Application and control of energy storage systems in smart grid

Wang, Yu

2016

Wang, Y. (2016). Application and control of energy storage systems in smart grid. Doctoral thesis, Nanyang Technological University, Singapore.

<http://hdl.handle.net/10356/69420>

<https://doi.org/10.32657/10356/69420>

NANYANG
TECHNOLOGICAL
UNIVERSITY

**APPLICATION AND CONTROL OF ENERGY
STORAGE SYSTEMS IN SMART GRID**

WANG YU

**INTERDISCIPLINARY GRADUATE SCHOOL
ENERGY RESEARCH INSTITUTE @ NTU (ERI@N)**

2016

APPLICATION AND CONTROL OF ENERGY STORAGE SYSTEMS IN SMART GRID

WANG YU

**Interdisciplinary Graduate School
Energy Research Institute @ NTU (ERI@N)**

A thesis submitted to the Nanyang Technological
University in partial fulfilment of the requirement for
the degree of
Doctor of Philosophy

2016

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

8/8/2016

.....
Date

Wang Yu

.....
Wang Yu

Abstract

Due to the depletion of traditional fossil fuels and the increase in air pollution and greenhouse gas emissions, the demand on renewable energy in the world will continuously grow. Recently, renewable energy sources and energy storage systems (ESSs) based distributed generation (DG) units have been largely integrated into distribution networks to deal with the problems caused by fossil fuels. Many power conversion methods and the corresponding control strategies have been proposed and investigated for the integration of DG units in conventional power systems. Therefore, it is necessary to improve the current techniques and develop new control and management techniques for the integration of various sources based DG units into utility grid or microgrids for better utilization efficiency. This thesis presents several control schemes for application of ESSs in existing power systems.

For distribution networks with high penetration of photovoltaics (PVs) and electric vehicles (EVs), the distribution networks may encounter voltage rise/drop issues during peak generation/load period. First, distributed ESSs are proposed to solve the voltage rise/drop issues in distribution networks through a coordinated control method. The coordinated control method is achieved by both distributed and localized controls of multiple ESSs. The distributed control using consensus algorithm regulates the feeder voltages within the required limits, while the localized control regulates the real-time state of charge (SoC) of each ESS within the desired SoC range. The entire control structure ensures voltage regulation while effective utilization of storage capacity during daily operation under different weather conditions.

Then, the first research work is extended that distributed electric vehicle chargers (EVCs) are applied to deal with the voltage rise/drop issues in distribution networks.

With the concept of vehicle-to-grid (V2G), plug-in EVs at EVCs can be served as energy storage devices and utilized for voltage regulation. Therefore, a two-stage coordination method of distributed EVCs is proposed to regulate the voltages in distribution networks. In the stage one, the distributed voltage control is proposed to coordinate each EVC for voltage regulation. In the stage two, algorithms for estimating the V2G capacity of the plug-in EVs and determining the real and reactive power outputs of EVCs are proposed, so that the voltage regulation is achieved within the required operation limits. The entire control structure ensures that the voltages along the distribution feeders are within the allowable voltage range through coordinated control of the power output of each EVC during daily operation.

Finally, the application of distributed ESSs in an islanded ac microgrid is investigated. In order to achieve power balancing and SoC management of the microgrid, a hierarchical control scheme is proposed to coordinate all available PVs, ESSs and loads in the system. The primary control is realized by a novel model predictive control, which provides fast dynamic response and small steady-state error for power inverters in the microgrid. The secondary control is performed by consensus based distributed control, which provides distributed control signals for primary controlled inverters and loads at each agent. With the proposed control scheme, the power balancing and SoC management can be achieved by managing the power output of each available unit in a hierarchical way. The proposed methodologies and control algorithms throughout the research is verified in MATLAB/Simulink under various system topologies and different types of PV and load data.

Acknowledgements

This thesis would not have been possible without the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this study.

First, I wish to express my utmost gratitude to my supervisor, Associate Professor So Ping Lam, for his continuous insight, enthusiasm and encouragement throughout the whole research program. His deep knowledge on electric power systems, power quality and smart grids has been very valuable for my research. He has always been my inspiration and role model as I hurdle all the obstacles in the completion of this research program. I would also like to sincerely thank Associate Professor Chan Chi Chui Julian. His professional attitude and support deserve special acknowledgment. I am deeply impressed by their serious attitude and enthusiasm towards academic research which will have positive effect on my future research and work.

Then, I would like to thank Tan Kuan Tak, Peng Xiaoyang, Thomas John and Wang Benfei, who are my fellows. Tan Kuan Tak helps me a lot during my PhD studies. As a senior student, he generously shares his experience on research and makes a good example of a PhD student for me. Moreover, he patiently participates in writing and revision of my papers. Peng Xiaoyang provides me assistance in learning and understanding some control theories and operation principles of microgrids. Thomas John works with me on the model predictive control of power inverters in microgrids. Wang Benfei gives me many useful suggestions and comments during my PhD study. I would also like to thank my group members for the in-depth and fruitful discussions on the research work. They are Ravi Kishore, Nandha Kumar, Sivaneasan Balakrishnan and Wang Zhe.

Furthermore, I am grateful to Nanyang Technological University for providing me an opportunity to pursue my graduate study with a research scholarship. I am also thankful for the technical support provided by the laboratory staff Chia-Nge Tak Heng, Lin Zhi Ren and Foo Mong Keow, Thomas in Clean Energy Research Laboratory. They generously offer their help during my study in the laboratory. It is their careful administration that makes the laboratory a comfortable and convenient place for research.

Last but not least, I want to present my deepest appreciation to my family. Their endless love and persistent encouragement are the most greatly sources of motivation.

Table of Contents

Abstract	i
Acknowledgements	iii
Table of Contents	v
Table Captions	ix
Figure Captions	xi
Abbreviations	xv
 Chapter 1 Introduction	 1
1.1 Background and Motivations	2
1.1.1 Background	2
1.1.2 Motivations	6
1.2 Objectives and Scope	7
1.3 Contributions of Thesis	9
1.4 Organization of Thesis	12
References.....	14
 Chapter 2 Literature Review	 19
2.1 Energy Storage Systems.....	20
2.1.1 Comparison of Energy Storage Technologies.....	20
2.1.2 Energy Storage for Utility Grid	24
2.1.3 Energy Storage for Transportation.....	28

2.2	Voltage Regulation Methods in Distribution Networks	31
2.3	Control Hierarchy of Power Systems.....	36
2.3.1	Primary Control	37
2.3.2	Secondary Control	40
2.3.3	Tertiary Control	44
2.4	Consensus Algorithm	45
2.5	Summary	45
	References.....	50

Chapter 3 Coordinated Control of Distributed Energy Storage Systems for Voltage Regulation in Distribution Networks

		63
3.1	Introduction	64
3.2	Problem Description and Analysis	64
3.3	Proposed Control Method	67
3.3.1	Vanadium Redox Battery	68
3.3.2	Distributed Control Method.....	70
3.3.3	Localized Control Method	73
3.4	Results and Discussions	76
3.4.1	Case Study: 6-Bus Distribution Feeder.....	76
3.4.2	Case Study: 13-Bus Distribution Network	87
3.5	Conclusion.....	91
	References.....	92

Chapter 4 Two-stage Coordination of Distributed Electrical Vehicle Chargers for Voltage Regulation in Distribution Networks.....

		95
4.1	Introduction	96
4.2	Modeling and Assumptions.....	97
4.2.1	Lithium-ion Battery Model	97

4.2.2	Assumptions.....	99
4.3	Proposed Voltage Regulation Method	100
4.3.1	Stage One: Distributed Voltage Control	101
4.3.2	Stage Two: Localized Power Allocator.....	104
4.4	Results and Discussions	107
4.4.1	Test Case 1: Sunny PV and Light Load Condition	110
4.4.2	Test Case 2: Cloudy PV and Heavy Load Condition	114
4.5	Conclusion.....	118
	References.....	119

Chapter 5 Hierarchical Control and Power Management of Islanded Microgrids with Energy Storage Systems and Renewable Energy Sources..

5.1	Introduction	122
5.2	System Description	122
5.2.1	System Configuration	122
5.2.2	Structure and Control Scheme of ESS/PV.....	124
5.3	Model Predictive Control of Voltage Source Inverters.....	125
5.3.1	Modeling of Voltage Source Inverters	125
5.3.2	Proposed Primary Model Predictive Control.....	127
5.4	Consensus Based Distributed Control.....	129
5.4.1	Communication Network and Consensus Algorithm	129
5.4.2	Proposed Secondary Distributed Control.....	131
5.4.3	Distributed Signal Allocation.....	132
5.5	Results and Discussions	135
5.5.1	Test Case 1: Short-Term PV Generation and Load Demand Variation..	136
5.5.2	Test Case 2: Long-Term Power Imbalance and PV Curtailment	139
5.5.3	Test Case 3: Long-Term Power Imbalance and Load Shedding.....	142
5.6	Conclusion.....	144

References	145
Chapter 6 Conclusions and Future Work	147
6.1 Conclusions	148
6.2 Future Work.....	151
List of Publications	155

Table Captions

Table 2.1	Characteristics of energy storage technologies [3].....	22
Table 2.2	Charging power levels of EVCs [35]	29
Table 2.3	Comparison of typical voltage regulation methods	33
Table 3.1	Parameters of the VRB based ESS	69
Table 3.2	Parameters of the proposed control method.....	76
Table 3.3	Parameters of the simulation system.....	77
Table 4.1	Data fitting results of the lithium-ion battery.....	98
Table 4.2	Parameters of the simulation system.....	108
Table 4.3	Usage data of distributed EVCs.....	109
Table 5.1	Parameters of the simulation system.....	135
Table 5.2	Parameters of the proposed control scheme.....	136

Figure Captions

Figure 1.1	Renewable generation capacities in World, EU-28, BRICS and top seven countries at the end of 2015 [9].	3
Figure 1.2	Classification of electrical energy storage technologies according to energy form [17].	4
Figure 2.1	Different energy storage technologies for grid application [15].	24
Figure 2.2	Control hierarchy of power electronic interfaced power system.	37
Figure 2.3	Control architecture of centralized and distributed secondary control.	41
Figure 3.1	A typical radial distribution feeder with multiple buses.	64
Figure 3.2	Voltage magnitudes along radial distribution feeder. (a) Voltage rise. (b) Voltage drop.	66
Figure 3.3	The structure of proposed control method for customer at i th bus. ..	68
Figure 3.4	The OCV/SoC characteristic curve of a single VRB cell.	69
Figure 3.5	The control scheme of the proposed distributed control.	70
Figure 3.6	Communication graph for N -bus radial distribution feeder.	72
Figure 3.7	Single line diagram of the 6-bus test feeder.	77
Figure 3.8	Influence on feeder voltages of bus number and power injection. ..	77
Figure 3.9	PV generation, residential load demand and ESS power for test case 1.	79
Figure 3.10	Power injection with/without ESSs for test case 1.	79
Figure 3.11	24-h voltage profiles without ESSs for a sunny day.	80
Figure 3.12	24-h voltage profiles with ESSs and proposed method for a sunny day.	80
Figure 3.13	SoC profiles for test case 1.	81
Figure 3.14	PV generation and residential load demand for test case 2.	82
Figure 3.15	24-h voltage profiles without ESSs for a cloudy day.	83

Figure 3.16	24-h voltage profiles with ESSs and proposed method for a cloudy day.....	83
Figure 3.17	Power outputs of ESSs for test case 2.....	84
Figure 3.18	SoC profiles of ESSs for test case 2.....	85
Figure 3.19	Voltage profiles with droop based method.....	86
Figure 3.20	Power curtailed with constant droop based method.	87
Figure 3.21	Configuration of the 13-bus residential distribution network.....	88
Figure 3.22	Communication graph for the 13-bus distribution feeder.....	88
Figure 3.23	24-hr voltage profiles without ESSs.	89
Figure 3.24	24-hr voltage profiles with ESSs and proposed method.....	89
Figure 3.25	Power outputs of ESSs 4, 7, 10 and 12.....	90
Figure 3.26	SoC profiles of ESSs 4, 7, 10 and 12.....	90
Figure 4.1	The equivalent circuit model of the lithium-ion battery.....	98
Figure 4.2	The charging characteristic of the lithium-ion battery.	99
Figure 4.3	The discharging characteristic of the lithium-ion battery.	99
Figure 4.4	Entire control structure of the proposed voltage regulation method. 101	
Figure 4.5	Configuration of the 17-bus residential distribution network.....	108
Figure 4.6	PV generation and load profiles for simulation study.....	109
Figure 4.7	Voltage profiles with uncoordinated EV charging for test case 1. .	111
Figure 4.8	Voltage profiles with the proposed method for test case 1.....	111
Figure 4.9	Real and reactive power absorption and SoC profile of each EVC for test case 1.....	112
Figure 4.10	Voltage profiles with uncoordinated EV charging for test case 2...	115
Figure 4.11	Voltage profiles with the proposed method for test case 2.	115
Figure 4.12	Real and reactive power absorption and SoC profile of each EVC for test case 2.....	116
Figure 5.1	The configuration of an ac microgrid with communication	

	agents.....	123
Figure 5.2	Structure and hierarchical control scheme of each ESS/PV unit. ...	124
Figure 5.3	Proposed model predictive controller for primary control.	128
Figure 5.4	Thresholds of load shedding and load recovering.	134
Figure 5.5	Events of the simulation for test case 1.	137
Figure 5.6	Real power outputs of ESSs for test case 1.....	137
Figure 5.7	Real power outputs of PVs for test case 1.	137
Figure 5.8	SoC profiles for test case 1.	138
Figure 5.9	Control objective of the leader for test case 1.....	138
Figure 5.10	Real power outputs of ESSs for test case 2.....	140
Figure 5.11	Real power outputs of PVs for test case 2.	140
Figure 5.12	SoC profiles for test case 2.	141
Figure 5.13	Power reference changes for test case 2.	141
Figure 5.14	Real power outputs of ESSs for test case 3.....	143
Figure 5.15	Real power outputs of PVs for test case 3.	143
Figure 5.16	SoC profiles for test case 3.	143

Abbreviations

AC	Alternating Current
CAES	Compressed Air Energy Storage
CB	Circuit Breaker
CCM	Current Control Mode
DC	Direct Current
DER	Distributed Energy Resource
DG	Distributed Generation
EDLC	Electrochemical Double Layer Capacitor
EPRI	Electric Power Research Institute
ESS	Energy Storage System
EU	European Union
G2V	Grid-to-Vehicle
LV	Low-Voltage
MAS	Multi-Agent System
MPC	Model Predictive Control
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
NTU	Nanyang Technological University
OLTC	On-Load Tap Changer
OPF	Optimal Power Flow
PHES	Pumped Hydro Energy Storage
PI	Proportional-Integral
PQ	Power Quality
PR	Proportional- Resonant
PU	Per Unit
PV	Photovoltaic

RES	Renewable Energy Source
SM	Smart Meter
SOC	State of Charge
SOD	State of Discharge
TOU	Time-of-Use
UPS	Uninterruptible Power Supply
US	United States
V2G	Vehicle-to-Grid
VCM	Voltage Control Mode
VRB	Vanadium Redox Battery
VSI	Voltage Source Inverter
WT	Wind Turbine

Chapter 1

Introduction

This chapter presents the background of this research work, which includes the developments, advantages and challenges of energy storage for smart grid applications. Motivated by reducing the carbon emissions, air pollution and the demand of fossil fuels, renewable energy sources together with energy storage systems have been largely penetrated into existing power systems. This thesis aims to design effective control methods for better utilization of energy storage systems in distribution networks or microgrids with high renewable penetrations. Besides, the research contributions and organization of the thesis are also presented.

1.1 Background and Motivations

1.1.1 Background

Nowadays, the dependence on traditional fossil fuels such as coal and oil has been and will continue to be a major concern of climate change and air pollution globally. These environmental problems and diminishing supply of fossil fuels accelerate the development of renewable energy technologies [1]-[3]. Therefore, more and more renewable energy sources (RESs) and energy storage systems (ESSs) have been penetrated into existing distribution networks or microgrids through power electronics interface. The energy production becomes more and more decentralized other than conventional centralized generation. This type of power generation is termed as distributed generation (DG) and is becoming an increasingly popular solution for the future green energy development. In the meantime, efficient and reliable communications and advanced control technologies, together with increasing application of smarter electrical facilities, such as storage batteries, electric vehicles (EVs) and smart meters, have resulted in a new power grid, also named smart grid. The smart grid controls the behaviors of electrical devices based on the information gathered from suppliers to consumers, which will greatly increase efficiency, reliability, power quality and economics of the system. Consequently, the entire power system will benefit from these new developments and become more intelligent, interactive and flexible [4]-[7].

Figure 1.1 Renewable generation capacities in World, EU-28, BRICS and top seven countries at the end of 2015 [9].

