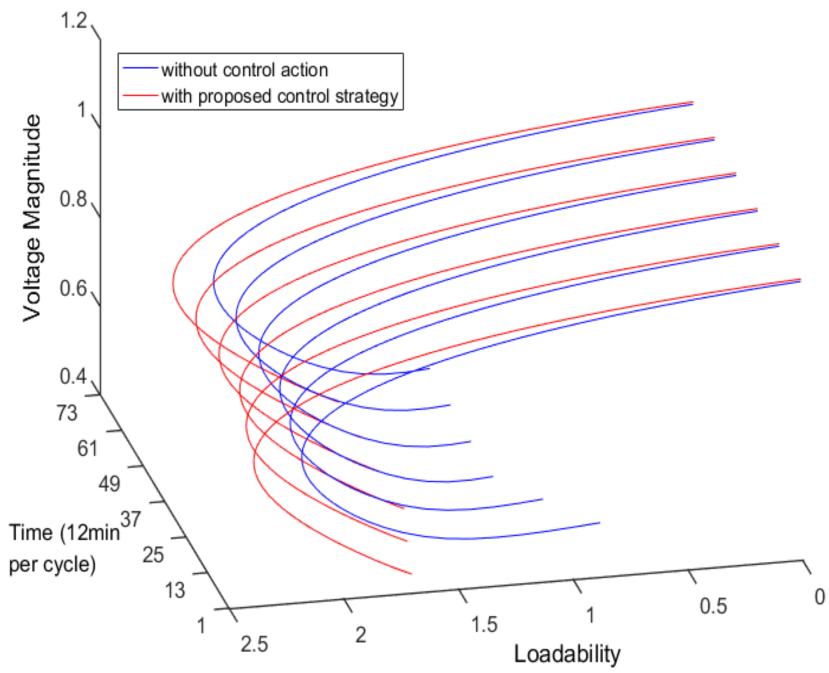

Figure 4.16: PV Curves Comparison Based on Real Data

load patterns rang from 100% to 150% of the base loading level. Three wind farms are connected to bus 1, bus 9, and bus 26, with the rated power 500 MW, 500 MW, and 800 MW, respectively [134].

The process of threshold selection is the same as described in previous simulation. 100 sets of randomized load data are used in the proposed method to calculate the transmission cost for both approaches. Based on the cost comparison, 29.5 is set as the threshold value.

Due to the significant uncertainties of wind generations as well as the large calculated amount in large power systems, the intelligent system strategy is introduced. To train the ELM model, a comprehensive stability database is necessary. In practice, this can be obtained by performing simulations on various scenarios and/or fault recordings. In this chapter, we artificially generate such a database through power flow calculation and proposed control strategy. A total of 700 different operating states covering a variety of different load/generation patterns ranging from 80% to 120% of the base loading level are generated.

Once the model is well trained, it can be applied on-line. As soon as the voltages

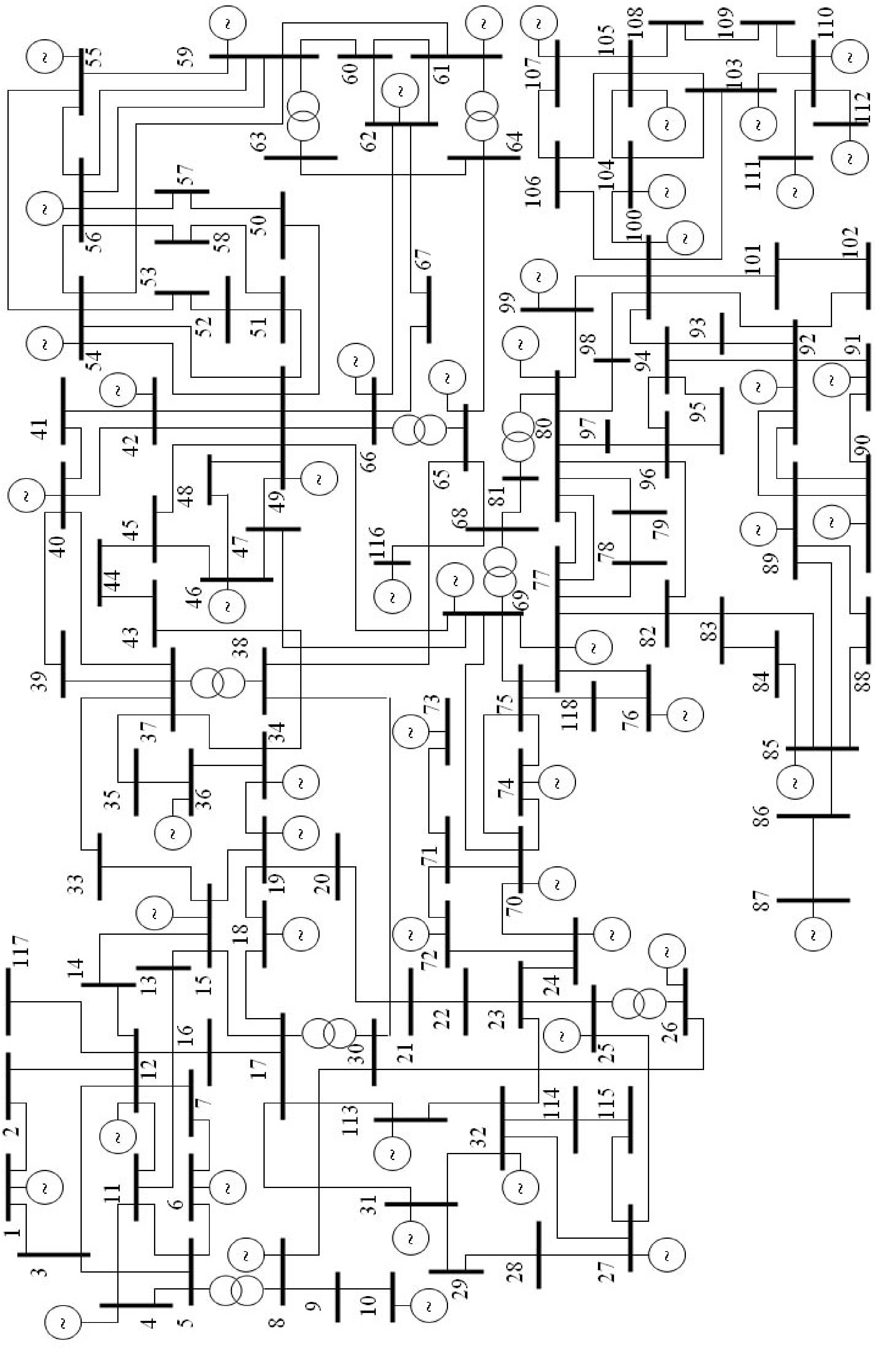

Figure 4.17: IEEE 118 Bus System

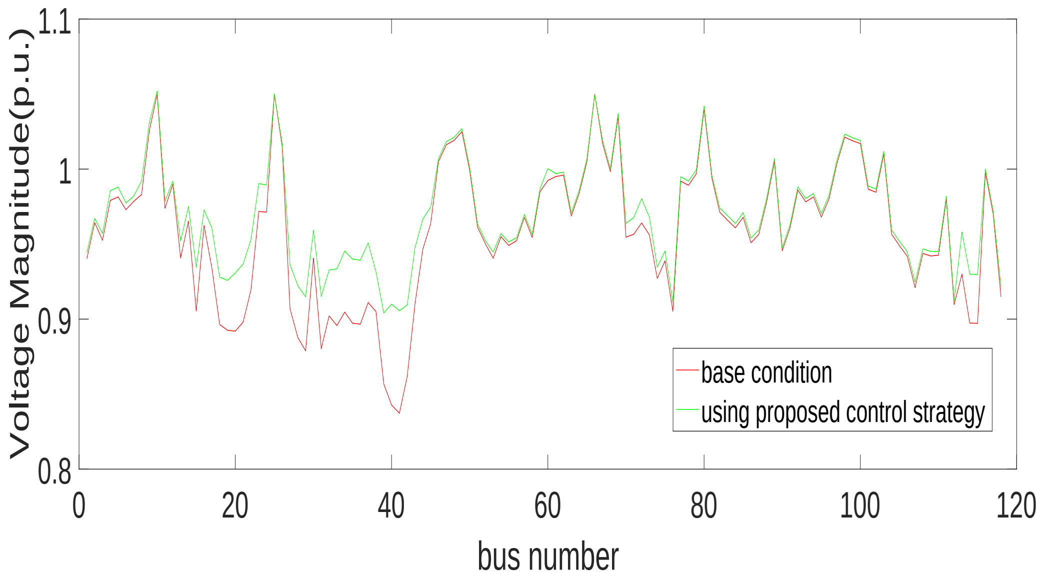

Figure 4.18: Voltage Profiles Enhancement by Using Proposed Control Strategy

are available (e.g., measured by PMUs), the voltage stability can be determined instantaneously. The testing set is used to validate the trained IS model. For fast computation purpose, ELM was tested with randomly generated training and testing data sets. It was trained with 500 sets of real load and wind generation data. 200 sets of data were used for validation. A comparison of classification speed is given in Table 4.1

Table 4.1: Comparison of Classification Speed

Method	Extreme Learning Machine	Direct Classification
Time(s)	45.8	63.7

It is obvious that using intelligent system has great advantage in terms of classification speed. Moreover, ELM has a very high classification accuracy which reaches 95.8%.