In the last decade, renewable energy markets are continuing to grow rapidly and at least 30 nations all over the world already have renewable energy contributing more than 20 percent of total energy supply [8]. According to REN21's 2016 report, renewable energy has reached 23.7% worldwide electricity generation in 2015 [9]. The renewable generation capacities of several large countries and groups at the end of 2015 are shown in Figure 1.1. Among all the renewable energy generation, solar panels and wind turbines are the most widely used, since they are clean, infinite, scalable and cost-effective [10], [11]. However, photovoltaic (PV) generation keeps fluctuating due to the daily solar irradiance changes, and wind generation is affected largely by the seasonal variation of wind at the installed location [12], [13]. PV and wind generation cannot guarantee constant power supply due to their stochastic and intermittent characteristics, which will influence the stability, reliability and power quality of power systems [14], [15].

Energy storage is a relative new phenomena following in the wake of increased installation of renewable energy generation in the 21st century. As various problems caused by the penetration of solar panels and wind turbines generation become more common, energy storage is considered as one promising solution to deal with them [16]. For all kinds of energy storage technologies, there are two modes of operation, which are charging mode and discharging mode. Different kinds of energy storage technologies transform different forms of energy to electricity and vice versa. A widely used approach for classification of energy storage technologies is according to the form of energy used. Electrical energy storage technologies can be categorized by the form of storing energy into five groups: mechanical, electrochemical, chemical, electrical and thermal energy storage [17]. The electrical energy storage devices belonging to each classification are shown in Figure 1.2.

Figure 1.2 Classification of electrical energy storage technologies according to energy form [17].

Large investments have been placed on research and application of energy storage technologies in countries such as Germany, the United States (U.S.) and China where the installation of renewable energy generation has progressed fast over the last few years [18], [19]. Energy storage systems including batteries, ultra-capacitors, flywheels, etc. have been widely utilized for both grid-connected power systems and off-grid renewable generation in remote areas. For grid-connected application, ESSs are of great importance since they can cope with the intermittency and power variation caused by RESs in power systems, which increase system stability and reliability significantly [20], [21]. Furthermore, the incorporation of ESSs are also critical for improving the power quality and voltage profiles of distribution networks, and performing various demand side management functions such as peak shaving and load shifting [22]-[24]. While for off-grid application, ESSs play the key role to balance the renewable generation and load consumption instantaneously in order to keep the frequency and voltage of the islanded microgrid stable [25].

Another important aspect related to the adoption of energy storage technologies is transportation electrification, which is an effective way to substantially reduce the carbon emissions and air pollution [26]-[28]. In the last decade, EVs have been receiving widespread attention because of their green and economic features. Therefore, for the sake of environmental protection and reduction of reliance on fossil fuels, governments of many countries such as U.S., European Union, China and Japan significantly invest in this field and promulgate corresponding policy for the development of EVs [29], [30]. Based on moderate expectations, by 2020 up to 35% of the total vehicles in the U.S. will be EVs according to the Electric Power Research Institute (EPRI) [31]. Plug-in EVs can be connected to power grid through electric vehicle chargers (EVCs) and operated in discharge mode known as vehicle-to-grid (V2G) or in charge mode known as grid-to-vehicle (G2V) [32]. With the fact that private vehicles are parked, on average, 93%–96% of their lifetime, EVs can be

viewed as mobile ESSs, which have many similar functions as stationary ESSs for grid application [33]-[35]. The V2G concept has attracted attention of both grid operators and vehicle owners. However, effective utilization of storage capacity and proper recharging strategies of EVs are necessary to realize the benefits of V2G capabilities.

1.1.2 Motivations

The driving forces, which are from the urgent demand for reduction carbon emissions, air pollution and needs on fossil fuel, promote the growing research interest and investment in renewable energy and energy storage technologies. The integration of RESs into the existing distribution networks will lead to power variation as well as more complex power flow, which will change the voltage profiles of distribution networks dramatically. The impacts of increasing penetration of RESs on the existing distribution grids need to be investigated. In order to facilitate applications of renewable energy, energy storage has become an emerging topic for both utility grid and transportation. The research on ESSs and EVs for renewable energy penetration and grid ancillary services is becoming more and more attractive and important. In addition, one significant characteristic of modern power systems is that RESs and ESSs based DG units are interfaced to the system through power electronics devices and the control of the system is primarily referred to the coordinated control of the interfacing inverters of DG units. Hence, the major challenges in this research are to find effective methods to model, control and supervise of various sources based DG units.

In review of the above situations, the motivation of this thesis is to design effective control strategies for different system structures consisting of RESs, ESSs and EVs to solve the problems when integrating of renewable energy into power systems.

With the control strategies developed in this research work, ESSs and EVs should be able to deal with the voltage problems which arise due to the renewable penetration and load demand in distribution networks. Furthermore, ESSs can be utilized to solve the power balancing and power management problems in islanded microgrids. Throughout this research, the state of charge (SoC) of storage batteries in ESSs should be monitored and controlled properly, to avoid depletion or saturation of the storage batteries. In general, the proposed control strategies should contribute to the penetration of renewable energy and realize the benefits of energy storage techniques in the smart grid.

1.2 Objectives and Scope

With the challenges and motivations to be explored, the objectives of this thesis are to solve problems related to the application, modeling, control and operation of the ESSs in the smart grid. In this thesis, the ESSs are mainly applied for voltage regulation in distribution networks and power balancing in microgrids. In order to design effective control systems, mathematic models of electrical components such as power inverters, solar panels and storage batteries are needed to be built. Then control systems can be developed to control the parameters provided by the mathematic models to achieve the different control objectives. After that, simulation platform including system data such as line impedances, PVs, EVs and loads must be implemented to validate the performance of the proposed control method. At last, the results under different conditions are to be demonstrated and discussed. The detailed objectives of this thesis are listed as follows:

1. The first objective is to design a coordinated control method to control the power outputs of distributed ESSs for voltage regulation in distribution networks with high PV penetration. Generally, during peak PV generation period, the voltages are

mitigated by charging the ESSs, and the stored energy is discharged for voltage support during peak load period. The impact of storage devices integrated with PV system on feeder voltages needs to be investigated in detail. Proper battery model is to be developed to simulate the behavior of ESSs for grid-scale application. The proposed coordinated control method is aimed to regulate the voltages in the distribution networks with the required limits and fully utilize the available storage capacity of ESSs during daily operation. Therefore, both distributed voltage controller and localized SoC controller will be properly designed to achieve the control objective.

2. The second objective is to apply distributed EVCs and their charging EVs for voltage regulation in distribution networks with high penetration of PVs and EVs. With the concept of V2G, plug-in EVs can also be served as energy storage devices and contribute to voltage regulation in distribution networks. When the real power of the plug-in EVs is not available for voltage regulation, the reactive power of EVCs can be utilized as a backup. First, voltage regulation method of distributed EVCs will be designed. The coordination of distributed EVCs can be achieved through communication links between them using consensus algorithm. Then algorithms for the estimation of V2G capacity of the plug-in EVs and determination of the real and reactive power outputs of each EVC are to be developed, so that the voltage regulation objectives can be achieved within the required operation limits.

3. The third objective is to investigate the application of ESSs in an islanded microgrid. Different from the conditions of grid-connected application, the main function of ESSs is to balance the PV generation and load demand within the islanded microgrid in order to maintain the frequency and voltage stability. To achieve fast dynamic response and small steady-state error of power output, model predictive control (MPC) of power inverters will be adopted. The discrete time state-

space models need to be derived using the equivalent circuit model depending on the control objectives of the power inverter. A hierarchical control strategy will be designed to coordinate all available units including ESSs, PVs and loads together for the power balancing and SoC management in the microgrid. PV curtailment and load shading will be conducted if the remaining capacities of ESSs are not enough during the operation of the microgrid.

4. Finally, to verify the performance of the proposed control methods in this thesis, simulation platforms are to be built using MATLAB/Simulink. The proposed control methods will be implemented in simulation platforms and tested under various scenarios. The simulation results will be demonstrated that the entire system is able to operate stably and the control design is accurate and effective under various operation conditions. Different types of PV and load profiles will be used to test both steady-state and dynamic performance of the proposed control methods.

1.3 Contributions of Thesis

The main contributions of this thesis are summarized as follows:

1. In this thesis, different control strategies are proposed for the application of ESSs in distribution networks and microgrids. The centralized control requires fast and reliable communication links, and the reliability of the control system is highly dependent on the performance of the centralized controller. While the decentralized control is difficult to achieve fully coordination between available units due to lack of global information. Since the limitation of centralized and decentralized controls, distributed control is adopted to coordinate available units in this thesis. When distributed control is applied to control EESs in distribution networks, further research which considers actual PV and load profiles, different capacities and SoCs

of ESSs and various topologies of distribution networks still needs to be done. Besides, DG units are assumed as ideal power sources and the type and capacity of DG units are not considered in many research works so far. The SoC and power limits of energy storage based DG unit will greatly influence the stability and reliability of the system during operation, especially in distribution networks with high PV penetration and variable loads. Therefore, characteristics and constraints of ESSs are taken into account for control system design in this research work.

2. This thesis addresses how to coordinate distributed ESSs to solve the voltage rise/drop issues in low-voltage (LV) distribution networks. A coordinated control method which includes both distributed and localized controls is proposed. For the distributed control design, a consensus algorithm is proposed to coordinate all available ESSs to regulate the feeder voltages. If the voltages at certain buses violate voltage limits, the consensus algorithm will determine the power output of each ESS to eliminate the voltage violation. For localized control design, a SoC control strategy is proposed to control the SoC of each ESS within an allowable range of the desired SoC. The SoC control avoids depletion or saturation of ESSs under different operation conditions. The entire control method ensures voltage regulation while effectively utilizes all available capacities of ESSs during daily operation. Besides, the ESS is modeled as vanadium redox battery (VRB) whose SoC is estimated for the SoC control. Case studies with real PV and load data under different weather conditions are implemented to verify the performance of this method. In addition, the effectiveness of the proposed method in distribution networks with multiple laterals is also validated.

3. Inspired by the previous research work on distributed ESSs, the real and reactive power outputs of distributed EVCs are applied to solve the voltage regulation problem in distribution networks with high penetration of PVs and EVs. To delineate

the behaviors of battery storage devices on EVs, a lithium-ion battery model is derived by fitting the experimental data. A novel two-stage coordination method of distributed EVCs for voltage regulation is proposed. The first control stage obtains the voltage regulation target by measuring voltages of critical buses and distributes the control signal to each EVC through communication links. The second control stage determines the amount of real and reactive power which can be provided by each EVC, considering the constraints and charging objectives of each EVC and its charging EV. Different types of PV and load profiles are utilized to evaluate the performance of the proposed method in a practical distribution network.

4. Finally, a hierarchical control scheme is proposed for islanded ac microgrids formed by the ESSs, PV systems, and loads. To achieve fast dynamic response and small steady-state error of voltage source inverters (VSIs), a novel N-step MPC is developed for the primary control. Depending on different cost functions of MPC method, the VSI of each unit can operate in current control mode (CCM) or voltage control mode (VCM). The secondary control is achieved through communication links between each unit using the consensus algorithm. The objective of secondary control is to solve large power imbalance and overcharging/overdischarging problems in the microgrid. This control scheme ensures the power balancing and energy management can be achieved hierarchically under different PV and load conditions. Both short-term and long-term simulation studies are conducted to demonstrate the performance of the proposed hierarchical control method.

1.4 Organization of Thesis

The thesis is organized into six main chapters as follows:

Chapter 1: Introduction

This chapter provides background information of energy storage technologies including their developments, applications, advantages and challenges. The motivations, objectives and contributions of this thesis, as well as the organization of this thesis are also discussed.

Chapter 2: Literature Review

In this chapter, a comprehensive review of the related research work on the application and control of energy storage technologies in utility grid and transportations is presented. Then, the voltage regulation problem in the distribution networks, which is one of the main focuses of this thesis, is discussed in detail. After that, a review on the state-of-art control hierarchy of power systems is provided. Finally, the consensus algorithm, which is the critical control method adopted in this thesis, is discussed.

Chapter 3: Coordinated Control of Distributed Energy Storage Systems for Voltage Regulation in Distribution Networks

In this chapter, distributed ESSs are proposed to solve the voltage rise/drop issues in LV distribution networks with high penetration of rooftop PVs. The impact of energy storage device integrated with PV source on feeder voltages is investigated in detail. A coordinated control method which includes both distributed and localized controls

is proposed for distributed ESSs. The entire control structure ensures voltage regulation while effective utilization of storage capacity under various operation conditions. The proposed control method is evaluated in two typical LV distribution networks with real PV and load data, and the simulation results validate the effectiveness of this method.

Chapter 4: Two-stage Coordination of Distributed Electrical Vehicle Chargers for Voltage Regulation in Distribution Networks

A two-stage coordination method of distributed EVCs is proposed to regulate the voltages in distribution networks in this chapter. In the stage one, the distributed voltage control is proposed to coordinate each EVC for voltage regulation. In the stage two, the power allocator is developed to determine the active and reactive power outputs of each EVC, so that the voltage regulation is achieved within the required operation limits. The proposed two-stage control ensures that the voltages along the distribution network are within the allowable voltage range by coordinated control of the power output of each EVC during daily operation. The proposed voltage control method is evaluated in a LV residential network under various operation conditions and the simulation results validate the effectiveness of the proposed method.

Chapter 5: Hierarchical Control and Power Management of Islanded Microgrids with Energy Storage Systems and Renewable Energy Sources

In this chapter, a hierarchical control scheme is presented for PV systems, ESSs and loads in an islanded ac microgrid to deal with both the short-term and long-term power imbalance. The primary control is realized by a novel MPC method, which provides fast dynamic response and small steady-state error for power inverters in

the microgrid. The secondary control is performed by consensus based distributed control, which provides distributed control signal for primary controlled inverters and loads. With the proposed control scheme, the power balancing and SoC management can be achieved by controlling the power output of each available unit in a hierarchical way. The control scheme is implemented in an ac microgrid and the simulation results demonstrate the performance of the proposed approach.

Chapter 6: Conclusions and Future Work

An overall conclusion of this research is discussed in this chapter. Moreover, areas for further research are proposed as well.

References

- [1] B. K. Bose, "Global warming: energy, environmental pollution, and the impact of power electronics," *IEEE Industrial Electronics Magazine*, vol. 4, no. 1, pp. 6-17, Mar. 2010.
- [2] N. L. Panwar, S. C. Kaushik, and S. Kothari, "Role of renewable energy sources in environmental protection: a review," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 3, pp. 1513-1524, Apr. 2011.
- [3] T. Strasser, F. Andren, J. Kathan, *et al.*, "A review of architectures and concepts for intelligence in future electric energy systems," *IEEE Trans. Industrial Electronics*, vol. 62, no. 4, pp. 2424-2438, Apr. 2015.
- [4] S. Chowdhury, S. P. Chowdhury, and P. Crossley, *Microgrids and Active Distribution Networks*. UK: Institution of Engineering and Technology, 2009, pp. 1-13.
- [5] J. M. Guerrero, M. Chandorkar, T. Lee, and P. C. Loh, "Advanced control architectures for intelligent microgrids-part I: decentralized and hierarchical

- control,” *IEEE Trans. Industrial Electronics*, vol. 60, no. 4, pp. 1254-1262, Apr. 2013.
- [6] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuña, and M. Castilla, “Hierarchical control of droop-controlled AC and DC microgrids-a general approach toward standardization,” *IEEE Trans. Industrial Electronics*, vol. 58, no. 1, pp. 158-172, Jan. 2011.
- [7] J. Driesen and F. Katiraei, “Design for distributed energy resources,” *IEEE Power and Energy Magazine*, vol. 6, no. 3, pp. 30-40, May/Jun. 2008.
- [8] J. C. Wu, K. D. Wu, H. L. Jou, and S. K. Chang, “Small-capacity grid-connected solar power generation system,” *IET Power Electronics*, vol. 7, no. 11, pp. 2717-2725, Nov. 2014.
- [9] Renewables 2016 Global Status Report. [Online]. Available: <http://www.ren21.net/status-of-renewables/global-status-report/>.
- [10] Y. Duan and R. G. Harley, “Present and future trends in wind turbine generator designs,” in *Proc. Power Electronics and Machines in Wind Applications*, 2009, pp. 1-6.
- [11] G. J. Shirek and B. A. Lassiter, “Photovoltaic power generation: modeling solar plants' load levels and their effects on the distribution system,” *IEEE Industry Applications Magazine*, vol. 19, no. 4, pp. 63-72, Aug. 2013.
- [12] J. C. Wu and Y. H. Wang, “Power conversion interface for small-capacity wind power generation system,” *IET Generation, Transmission and Distribution*, vol. 8, no. 4, pp. 689-696, Apr. 2014.
- [13] A. M. Azmy and I. Erlich, “Impact of distributed generation on the stability of electrical power systems,” in *Proc. IEEE Power Engineering Society General Meeting*, 2005, pp. 1056-1063.
- [14] J. A. Martinez and J. Martin-Arnedo, “Impact of distributed generation on distribution protection and power quality,” in *Proc. IEEE Power Engineering Society General Meeting*, 2009, pp. 1-6.