Fig.4.18 shows a voltage profile comparison. Two fold lines are obtained based on a given operation point. Both real load and wind generation data are applied in this test. Red line is drawn under normal condition. It can be seen that bus 41 has the lowest voltage magnitude and voltages on a few buses are relative lower, which are lower than 0.9 p.u.. Proper control actions should be taken. After optimisation by using proposed control strategy, the new voltage profile is drawn with blue colour. The main generation are installed on some buses (PV buses), hence their voltage magnitude maintains at 1.05. It is noted that all the buses reach the pre-defined voltage magnitude (0.9). It can be seen that the voltage level is improved significantly when the subsection control algorithm is applied.

4.3 Conclusion

A voltage stability enhancement method based on L-index sensitivities is presented. Both wind generators and compensators are taken into account. It has been proved that it is feasible to enhance the voltage stability with the proposed method, which provides fast computation and self-determined L-index value. The L-index based voltage stability control method is applied in a modified IEEE 14 bus system. The voltage profiles are improved by using the proposed method. One hundred sets of loads and wind generators are used to verify the method. Meanwhile, both maximum and minimum voltage profiles are extracted to indicate its benefits. In addition, the loadability enhancements with different control steps are illustrated by using PV curves. It is worth note that voltage stability can be enhanced with most sensitive control actions.

Additionally, a L-index based subsection voltage stability enhancement method is presented in this chapter, which includes a proposed L-index sensitivities based control method and an overall L-index optimisation method. Threshold is selected based on the transmission cost to determine the proper control algorithm. Under normal conditions, the use of L-index sensitivities is crucial to identify the location of most effective controls. This provides a great advantage to the methodology as it reduces the dimension and complexity of the control search problem. Under weak conditions, minimisation L-index can always keep the operating point away from the collapse point.

Simulation results have shown that the approach can successfully switch reactive power elements in order to enhance voltage stability. Simulation results on the IEEE 30-bus shown the effectiveness of the proposed L-index sensitivity based control method. Also, voltage magnitudes can be improved to reach the desire value. In the simulation of IEEE 118-bus system, ELM is introduced as classifier. The simulation results verified that it can effectively increase the performance over a computational classification. The implementation of additional control variables and tests on larger networks can be studied in the further research.

Chapter 5

Voltage Stability Assessment Using Partial PMU Measurements

As discussed in Chapter 2, the disadvantage of the traditional voltage stability analysis methods are offline and require much time, which means they cannot be used in time sensitive system and also not suitable for power system operation even with high penertration of renewable energy [89]. Thus, PMUs are introduced in the modern power system, which helps the system operators that the voltage stability of a network can be analysed in real-time [135]. And also it able to take control actions to prevent voltage collapse.

In chapter 3 and chapter 4, the proposed voltage stability enhancement methods are using full PMU measurements. However,due to the high cost of PMU installation, it is practically impossible to install PMUs at all buses. Hence, estimation of complete set of bus voltage phasors based on phasors from placed PMUs at certain buses is a feasible way, rather than placing them at all buses of the network. It is target to achieve a full observability of the network with the least number of PMUs. [136]. Therefore, solving the placement of PMU (OPP) problem is crucial that determine the proper buses. Chapter 2 has reviewed different topologies for formulating OPP .

The main idea of the proposed method is, voltage stability assessment method using partial PMU measurements. Eigenvalue or singular value analysis of Jacobian matrix has long been utilized to studied long-term voltage stability in the past research. However, such indices have traditionally disadvantages such as time consuming and dependent on the accuracy of system parameters as well as topology. Therefore, L-index is introduced for voltage stability assessment.

This chapter presents a voltage stability assessment method using partial Phasor measurement unit (PMU) measurements. Firstly, a new optimisation formulation, which minimize the number of PMUs considering the most sensitive buses, is proposed. Next, extreme learning machine (ELM) is used for fast state estimation. In this way, the states at buses without PMUs can be rapidly obtained based on the PMUs measurements. After that, voltage stability can be assessed by using L-index.The full set of measurements is not required. L-index is firstly calculated under the idealized assumption of PMU measurements assumed available at every bus. Then, L-index with full set of measurements is used to verify the effectiveness of the proposed voltage stability assessment method using PMU measurements which are available from a limit subset of buses. The proposed voltage stability assessment method is tested on the IEEE 118 bus test system and the results are presented. The results show that the error of voltage and L-index between method using partial PMU measurements and full PMU measurements. The effectiveness of fast assessment method using partial PMU measurements is verified. The contribution of this Chapter can be seen as follows:

- A PMU placement method for voltage stability considering the most sensitive buses is proposed.

- The voltage stability assessment method can be implemented with limited subsets of PMU measurements.

This chapter is organized as follows. In Section 5.1, network observability analysis is presented. In Section 5.2, two PMU placement methods are introduced and a PMU placement method based on optimal PMU placement method considering the most sensitive buses is proposed. PMU redundancy is discussed in Section 5.3. Section 5.4 shows the proposed methodology for fast voltage stability assessment. Section 5 shows results of optimal PMU placement and verifies the proposed method in IEEE 14 bus systems based on dynamic load and wind generation data. Conclusions are given in Section 6.

5.1 Network Observability Analysis

If both voltage and current are known on a given bus, then the bus can be defined as observable. In this way, fully observable of a network means the buses in this network can be observed through direct and indirect measurements. There are several methods to identify the observability of a system, which can be categorized into: Numerical observability and Topological observability.

In order to analyse the observability of a network, several rules are necessary to be stated before further illustration, they are based on the fundamental circuit theory, such as current and voltage laws. Then the rules can be applied to analyse and identify the observability of the network.

- Rule 1: In case of a PMU is installed at bus A, it's voltages and currents can be directly measured as well as all connected branches. So that bus A is directly observable.

- Rule 2: With the given voltages and currents of branch which is connected to bus A, the voltage bus B on the other connected branch can also be calculated, which makes the bus B observable indirectly. observable.

- Rule 3: In case of voltages of the ends of a branch are provided, current of this branch can be obtained.

For a clearly illustration, a example is given which shows in Fig. 5.1, firstly a PMU is installed at bus 2, the voltage at bus 2 and current are flown through line 8, which can be measured based on the rule 1. So that, bus 2 can be observed directly. Based on the rule 2, Bus 8 can be observed indirectly by using voltage of bus 2 and current of line 8. The same as if bus 4 has a PMU installed, based on the rule 2, buses 1, 5 and 9 can be observed. Based on the rule 3, line 5 current can be calculated. Additionally, a PMU is installed on bus 6, which make buses 3, 5 and 7 can be observed. And line 9 current can be calculated. In this way, with the PMUs on buses 2,4,6, the whole power system can be observed based on the measurements from these three PMU.

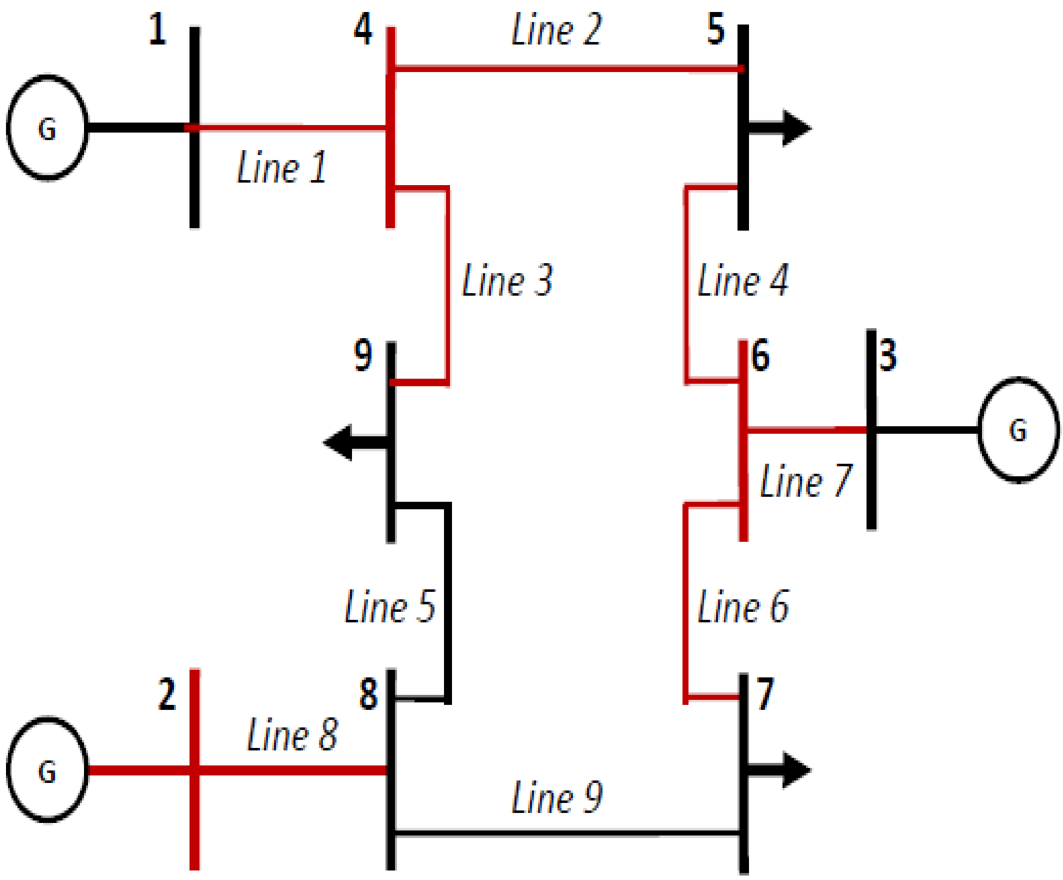

Figure 5.1: 9-Bus Test System

5.2 PMU Placement Method

PMUs will be widely spread in the power system with advanced application. It is the fact that PMUs are able to deliver the data packages with time stamp, which has a great help in voltage stability control in real time. Moreover, with the technology of PMU placement method, the power system can be observed by the limited numbers of PMUs. All the currents and voltages can be obtained from measurements and calculations. Therefore, in order to minimise cost while obtain the full observability, reducing dimensionality of phasor measurement units is the main objective in this chapter.

Due to the increasing size of PMU data and high cost of PMU, how to reduce the number of PMUs becomes a popular research problem. Some researchers studied dimensionality analysis and reduction of PMU data, however, they were considered separately . Dimensionality reduction method is widely used. PCA is able to reduces the dimensionality by preserving the most variance of the original data [137]. It has been attract different research areas such as coherency identification, extraction of fault features, and fault location [138] [139] [140] because of its fast computation feature.

In this chapter, the PMU placment problem is considered through both topological and numerical point of view.

To develop a PMU placement algorithm which can provide full observability and select most sensitive buses, we propose a optimal placement and principal component analysis (PCA) based approach to reducing the dimensionality of PMU numbers.

5.2.1 Optimal PMU Placement Method

[120] applied the topology-based analysis in solving optimal PMU placement problem, as the topology-based analysis only requires parameters of the network, such as branches as well as bus connectivity. The objective optimal placement function is mathematically formulated as

$$obj = min \sum_{i=1}^{D} P_i \tag{5.2.1}$$

$$Subject\ to\ A \cdot f(P) \geq B \tag{5.2.2}$$

where "obj" is objective function and "P_i " is binary PMU position at bus i. It is assumed that the installation cost for each PMU are the same, and hence the objective is only to minimise the PMU numbers. $[A]_{D\times D}$ is a binary connectivity matrix, which is obtained from Y-bus matrix. The elements of A-matrix are evaluated

$$[A_{i,j}]_{D\times D} = \begin{cases} 1, & \text{if } i = j. \\ 1, & \text{if } \textit{bus i and j are connected.} \\ 0, & \text{if } \textit{otherwise.} \end{cases} \tag{5.2.3}$$

$[P]_{1\times D}$ is a binary PMU position array whose elements are as follows:

$$[P]_{1\times D} = \begin{cases} 1, & \text{if } \textit{a PMU is placed at bus i.} \\ 0, & \text{if } \textit{otherwise.} \end{cases} \tag{5.2.4}$$

The constraint in (5.2.2) is defined as network observability. For a complete observable system, the elements of $[B]_{D\times 1}$ are as follows:

$$[B_i]_{D1} \geq [111....111]^T. \tag{5.2.5}$$

It is noted that the optimal PMU placement problem is formulated as a Binary integer Linear programming (BILP) model which is an integer programming model in which each variable can only take on a value of 0 or 1. This represents the no PMU or PMU installed for the certain buses.

Here is an example to achieve complete observability for an 8-bus test system which is shown in Fig. 5.1, the constraints can be formulated as

$$\left\{ \begin{array}{c} f_1 = P_1 + P_4 \geq 1 \\ f_2 = P_2 + P_8 \geq 1 \\ f_3 = P_3 + P_6 \geq 1 \\ f_4 = P_1 + P_4 + P_5 + P_9 \geq 1 \\ f_5 = P_4 + P_5 + P_6 \geq 1 \\ f_6 = P_3 + P_5 + P_6 + P_7 \geq 1 \\ f_7 = P_6 + P_7 + P_8 \geq 1 \\ f_8 = P_2 + P_7 + P_8 + P_9 \geq 1 \\ f_9 = P_4 + P_8 + P_9 \geq 1 \end{array} \right\} \tag{5.2.6}$$

In (5.2.6), "+" is used as a logical operator "OR." (5.2.6) shows that, in order to obtain the observability of to bus 4, at least one PMU should be be installed at any of the buses 1, 4, 5, or 9. In the same way, the second constraint $f_5 = P_4 + P_5 + P_6$

shows that at least one PMU should be installed at any one of the buses 4, 5,or 6, then, bus 4 is observable. By solving the OPP problem, the solution shows that using the minimum number PMUs buses 2, 4, 6 can obtain the full observability of the network .

5.2.2 Dimensionality Reduction Method

Firstly, p is defined as the number of available PMUs in the entire power system, each provides l measurements. For a certain time, there are $N = p \times l$ measurements to be collected. The PMU measurements are always contains the system status, such as voltages and currents. In this chapter, we conduct the dimensionality analysis for voltages. In other words, only voltages are required for voltage stability assessment by using L-index which will be presented in $III - B$. Define the measurement matrix $Y = \begin{bmatrix} y_1 & \cdots & y_N \end{bmatrix}$ containing the N measuremens. Each measurement has n past samples, i.e.,$y_i = \begin{bmatrix} y_i^1 & \cdots & y_i^N \end{bmatrix}$. The PCA-based dimensionality analysis is described as follows.

1) C_Y calculation of the covariance matrix.

2) C_Y calculation of the N eigenvalues and eigenvectors.

3) N eigenvalue sorting in decreasing order, while eigenvectors are defined as the principal components (PCs).

4) The highest m selection within all the PCs.

5) New m-dimensional subspace formulation from the top PCs

5.2.3 Proposed PMU Placement Method

Two PMU placement methods are presented in the previous part. Optimal PMU placement method is formulated as (5.2.1)-(5.2.5). The objective is to minimise the number of PMUs while preserving the system observability. In other words, the solution of the optimal problem will decide the minimal quantity and place of PMU to monitor the whole network. However, the most sensitive buses may not be monitored directly in terms of voltage stability. Therefore, dimensionality reduction method is introduced. PCA is the main linear technique for dimensionality reduction. It performs a linear mapping of the data to a lower-dimensional space in such a way that the variance of the data in the low-dimensional representation is maximized. In this way, the corresponding buses of low dimensional space will be selected as installation buses in addition to the solution of optimal PMU placement method.

The flowchart in Fig 5.2 shows the proposed PMU placement method. The PMU measurements Y are firstly loaded. The covariance matrix C is calculated form the PMU measurement Y. Then calculate N principal component (PCs) and rearrange them in decreasing order based on eigenvalues. Then, highest M eigenvalues are selected among the N eigenvalues. In this paper, the proportion of selected highest m in PCs is set at 10%. A set of bus numbers L can be obtained from the buses which have the highest M eigenvalues. Then, network parameters are read from the system. Both network observability B and selected buses L are defined in the constraint. So that, the proposed optimal PMU placement, considering the most sensitive buses L can be formulated as

$$obj = min \sum_{i=1}^{D} P_i \tag{5.2.7}$$

$$\begin{aligned} &Subject\ to\ A \cdot f(P) \geq B \\ &P_L = [111....111]^T \end{aligned} \tag{5.2.8}$$

where P_L is a binary PMU position array for the selected buses L. P_L in constraint (5.2.8) shows they are set as default buses with PMUs. In other words, L are