- [15] S. Vazquez, S. M. Lukic, E. Galvan, L. G. Franquelo, and J. M. Carrasco, "Energy storage systems for transport and grid applications," *IEEE Trans. Industrial Electronics*, vol. 57, no. 12, pp. 3881–3895, Dec. 2010.
- [16] B. R. Alamri and A. R. Alamri, "Technical review of energy storage technologies when integrated with intermittent renewable energy," in *Proc. International Conference on Sustainable Power Generation and Supply*, Apr. 2009, pp.1–5.
- [17] Electrical energy storage project team, "Electrical energy storage." International Electrotechnical Commission, Dec. 2011.
- [18] B. B. Mckeon, J. Furukawa and S. Fenstermacher, "Advanced lead–acid batteries and the development of grid-scale energy storage systems," *Proceedings of the IEEE*, vol. 102, no. 6, pp. 951-963, Mar. 2014.
- [19] "Battery energy storage for smart grid applications," EUROBAT, 2013.
- [20] S. Bacha, D. Picault, B. Burger, I. E. Otadui, *et al.*, "Photovoltaics in microgrids: an overview of grid integration and energy management aspects," *IEEE Industrial Electronics Magazine*, vol. 9, no. 1, pp. 33-46, Mar. 2015.
- [21] M. J. Alam, K. M. Muttaqi, and D. Sutanto, "A novel approach for ramp-rate control of solar PV using energy storage to mitigate output fluctuations caused by cloud passing," *IEEE Trans. Energy Conversion*, vol. 29, no. 2, pp. 507-518, Mar. 2014.
- [22] I. Serban and C. Marinescu, "Control strategy of three-phase battery energy storage systems for frequency support in microgrids and with uninterrupted supply of local loads," *IEEE Trans. Power Electronics*, vol. 29, no. 9, pp. 5010-5020, Sep. 2013.
- [23] R. Sebastian, "Application of a battery energy storage for frequency regulation and peak shaving in a wind diesel power system," *IET Generation, Transmission and Distribution*, vol. 10, no. 3, pp. 764-770, Feb. 2016.

- [24] H. Kakigano, Y. Miura, and T. Ise, "Distribution voltage control for DC microgrids using fuzzy control and gain-scheduling technique," *IEEE Trans. Power Electronics*, vol. 28, no. 5, pp. 2246-2258, Sep. 2012.
- [25] S. J. Lee, J. H. Kim, C. H. Kim, S. K. Kim, *et al.*, "Coordinated control algorithm for distributed battery energy storage systems for mitigating voltage and frequency deviations," *IEEE Trans. Smart Grid*, vol. 7, no. 3, pp. 1713-1722, Jun. 2015.
- [26] L. Situ, "Electric vehicle development: the past, present and future," in *Proc. IEEE International Conference on Power Electronics Systems and Applications*, 2009, pp. 20-22.
- [27] S. Amjad, S. Neelakrishnan, and R. Rudramoorthy, "Review of design considerations and technological challenges for successful development and deployment of plug-in hybrid electric vehicles," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 13, pp. 1104-1110, Apr. 2010.
- [28] E. Karden, S. Ploumen, B. Fricke, T. Miller, and K. Snyder, "Energy storage devices for future hybrid electric vehicles," *Journal of Power Sources*, vol. 168, no. 1, pp. 2-11, May 2007.
- [29] J. Du and M. Ouyang, "Review of electric vehicle technologies progress and development prospect in China," in *Proc. Electric Vehicle Symposium and Exhibition*, 2013, pp. 17-20.
- [30] K. Rajashekara, "Present status and future trends in electric vehicle propulsion technologies," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 1, pp. 3-10, Mar. 2013.
- [31] M. Duvall and E. Knipping, "Environmental assessment of plug-in hybrid electric vehicles. Volume 1: nationwide greenhouse gas emissions," EPRI/NRDC, Palo Alto, CA, Final Rep. 1015325, 2007, pp. 1-56.

- [32] W. Kempton and J. Tomic, “Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy,” *Journal of Power Sources*, vol. 144, no. 1, pp. 268–279, 2005.
- [33] H. Turton and F. Moura, “Vehicle-to-grid systems for sustainable development: An integrated energy analysis,” *Journal of Technological Forecasting and Social Change*, vol. 75, no. 8, pp. 1091–1108, Oct. 2008.
- [34] U. C. Chukwu and S. M. Mahajan, “V2G parking lot with PV rooftop for capacity enhancement of a distribution system,” *IEEE Trans. Sustainable Energy*, vol. 5, no. 1, pp. 119–127, Sep. 2013.
- [35] H. M. Yang, C. Y. Chung, and J. H. Zhao, “Application of plug-in electric vehicles to frequency regulation based on distributed signal acquisition via limited communication,” *IEEE Trans. Power Systems*, vol. 28, no. 2, pp. 1017–1026, Aug. 2012.

Chapter 2

Literature Review

In this chapter, a comprehensive review of the related research works on energy storage technologies for grid and transportation applications is presented in detail. Then, as the main problem to be solved in this thesis, voltage rise/drop issues and corresponding regulation methods are discussed. After that, a review of state-of-art control hierarchy of modern power system is conducted. Besides, consensus algorithm which is the basic control method adopted in this thesis is introduced. Finally, the literature review has been summarized.

2.1 Energy Storage Systems

Energy storage refers to a process of converting electrical energy from power systems into a form that can be stored for converting back to electrical energy when needed [1]-[2]. Due to the development of renewable energy technologies, energy storage systems have been widely applied for utility grid and transportation applications [3]. For utility grid application, energy storage plays an important role in integration of renewable energy into power systems and ancillary services such as peak load shaving, reserve, frequency and voltage regulation. According to the report of market research company HIS, grid connected energy storage will increase rapidly and reach 6GW in 2017, and will be over 40GW in 2020 [4]. On the other hand, hybrid electric vehicles and battery electric vehicles have been developed for decades and already in service in order to reduce CO₂ emissions and fossil fuel consumption. V2G capacities of plug-in EVs can offer a possible backup for RESs including solar and wind energy, contributing integration of intermittent renewable energy generation in power systems. V2G technologies can also provide additional opportunities for grid operators, such as reactive power compensation, active power control, load levelling by valley filling/peak load shaving, and harmonic current filtering [5].

2.1.1 Comparison of Energy Storage Technologies

Different energy storage technologies can be compared from technical and economic point of view. The investment cost of various energy storage technologies is studied in [6]-[8], which will not be taken into consideration in this research. The main technical characteristics of energy storage are energy density, power density, energy efficiency, life cycle (life time), and self-discharge, which are explained as follows [9], [10].

- 1) Energy density (Wh/kg) and power density (W/kg) are the energy to weight ratio and the power to weight ratio respectively. Power density refers to the ability of energy storage to provide instantaneous power, while energy density specifies the ability to provide continuous energy over a period of time. Energy storage with high power density can discharge large amounts of power on demand, and energy storage with high energy density can discharge energy for a long period.
- 2) Energy efficiency (%) is the ratio of released energy to stored energy or the output and input electricity without concerning of self-discharge.
- 3) Life cycle or durability (cycles) is the number of times which energy storage can release the designed energy level after each recharge. One cycle means one charge and one discharge.
- 4) Self-discharge is the ratio of initial stored energy to dissipated energy over a non-use time.

The technical characteristics of various energy storage technologies are summarized in Table 2.1 [3]. As shown in Table 2.1, electrochemical double layer capacitors (EDLC) and flywheel have the highest energy efficiency, while compressed air energy storage (CAES) has very low energy efficiency and Ni-MH has the lowest energy efficiency among battery energy storage technologies (i.e. Lead-Acid, Ni-Cd, Ni-MH, Lithium-ion, Li-polymer, NaS and VRB). The mechanical energy storage technologies which include pumped hydro energy storage (PHES), CAES, and flywheel have very long life cycle and are very durable. Battery energy storage usually have short life cycle while lead-acid battery (lead-acid) is the shortest in this group. Although EDLC and flywheel have long life time, their self-discharge is quite high. It means EDLC and flywheel are very suitable for short-term storage application, considering their high self-discharge and high energy efficiency. The

self-discharge can be neglected for PHES and VRB, which means they are very suitable for long-term storage application.

Table 2.1 Characteristics of energy storage technologies [3]

Type	Energy Density (Wh/kg)	Power Density (W/kg)	Energy Efficiency (%)	Life Cycle (cycles)	Self-Discharge
Lead-Acid	20-35	25	70-80	200-2000	Low
Ni-Cd	40-60	140-180	60-90	500-2000	Low
Ni-MH	60-80	220	50-80	<3000	High
Li-ion	100-200	360	70-85	500-2000	Medium
Li-polymer	200	250-1000	70	>1200	Medium
NaS	120	120	70	2000	-
VRB	25	80-150	80	>16000	Negligible
EDLC	<50	4000	95	>50000	Very High
PHES	0.3	-	65-80	>20 years	Negligible
CAES	10-30	-	40-50	>20 years	-
Flywheel (steel)	5-30	1000	95	>20000	Very High
Flywheel (composite)	>50	5000	95	>20000	Very High

In general, energy storage technologies can be separated into two groups: high energy density and low power density, and low energy density and high power density. Energy storage with high energy density and low power density like batteries is suitable for a long period service (about an hour) but its time response is large. Energy storage with low energy density and high power density such as supercapacitor and flywheel provides fast time response but it cannot be in service for a long period (in several seconds to minutes). Different energy storage technologies should be chosen according to the applications, considering the characteristics in Table 2.1.

In this thesis, two kinds of battery energy storage technologies are applied, which are VRB and lithium-ion battery. The energy storage systems refer to the battery packs with multiple battery cells series and parallel connected, which penetrated into power systems at the dc part of power inverters. As shown in Table 2.1, VRB has relatively small energy density and power density compared with lithium-ion battery. While the advantages of VRB are the long life cycle and low self-discharge rate. For utility grid application or renewable energy integration, energy storage capacity, energy efficiency and life cycle are key performance criteria. The VRB exhibits many advantages such as independent power and energy ratings, fast charge and discharge response time, high energy efficiency, long life cycle, low self-discharge, and convenient for SoC estimation, which makes VRBs very suitable for utility applications [11], [12]. For transportation applications, portability, scalability, and energy and power density are key performance criteria. Lithium-ion battery has both very high energy density and power density compared with other batteries. This characteristic makes lithium-ion battery the mostly used batteries in transportation application because it needs small weight and volume for high energy and power [13]-[15].

In addition, storage capacity is a primary limitation of energy storage. Energy storage cannot absorb or supply energy if they are already full or empty respectively. Since either energy stored or energy used by energy storage has to be elaborated, the concept of state of charge and depth of discharge (DoD) are introduced [16], [17]. State of charge defines the level of energy which remains in energy storage comparing to the total capacity of energy storage in percentage. Depth of discharge is the contrary of SoC. It defines how much energy is used or discharges in percentage to the total capacity. In control system, SoC is one important parameter which has profound impacts on the control strategy of energy storage. For example, if energy storage cannot supply energy because SoC is very low, control strategy has

to recharge storage as soon as possible and other sources have to be responsible for supplying compensating energy.

2.1.2 Energy Storage for Utility Grid

Energy storage technologies have been widely utilized in modern smart grid for different applications. According to the function or role of ESSs in smart grid, they can be classified into three main applications, which are: grid ancillary services for power quality improvement, uninterrupted power supply (UPS) for off-grid systems, and energy management for optimal operation. These applications will contribute to the penetration of renewable energy into the existing power system and improvement the power quality as well as the efficiency of the entire system. The power/capacity ranges of different energy storage technologies are shown in Figure 2.1 [15]. Figure 2.1 also shows the suitability of various ESSs for utility grid application. In the following subsections, some related research works of this field are reviewed.

Figure 2.1 Different energy storage technologies for grid application [15].

1) Grid Ancillary Services

The grid ancillary services of ESSs for power quality improvement usually last for a few seconds to a few hours, which include RESs intermittency mitigation [18]-[20], frequency and voltage regulation [21]-[23].

The ESS has become one major method for smoothing solar and wind power generation fluctuations. In [18], a method where the ramp-rate of PV panel output is measured to control the ramp-rate of inverter output to a desired level by utilizing the ESS is proposed. During the ramping up/down period, the desired ramp-rate is controlled by the ESS according to an inverse relationship with the ramp-rate of PV panel output to improve the performance of PV fluctuation mitigation. For the same purpose, a power smoothing strategy for a 1-MW grid-connected PV power plant is proposed in [19]. To smooth the fluctuating power output of the PV plant, a hybrid ESS composed of a VRB and a supercapacitor bank is applied. The power management system of the hybrid ESS is designed to reduce the required power rating of the supercapacitor to one-fifth of the VRB rating and to avoid the operation of the VRB at low power levels, which increases its overall efficiency. In addition, a smoothing control method for reducing hybrid PV/wind system power output fluctuations and regulating the SoC of battery ESS under different operation conditions is proposed in [20].

The frequency and voltage variation is another issue brought by the penetration of RESs, which can be solved by utilizing ESSs. The integration impact of battery ESSs on the short-term frequency control in autonomous microgrids is investigated in [21]. This research improves the short-term frequency stability in the microgrid by a control method of ESSs and enhances both inertial response and adaptive droop characteristic. In [22], a power system consisting of a high penetration of wind generation and ESS is investigated for the regulation of grid frequency. A strategy

called SoC feedback control is proposed to improve the performance of the grid frequency deviation response and control the SoC of the ESS. In [23], a coordinated control strategy to compensate for inertia of the wind farm is proposed. This strategy can improve the temporary frequency support ability of the wind turbine generators based on the coordinated control of the wind turbine generators and the ESSs.

2) UPS Application

The UPS refers to the operation of ESSs in off-grid power systems or islanded microgrids, which has been studied by many researchers for both ac and dc microgrids [24]-[27].

In grid-connected condition, power can be imported from the grid to charge the battery packs of ESSs. While in stand-alone condition, the ESSs can supply local load demand together with other sources. A line-interactive UPS for ac microgrids and the corresponding control system are introduced and discussed in [24]. Seamless transfer between grid-connected and stand-alone operation of the microgrid is achieved by a frequency and voltage drooping method. The drooping coefficients are properly chosen to limit the power absorbed by the UPS when connecting back to the utility grid as well as improve the transient response. In [25], a cooperative control strategy of distributed energy resources (DERs) and the ESS during islanded operation is proposed and evaluated by both simulation and experiment. The ESS is controlled by a primary control to handle the short-term frequency and voltage regulation, while the secondary control make the DERs respond if the frequency and voltage deviation last for a long time.

In the last few years, much attention has been paid on dc microgrids. DC microgrids enable dc output sources such as PV systems, storage batteries, and fuel cells to be interconnected without ac/dc conversion, which improve the system efficiency. For

dc microgrids which have multiple ESSs, a voltage control method which combines fuzzy control and gain-scheduling approaches to realize both power sharing and energy management is proposed in [26]. The research results demonstrate that the dc voltages in the system are regulated within $340V \pm 5\%$, and the SoCs of multiple ESSs are almost equal. In [27], a SoC-based adaptive droop control method is presented to balance the SoCs of distributed ESSs in dc microgrids. This control method is achieved in a decentralized way, in which the droop coefficient is inversely proportional to the n th order of SoC, so that the load demand is equally shared among the distributed ESSs in the system.

3) Energy Management

Energy management is another important application area of energy storage, which includes load leveling, peak shaving, system reverse, economic dispatch, etc. [28]-[30]. Sizing of ESSs is also an important topic to achieve the energy management function of ESSs [31], [32].

Energy management or scheduling of distributed ESSs plays an essential role in the process of improving the efficiency, reliability and economics of power grids. In [28], a smart power system in which users are equipped with energy storage devices is considered. By scheduling the energy consumption and storage of users by a central controller, the energy payment can be minimized. A distributed economic dispatch strategy for microgrids with multiple ESSs is introduced in [29]. This strategy overcomes the challenges of dynamic couplings among all decision variables and stochastic variables in a centralized dispatching formulation. In [30], an algorithm that uses demand profile information and a minimal set of ESS parameters is formulated to obtain the ESS operation schedules to achieve peak demand shaving and load-levelling. In [31], an effective sizing strategy for distributed battery ESSs in the distribution networks under high PV penetration level is proposed. The main

objective of this method is to optimize the size of distributed battery ESSs and derive the cost-benefit analysis when ESSs are applied for voltage profile improvement and peak load shaving. In [32], a comprehensive planning framework is introduced for ascertaining the most cost effective siting and sizing of ESSs that maximizes their benefits in distribution networks. A probabilistic approach is adopted that includes the consideration of the stochastic nature of system components. This approach allows determining the optimal operation of ESSs at each load state. In general, the time scale of energy management for ESSs can vary from a few hours to months, which usually has longer time scale than power quality services.