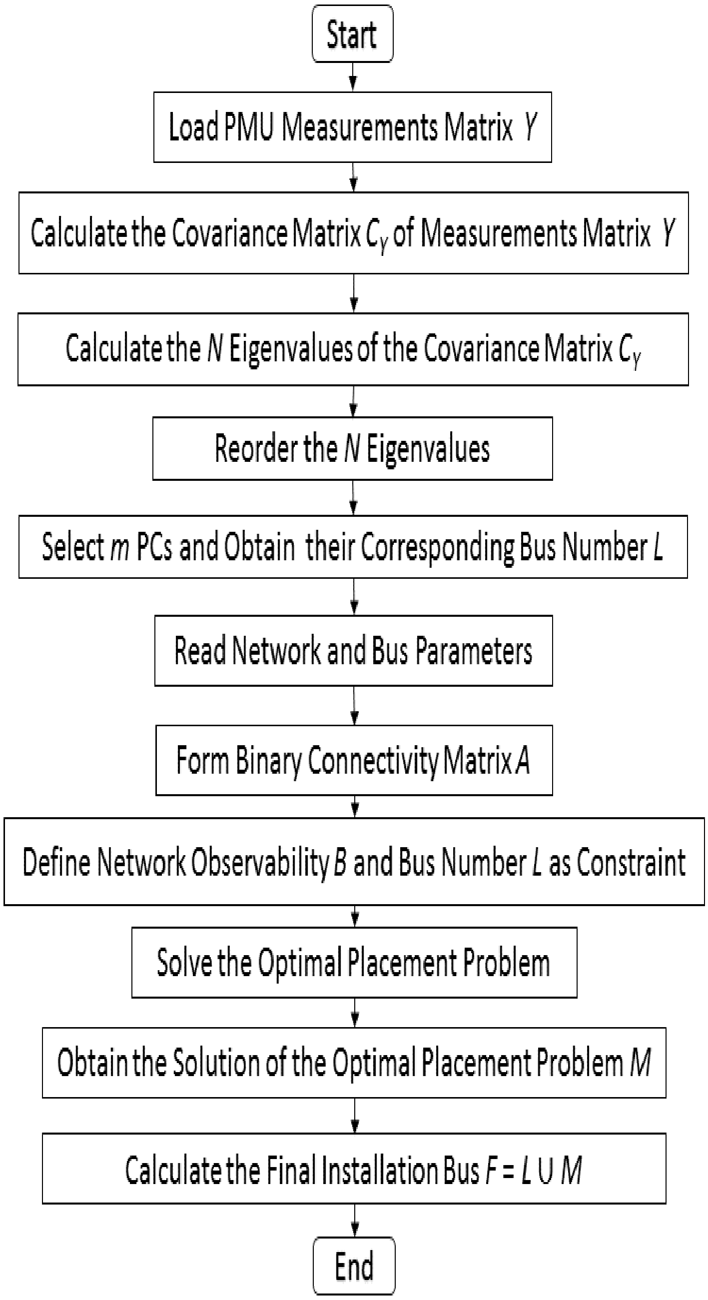

Figure 5.2: PMU Placement Selection Flowchart

the most sensitive bus numbers. Thus, PMUs are installed on those buses. The size of P_L is the number of selected buses, which is set as 10% of total buses. The optimal problem (5.2.7) can be solved with binary connectivity matrix A and network observability B. By solving the optimal problem, a set of bus numbers M can be obtained. Finally, PMU installation bus number set F can be calculated using union of sets L and M. With the PMU placement of well selected buses, the network has full observability while the most sensitive buses are monitored directly.

5.3 PMU Redundancy

The failure of a single or multiple PMUs is considered in this chapter. The proposed method should have redundancy that be able to provide the whole network observability, even with the PMU failures. On the right hand side vector B of (5.2.8) is equal to 1, which means each bus can be observed by at least one PMU. Based on consideration of PMU failures, when the an element in B changed to 2, it means that the certain bus can be observed by at least two PMU. If the vector B in (5.2.8) changed to 2, it means that the every bus can be observed by at least two PMU. In other way, each every bus is allowed to fail, so that the full observability can always be obtained. In this way, it is expect that a higher number PMUs will be obtained by solving the optimisation problem. However, a trade off should be made between the economic and the monitoring reliability. Furthermore, the method can also be extended for the consideration of multiple PMUs failures as well as high monitoring reliability.

5.4 Voltage Stability Assessment

The basic idea in this chapter is to assess the voltage stability by using measurements. Both observability and principle component are considered in optimal PMU placement. L-index is introduced as it is a voltage stability assessment method and only requires voltages at each bus. Therefore, estimation of voltage is the cruical part of this study.

5.4.1 Voltage estimation using PMU data

In this chapter, the proposed algorithm is targeted to assess the voltage stability in real time. The information are assumed available for the buses with installed PMUs, such as voltage magnitudes and phase angles. Based on this assumption, the progress is express as follows. Using PMU measurements to estimate the voltages at buses, where PMUs are not installed. Once the voltage at each bus in the entire network is achieved, the voltage stability can be assessed. However, the traditional method is time consuming. In order to reduce the computation time, the intelligent system (IS) is introduced for status estimation. The whole network conventional measurements are utilized to train the intelligent models as offline manner. Once, the models is well-trained, it can be used for online voltage stability assessment. Compared to the conventional methods, IS has great advantages, such as high computation speed, less required input data and so on. These features make it much more effective and meet the requirements of real time assessment.

Extreme learning machine is introduced, which is a feed-forward neural network for classification. It is reported that they can outperform support vector machines (SVM) and SVM provides suboptimal solutions in classification [131]. ELM model should firstly be well trained. A database is required, which includes loads, voltage magnitudes on every buses, and also the classification results from calculation of the subsection control method. After the model training is complete, it can be applied on-line. This ELM model is intended to be implemented at a central location like a control centre. The voltage magnitudes are obtained from PMUs and send to the control centre, voltage stability will be classified rapidly. Thereafter, one of the control algorithm will be executed. The control actions will be taken once the computation process is complete.

5.4.2 L-index Based Voltage Stability Assessment

L-index in [123] will be used and adopted in this paper for on-line voltage stability enhancement as it is a kind of admittance matrix based method. The elements of admittance matrix are usually readily available. It is not necessary to update admittance matrix until the change of network has been made. Compared to Jacobian matrix based method, e.g. singular value approach, the matrix should be updated at every operating point. In this way, the voltage stability can be identified quickly from a prior known admittance matrix. During the emergency condition, this approach does not need global knowledge or the new admittance matrix of the system. Moreover, it was recommended that the minimum singular value approach could be used for long-term planning and 'off line' operational planning studies in voltage stability [122]. Hence, bus admittance matrix-Based method has better performance in term of computation speed so that it can meet the requirements of power system with rapid change in load. L-index is computed as

$$L_j = \left| 1 - \sum_{i=1}^{g} F_{ji} \frac{V_i}{V_j} \right| \tag{5.4.9}$$

where V indicates the voltages at the bus and subscripts j and i are used to differentiate between load and generator bus numbers. $1, ..., g$ are the generators. F_{ji} in (4) is the element of the F_{lg} matrix which is obtained by admittance matrix calculation. The relationship between voltage and current is stated below,

$$\begin{bmatrix} V_l \\ I_g \end{bmatrix} = \begin{bmatrix} Z_{ll} & F_{lg} \\ K_{gl} & Y_{gg} \end{bmatrix} \begin{bmatrix} I_l \\ V_g \end{bmatrix} \tag{5.4.10}$$

where F_{lg} is computed as $[F_{lg}] = -[Y_{ll}]^{-1}[Y_{lg}]$. Y_{ll} is the self-admittance at the node l and Y_{lg} is the mutual admittances between the nodes l and g.

L-index indicates the level of voltage stability. Its value should be between 0 and 1. When a load bus has no load, L-index value of this load bus is equal to 0. When L-index value is 1, it means voltage stability collapse. Therefore, the lower the L-index value the more stable the voltage stability.

5.4.3 Voltage Stability Assessment Diagram

Extreme learning machine (ELM) is introduced in voltage stability assessment. As a learning algorithm for single-hidden layer feedforward neural network, ELM randomly selects weights and biases for hidden nodes, and analytically determines the output weights by finding least square solution. The ELM-based method not only provides much faster on-line state estimation speed, but also outperforms the conventional methods for its less data requirement thus making it an ideal candidate for future smart grid applications.

By learning from a PMU measurements database, the non-linear relationship between the measurements from PMU installed buses (input) and the parameters of buses without PMUs (output) can be extracted and reformulated in a ELM. During the on-line application phase, the systems stability can be assessed as soon as the input is available.

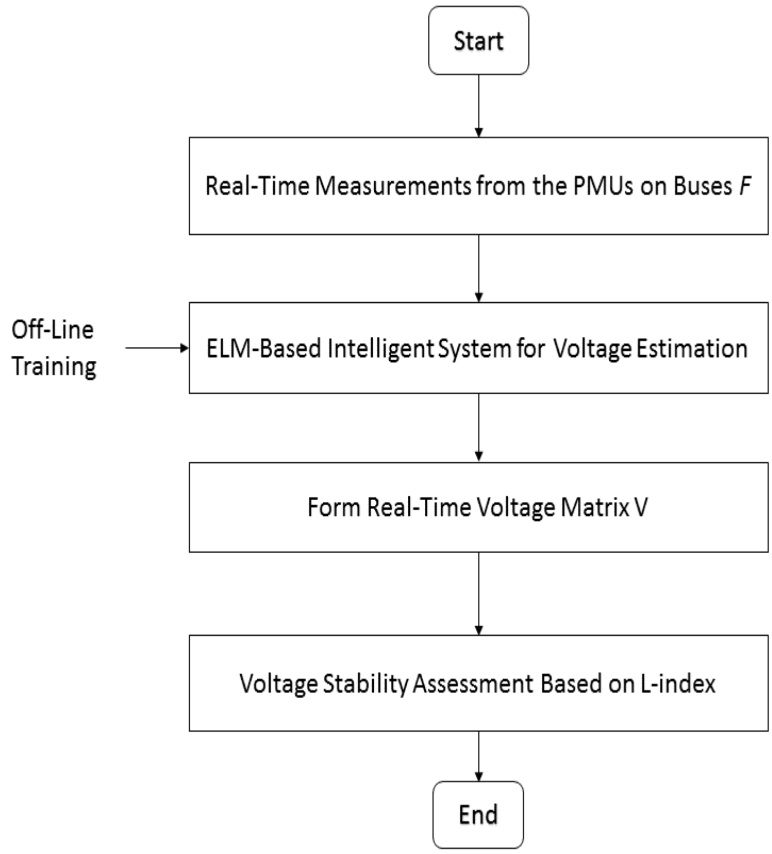

Figure 5.3: Voltage Stability Assessment Diagram

Fig. 5.3 shows the control flow chart based on intelligent system. ELM model should firstly be well trained. A voltage database is required. It can be obtained from power flow results by using Newton-Raphson method based on different load levels. After the model training is complete, it can be applied on-line. This ELM model is intended to be implemented at a central location like a data concentrator.

The voltages are obtained from installed PMUs and send to the concentrator, the voltages of buses without PMUs will be estimated rapidly. In this way, the full voltage matrix V can be formed. Thereafter, a L-index value is obtained from L-index calculation, it indicates the voltage stability at the present operating time.

5.5 Simulation results

In this section, we present case studies of the optimal PMU placement analysis considering PMU redundancy and analysis of the proposed voltage stability assessment method.

5.5.1 Optimal PMU placement Analysis

The PMU placement optimization algorithm is implemented in MATLAB environment. The input of this tool is a "csv" file containing the bus connectivity information of the power system which is depends on the selected test model. There are two columns in the "csv" file, the first column is the "From Bus" information and the second column is "To Bus" information. Case studies are performed on the test 39 bus system (Fig. 5.4), IEEE 57 bus system (Fig. 5.5).

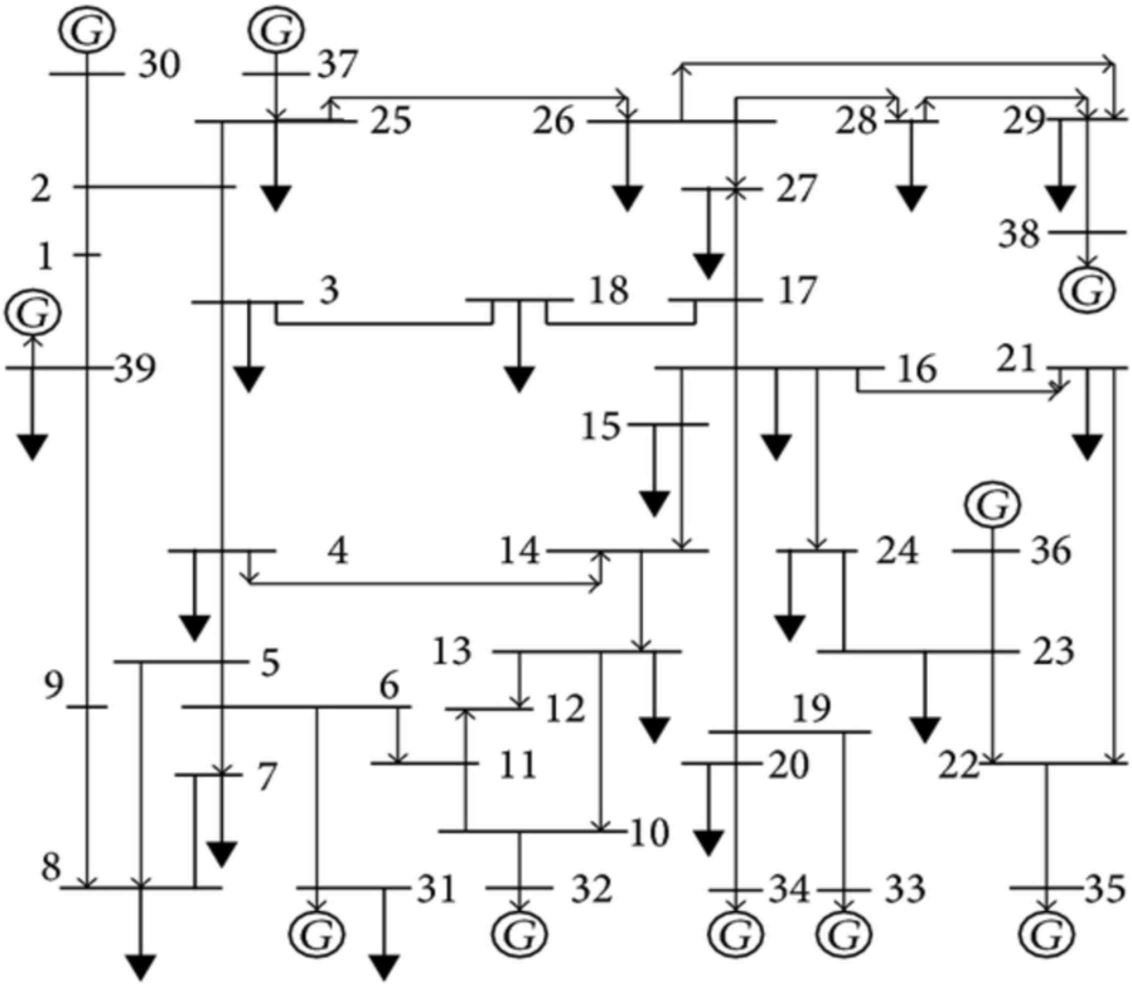

Figure 5.4: IEEE 39 Bus System

IEEE 39 bus system is a 10-machine New-England Power System which contains 19 constant impedance loads totaling 6097.1 MW and 1408.9 MVAr.