2.1.3 Energy Storage for Transportation

Electric vehicles have a large potential amount of storage capacity, since the energy stored in the battery is not fully used by most of EVs in regular daily trips. The utilization of spare battery capacity of EVs for grid support applications with V2G concept is becoming popular and important. V2G concept describes that EVs can communicate with the power system to provide demand respond services by either delivering electricity into the grid or throttling their charging rate. When plugged into an electricity network, the EV can act either as a controllable load or an energy storage unit in the system. The stability and reliability of the renewable energy penetrated power system will be enhanced with the vast storage of EVs connected to the grid. In order to provide ancillary service from the V2G system, a group of EVs is necessary to coordinate together as an aggregator. The EV aggregators are expected to collect EVs into a group through electrical connection and communication, which create a larger, more desirable system for the utility application [33]. EVs can be charged in EV charging stations, car parks and home with charging outlets. Industry has defined three typical rates of EVCs, which can be classified into three power levels, as shown in Table 2.2 [34]. Normal EV

charging can be achieved by Level 1 and Level 2 EVCs, while fast charging of EVs is implemented by Level 3 EVC.

Table 2.2 Charging power levels of EVCs [35]

Power Level	Description	Power Level
Level 1	Opportunity charger (any available outlet)	1.4kW (12A) 1.9kW (20A)
Level 2	Primary dedicated charger	4kW (17A) 19.2kW (80A)
Level 3	Commercial fast charger	Up to 100kW

The EV charging pattern is an important factor which will influence the load demand profiles as well as the voltage profiles in distribution networks. To be summarized, there are three different EV charging patterns: constant EV charging, price-based EV charging, and V2G. Constant EV charging represents the situation where no upper level controller coordinates the EV charging. The EV will charge with a constant charging power once plugged into the grid and stop charging when either the battery is fully charged or the EV is plugged out from the grid. In residential area, EV charging with constant power tends to coincide with evening peak load demand. This will increase the burden of distribution networks and also cause severe voltage drop issue. Therefore, this charging pattern is only suitable for low EV penetration condition where EVs are just treated as passive loads. Price-based EV charging allocates EV charging activities over time in a cost-minimizing manner while retaining driving feasibility. The EV charging will consider the time of use tariff and consequent to off peak charging. Price-based EV charging is an EV management problem which can be formulated into an optimization problem. With this charging pattern, the EV charging is directly managed and can be treated as a responsive load. The last charging pattern ‘V2G’ enables the EV owners to sell electricity back and

provides ancillary services for utility grid. Ancillary services are necessary in the power system for maintaining grid reliability and power quality, balancing supply and demand, and supporting the transmission of power from generation to consumption. The ancillary services provided by V2G include: load levelling and peak power management [36], [37], quick frequency and voltage regulation [38]-[40], and effective renewable supporting and balancing [41], [42]. As V2G technology is the main focus of this thesis, the application of V2G is further discussed below.

1) Load Leveling and Peak Load Shaving

Depending on the stress on the grid during peak load periods, the peak-shaving support from the EVs can be very useful. The battery packs of EVs have limited capacity and the capacity usage is also constrained by travel requirements. Therefore, in [36], a control strategy is proposed for an effective utilization of the available EV capacity for peak shaving. Dynamic adjustments in EV discharging rates are developed to fully utilize the limited EV battery capacity when peak shaving is most valuable based on the demand pattern. In [37], the modeling of a multi charging station for EVs and its utilization for grid support is investigated. A control architecture is proposed based on fuzzy control techniques, which maintains the node voltage within the prescribed limit by valley filling and peak shaving.

2) Frequency and Voltage Regulation

With frequency regulation capabilities of EVs, a V2G control strategy is proposed for the aggregator to dispatch regulation requirements to EVs and EV charging stations in [38]. In each EV charging station, the frequency regulation control is calculated based on the V2G power at present time, and V2G power is presented considering both frequency regulation and charging demands. In [39], a V2G control method is proposed for EVs to take part in primary frequency control considering

charging demands from EV users in a decentralized way. The battery SOC holder along with adaptive frequency droop control is proposed to maintain the SoC of the EV battery around the residual SOC. A V2G reactive power support strategy for optimal coordinated voltage regulation in distribution networks with high DG penetration is proposed in [40]. The proposed algorithm employs EVs, DGs, and on-load tap changers (OLTCs) to satisfy EV charging demands and grid voltage requirements with relaxed tap operation, and minimum DG active power curtailment.

3) Renewable Supporting and Balancing

The V2G capacities of EVs can provide additional reserve for renewable generation in power system. When the power injected to the grid from RESs become very high, either the centralized power plants or the DG units must decrease their power generation. EVs can help match generation and consumption by charging and discharging batteries, so that the utility generators do not need to reduce the power output. A distributed V2G control scheme providing a distributed spinning reserve for the unexpected intermittency of RESs is proposed in [41]. The EV user's requirement is satisfied by performing a scheduled charging for the V2G control. The authors in [42] aims to examine the potential and technical benefits of using PV systems as energy suppliers for charging EVs. An urban scale integrated system with the self-consumption evaluation is presented in order to optimize the interaction between the PV system and charging station for EVs.

2.2 Voltage Regulation Methods in Distribution Networks

In the last few years, the rapid developments of renewable technology have led to a significant growth in the amount of DGs in distribution networks. The increasing penetration of DG units will cause two major voltage problems: voltage rise and drop issues. With high penetration of rooftop PVs, PV generation may largely exceed

customer load demand in the midday. The reverse power flow from customer end to the utility grid can potentially cause unacceptable voltage rise along the distribution network [43]-[45]. On the other hand, the massive charging of plug-in electric vehicles will introduce additional power demand, which may result in unacceptable voltage drop along the distribution network [46]-[48]. So there is a possibility of voltage limits violation during both peak load and peak PV generation periods, which may lead to poor power quality and even equipment failure.

Many techniques have been proposed to deal with the voltage rise/drop issues in distribution networks. These methods can be employed by both utility operators and customers. The utility grid facilities have been installed and utilized by operators for voltage regulation, which include increasing the conductor size [49], installing voltage regulators (switched capacitors) [50]-[52], and changing the set points of secondary transformer tap [53], [54]. Voltage regulators and tap-changing transformers have been widely used for voltage regulation in traditional distributed networks where the power flow is unidirectional and the load demand is easy to predict. However, the power flow in distribution networks becomes bidirectional and the load demand becomes hard to predict due to the penetration of RESs and EVs. The bidirectional power flow and power variation could cause frequent switching of the set points of the voltage regulators and transformers. Nowadays, as the fast development of rooftop PVs and plug-in EVs in residential distribution networks, power generation and load demand at customer end can also be utilized for voltage regulation. The methods include curtailing the power of PV generation [55], [56], reactive power compensation of PV inverters [57], [58], utilizing energy storage systems [59], [60], and demand response [61], [62]. Table 2.3 summarizes the features and drawbacks of typical voltage regulation methods as mentioned above.

To achieve voltage regulation in modern distribution networks, these voltage regulation methods can be optimized and controlled according to their features. For on load tap changing transformers, voltage regulators and switched capacitors which have the limitations on taps/switches change, the system voltage regulation can be formulated as an optimization problem. The taps/switches can be optimized by the grid operators based on the renewable generation and load prediction. The real-time control can be adopted by DG units to deal with voltage variations caused by the uncertainty of renewable energy. In this thesis, the research is mainly focused on the real-time voltage regulation provided by DG units at customer side. Therefore, the voltage regulation methods from customer side are further discussed as follows.

Table 2.3 Comparison of typical voltage regulation methods

Voltage regulation methods	Features	Drawbacks
Increasing the conductor size [49]	Increase the power rating of the distribution system, relieve both voltage drop/rise	Rapid increasing renewable generation leads to frequently upgrading of distribution lines
Voltage regulators [50]-[52]	Mainly used for MV networks, limited tap change	Installation cost of voltage regulators, not suitable for frequent tap change.
Secondary transformer [53], [54]	Change the voltage profiles along the distribution feeder directly	Frequently changing the transformer taps reduce the transformer lifetime
Reactive power compensation [57], [58]	Utilize reactive power for voltage regulation, limited reactive power capacity	Less effective in LV distribution networks, increase power loss
Power curtailment of DG units [55], [56]	Easy to implement, no additional cost	Reduce the production of PV generation, less effective in MV distribution networks
Energy storage systems [59], [60]	Enhance the production of PV generation, fast response time	Installation cost of ESSs
Demand response [61], [62]	Customers behave as responsive loads.	Limited by the types of load at customer side.

A local voltage regulation technique that utilizes 15s PV power forecasts to avoid upcoming upper voltage limit violation or overvoltage scenario is proposed in [55]. The proposed algorithm employs an active power curtailment based on these PV power forecasts, when the reactive power estimate given by a droop-based method cannot provide the desired voltage regulation within predefined power factor limits. The curtailment threshold values are calculated in such a way that this voltage regulation technique can reduce possible voltage limit violations. In [56], the use of droop-based active power curtailment techniques for overvoltage prevention in radial LV feeders as a means for increasing the installed PV capacity and energy yield is discussed. Two schemes are proposed and tested in a typical 240V/75kVA Canadian suburban distribution feeder for 12 houses with roof-top PV systems. The droop-based curtailment proposed in [55], [56] is decentralized control approach. Each PV system will curtail the PV output according to only local voltage measurement. The disadvantage of PV curtailment for voltage regulation is that this method reduces the production of PV generation.

One of the solutions for voltage rise issue in distribution networks is reactive power compensation by PV systems. German Grid Codes introduces an active power dependent standard characteristic curve for inverter-coupled distributed generators. In the active power dependent method, the reactive power is determined based on the local feed-in active power of each PV system. [57] utilizes the voltage sensitivity matrix and quasi-static analysis in order to locally and systematically develop a coordinated characteristic for every PV system in the distribution network. This method regulates the feeder voltages under the upper steady-state voltage limit. In [58], a voltage control method for PV inverters that maintains the feeder voltages within acceptable ranges by providing and absorbing reactive power is implemented. This method can be viewed as a form of distributed reactive power based voltage control, which is conventionally conducted by coordinated control of capacitor based

voltage regulators and tap changing transformer. The reactive power compensation for voltage regulation is originally applied in transmission system where the line reactance X is much larger than resistance R . However, R/X ratio in LV distribution networks is much larger than that in transmission networks, which makes reactive power compensation less effective.

As the cost of adding batteries to residential PV systems has continued dropping in recent years, ESSs become a promising solution for voltage regulation in distribution networks. In [59], a coordinated control of distributed ESS with traditional voltage regulators including the OLTC and step voltage regulators is proposed to solve the voltage rise problem caused by the high PV penetration in the LV distribution network. The main objective of this coordinated control is to relieve the tap changer transformer operation stress, shave the distribution network peak load and decrease the transmission and distribution resistive power losses under high solar power penetration. The author in [60] presents utilization of PVs and battery ESSs coordinately to address voltage rise/drop issues. The power and capacity of PV inverters together with droop-based ESSs is evaluated for urban and rural distribution feeders with different R/X ratios. The results demonstrate that for the urban feeders with low resistance, reactive compensation of PV inverters is sufficient to maintain acceptable voltage profile. But for the rural feeders with high resistance, the power outputs of both PV inverters and ESSs are required.

Demand response at customer side has traditionally targeted peak shaving problem for the optimal allocation of power consumption on a time scale that ranges from minutes to hours. As the fast development of advanced monitoring and communication infrastructure, the real-time demand response has potential to provide ancillary services for distribution networks. In [61], a large-scale ice-thermal storage has been viewed as a smart load for fast voltage control and demand side

management in renewable energy penetrated power systems. The possibility of modifying a conventional thermal load has been practically demonstrated in a refrigerator using power electronics technology. The results have demonstrated that voltage and frequency fluctuations can be mitigated using ice-thermal storage in urban buildings in weak power grids. In [62], a decentralized demand response control mechanism has been proposed to provide ancillary services to the utility grid using a large amount of elastic appliances. The voltage control requirement of the grid can be continuously supported by broadcasting low-bit rate control signals.

2.3 Control Hierarchy of Power System

With respect to the control architecture of a power system, there are two distinctive and opposite approaches: centralized and decentralized controls. A fully centralized control depends much on the performance of the central controller which does the required calculations and decides the control behaviors for all the controllable units, which requires extensive communication between the central controller and controllable units [63]. On the other side, a fully decentralized control controls each unit only by the local controller, measuring local information and is neither fully aware of system-wide parameters nor other controllers' behaviors [64]. As power systems usually cover large geographic areas, it is impractical to implement a fully centralized control due to the extensive communication and computation requirements. Due to the strong connection between the operations of controllable units in the system, a fully decentralized control is also not possible. The hierarchical control scheme, consisting of three control levels: primary, secondary and tertiary, is a compromise approach between fully centralized and fully decentralized control schemes. The differences between each control level are response speed and time scale where they need to operate, and infrastructure requirements. Although distribution networks or microgrids are not necessary as geographically large as

conventional power systems, they can also benefit from this control hierarchy because of the large number of controllable DG units which have power electronics interface with fast transient performance [65]-[67]. The control hierarchy of power system with inverter based DG units is shown in Figure 2.2. The rest of this section presents an overview of each level in the control hierarchy.

Figure 2.2 Control hierarchy of power electronic interfaced power system.

2.3.1 Primary Control

Primary control is the first level in the control hierarchy which features the fastest dynamic response compared to the other control levels. The primary controller only depends on local measurements and has no communication requirements. Controller speed requirement, islanding detection, grid synchronization, output control and power sharing control are included in this category [68], [69]. Voltage source inverters as the interface for DG units or as a part of back-to-back converters, require a specially designed control to simulate the inertia characteristic of synchronous generators and provide appropriate power output. For this purpose, primary control

of power converters is composed of two stages: inverter output control and power sharing control.

The first stage of primary control is inverter output control which normally consists of an outer voltage control loop and an inner current regulation loop. The primary control of electronically coupled DG units in power systems has become an important research topic. A general overview of inverter output control is given in [70], [71], in which power inverter controllers are categorized into three kinds based on their reference frame: synchronous (dq), stationary ($\alpha\beta$) and natural (abc). The synchronous reference frame is linked with dc variables and proportional-integral (PI) based controllers. The stationary reference frame is related to sinusoidal variables and proportional-resonant (PR) controllers. The natural reference frame used controllers realized in the form of PI, PR, hysteresis, or deadbeat [70]. Depending on their operation in power systems, the control of inverters can be classified into voltage control mode and current control mode. The inverters in VCM are operated as ac voltage sources and controlled to supply the reference voltage amplitude and frequency. The inverters in CCM are operated as current sources and controlled to supply the reference real and reactive power. These power inverters are suitable to operate in parallel with other inverters in power systems. Particularly, the inverters for PV and wind turbine will operate in CCM to provide their maximum power at most of their operation time [72].

Recently, MPC as an alternative method for inverter output control has been widely investigated in literature [73]-[77]. Compared with other control methods, MPC offers many advantages, for example it can have a variety of control objectives, be simply implemented to multi-input multi-output systems, have a good dynamic response, and easily include nonlinearities and constraints in the design of the controller [73]. MPC applied to power electronics can be classified into two main

categories: continuous control set MPC and finite control set MPC. In order to simplify the implementation of MPC, finite control set MPC is usually applied because it takes advantage of the inherent discrete nature of power converters. The finite control set MPC controls select the switching signals of power converters only from a finite set of switching states. The prediction based on state-space model of each step is applied to minimize a cost function, and the switching state with minimum value of cost function is chosen. This control method has already been widely utilized for power converters and motor drive applications [74]. In [75], the state-of-art development of finite control set MPC in power electronics has been reviewed in detail. Some applications of this technology including drives, active filters, power conditioning, distributed generation and renewable energy are covered. In [76], the authors show that the predictive control framework allows one to embellish classical linear controllers (PI, PR) with novel features and design new control architectures to address various challenges posed by power electronics applications. In [77], an MPC strategy for a grid connected three-level neutral point clamped converter is presented. An LCL filter is used to reduce the harmonics generated by the neutral point clamped inverter.

The second stage of the primary control is known as the power sharing control. Different from inverter output control, the power sharing control is responsible for sharing the active and reactive power imbalance properly in the power systems [68], [70], [78]. The second stage of the primary control can be classified depends on whether or not the concept of droop is performed. The power sharing control which is implemented by a centralized control scheme can also be viewed as a part of the secondary control. The idea of P/f and Q/V droop control method is initially from the steady-state operation of conventional synchronous generators, and the droop control method can be artificially applied for electronically interfaced DG units. The external droop control loop functions to share active and reactive power among DG units.

Besides, the droop control can improve the system stability and performance and adjust both the frequency and amplitude of the output voltage without communication [79]. The droop control relationship can be expressed as

$$\omega = \omega^* - m(P - P^*) \quad (2.1)$$

$$V = V^* - n(Q - Q^*) \quad (2.2)$$

where ω and V are the measured output frequency and voltage, ω^* and V^* are their references. m and n coefficients define the droop slopes are based on steady-state performance criteria [80]. P and Q are calculated active and reactive power, P^* and Q^* are their references. The main limitation of conventional droop control method is that there will be frequency and voltage deviations in the microgrid. To eliminate the deviation caused by droop method, communication between each unit is required for higher level control [81], [82].

2.3.2 Secondary Control

Secondary control, also known as energy management system (EMS), is designed for the stable and efficient operation of microgrids or distribution networks in both grid-connected and islanded condition. Secondary control is the highest level in the control hierarchy for a single system operating in islanded condition. Secondary control usually operates for a longer time scale as compared to the primary control which allows enough time to perform complex calculations. The communication bandwidth requirement can be reduced by using sampled measurements of the system variables. The low bandwidth communication can be easily achieved in distribution networks or microgrids with limited geographical area with standard communication protocols, which only requires slowly changing parameters such as set point for real and reactive power [83]. Generally, the functions of secondary

control include energy management, frequency and voltage restoration, increasing power sharing accuracy and power quality enhancement.

The secondary control can be realized in a centralized or distributed architecture. The implementation of a centralized architecture needs all the required control data and information can be collected simultaneously and optimized at a central controller. Furthermore, the centralized EMS does not provide the DG units with plug and play capability. On the contrary, a distributed architecture allows new DG units to be integrated into distribution grid easily without requiring any changes to the control settings. However, the employment of a distributed controller requires proper algorithms to coordinate between the DG units. The control architectures of centralized and distributed secondary control are shown in Figure 2.3. The centralized and distributed control architectures to realize secondary control are described in detail in following subsections.

Figure 2.3 Control architectures of centralized and distributed secondary control.

1) Centralized Architecture

In the approach to realize a centralized secondary control, important information such as the generation capacities and the operating limits of DG units, load

measurements from smart meters and energy sensors, transformer tap positions and circuit breaker status are all transmitted to a central controller for monitoring and processing either through wireline or wireless communication technologies. Based on the information gathered, the central controller will compute an appropriate optimal operating condition for the microgrid and generate the reference power and voltage set-points for the primary controllers of all the DG units.

The centralized energy management of microgrid is usually formulated into a multi-objective optimization problem and different techniques have been proposed in several research works [84], [85]. To address the renewable penetration into microgrid, the authors in [84] propose the off-line optimization approach to achieve energy management for a single microgrid system. To minimize the total energy cost of the conventional energy drawn from the main grid over a finite horizon, this approach optimizes the energy charged/discharged by ESSs over time subject to practical load and storage constraints. A centralized energy management method for a microgrid that includes RESs, diesel generators, battery ESSs and various loads is proposed in [85]. To address various uncertainties, a risk-constrained scenario-based stochastic programming framework is proposed using the conditional value at risk method. The designed model is solved by two levels of stochastic optimization methods.

There are also many research works focusing on grid ancillary services using the secondary central controller [86]-[88]. A centralized control system that coordinates parallel operations of different DG inverters within a microgrid is proposed in [86]. A novel MPC algorithm is employed by the control design for the DG inverters, which allows faster computational time for large power systems by optimizing the steady-state and the transient control problems separately. Harmonic compensation, load sharing, voltage regulation and fault level increase is achieved by coordinate

control of different DG units during both grid-connected and islanded operations. In order to have a reliable communication with minimal end-to-end delay during the event of node failure, a find reliable link scheme is proposed in [87]. The low bandwidth communication among the distributed generators and control center can overcome the system operation challenges posed by network line parameters, failure of distributed generators and power shortage in the system. In [88], a vehicle-to-grid reactive power support strategy for optimal coordinated voltage regulation in distribution networks with high DG penetration is presented. The voltage regulation problem is formulated as a nonlinear programming in the centralized control and consists of three consecutive stages, in which successive stages apply the outputs of their preceding stages as constraints.

2) Distributed Architecture

The decentralized secondary control aims to manage the energy in a microgrid while allowing all DG units and loads to operate independently. Although the decentralized control approach still employs a hierarchical architecture consisting of a central controller and several local controllers for the exchange of data, the key feature that distinguishes itself from the centralized control approach is that the decisions on the control variables are made at the local controllers. The central controller is responsible for managing the overall operation of the microgrid together with the distribution grid to achieve economical and reliable operation while the task of the local controllers is to control individual DG units or an aggregation of them to meet both local and global objectives by communicating with other local controllers and the central controller [89].

To achieve the distributed secondary control architecture, the multi-agent system (MAS) framework has been proposed in many research works [90]-[92]. In the MAS, large complex control tasks are decomposed into simpler and manageable ones, and are then allocated to various intelligent agents which are provided with

local information to achieve multiple local and global objectives, without any intervention from the central controller. The distributed management of building energy system with MAS control architecture is proposed in [90]. This method utilizes a semi-centralized decision-making methodology for battery energy management system for electrical, heating, and cooling energy zones with combined heat and power system optimizations aimed at improving energy efficiency and reducing energy costs. In [91], DG units and price-sensitive loads are proposed to participate in a microgrid energy market. Each DG unit and price-sensitive load are controlled by the respective agents which performs various functions such as scheduling, coordination and market clearing subject to the DG unit and load constraints. Every agent is assigned to one of objectives of other agents to maximize DG unit and load surpluses. The authors in [92] illustrate the application of a MAS-based scheme for the optimization problem in power system. The voltage regulation problem is solved by dispatching the power outputs of DG units on a distribution feeder using MAS based control net protocol. Fast communication speed among the DGs is required to ensure fast response time in emergency conditions.

2.3.3 Tertiary Control

Tertiary control is the highest level of control and to manage the operation of the microgrid in grid-connected condition. Depending on the requirements of the utility grid, tertiary control sets long-term and optimal set points for lower level controller. The tertiary control is responsible for coordinating the operations of several microgrids interacting with each other in the system, and communicating requirements like unit commitment, economic dispatch, optimal power flow, voltage support and frequency regulation from the main power grid. This control level typically operates in tens of minutes, providing signals to secondary level controls at microgrids and other subsystems that form the full grid. Tertiary control can be

considered as a part of the main utility grid, and not the microgrid. This control level is not discussed further in this thesis [93].

2.4 Consensus Algorithm

Consensus problems have a long history in computer science and form the foundation of the field of distributed computing. Formal study of consensus problems in groups of experts was originated in management science and statistics in 1960s [94]. In recent years, the consensus problem of MAS has received increasingly attention. This is partly due to the applications of MAS in many areas such as cooperative control of automatic vehicles, flocking of birds, distributed sensor networks, attitude alignment for cluster of satellites and congestion control in communication networks [95]. When multiple agents agree to the value of a variable of interest, they are said to have reached consensus. Information consensus guarantees that agents sharing information over a communication network topology have a consistent view of information that is critical to the coordination task. To achieve consensus, there must be a shared variable of interest, called the information state, as well as appropriate algorithmic methods for negotiating to reach consensus on the value of that variable, called the consensus algorithms. In general, consensus algorithms are designed to be distributed, assuming only neighbor-to-neighbor interaction between each agent. Each agent updates the value of their information states based on the information states of their neighbors. The goal is to design an updated control law so that the information states of all the agents in the network converge to a common value. The graph theory and consensus algorithm are introduced as follows:

The communication network of a multi-agent system can be described by a graph, which is defined as $G = (V, E)$ with a set of N nodes $V = \{v_1, v_2, \dots, v_N\}$ and a set of

edges $E = V \times V$. Each node is assigned with an agent in the system, and edges represent communication links for data exchange. If communication links are bidirectional, $(v_i, v_j) \in E \Rightarrow (v_j, v_i) \in E \forall i, j$, the graph is said to be undirected, otherwise it is directed. The set of neighbors of i th node is denoted N_i . Equivalently, if $j \in N_i$, then v_i receives information from v_j . A matrix called adjacency matrix $\mathbf{A} = [a_{ij}]$ is associated to the edges. A_{ij} represents the weight for information exchanged between agents i and j , where $a_{ij} > 0$ if agents i and j are connected through an edge $(v_i, v_j) \in E$, otherwise, $a_{ij} = 0$. The Laplacian matrix $\mathbf{L}$ is defined as $\mathbf{L} = \mathbf{D} - \mathbf{A}$, where $\mathbf{D}$ is called in-degree matrix and is defined as $\mathbf{D} = \text{diag}\{d_i\}$ with $d_i = \sum_{j \in N} a_{ij}$. A directed path from node i to node j is a sequence of edges. A leader node can be added to the graph and connected to at least one node by unidirectional edges. The nodes connected to the leader node and the corresponding connecting edge are called pinned nodes and pinning edge respectively [96], [97].

In the cooperative synchronization problem, also called leaderless consensus, all agents synchronize to a common value that is not prescribed. Each agent updates the information state with the most common continuous-time consensus algorithm given by

$$\dot{x}_i(t) = \sum_{j \in N_i} a_{ij}(t)(x_j(t) - x_i(t)) \quad (2.3)$$

where $i=1,2,\dots, n$; n is the number of agents in the system; x_i and x_j are the information states of agent i and its neighboring agent j .

While in the tracking synchronization problem, also called pinning control, all agents synchronize to leader nodes that act as a command generator. The consensus algorithm updates the information state for both pinned and unpinned agents as

$$\dot{x}_i(t) = \sum_{j=1}^n a_{ij}(t)(x_j(t) - x_i(t)) + g_i(x_{ref}(t) - x_i(t)), i = 1, \dots, n. \quad (2.4)$$

where x_{ref} and g_i are the local set point and pinning gain of the i th agent respectively. The pinning gain g_i is positive if the agent i is pinned by a leader node, and is zero otherwise.

Consensus based distributed control has been adopted by many research works in controlling the DG units in distribution networks [98]-[101]. In [98], a fully distributed multi agent based load restoration algorithm is proposed. According to the algorithm, each agent makes synchronized load restoration decision according to discovered information. The author extends his work and apply the consensus based distributed control for optimal charging rate control of plug-in EVs in [99]. The proposed strategy is implemented based on a multi-agent system framework, which is convenient for plug and play operation which allows EVs to join and leave at arbitrary times. In [100], a distributed control algorithm that controls the power output of multiple PV generators in a distribution network is developed. The consensus based cooperative control method is applied to make distributed PV generators converge and operate at a certain ratio of power outputs, which is determined by the conditions of the distribution network. In [101], a distributed control and generation estimation approach is developed to dispatch multiple DGs, each of which consists of a PV and a controllable load. A distributed weights adjustment algorithm adaptively makes the adjacency matrix doubly stochastic so that the aggregated power generation capacity can be estimated. Then, the expected consensus operational point of the DGs is calculated by those DGs that can obtain power dispatch command from the supervisory control and data acquisition system and is propagated to the rest of the DGs with a consensus algorithm.

The consensus algorithm has also been widely applied for secondary and tertiary

control in microgrids in many research works [102]-[104]. In [102], a distributed control approach is proposed for the voltage restoration which enables the voltages of all the DG units converging to the reference values in finite time. In the meantime, frequency restoration is realized by a consensus-based distributed frequency control, considering constraints of certain control input. A distributed hierarchical control framework to ensure reliable operation of dc microgrid clusters is proposed in [103]. In the secondary level of the hierarchical control, a distributed consensus-based voltage regulator is introduced to eliminate the average voltage deviation in the microgrids. Then another distributed policy is employed to regulate the power flow among the microgrids according to their local SOC. A distributed tertiary control method is proposed to handle power sharing among a cluster of dc microgrids in [104]. The load sharing among the DERs within a dc microgrid is managed by primary and secondary control. The tertiary level control is required to provide the higher level load sharing among multiple microgrids within a cluster. The proposed control method applies a cooperative approach to adjust voltage set points for each individual microgrid and navigate the power flow among them accordingly. An updating policy using load mismatch among neighbor microgrids is also proposed to adjust voltage set points and mitigate such mismatches.

2.5 Summary

The integration of power electronic interfaced DG units into the existing power systems will continue increasing in the near future due to rapid advancement of technological and liberalization of the electricity market. However, the high penetration of RESs and EVs with intermittent and stochastic characteristics will bring along many stability, reliability and power quality issues in future power systems. The main challenges that should be taken into consideration include, but not limited to, the stability problems caused by low inertia of power electronic interfaced systems, the reliability of DG units and communication based control

strategies, and the power quality issues caused by the integration of DG units. Particularly, the power generation and load demand mismatch caused by the variability of RESs will lead to severe frequency and voltage control problems. Therefore, the development of suitable control strategies is essential to ensure reliable and stable operation of power systems. Furthermore, the coordinated control of large amount of DG units having different operating characteristics and constraints will pose a great challenge due to limited communication and possible conflicting operating requirements between the different types of DG units.

In this chapter, many research works related to increasing the integration of renewable energy into the existing power systems and the power quality issues caused by high renewable penetration have been reviewed. However, there are still limitations and gaps of existing works which require further research attention. When the penetration rate of RESs is further increasing at different voltage levels of power systems, there will be various problems to be solved. At transmission voltage level, the high penetration of RESs will bring new frequency and stability issues. At distribution level, the load profiles of demand side as well as the voltage profiles of distribution networks will change dramatically due to the increasing penetration of DG units. Especially for LV residential networks, the system R/X ratio is high and bus voltages are very sensitive to real power output, which make the voltage regulation methods quite different compared with high voltage levels. The research work of this thesis is focused on voltage regulation issues in residential LV networks and it is a challenge to promote future renewable penetration. In addition, the battery characteristics of ESSs and EVs for voltage regulation application have not been considered by many research works so far. Therefore, proper battery models need to be built and battery parameters such as SoC, efficiency, self-discharge rate, state-of-health, lifetime and cost should be further considered for grid application. Specific control strategies should be designed considering operation constraints and limits of

ESSs and EVs. Furthermore, most research works on voltage regulation problems so far have been achieved in decentralized or centralized control architecture. The main limitation of decentralized control is the lack of global information such that it is hard to achieve coordination between each controllable unit. The application of centralized control architecture for real-time control also faces some drawbacks, such as communication burden and reliability of central controller. As a compromise of decentralized and centralized control, distributed control has become a promising solution for real-time control of DG units which can achieve coordination between DG units with sparse communication. As a typical method to achieve distributed control, consensus algorithm for multi-agent systems has been discussed and adopted in this thesis.

References

- [1] J. N. Baker and A. Collinson, "Electrical energy storage at the turn of the millennium," *Power Engineering Journal*, vol. 13, no. 3, pp. 107–112, Jun. 1999.
- [2] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, "Progress in electrical energy storage system: a critical review," *Progress in Natural Science*, vol. 19, no. 3, pp. 291–312, Mar. 2009.
- [3] S. Vazquez, S. M. Lukic, E. Galvan, L. G. Franquelo, and J. M. Carrasco, "Energy storage systems for transport and grid applications," *IEEE Trans. Industrial Electronics*, vol. 57, no. 12, pp. 3881–3895, Dec. 2010.
- [4] E. Maza, "Grid-connected storage market set to explode," Energy Storage Association, Jan. 2014.
- [5] M. Yilmaz and P. T. Krein, "Review of the impact of vehicle-to-grid technologies on distribution systems and utility interfaces," *IEEE Trans. Power Electronics*, vol. 28, no. 12, pp. 5673–5689, Nov. 2012.
- [6] Energy storage opportunities and challenges. Ecofys, 2014.

- [7] S. M. Schoenung, “Characteristics and technologies for long-term vs. short-term energy storage: a study by the DOE energy storage systems program,” Sandia National Laboratories, SAND2001-0765, Mar. 2001.
- [8] I. Gyuk, M. Johnson, J. Vetrano, K. Lynn, *et al.*, “Grid energy storage,” U.S. Department of Energy, Dec. 2013.
- [9] Grid integration of large-capacity renewable energy sources and use of large-capacity electrical energy storage. International Electrotechnical Commission, 2012.
- [10] H. Ibrahim, A. Ilinca, and J. Perron, “Energy storage systems-characteristics and comparisons,” *Renewable Sustainable Energy Reviews*, vol. 12, no. 5, pp. 1221–1250, Jun. 2008.
- [11] M. Mohamed, P. Leung, and M. Sulaiman, “Performance characterization of a vanadium redox flow battery at different operating parameters under a standardized test-bed system,” *Applied Energy*, vol. 137, pp. 402–412, Jan. 2015.
- [12] T. A. Nguyen, M. L. Crow, and A. C. Elmore, “Optimal sizing of a vanadium redox battery system for microgrid systems,” *IEEE Trans. Sustainable Energy*, vol. 6, no. 3, pp. 729–737, Apr. 2015.
- [13] J. Jaguemont, L. Boulon, and Y. Dube, “Characterization and modeling of a hybrid-electric-vehicle lithium-ion battery pack at low temperatures,” *IEEE Trans. Vehicular Technology*, vol. 65, no. 1, pp. 1–14, Jan. 2015.
- [14] A. Hoke, A. Brissette, K. Smith, A. Pratt, *et al.*, “Accounting for lithium-ion battery degradation in electric vehicle charging optimization,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 3, pp. 691–700, Apr. 2014.
- [15] V. A. Boicea, “Energy storage technologies: The past and the present,” *Proceedings of the IEEE*, vol. 102, no. 11, pp. 1777–1794, Nov. 2014.