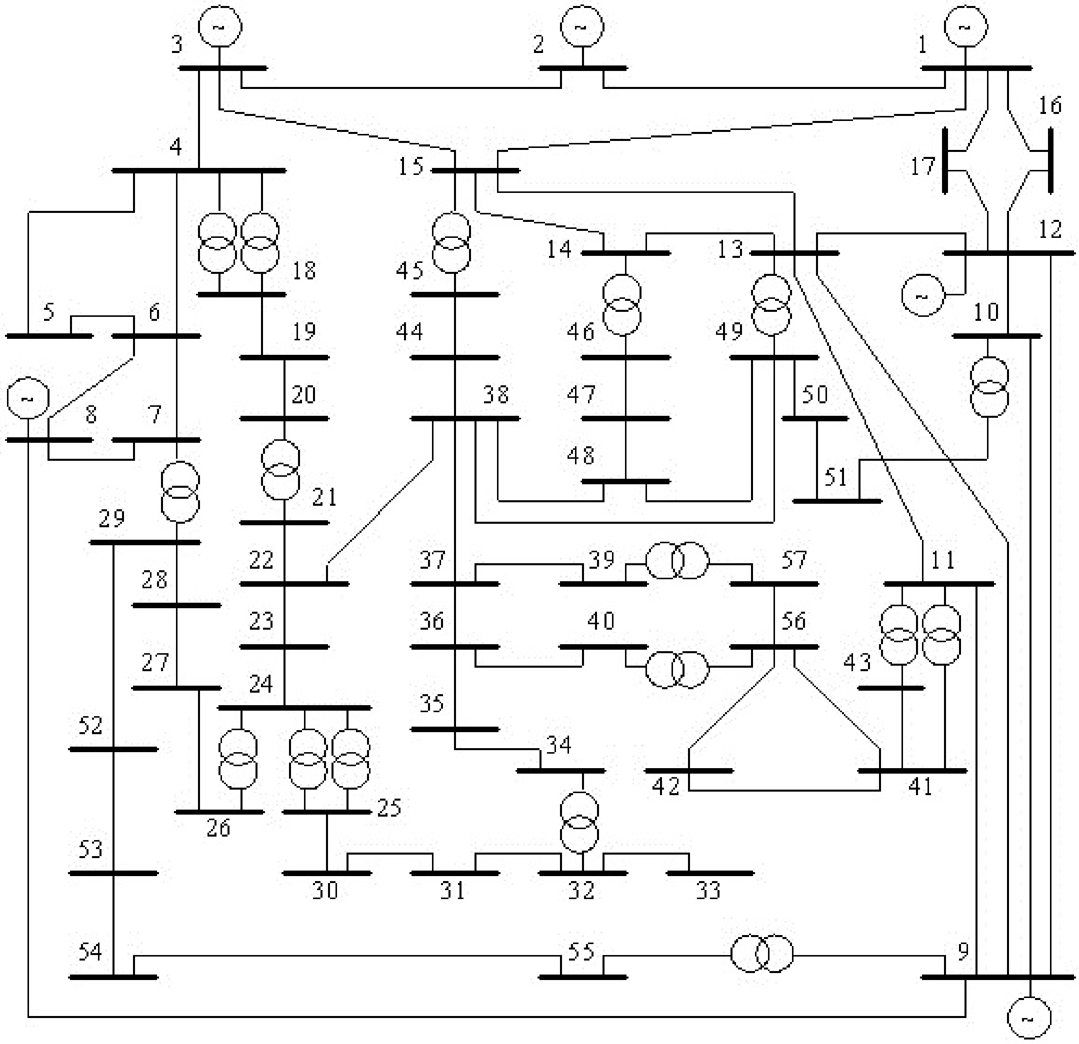

Figure 5.5: IEEE 57 Bus System

The IEEE 57-bus test case represents a simple approximation of the American Electric Power system (in the U.S. Midwest) as it was in the early 1960s. There are 57 buses, 7 generators, and 42 loads in the IEEE 57-bus test case system.

The optimal PMU placement optimal method has been tested with two different IEEE test bus systems while considered both without PMU loss and single PMU loss. In case of there is no PMU loss, the vector B in the constraint (5.2.8) is set to 1, which means each bus can be assuringly observed by at least one PMU. In order to avoid failure of a PMU and cause the network unobservable, the vector B in the constraint (5.2.8) is set to 2, so that each bus can be observed by two PMUs For comparison purpose, placement results for two test systems without PMU loss are shown in Table 5.2. The comparison is performed with the method described in Section 5.2.1 which uses Binary integer linear programming. Even within the same network, different combination of PMU placements are possible at the same minimum number of PMUs, there are differences at the PMU bus locations.

Table 5.1: PMU placements for IEEE test systems without loss

Test System	Number of PMUs	Optimum Locations
IEEE 39 Bus	13	2,6,9,10,13,14,17,19,20,22,23,25,29
IEEE 57 Bus	17	1,4,6,13,20,22,25,27,29,32,36,39, 41,45,47,51,54

As stated before, when considering single PMU loss, the vector B in the constraint (5.2.8) is set to 2. The PMU placements results are shown as follows.

Table 5.2: PMU placements for IEEE test systems with single loss

Test System	Number of PMUs	Optimum Locations
IEEE 39 Bus	29	1,2,4,6,8,9,10,12,13,14,16,17,18,19, 20,22,23,25,26,29,30,31,32,33,34, 35,36,37,38
IEEE 57 Bus	33	1,3,4,6,9,12,15,19,20,22,24,26,28, 29,30,31,32,33,35,36,38,39,41,43, 45,46,47,50,51,53,54,56,57

5.5.2 Proposed Voltage Stability Assessment Method Analysis

In order to verify the proposed voltage stability assessment method, the proposed method is used to compare with full, exact computation of the bus voltages and L-index value, we randomly generate load data in the IEEE 118-bus test systems. For the stressed purpose, a total of 100 different operating states covering a variety of different load patterns ranging from 80% to 150% of the base loading level are generated and applied. To complete each load flow calculation, Matpower [132] was used with MATLAB R2012b on a desktop running Windows 7 64-bit operating system with an Intel i5 3.20-GHz processor. For the comparison studies, full availability of power flow measurement data at every bus was assumed as base condition. Under the assumption, IEEE 118-bus system with heavy load is studied to obtain voltages at every buses and select the most sensitive buses. It is assumed that three wind farms are connected to bus 1, bus 9, and bus 26, with the rated power 500 MW, 500 MW, and 800 MW, respectively [134]

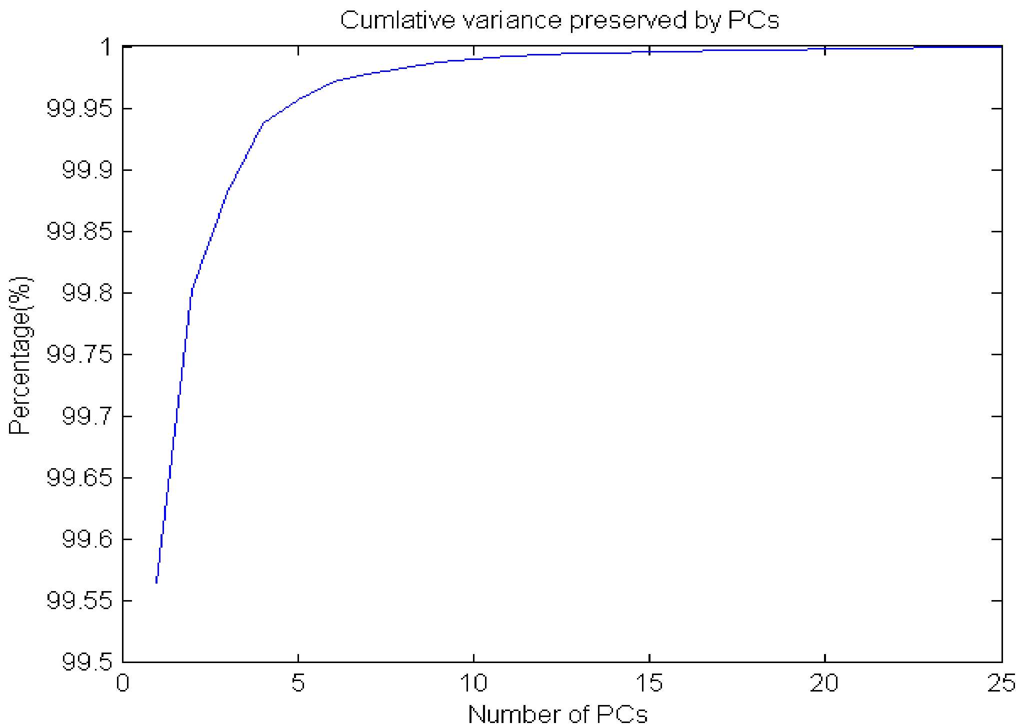

Figure 5.6: Cumulative Variance Preserved by PCs for IEEE 118 Bus System

After the eigenvalues and eigenvectors calculations of the covariance matrix, the eigenvectors (PCs) can be rearrange and sorted based on eigenvalues in decreasing order. Then, the cumulative variance calculated from PCA is shown in Fig 5.6. There are total 25 PCs. The first 10 PCs alone preserve over 99.97% of the variance.

Table 5.3: PMU Locations for IEEE 118-Bus System Only Using OPP Method

Method	Bus Number	Number of PMUs
Only OPP	2,3,5,7,9,10,11,12,15,17, 19,21,22,24,25,26,27,29,31, 32,34,36,37,40,42,44,45,46, 49,52,53,56,57,58,59,62,64, 65,67,68,70;71,73,75, 77,79, 80,84,85,86,87,89,91,92,94, 96,100,102,105,107,109,110, 111,112,115,116,117,118	68

Optimal PMU placement method is firstly applied in IEEE 118-Bus System. The PMUs placed based on the solution of the proposed PMU placement approach. Considering the PMU failures in the power system, therefore, it is necessary to take this into account in practical optimal placement. In this study, the proposed method considered single PMU failure while there is no conventional measurements. The results for PMU locations are shown in Table 5.3. It shows that a total of 68 PMUs are selected to achieve full observability of the system.

Table 5.4: PMU Locations for IEEE 118-Bus System Using Proposed Method

Method	Bus Number	Number of PMUs
Based on PCA	2,3,5,7,102,106,108,109,114,115,117,118	12
Optimal Placement Considering the Most Sensitive Buses	9,10,11,12,15,17,19,21,22,24, 25,26,27,29,31,32,34,36,37,40,42, 44,45,46,49,52,53,56,57,58,59,62,64, 65,67,68,70;71,73,75,77,79,80,84, 85,86,87,89,91,92,94,96,100,105, 107,110,111,112,116	59
Proposed Method	2,3,5,7,9,10,11,12,15,17,19,21,22,24, 25,26,27,29,31,32,34,36,37,40,42,44, 45,46,49,52,53,56,57,58,59,62,64,65, 67,68,70,71,73,75,77,79,80,84,85,86, 87,89,91,92,94,96,100,102,105,106,107, 108,109,110,111,112,114,115,116,117,118	71

Table 5.4 demonstrates results for the proposed method applied in the 118-bus system and shows the places of PMUs using proposed method in steps. Firstly, 12 buses are selected as the most sensitive buses L based on PCA analysis. Then, the proposed PMU placement method formulation (5.2.7) can be solved with constraint (5.2.8). The solution shows 59 PMUs for optimal placement when considering the most sensitive buses. The final result for the proposed method is obtained by union two sets of bus numbers. The total required PMUs is 71. By using the proposed method, the most sensitive buses can be monitored and also the full observability can be achieved. Compared to the results of only using OPP, the proposed method only requires three more PMUs.