- [16] Y. Zhang, C. H. Zhang, and X. F. Zhang, "State-of-charge estimation of the lithium-ion battery system with time-varying parameter for hybrid electric vehicles," *IET Control Theory & Applications*, vol. 8, no. 3, pp. 160–167, Feb. 2014.
- [17] Z. Chen, Y. H. Fu, and C. C. Mi, "State of charge estimation of lithium-ion batteries in electric drive vehicles using extended kalman filtering," *IEEE Trans. Vehicular Technology*, vol. 62, no. 3, pp. 1020–1030, Dec. 2012.
- [18] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, "Mitigation of rooftop solar PV impacts and evening peak support by managing available capacity of distributed energy storage systems," *IEEE Trans. Power Systems*, vol. 28, no. 4, pp. 3874–3884, Nov. 2013.
- [19] G. S. Wang, M. Ciobotaru, and V. G. Agelidis, "Power smoothing of large solar PV plant using hybrid energy storage," *IEEE Trans. Sustainable Energy*, vol. 5, no. 3, pp. 834–842, Mar. 2014.
- [20] X. J. Li, D. Hui, and X. K. Lai, "Battery energy storage station (BESS)-based smoothing control of photovoltaic (PV) and wind power generation fluctuations," *IEEE Trans. Sustainable Energy*, vol. 4, no. 2, pp. 464–473, Mar. 2013.
- [21] I. Serban, R. Teodorescu, and C. Marinescu, "Energy storage systems impact on the short-term frequency stability of distributed autonomous microgrids, an analysis using aggregate models," *IET Renewable Power Generation*, vol. 7, no. 5, pp. 531–539, Sep. 2013.
- [22] J. Dang, J. Seuss, L. Suneja, and R. G. Harley, "SoC feedback control for wind and ESS hybrid power system frequency regulation," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2, no. 1, pp. 79–86, Nov. 2013.

- [23] L. Miao, J. Y. Wen, C. Y. Yue, *et al.*, “Coordinated control strategy of wind turbine generator and energy storage equipment for frequency support,” *IEEE Trans. Industry Applications*, vol. 51, no. 4, pp. 2732–2742, Jan. 2013.
- [24] M. A. Abusara, J. M. Guerrero, and S. M. Sharkh, “Line-interactive UPS for microgrids,” *IEEE Trans. Industrial Electronics*, vol. 61, no. 3, pp. 1292–1300, May 2013.
- [25] J. Y. Kim, J. H. Jeon, S. K. Kim, C. H. Cho, *et al.*, “Cooperative control strategy of energy storage system and microsources for stabilizing the microgrid during islanded operation,” *IEEE Trans. Power Electronics*, vol. 25, no. 12, pp. 3037–3048, Sep. 2010.
- [26] H. Kakigano, Y. Miura, and T. Ise, “Distribution voltage control for DC microgrids using fuzzy control and gain-scheduling technique,” *IEEE Trans. Power Electronics*, vol. 28, no. 5, pp. 2246–2258, Sep. 2012.
- [27] X. N. Lu, K. Sun, J. M. Guerrero, J. C. Vasquez, *et al.*, “State-of-charge balance using adaptive droop control for distributed energy storage systems in DC microgrid applications,” *IEEE Trans. Industrial Electronics*, vol. 61, no. 6, pp. 2804–2815, Aug. 2013.
- [28] H. K. Hguyen, J. B. Song, and Z. Han, “Distributed demand side management with energy storage in smart grid,” *IEEE Trans. Parallel and Distributed Systems*, vol. 26, no. 12, pp. 3346–3357, Nov. 2014.
- [29] M. Mahmoodi, P. Shamsi, and B. Fahimi, “Economic dispatch of a hybrid microgrid with distributed energy storage,” *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2607–2614, Feb. 2015.
- [30] S. U. Agamah and L. Ekonomou, “Peak demand shaving and load-levelling using a combination of bin packing and subset sum algorithms for electrical energy storage system scheduling,” *IET Science, Measurement & Technology*, vol. 10, no. 5, pp. 477–484, Jul. 2016.

- [31] Y. Yang, H. Li, A. Aichhorn, J. P. Zheng, *et al.*, “Sizing strategy of distributed battery storage system with high penetration of photovoltaic for voltage regulation and peak load shaving,” *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 982–991, Sep. 2013.
- [32] A. S. A. Awad, T. H. M. El-fouly, and M. M. A. Salama, “Optimal ESS allocation for benefit maximization in distribution networks,” *IEEE Trans. Smart Grid*, in press.
- [33] D. Wu, D. C. Aliprantis, and L. Ying, “Load scheduling and dispatch for aggregators of plug-in electric vehicles,” *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 368–376, Mar. 2012.
- [34] SAE electric vehicle and plug-in hybrid electric vehicle conductive charge coupler, SAE Standard J1772, Jan. 2010.
- [35] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, “A controllable local peak-shaving strategy for effective utilization of PEV battery capacity for distribution network support,” *IEEE Trans. Industry Applications*, vol. 51, no. 3, pp. 2030–2037, Nov. 2014.
- [36] A. Schuller, *et al.*, “Charging strategies for battery electric vehicles: economic benchmark and V2G potential,” *IEEE Trans. Power System*, vol. 29, no. 5, pp. 2014–2022, Sep. 2014.
- [37] M. Singh, P. Kumar, and I. Kar, “A multi charging station for electric vehicles and its utilization for load management and the grid support,” *IEEE Trans. Smart Grid*, vol. 4, no. 2, pp. 1026–1037, Jan. 2013.
- [38] H. Liu, Z. H. Hu, Y. H. Song, J. H. Wang, *et al.*, “Vehicle-to-grid control for supplementary frequency regulation considering charging demands,” *IEEE Trans. Power Systems*, vol. 30, no. 6, pp. 3110–3119, Dec. 2014.
- [39] H. Liu, Z. H. Hu, Y. H. Song, and J. Lin, “Decentralized vehicle-to-grid control for primary frequency regulation considering charging demands,” *IEEE Trans. Power Systems*, vol. 28, no. 3, pp. 3480–3489, Mar. 2013.

- [40] M. A. Azzouz, M. F. Shaaban, and E. F. El-Saadany, "Real-time optimal voltage regulation for distribution networks incorporating high penetration of PEVs," *IEEE Trans. Power Systems*, vol. 30, no. 6, pp. 3234–3245, Jan. 2015.
- [41] Y. Ota, H. Taniguchi, T. Nakajima, K. M. Liyanage, *et al.*, "Autonomous distributed V2G (vehicle-to-grid) satisfying scheduled charging," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 559-564, Oct. 2011.
- [42] S. Weckx and J. Driesen, "Load balancing with EV chargers and PV inverters in unbalanced distribution grids," *IEEE Trans. Sustainable Energy*, vol. 6, no. 2, pp. 635–643, Mar. 2015.
- [43] R. Tonkoski, D. Turcotte, and T. H. M. El-Fouly, "Impact of high PV penetration on voltage profiles in residential neighborhoods," *IEEE Trans. Sustainable Energy*, vol. 3, no. 3, pp. 518-527, Jul. 2012.
- [44] M. Hasheminamin, V. G. Vassilios, V. Salehi, R. Teodorescu, *et al.*, "Index-based assessment of voltage rise and reverse power flow phenomena in a distribution feeder under high PV penetration," *IEEE Journal of Photovoltaics*, vol. 5, no. 4, pp. 1158-1168, May 2015.
- [45] G. G. Pillai, G. A. Putrus, and N. M. Pearsall, "Impact of distribution network voltage rise on PV system energy yield," in *Proc. 2013 Annual IEEE India Conference (INDICON)*, Dec. 2013, pp. 1-5.
- [46] C. Zhang, C. Chen, J. W. Sun, P. W. Zheng, *et al.*, "Impacts of electric vehicles on the transient voltage stability of distribution network and the study of improvement measures," in *Proc. 2014 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, pp. 1-6, Dec. 2014.
- [47] X. Luo and K. W. Chan, "Real-time scheduling of electric vehicles charging in low-voltage residential distribution systems to minimise power losses and improve voltage profile," *IET Generation, Transmission and Distribution*, vol. 8, no. 3, pp. 516-529, Mar. 2014.

- [48] P. Richardson, D. Flynn, and A. Keane, "Optimal charging of electric vehicles in low-voltage distribution systems," *IEEE Trans. Power Systems*, vol. 27, no. 1, pp. 268-279, Jun. 2011.
- [49] C. L. Masters, "Voltage rise: The big issue when connecting embedded generation to long 11kV overhead lines," *Power Engineering Journal*, vol. 16, pp. 5-12, 2002.
- [50] M. E. Elkhatab, R. El Shatshat, and M. M. A. Salama, "Optimal control of voltage regulators for multiple feeders," *IEEE Trans. Power Delivery*, vol. 25, no. 4, pp. 2670-2675, Dec. 2009.
- [51] H. Ravindra, M. O. Faruque, K. Schoder, M. Steurer, *et al.*, "Dynamic interactions between distribution network voltage regulators for large and distributed PV plants," in *Proc. Transmission and Distribution Conference and Exposition (T&D)*, May 2012, pp. 1-8.
- [52] S. Kongtripop, T. Kasirawat, C. Pongsriwat, and S. Premrudeepreechacharn, "Effect of voltage variation from distributed generation on very long distribution line with multiple voltage regulators," in *Proc. 2009 Asia-Pacific Power and Energy Engineering Conference*, Mar. 2009, pp. 1-4.
- [53] M. Todorovski, "Transformer voltage regulation-compact expression dependent on tap position and primary/secondary voltage," *IEEE Trans. Power Delivery*, vol. 29, no. 3, pp. 1516-1517, Apr. 2014.
- [54] B. A. Robbins, H. Zhu, and A. D. Dominguez-Garcia, "Optimal tap setting of voltage regulation transformers in unbalanced distribution dystems," *IEEE Trans. Power Systems*, vol. 31, no.1, pp. 256-267, Feb. 2015.
- [55] S. Ghosh, S. Rahman, and M. Pipattanasomporn, "Distribution voltage regulation through active power curtailment with PV inverters and solar generation forecasts," *IEEE Trans. Sustainable Energy*, in press.
- [56] R. Tonkoski, L. A. C. Lopes, and T. H. M. El-Fouly, "Droop-based active power curtailment for overvoltage prevention in grid connected PV inverters,"

- in *Proc. 2010 IEEE International Symposium on Industrial Electronics*, pp. 2388-2393, Jul. 2010.
- [57] P. M. S. Carvalho, P. F. Correia, and L. A. F. Ferreira, "Distributed reactive power generation control for voltage rise mitigation in distribution networks," *IEEE Trans. Power Systems*, vol. 23, no. 2, pp. 766–772, May 2008.
- [58] P. Jahangiri and D. C. Aliprantis, "Distributed volt/var control by PV inverters," *IEEE Trans. Power Systems*, vol. 28, no. 3, pp. 3429-3439, Aug. 2013.
- [59] X. H. Liu, A. Aichhorn, L. M. Liu, and H. Liu, "Coordinated control of distributed energy storage system with tap changer transformers for voltage rise mitigation under high photovoltaic penetration," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 897-906, Feb. 2012.
- [60] M. N. Kabir, Y. Mishra, G. Ledwich, Z. Y. Dong, *et al.*, "Coordinated control of grid-connected photovoltaic reactive power and battery energy storage systems to improve the voltage profile of a residential distribution feeder," *IEEE Trans. Industrial Informatics*, vol. 10, no. 2, pp. 967-977, Jan 2014.
- [61] X. Luo, C. K. Lee, W. M. Ng, *et. al*, "Use of adaptive thermal storage system as smart load for voltage control and demand response," to be published *IEEE Trans. Smart Grid*.
- [62] K. Christakou, D. C. Tomozei, J. Y. Leboudec, and M. Paolone, "GECN: primary voltage control for active distribution networks via real-time demand-response," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 622-631, Mar. 2014.
- [63] N. Pogaku, M. Prodanovic, and T. C. Green, "Modeling, analysis and testing of autonomous operation of an inverter-based microgrid," *IEEE Trans. Industrial Electronics*, vol. 22, no. 2, pp. 613-625, Mar. 2007.
- [64] M. D. Ilic and S. X. Liu, *Hierarchical Power Systems Control: Its Value in a Charging Industry (Advances in Industrial Control)*. London: Springer, 1966.

- [65] Y. A.-R. I. Mohamed and A. A. Radwan, "Hierarchical control system for robust microgrid operation and seamless mode transfer in active distribution systems," *IEEE Trans. Smart Grid*, vol. 2, no. 2, pp. 352-362, Jan. 2011.
- [66] A. Bidram and A. Davoudi, "Hierarchical structure of microgrids control system," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1963-1976, Dec. 2012.
- [67] R. Majumder, G. Bag, and K. H. Kim, "Power sharing and control in distributed generation with wireless sensor networks," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 618-634, Jun. 2012.
- [68] F. Katiraei, M. R. Iravani, and P. W. Lehn, "Micro-grid autonomous operation during and subsequent to islanding process," *IEEE Trans. Power Delivery*, vol. 20, no. 1, pp. 248-257, Jan. 2005.
- [69] C. T. Lee, R. P. Jiang, and P. T. Cheng, "A grid synchronization method for droop-controlled distributed energy resource converters," *IEEE Trans. Industry Application*, vol. 49, no. 2, pp. 954-962, Jan. 2013.
- [70] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Industrial Electronics*, vol. 53, no. 5, pp. 1398-1409, Oct. 2006.
- [71] A. Timbus, M. Liserre, R. Teodorescu, P. Rodriguez, and F. Blaabjerg, "Evaluation of current controllers for distributed power generation systems," *IEEE Trans. Power Electronics*, vol. 24, no. 3, pp. 654-664, Mar. 2009.
- [72] J. T. Bialasiewicz, "Renewable energy systems with photovoltaic power generators: Operation and modeling," *IEEE Trans. Industrial Electronics*, vol. 55, no. 7, pp. 2752-2758, Jul. 2008.
- [73] P. Cortes, G. Ortiz, J. I. Yuz, J. Rodriguez, J. Vazquez, and L. G. Franquelo, "Model predictive control of an inverter with output LC filter for UPS applications," *IEEE Trans. Industrial Electronics*, vol. 56, no. 6, pp. 1875-1883, Feb. 2009.

- [74] S. Kouro, P. Cortes, R. Vargas, U. Ammann, and J. Rodriguez, "Model predictive control-A simple and powerful method to control power converters," *IEEE Trans. Industrial Electronics*, vol. 56, no. 6, pp. 1826-1838, Jun. 2009.
- [75] J. Rodriguez, M. P. Kazmierkowski, J. R. Espinoza, P. Zanchetta, et al., "State of the art of finite control set model predictive control in power electronics," *IEEE Trans. Industrial Informatics*, vol. 9, no. 2, pp. 1003-1016, May 2013.
- [76] G. Mirzaeva, G. C. Goodwin, B. P. McGrath, C. Teixeira, et al., "A generalized MPC framework for the design and comparison of VSI current controllers," *IEEE Trans. Industrial Electronics*, in press.
- [77] H. Miranda, R. Teodorescu, P. Rodriguez, and L. Helle, "Model predictive current control for high-power grid-connected converters with output LCL filter," *2009 35th Annual Conference of IEEE Industrial Electronics*, Nov. 2009, pp. 633-638.
- [78] J. A. P. Lopes, C. L. Moreira, and A. G. Madureira, "Defining control strategies for microgrids islanded operation," *IEEE Trans. Power Systems*, vol. 21, no. 2, pp. 916-924, May 2006.
- [79] J. C. Vasquez, J. M. Guerrero, E. Gregorio, P. Rodriguez, R. Teodorescu, and F. Blaabjerg, "Adaptive droop control applied to distributed generation inverters connected to the grid," in *Proc. IEEE International Symposium on Industrial Electronics ISIE'08*, 2008, pp. 1-6.
- [80] Y. Li, D. M. Vilathgamuwa, and P. C. Loh, "Design, analysis, and real-time testing of a controller for multibus microgrid system," *IEEE Trans. Power Electronics*, vol. 19, no. 5, pp. 1195-1204, Sep. 2004.
- [81] J. C. Vasquez, J. M. Guerrero, M. Savaghebi, J. E. Garcia, et al., "Modeling, analysis, and design of stationary-reference-frame droop-controlled parallel three-phase voltage source inverters," *IEEE Trans. Industrial Electronics*, vol. 60, no. 4, pp. 1271-1280, Apr. 2012.