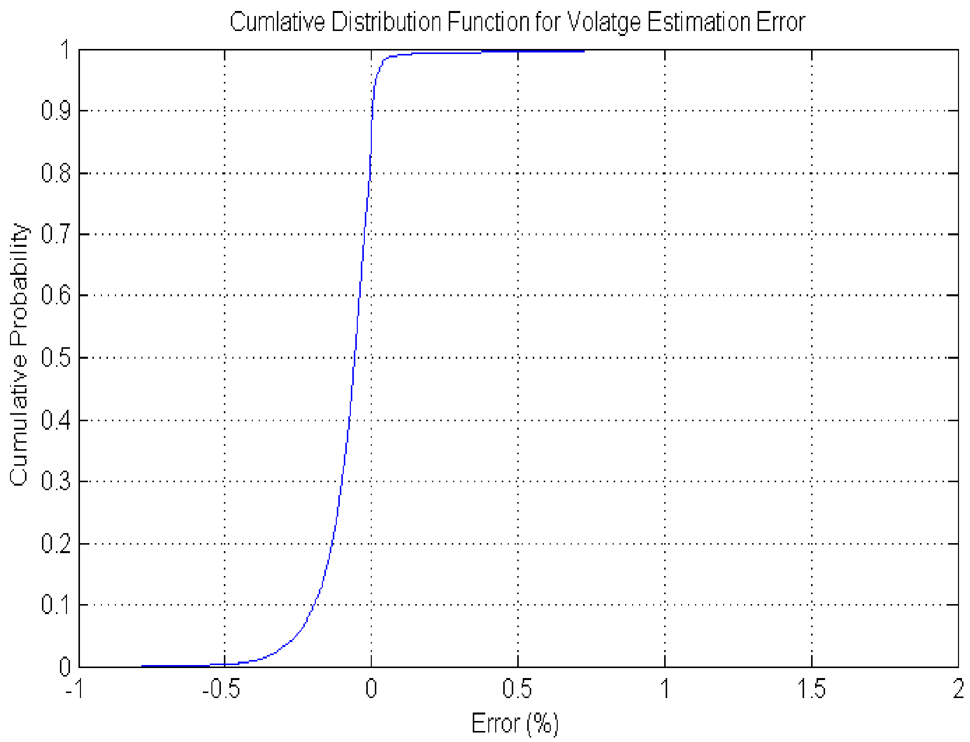

Figure 5.7: Voltage Estimation Error Analysis

Since the PMU locations are selected, a comparison of the network performance between partial PMUs using proposed method and full PMUs is provided. It is initially assumed that PMUs are installed on every buses of the network and the measurements are used as the database. While, based on the selected PMU locations, the non-linear relationship between the measurements from PMU installed buses (input) and the parameters of buses without PMUs (output) can be extracted and reformulated in a ELM. Then, the well trained ELM is applied in the voltage estimation.

Fig 5.7 shows the cumulative distribution function for voltage estimation error. The error is formulated as

$$\varepsilon_{voltage} = \left| \frac{V_p - V_b}{V_b} \right| \cdot 100\% \tag{5.5.11}$$

where V_p is the estimated voltage using trained ELM and V_b is the voltage extracted from database. It shows that the ELM has a high accuracy in voltage estimation, where the error maintains within $\pm 0.5\%$.

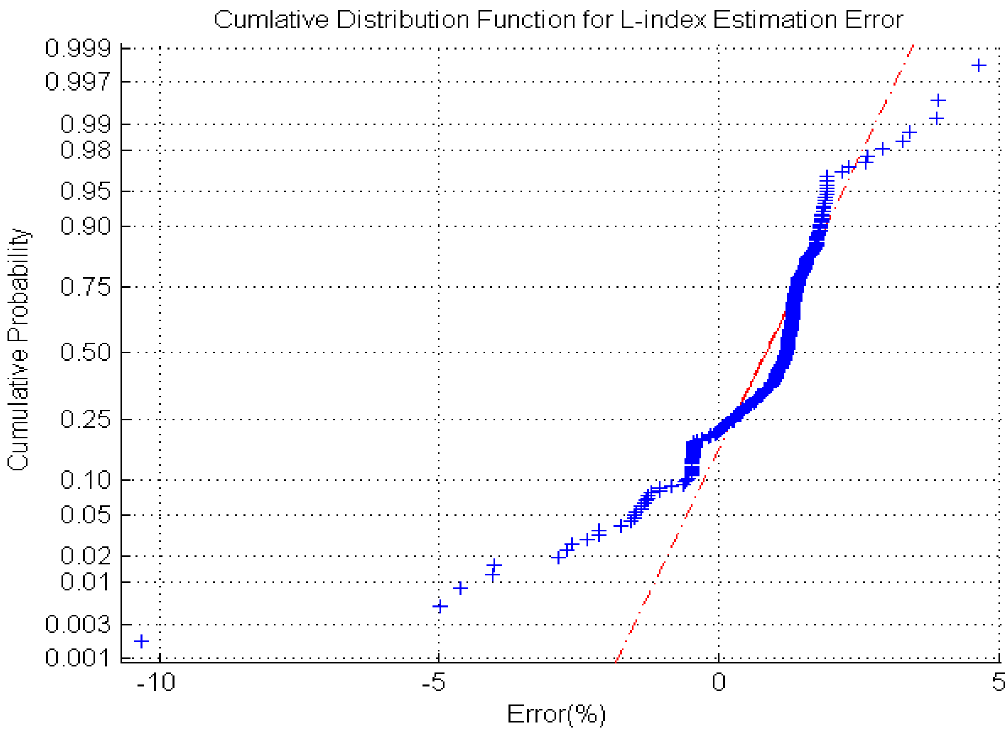

Figure 5.8: L-index Estimation Error Analysis

During the on-line voltage stability assessment. L-index is calculated by using (9) based on the estimated voltages. Fig. 5.8 indicates the cumulative distribution function for L-index estimation error. The error is formulated as

$$\varepsilon_{L-index} = \left| \frac{L_p - L_b}{L_b} \right| \cdot 100\% \qquad (5.5.12)$$

where L_p is the estimated L-index using partial PMUs measurements and estimated voltage and L_b is calculated based on the full PMUs measurements. It can be seen that the error is mainly within ±3%. The error bound is at an accept level, and it verifies the effectiveness of the proposed method.

5.6 Chapter Summary

In this chapter, network observability is presented. Three rules are used to estimate the observability of each bus. A 9 bus system is used as a example. Two PMU placement methods are illustrated and a novel method is proposed based on optimal PMU placement and dimensionality reduction. Then, PMU redundancy is discussed. The constraint B can be set as required in accordance to the consideration of PMU loss. In order to guarantee the observability of each bus via at least one PMU as if the failure of a PMU. Then, a new optimisation formulation is proposed which minimize the number of PMUs considering the most sensitive buses. The full set of measurements is not required. Next, extreme learning machine (ELM) is used for fast state estimation. A ELM model is trained based on a database, which includes loads and voltage magnitudes. After the ELM is well trained, it can be used to estimate voltages, where buses without PMUs, by using measurements from installed PMUs. Thereafter, voltage stability can be assessed by using L-index based on voltage measurement and voltage estimation. As L-index only require voltages at each buses, and also fast computation is one of its characteristics which can meet dynamic requirements.

In the section of Simulation results, we present case studies of the optimal PMU placement analysis in IEEE 39 Bus system and IEEE 57 Bus system considering PMU redundancy. Moreover, the proposed voltage stability assessment method is tested on the IEEE 118 bus test system and the results are presented. The results show that the error of voltage and L-index between method using partial PMU measurements and full PMU measurements. The effectiveness of fast assessment method using partial PMU measurements is verified.

Chapter 6

Discussion and Conclusions

In this chapter, we will summarize the main results which was obtained from previous chapters. There are three aspects, dynamic voltage stability enhancement, voltage stability enhancement considering weak buses with full PMU measurements, voltage stability assessment with partial PMU measurements. Based on the discussions, future works are discussed, which will be helpful to the researches on transient stability .

6.1 General Discussion of Results

6.1.1 Voltage Stability Enhancement in Power System

As demonstrated in Chapter 3, we use both mathematical expression and PV curves to illustrate the relationship between voltage and power. Mathematical expression is based on Jacobian which is obtained from power flow calculation. PV curve is plotted by using continuation power flow. It shows the maximum power can be transferred through the transmission line. Different voltage stability analysis tools are discussed. Two main methods, Jocobian matrix based method and bus admittance matrix based, are compared. Due to the requirements of on-line monitoring and high computation efficiency, L-index is used as voltage stability metric in this study. It is based on impedance matrix and requires less computation time. Lower L-index value means higher voltage stability that more power can be transferred.