- [82] C. Ahumada, R. Cardenas, D. Saez, and J. M. Guerrero, "Secondary control strategies for frequency restoration in islanded microgrids with consideration of communication delays," *IEEE Trans. Smart Grid*, vol. 7, no. 3, pp. 1430-1441, Aug. 2015.
- [83] M. Prodanovic and T. C. Green, "High-quality power generation through distributed control of a power park microgrid," *IEEE Trans. Industrial Electronics*, vol. 53, no. 5, pp. 1471-1482, Oct. 2006.
- [84] K. Rahbar, J. Xu, and R. Zhang, "Real-time energy storage management for renewable integration in microgrid: an off-line optimization approach," *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 124-134, Sep. 2014.
- [85] J. S. Shen, G. Bag, and K. H. Kim, "A microgrid energy management system and risk management under an electricity market environment," *IEEE Access*, vol. 4, pp. 2349-2356, Apr. 2016.
- [86] K. T. Tan, X. Y. Peng, P. L. So, Y. C. Chu, *et al.*, "Centralized control for parallel operation of distributed generation inverters in microgrids," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1977-1987, Aug. 2012.
- [87] R. Majumder, C. W. Jiang, Y. Y. Liu, and X. Wang, "Power sharing and control in distributed generation with wireless sensor networks," *IEEE Trans. Smart Grid*, vol. 3, no. 2, pp. 618-634, Feb. 2012.
- [88] M. A. Azzouz, M. F. Shaaban, and E. F. El-Saadany, "Real-time optimal voltage regulation for distribution networks incorporating high penetration of PEVs," *IEEE Trans. Power Systems*, vol. 30, no. 6, pp. 3234-3245, Jan. 2015.
- [89] F. Katiraei, M. R. Iravani, N. Hatziargyriou, and A. Dimeas, "Microgrids management: Controls and operation aspects of microgrids," *IEEE Power and Energy Magazine*, vol. 6, no. 3, pp. 54-65, 2008.
- [90] P. Zhao, S. Suryanarayanan, and M. G. Simoes, "An energy management system for building structures using a multi-agent decision-making control

- methodology,” *IEEE Trans. Industry Applications*, vol. 49, no. 1, pp. 322-330, Nov. 2012.
- [91] Y. S. F. Eddy, H. B. Gooi, and S. X. Chen, “Multi-agent system for distributed management of microgrids,” *IEEE Trans. Power Systems*, vol. 30, no. 1, pp. 24-34, May 2014.
- [92] M. E. Baran and I. M. El-Markbi, “A multiagent-based dispatching scheme for distributed generators for voltage support on distribution feeders,” *IEEE Trans. Power Systems*, vol. 22, no. 1, pp. 52-59, Feb. 2007.
- [93] D. E. Olivares, A. M. Sani, A. H. Etemadi, C. A. Canizares, et al., “Trends in microgrid control,” *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1905-1919, May 2014.
- [94] R. O. Saber, J. A. Fax, and R. M. Murray, “Consensus and cooperation in networked multi-agent systems,” *Proceedings of the IEEE*, vol. 95, no. 1, pp. 215-233, Jan. 2007.
- [95] R. O. Saber and R. M. Murray, “Consensus problems in networks of agents with switching topology and time-delay,” *IEEE Trans. Automatic Control*, vol. 49, no. 9, pp. 1520-1533, Sep. 2004.
- [96] C. Godsil and G. Royle, *Algebraic Graph Theory*. New York, NY, USA: Springer, 2001.
- [97] Z. Qu, *Cooperative Control of Dynamic Systems: Applications to Autonomous Vehicles*. New York, NY, USA: Springer-Verlag, 2009.
- [98] Y. L. Xu and W. X. Liu, “Novel multiagent based load restoration algorithm for microgrids,” *IEEE Trans. Smart Grid*, vol. 2, no. 1, pp. 152-161, Mar. 2011.
- [99] Y. L. Xu, “Optimal distributed charging rate control of plug-in electric vehicles for demand management,” *IEEE Trans. Power Systems*, vol. 30, no. 3, pp. 1536-1545, May 2015.

- [100] H. H. Xin, Z. H. Qu, J. Seuss, and A. Maknouninejad “A self-organizing strategy for power flow control of photovoltaic generators in a distribution network,” *IEEE Trans. Power Systems*, vol. 26, no. 3, pp. 1462-1473, Aug. 2011.
- [101] H. H. Xin, Y. Liu, Z. H. Qu, and D. Q. Gan, “Distributed control and generation estimation method for integrating high-density photovoltaic systems,” *IEEE Trans. Energy Conversion*, vol. 29, no. 4, pp. 988-996, Sep. 2014.
- [102] F. H. Guo, C. Y. Wen, J. F. Mao, and Y. D. Song, “Distributed secondary voltage and frequency restoration control of droop-controlled inverter-based microgrids,” *IEEE Trans. Industrial Electronics*, vol. 62, no. 7, pp. 4355-4364, Dec. 2014.
- [103] Q. Shafiee, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, “Hierarchical control for multiple dc-microgrids clusters,” *IEEE Trans. Energy Conversion*, vol. 29, no. 4, pp. 922-933, Oct. 2014.
- [104] S. Moayedi and A. Davoudi, “Distributed tertiary control of dc microgrid clusters,” *IEEE Trans. Power Electronics*, vol. 31, no. 2, pp. 1717-1733, Feb. 2016.

Chapter 3*

Coordinated Control of Distributed Energy Storage Systems for Voltage Regulation in Distribution Networks

In this chapter, distributed energy storage systems are proposed to solve the voltage rise/drop issues in LV distribution networks with high penetration of rooftop PVs. The impact of energy storage integrated with PV source on feeder voltages is investigated in detail. A coordinated control method which includes both distributed and localized controls is proposed to control the operation of distributed ESSs.

*This chapter published substantially as Y. Wang, K. T. Tan, and P. L. So, “Coordinated control of distributed energy storage systems for voltage regulation in distribution networks,” *IEEE Trans. Power Delivery*, vol. 31, no. 3, pp. 1132-1141, Jul. 2015.

3.1 Introduction

This chapter addresses how to coordinate distributed ESSs in LV distribution networks for voltage regulation. The capacity and SoC of each ESS are taken into account to accommodate daily operation. A coordinated control method which includes both distributed and localized controls is proposed. For the distributed control, a consensus algorithm is proposed to regulate voltages along the distribution feeder. If the voltages at certain buses violate voltage limits, the consensus algorithm will estimate the power outputs of ESSs to eliminate the voltage violation. For localized control, a SoC control strategy is proposed to control the SoC of each ESS. The SoC control avoids depletion or saturation of ESSs for different operation conditions. The entire control method ensures voltage regulation while effectively utilizes all available capacities of ESSs in the system. The ESS is modeled as VRB whose SoC is estimated for the SoC control. Various case studies are implemented to verify the performance of the proposed method.

3.2 Problem Description and Analysis

Figure 3.1 A typical radial distribution feeder with multiple buses.

A typical radial distribution feeder with multiple buses as shown in Figure 3.1 is used to illustrate the voltage rise/drop issues. In Figure 3.1, each bus comprises a PV source, an ESS and a local load, which is viewed as a customer. The integration of ESS into PV source forms a dispatchable DG unit, which is convenient to control for both grid-connected and islanded operations [1].

Generally, the power imbalance between PV generation and load demand will cause power flow along the distribution feeder. Depending on the direction and amount of the power flow, voltages along the feeder will rise/drop to some extent. Especially at the end of the feeder, the voltage may exceed the limits during peak PV generation or peak load period. Distribution networks are usually allowed a maximum voltage deviation of 5%-10% (depend on national standards) from the secondary transformer to the customer located at the end of the feeder [2]. Therefore, methods that reduce the power imbalance between PV generation and load demand can mitigate the voltage rise/drop issues. This can be achieved by utilizing distributed ESSs at the customer side. The functions of ESSs are to reduce the net power injection at each bus during the day and reduce the power absorption during the night. Therefore, the current flow in the distribution feeder will be reduced so that the voltage at the end of the feeder will be regulated within the voltage limits.

Figure 3.2 shows the voltage magnitudes along radial distribution feeder. The voltage rise along the feeder during peak PV generation period is shown in Figure 3.2(a). The voltage drop along the feeder during peak load period is shown in Figure 3.2(b). The solid line shows the voltage along the feeder with only PV penetration. In this condition, the voltage at the end of the feeder exceeds the voltage limits. With proper operation of ESSs, the power imbalance between PVs and loads will be reduced. The voltages along the feeder will be regulated to the dashed line which is within the limits. This problem is further illustrated as follows.

Figure 3.2 Voltage magnitudes along radial distribution feeder. (a) Voltage rise. (b) Voltage drop.

Considering the radial feeder shown in Figure 3.1, from the perspective of power injection, the complex power injected at i th bus S_i is composed of PV power, ESS power and load power. The voltage relationship and current flow between $(i-1)$ th bus and i th bus in vector form can be expressed by using power flow analysis as follows:

$$S_i = V_i I_{inj,i}^* \quad (3.1)$$

$$I_i = \sum_{k=i}^N I_{inj,k} = \sum_{k=i}^N \frac{S_k^*}{V_k^*} \quad (3.2)$$

$$V_i = V_{i-1} + I_i (R_i + jX_i) \quad (3.3)$$

where V_i and V_i^* are the voltage and its conjugate at i th bus, $I_{inj,i}$ is the current injected at i th bus, I_i and $R_i + jX_i$ are the current and impedance between $(i-1)$ th bus and i th bus. The voltage deviation between two adjacent buses can be expressed using the real part in (3.3)

$$\Delta V_i = V_i - V_{i-1} = \frac{\sum_{k=i}^N P_k \cdot R_k + \sum_{k=i}^N Q_k \cdot X_k}{V_{i-1}} \quad (3.4)$$

Thus the voltage deviation between the transformer bus V_0 and the last bus V_N can

be derived as

$$V_N - V_0 = \sum_{i=1}^N \Delta V_i = \sum_{i=1}^N \frac{\sum_{k=i}^N P_k \cdot R_k + \sum_{k=i}^N Q_k \cdot X_k}{V_{i-1}} \quad (3.5)$$

where P_k and Q_k are the real and reactive power injected at i th bus respectively.

According to (3.4) and (3.5), both real and reactive power can be utilized to reduce the voltage deviation. However, for typical distribution networks with large R/X ratio, real power is more effective to compensate the voltage deviation compared to reactive power. Large amount of reactive power requires higher power rating inverters and leads to higher losses as well as lower power factors along the LV distribution feeder [3]. In the meantime, compared with PV curtailment method proposed in [2], the utilization of ESSs can improve the efficiency of PV generation. In this chapter, the function of ESSs is to reduce the real power injected by customers during the day and the real power absorbed by customers during the night. Therefore, the current flow in the distribution feeder will be reduced so that the voltage rise/drop along the feeder can be mitigated.

3.3 Proposed Control Method

The structure of the proposed control method for customer at i th bus is shown in Figure 3.3, in which the solid lines show the power flow and the dotted lines show the control signal flow. For each customer, PV panels and storage devices are fed to the DC link through the boost converter and the bidirectional converter respectively. The power transfer between the DC link and the AC grid is achieved by the DC/AC inverter. Maximum power point tracking (MPPT) control is adopted by the PV panels to obtain the power reference of the boost converter.

Figure 3.3 The structure of proposed control method for customer at i th bus.

As mentioned before, the objective of this research is to coordinate distributed ESSs for voltage regulation while effectively utilizes the available storage capacity under various operation conditions. The proposed control method includes both distributed and localized controls to achieve this goal. As shown in Figure 3.3, the distributed control signal utilization ratio u_i is generated by a consensus algorithm which is used to regulate the feeder voltages with distributed ESSs. The localized control signal availability ratio ϵ_i is provided by SoC control which is used to regulate the SoC of each ESS within the desired SoC range. Finally, the power output of the ESS is determined by multiplying u_i and ϵ_i with its rated power. A VRB model is implemented for grid application, and the SoC is estimated for localized SoC control. The details of the VRB model and proposed control method are explained in the following subsections.

3.3.1 Vanadium Redox Battery

Due to the high energy efficiency, high scalability, fast response, long time duration and low maintenance requirements, VRB is well suitable for grid-scale applications [4]. In this chapter, a residential VRB based ESS rated 5kW/20kWh is implemented

for grid energy storage purpose. The VRB is modeled based on the data presented in [4], [5]. The open-circuit voltage (OCV)/SoC characteristic curve of a single VRB cell is shown in Figure 3.4. The VRB will be operated in the linear region which ranges between 15%-85% of SoC. Each ESS consists of 38 VRB cells connected in series. The parameters for the VRB based ESS are shown in Table 3.1. In addition, the SoC of the VRB is estimated using the ampere-hour counting method as follows:

$$SoC(t) = SoC(t - \Delta t) + \Delta SoC \quad (3.6)$$

$$\Delta SoC = \frac{P_{bat} \Delta t}{C_B} = \frac{V_{bat} I_{bat} \Delta t}{C_B} \quad (3.7)$$

where C_B is the storage capacity of the VRB, Δt is the time interval, V_{bat} and I_{bat} are the output voltage and current of the VRB respectively.

Figure 3.4 The OCV/SoC characteristic curve of a single VRB cell.

Table 3.1 Parameters of the VRB based ESS

Cell Configuration	38 Series Cell Stack
Rated Power	5kW
Rated Capacity	20kWh
Operation Voltage	42-57V
SoC Region (SoC^{min} , SoC^{max})	15%, 85%

3.3.2 Distributed Control Method

The first objective of the proposed control method is to coordinate distributed ESSs for voltage regulation. A distributed control using consensus algorithm is applied for ESSs to regulate the feeder voltages within the voltage limits. Consensus algorithm is achieved by sharing variable of interest, called the information state among all available units. The initial information state is determined by the virtual leader which measures the information of the critical point [6], [7]. In this chapter, the information state of each ESS is represented by utilization ratio u .

For radial distribution feeder with multiple buses as shown in Figure 3.1, the last bus is the critical bus which has the highest/lowest voltage in the system. Thus the last bus is chosen as the virtual leader to initiate the ESSs coordination. The utilization ratio of the leader is determined by measuring the voltage of the last bus. The utilization ratio of the leader is then shared to available ESSs through communication links to determine the utilization ratio of each ESS to realize the desired voltage regulation objective. The control scheme of the proposed distributed control is shown in Figure 3.5.

Figure 3.5 The control scheme of the proposed distributed control.

To avoid overvoltage and undervoltage, the voltage upper and lower references (V^{up} and V^{low}) are chosen within the voltage limits (V^{max} and V^{min}) for the consensus algorithm. During both peak PV generation and peak load periods, for arbitrary bus

voltage V_i in distribution feeder, the condition given by (3.8) will be met with the proposed consensus algorithm:

$$V^{low} < V_i(t) < V^{up} \quad (3.8)$$

The utilization ratio of the leader u^{ref} is updated at discrete time steps. During peak PV generation period, if the voltage of the last bus V_N goes beyond upper voltage reference V^{up} , u^{ref} will be increased. During peak load period, if the voltage of the last customer goes below lower voltage reference V^{low} , u^{ref} will be reduced. During other periods, u^{ref} will be equal to the former value. In general, the utilization ratio of the leader will be updated as follows:

$$u^{ref}(t) = \begin{cases} u^{ref}(t-t_s) + k_1(V_N(t) - V^{up}) & \text{if } V_N(t) > V^{up} \\ u^{ref}(t-t_s) & \text{if } V^{low} < V_N(t) < V^{up} \\ u^{ref}(t-t_s) + k_2(V_N(t) - V^{low}) & \text{if } V_N(t) < V^{low} \end{cases} \quad (3.9)$$

where V_N is the voltage of the last bus, V^{up} and V^{low} are the upper and lower voltage references respectively. Parameters k_1 and k_2 are the control gains, which affect the convergence speed and control accuracy of the distributed control. t_s is the sampling interval. For daily operation, it should pay attention that the initial value of u^{ref} is 0. u^{ref} will be back to 0 when the control changes from charging mode to discharge mode, and vice versa.

The utilization ratio provided by the leader is then communicated to available ESSs through communication links. The instantaneous communication topology can be represented by the following matrix:

$$S(t) = \begin{bmatrix} s_{11}(t) & s_{12}(t) & \cdots & s_{1N}(t) \\ s_{21}(t) & s_{22}(t) & \cdots & s_{2N}(t) \\ \vdots & \vdots & \ddots & \vdots \\ s_{N1}(t) & s_{N2}(t) & \cdots & s_{NN}(t) \end{bmatrix} \quad (3.10)$$

where s_{ij} denotes the communication link between the i th and j th customers. $s_{ii} = 1$ for all i , $s_{ij} = 1$ if the utilization ratio of the j th bus is received by the i th bus at time t , and $s_{ij} = 0$ if otherwise. In this thesis, it is assumed that customers can only communicate with their neighbours, which means all $s_{(i)(i-1)} = 1$ and $s_{(i)(i+1)} = 1$ for radial feeder shown in Figure 3.1.