The capability of power transfer is also called loadability.

In order to keep voltage away from collapse point, a dynamic voltage stability enhancement method is presented which is based on minimisation of L-index. The L-index based voltage stability control method is verified in the IEEE 14 bus system. Both trust region method and genetic algorithm are implemented and compared. It is proved that it is feasible to enhance the voltage stability with proper coordination control of reactive power output of wind generators and other reactive controllers under dynamic conditions. In addition, using genetic algorithm can achieve lower L-index value than using trust region. However, using genetic algorithm has much more iteration to reach the lowest L-index value that requires more time, this may not meet the requirement of real time operation. Therefore, trust region is used in time domain simulation. The benefits of optimisation based on different wind generation and demand are illustrated. Further, loadability benefits in four seasons are compared. This proposed method can be easily extended to other different power networks where the power system is integrated with wind farms.

6.1.2 A Subsection Control Strategy Based on L-index for Voltage Stability Enhancement Using Full PMU Measurements

As demonstrated in Chapter 4, a voltage stability enhancement method based on L-index sensitivities is presented. Both wind generators and compensators are taken into account. It has been proved that it is feasible to enhance the voltage stability with the proposed method, which provides fast computation and self-determined L-index value. The L-index based voltage stability control method is applied in a modified IEEE 14 bus system. The voltage profiles are improved by using the proposed method. Additionally, one hundred sets of loads and wind generators are used to verify the method. Meanwhile, both maximum and minimum voltage profiles are extracted to indicate its benefits. In addition, the loadability enhancements with different control steps are illustrated by using PV curves. It is worth note that voltage stability can be enhanced with most sensitive control actions. Also, this proposed method can be easily extended to other different networks where the power system contains wind farms and compensators.

Additionally, a L-index based subsection voltage stability enhancement method is presented in this chapter, which includes a proposed L-index sensitivities based control method and an overall L-index optimisation method. Threshold is selected based on the transmission cost to determine the proper control algorithm. Under normal conditions, the use of L-index sensitivities is crucial to identify the location of most effective controls. This provides a great advantage to the methodology as it reduces the dimension and complexity of the control search problem. Under weak conditions, minimisation L-index can always keep the operating point away from the collapse point.

Simulation results have shown that the approach can successfully switch reactive power elements in order to enhance voltage stability. Simulation results on the IEEE 30-bus shown the effectiveness of the proposed L-index sensitivity based control method. Also, voltage magnitudes can be improved to reach the desire value. In the simulation of IEEE 118-bus system, ELM is introduced as classifier. The simulation results verified that it can effectively increase the performance over a computational classification.

6.1.3 Voltage Stability Assessment Using Partial PMU Measurements

It is generally accepted that a number of trends today, from markets to intermittent renewable integration, are causing the operating conditions in electric power networks to become more volatile with respect to time. In this context, there exists a strong need for estimating system stability on fast time scale. The algorithm presented in chapter 5, can be a solution for approximating a voltage stability indicator in near real time, using only measurement information that is becoming widely available through PMUs. This work has presented with the case of partial PMU placement for voltage stability assessment.

In chapter 5, network observability is presented. Three rules are used to estimate the observability of each bus. A 9 bus system is used as a example. Two PMU placement methods are illustrated and a novel method is proposed based on optimal PMU placement and dimensionality reduction. Then, PMU redundancy is discussed. The constraint B can be set as required in accordance to the consideration of PMU loss. In order to guarantee the observability of each bus via at least one PMU as if the failure of a PMU. Then, a new optimisation formulation is proposed which minimize the number of PMUs considering the most sensitive buses.The full set of measurements is not required. Next, extreme learning machine (ELM) is used for fast state estimation. A ELM model is trained based on a database, which includes loads and voltage magnitudes. After the ELM is well trained, it can be used to estimate voltages, where buses without PMUs, by using measurements from installed PMUs. Thereafter, voltage stability can be assessed by using L-index based on voltage measurement and voltage estimation. As L-index only require voltages at each buses, and also fast computation is one of its characteristics which can meet dynamic requirements.

In the section of Simulation results, we present case studies of the optimal PMU placement analysis in IEEE 39 Bus system and IEEE 57 Bus system considering PMU redundancy. Moreover, the proposed voltage stability assessment method is tested on the IEEE 118 bus test system and the results are presented. The results show that the error of voltage and L-index between method using partial PMU measurements and full PMU measurements. The effectiveness of fast assessment method using partial PMU measurements is verified. Also, L-index computation cost is not a limiting factor to apply the method to very large system in real time.

6.2 Future Directions of Research

As summarised in the previous section, the presented works in this thesis gives some potential new research directions in voltage stability research. They are detailed as follows.

6.2.1 Transient Voltage Stability Research

As demonstrated in Chapter 3 and 4, the voltage stability enhancement are proposed for steady state, we can maintain the voltage always away from collapse point, even with heavy load. However, the voltage may becomes unstable or collapse, due to short circuit or other reasons. Thus, the efforts will focus on voltage recovery under transient state. However, it is difficult to analyse transient voltage stability, due to the dynamics of load components are involved, for example, induction motors and HVDC converters Some transient voltage stability analysis have been studied. However, it is hard to compute differential variables of dynamic elements even with multiple samples of PMU measurements. Time-domain simulation method could be an effective way to overcome this problem.

6.2.2 Voltage Stability Enhancement Using Measurements From Installed PMUs

Simple and unordered synchronisation of multiple distributed generation networks may result in voltage distortion and voltage fluctuation which cause the system unstable [141]. The reliability and stability of the normal or a weak power system can be improved by reasonable control strategy. Here, the main objective is coordination control of reactive power output of generators and other compensator considering transient status. The multi agent system will be utilized as the main structure of the desired scheme, where each agent has the computation module of the algorithm.

Chapter 5 presents a framework for voltage stability assessment using Partial PMU Measurements. It is fact that the aim of voltage stability studies is to avoid voltage collapse and recovery from transient, thus assessment and monitoring is the first step. Future work will adapt the control method proposed in Chapter 4 that voltage stability can be enhanced by using partial PMU measurements. Besides, transient status will be taken into account.

6.2.3 PMUs in distrubution system

Nowadays, in the smart grid, PMUs are introduced in distribution system and become necessities for secure operation. Fourier analysis is the dominant method to analysis voltage and current waveforms. The accuracy of any discrete Fourier transform (DFT) based measurement algorithm are affected by spectral leakage [142]. And reporting latency is another problem in any DFT-based algorithm. The existing approaches are shown to be able to meet most or even all requirements for dynamic synchrophasor measurements, as specified in IEEE Standard C37.118-2011, but require longer measurement times [143]. Both of inaccuracy and latency of estimation state will effect the performance of control algorithm. On the other hand, PMUs provide dynamic visibility in the operation of power grid. However, high cost of PMU limits their widespread installation. It is possible to derive the benefits of PMU installation if some of the buses are monitored directly by installation of PMU and some are monitored indirectly, by the PMUs installed on connected buses [144]. In order to meet the requirements of real-time control, it is urgent to improve the performances of the algorithms in PMUs which are implemented in distributed generation network. The performances mainly are the accuracy and comoputation speed of state estimation.

6.2.4 Low voltage ride through (LVRT) performance of grid-connected inverter

The LVRT strategy is to increase the stability of the power system that the DG system stay connected to the network and provide voltage support by injecting a reactive current into the grid. A robust Phase Locked Loop(PLL) method is required for fast and accurate synchronization of the grid voltage. Under the unbalanced grid faults, conventional PLL methods require multiple digital signal processors (DSPs) to reduce the execution time of the algorithms for detect and eliminate any specified harmonic components. Besides, when the unbalanced voltage sags that lead to the phase jump happen, the PLL generates a sudden change in the phase angle. This makes an adverse effect on the current controllers [145]. Low voltage ride through

(LVRT) performance of grid-connected inverter is required to be improved.

6.3 Thesis Conclusion

In this thesis, enhancing dynamic voltage stability in distributed network has been studied. L-index based optimisation approach is a potential method to meet fast computation and on-line requirements. However, always using L-index minimisation programme is not the most economic way to enhance voltage stability as the most stable operation point requires high control efforts. A L-index sensitivities based control method is proposed to determine the most effective control actions under normal condition. While, the overall L-index minimisation method is introduced under weak condition. Higher control efforts help the voltage stability more stable. It has shown its cost efficiency and advantages for voltage stability enhancement. Besides, due to the high cost, the number of PMUs is a problem. Therefore, a voltage stability assessment method using partial PMU measurements is proposed. It is based on the optimal PMU placement while considering the most sensitive buses. The simulation results have shown that the proposed method is able to assess voltage stability in real time.

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