The utilization ratio for the i th customer is updated as follows:

$$u_i(t) = \sum_{j=1}^{N-1} d_{ij}(t)u_j(t-t_s) + d_{iN}(t)u^{ref}(t-t_s) \quad (3.11)$$

where $d_{ij}(k)$ is the (i, j) entry of a row stochastic matrix (i.e., row sum of 1) $D(t)$ which can be found in each discrete time data exchange by

$$d_{ij}(t) = \frac{\omega_{ij}s_{ij}(t-t_s)}{\sum_{k=1}^N \omega_{ik}s_{ik}(t-t_s)} \quad (3.12)$$

where the weights ω_{ij} are set to 1 in this research to share the required real power equally among distributed ESSs and s_{ij} are the entries of communication matrix, given in (3.10). The i th customer will know the i th row of matrix $D(t)$ to perform the consensus operation. The communication graph for the N -bus radial feeder can be presented using state transitions diagram as shown in Figure 3.6.

Figure 3.6 Communication graph for N -bus radial distribution feeder.

Although the proposed algorithm is derived under radial distribution feeder with one lateral, it is also applicable for distribution networks with multiple laterals. In such condition, the last bus at each lateral is the critical bus which has the highest/lowest voltage in that lateral. So the last bus of each lateral will be chosen as a virtual leader. If the last bus of this lateral is regulated within the voltage limits, the voltages along this lateral will be within the limits. The utilization ratios of available ESSs are still updated by (3.11) according to the communication matrices $S(t)$ and $D(t)$. This condition will be further illustrated in the second case study of this chapter.

3.3.3 Localized Control Method

The proposed distributed control will regulate the feeder voltages and determine the utilization ratio of each ESS. However, due to different SoC of ESSs and unpredictable weather/load conditions, the ESSs may get fully charged/discharged when they are needed. The second objective is to effectively utilize the available storage capacity in the network for voltage regulation. Therefore, for each ESS, a localized control based on local SoC information is implemented to adjust the charging/discharging speed.

The localized SoC control proposed in this research regulates the SoC of each ESS within a desired range of its predefined reference SoC. The estimated SoC $SoC(t)$ is compared with the reference SoC $SoC^{ref}(t)$ to determine the availability ratio ε . The reference SoC is a function of t , which donates expected SoC change of each ESS during daily operation. For the ESS charging mode of SoC control, ε is defined by the following equation:

$$\varepsilon(t) = \begin{cases} 0 & \text{if } SoC(t) - SoC^{ref}(t) \geq a \\ 1 - k_3(SoC(t) - SoC^{ref}(t)) & \text{if } b < SoC(t) - SoC^{ref}(t) < a \\ 1 & \text{if } SoC(t) - SoC^{ref}(t) \leq b \end{cases} \quad (3.13)$$

where parameters a and b are thresholds of SoC control, which define the allowable SoC deviation range from reference SoC. Parameter k_3 is equal to $1/(a-b)$. If $SoC(t)$ of the ESS is larger than $SoC^{ref}(t)+a$, the availability ratio becomes 0 to stop the charging of the ESS. If $SoC(t)$ is within the range $[SoC^{ref}(t)+b, SoC^{ref}(t)+a]$, the availability ratio is between 0 and 1 to slow down the charging of the ESS. If $SoC(t)$ of the ESS is smaller than $SoC^{ref}(t)+b$, the availability ratio becomes 1 to make full use of the ESS. The condition for the ESS discharging mode of SoC control is similar, which is not further illustrated here.

Finally, the required power output of i th ESS can be determined by

$$P_{ESS,i}^{ref}(t) = u_i(t) \times \varepsilon_i(t) \times P_{ESS,i}^{rated} \quad (3.14)$$

$$-1 < u_i(t) < 1, 0 < \varepsilon_i(t) < 1 \quad (3.15)$$

where $P_{ESS,i}^{rated}$ is the rated power output of ESS at i th bus.

It is noted that the operation of the ESS should also take into account power and energy constraints. The power limits and SoC limits of the ESS during operation can be described by (3.16) and (3.17) respectively

$$-P_{ESS}^{rated} \leq P_{ESS}(t) < P_{ESS}^{rated} \quad (3.16)$$

$$SoC^{min} < SoC(t) < SoC^{max} \quad (3.17)$$

When the proposed control method is applied for daily operation, there are several points should be considered. First, based on historical PV and load data, the total

storage capacity should be enough to deal with voltage rise/drop issues in the network. Next, although ESSs are installed for voltage regulation purpose, it is expected that the storage capacity is fully used for 24-h operation. Besides, the control method has charging and discharging modes to accommodate daily operation. There will be mode changes at specific time during the operation. Finally, the parameters of the proposed control method should be properly chosen. The upper and lower voltage references define how much power to be charged/discharged by ESSs with distributed control. The reference SoC defines how fast the ESSs should be charged/discharged during the operation. In this chapter, the upper and lower references are set as 1.05 p.u. and 0.96 p.u. respectively, so that the ESSs will get fully charged/discharged under different weather conditions (sunny and cloudy PV profiles in this chapter) with only distributed control. For other conditions, if the capacities of ESSs in the system are large, V^{up} and V^{low} can be set more close to 1p.u.. Whereas if the capacities of ESSs in the system are small, V^{up} and V^{low} can be set more close to voltage limits. The reference SoC, parameters a and b for localized SoC control should be chosen according to distributed control, which regulate the power output of the ESS if the SoC exceeds the desired SoC range during the operation. This control design ensures fully utilizing the capacity of ESSs while avoiding overcharge or overdischarge of ESSs. The parameters of the proposed control method are presented in Table 3.2.

Table 3.2 Parameters of the proposed control method

Parameter	Value
Voltage Reference (V^{low} , V^{up})	0.96p.u., 1.05p.u.
Distributed Control (k_1 , k_2)	0.001, 0.001
SoC Control Charging Mode (a , b , k_3)	0.05, 0, 20
SoC Control Discharging Mode (a' , b' , k_3')	-0.05, 0, -20

3.4 Results and Discussions

3.4.1 Case Study: 6-Bus Distribution Feeder

In this section, a distribution feeder consisting of six buses is implemented in Matlab/Simulink to investigate the performance of the proposed control method. The overhead residential feeder supplies electricity to five customers by a 100kVA, 22/0.4kV transformer. The distance between each bus is 100m. The single line diagram of the 6-bus test feeder is shown in Figure 3.7. The PV systems at the residential households are operated at unity power factor and have the capacity of 9kWp. A VRB rated at 5kW/20kWh is integrated with the rooftop PV system of each customer which is a typical size for residential rooftop PV applications [8]. The voltage at the secondary of the transformer is set at 230V (1.0p.u.). This research allows a maximum $\pm 6\%$ voltage deviation in distribution networks. The voltage upper reference (1.05p.u.) and lower reference (0.96p.u.) are chosen within this limit. The parameters of the simulation system are presented in Table 3.3. Figure 3.8 shows the influence on feeder voltages of bus number and real power injection of the test feeder. As shown in Figure 3.8, the last bus has the largest voltage deviation in the feeder for the same power injection at each bus. On the contrary, bus 1 of the test

feeder has the smallest voltage deviation. Moreover, the last bus is more sensitive than other buses to the power injection changes in the test feeder.

Figure 3.7 Single line diagram of the 6-bus test feeder.

Table 3.3 Parameters of the simulation system

Feeder Length	500m
Bus to Bus Distance	100m
Conductor Size	$0.549 + j0.072\Omega/\text{km}$
MV/LV Transformer Size	100kVA, 22/0.4kV
PV Size	9kWp
VRB Rating	5kW/20kWh
Maximum Voltage Deviation	$\pm 6\%$

Figure 3.8 Influence on feeder voltages of bus number and power injection.

To test the developed methodology in a realistic environment, two solar PV output profiles and a residential load profile are used. The PV data is measured using GL130 PV module. It was measured in the summer of the year 2014 at Clean Energy Research Laboratory, Nanyang Technological University, Singapore. 5-min PV data is used as input data for the PV systems. Customer loads are aggregated into a typical residential load profile, which is presented in [9]. The PV and load data are scaled up for this application. The simulation sampling interval is 0.4s. To cope with the simulation speed, the PV and load data hold the same value for every five minutes. Besides, this study focuses on distribution networks in a community scaled residential area. So it is assumed that customers present identical PV and load profiles in this thesis.

1) Test Case 1: Sunny Weather Condition

The first test case demonstrates the performance of the proposed control method under sunny weather condition with identical initial SoC of each ESS. The initial SoC of each ESS is 20%. The PV output, the load demand, the ESS power of the last bus (bus 5) of the radial test feeder is shown in Figure 3.9. The corresponding power injection at bus 5 with/without ESSs is shown in Figure 3.10. As PV generation, load demand and initial ESS condition are identical for each bus, ESSs at buses 1, 2, 3 and 4 have the same power outputs and SoC profiles as the ESS at bus 5, which are not shown here.

As shown in Figures 3.9 and 3.10, from 8:30h to 17:10h, there is more power generated by the PVs than consumed by the loads. Thus the feeder will export real power to the grid which results in voltage rise along the feeder. However, during the other periods, there is no energy produced by PVs so that the load demand is larger than PV generation. The feeder will import real power from the grid which results in

voltage drop. If ESS is installed at each bus, it will start charging at 9:45h when the voltage at bus 5 exceeds the upper voltage reference (1.05p.u.). The control changes to discharging mode at 17:00h. The ESSs will start discharging at 17:50h when the voltage at bus 5 below the lower voltage reference (0.96p.u.). In Figure 3.10, due to the operation of ESS at each bus, the power injection/absorption at bus 5 with ESSs (solid line) is smaller than the power without ESSs (dotted line). The energy stored during the daytime is utilized for voltage support during the evening.

Figure 3.9 PV generation, residential load demand and ESS power for test case 1.

Figure 3.10 Power injection with/without ESSs for test case 1.

Figure 3.11 24-h voltage profiles without ESSs for a sunny day.

Figure 3.12 24-h voltage profiles with ESSs and proposed method for a sunny day.

Figures 3.11 and 3.12 present the corresponding voltage profiles of each bus without and with ESSs respectively. In Figure 3.10, the maximum voltage (1.093p.u.) occurs at noon and the minimum voltage (0.912p.u.) occurs at evening both in bus 5. The voltage exceeds the upper voltage limit (1.06p.u.) from 10:00h to 15:45h. Buses 3, 4 and 5 experience overvoltage for at least a small period of time during the daytime. The voltage drops below the lower voltage limit (0.94p.u.) from 18:20h to 23:00h.

Buses 3-5 experience undervoltage for at least a small period of time during the evening. As shown in Figure 3.12, with ESSs installed at each bus and proposed control method, the voltage is regulated below V^{up} (1.05p.u.) for overvoltage period, and the voltage is regulated above V^{low} (0.96p.u.) for undervoltage period.

Figure 3.13 SoC profiles for test case 1.

The corresponding SoC profiles of the ESS at bus 5 are shown in Figure 3.13. The SoC changing speed is corresponding to the power output of the ESS. The SoC reference curve used in this test case for the SoC control is also shown in Figure 3.13. As shown in Figure 3.13, the SoC increases to 84.5% at the end of charging process and reduces to 19.8% at the end of discharging process. At the first part of charging process, the SoC profile is lower than the SoC reference, which means the ESS is fully available during this period and the availability ratio $\varepsilon=1$. At the second part of the charging process, the SoC profile is higher than the SoC reference, which means that the ESS is partly available and the availability ratio ε is between 0 and 1 to restrict the overcharging of the ESS. During most time of discharging process, the ESS is fully available for discharging. It is also observed in Figure 3.13 that the SoC profile without the SoC control (dotted line) will exceed the SoC operation range of the VRB at the end of charging process.

2) Test Case 2: Cloudy Weather Condition

The second test case further demonstrates the performance of the proposed control method under cloudy weather condition with different initial SoC of each ESS. In this test case, the initial SoCs of ESSs at buses 1, 2, 3, 4 and 5 are 50%, 35%, 30%, 25% and 20% respectively. ESS at bus 1 is plugged out at 12:00h, and plugged back into the feeder at 13:00h. Figure 3.14 shows the PV output and the load demand in this condition. In Figure 3.14, as there are several large variations of solar irradiation during the daytime, the total PV generation is smaller than in test case 1. Figures 3.15 and 3.16 present the voltage profiles of each bus without and with ESSs respectively in test case 2. In Figure 3.15, due to the variations of solar irradiation, overvoltage time is from 10:50h to 12:10h and 13:05h to 14:45h, which is shorter than in Figure 3.11. Buses 3, 4 and 5 still experience overvoltage and undervoltage for some period of time. As shown in Figure 3.16, with ESSs installed at each bus and proposed control method, voltages along the feeder are regulated within the voltage reference.

Figure 3.14 PV generation and residential load demand for test case 2.

Figure 3.15 24-h voltage profiles without ESSs for a cloudy day.

Figure 3.16 24-h voltage profiles with ESSs and proposed method for a cloudy day.

The corresponding power outputs and SoC profiles of ESSs are shown in Figures 3.17 and 3.18 respectively. The time sequences of the operation are explained as follows:

- 1) At 10:50h, the voltage of bus 5 exceeds the upper voltage reference. ESSs 2, 3, 4, and 5 start to charge while the power output of ESS 1 remains 0 until 11:30h. The reason is that the initial SoC of ESS 1 is 50%, which is out of the

- desired SoC range (larger than $(SoC^{ref}(t)+0.05))$ of SoC control. The availability ratio ε of ESS1 keeps 0 to prevent the charging of ESS1.
- 2) From 11:30h to 12:00h, the charging power of ESS 1 is smaller than the charging power of ESSs 2, 3, 4, and 5. The availability ratio ε of ESS 1 is between 0 and 1 but still smaller than 1.
 - 3) From 12:00h to 13:00h, ESS 1 is plugged out while ESSs 2, 3, 4 and 5 are still operated normally in the distribution feeder. The SoC of ESS 1 keeps the same value for an hour.
 - 4) From 13:00h to 15:10h, all ESSs are fully available ($\varepsilon=1$) for distributed control.
 - 5) From 15:10h to 17:00h, the charging speed of each ESS starts to slow down. The availability ratio ε of each ESS drops between 0 and 1 to reduce the charging power of each ESS.
 - 6) At 17:00h, the SoC control changes from charging mode to discharging mode.
 - 7) From 17:00h to 24:00h, each ESS starts to discharge when the voltage of bus 5 drops below lower voltage reference at 17:50h. The SoC of each ESS reduces during the discharging process.

Figure 3.17 Power outputs of ESSs for test case 2.

Figure 3.18 SoC profiles of ESSs for test case 2.

3) Test Case 3: Comparison with Droop Based Method

In this part, a comparison with droop based method proposed in [2] and [10] is made to further illustrate the features of the proposed method. The droop based method is a typical voltage regulation method which was first applied to curtail PV power in [2] and then applied in [10] to achieve decentralized control of distributed ESSs. This method uses local voltage to define how much power should be curtailed from PV inverters or stored in ESSs. The comparison is implemented with the same condition as in Test Case 1. Figure 3.19 shows the voltage profiles with droop based method. Figure 3.20 shows the power curtailed with constant droop based method during the daytime. As shown in Figure 3.20, the PV energy curtailed at buses 3, 4 and 5 are about 7kWh, 18.1kWh and 23.3kWh respectively. While the total energy generation for the sunny PV condition is about 58.6kWh. This means that 11.9%, 30.9% and 39.8% of total PV production are curtailed by PV at buses 3, 4 and 5 respectively.

Even though the curtailed energy can be stored in ESSs as proposed in [10], there are still several limitations of this method. ESSs are usually randomly deployed in

the system other than well planned. However, as shown in Figure 3.19, the requirement of storage capacity with constant droop method increases along the feeder. In the meanwhile, variable droop method allows random deployment of ESSs, but this method requires specific calculation of droop parameters according to system condition. In practical situation, parameters of the system are always changing. Real-time estimation of droop parameters makes this method difficult to realize. Besides, ESSs in distribution networks usually have plug and play ability, which leads to different SoCs of each ESS. The ESS at certain bus may be fully charged/discharged when it is needed. In order to regulate voltage at this particular bus, PV curtailment and reactive compensation is inevitable. Compared with droop based method, the proposed method allows arbitrary deployment of distributed ESSs as long as the total storage capacity is enough for voltage regulation. All available storage capacity in the system can be effectively utilized for voltage regulation.

Figure 3.19 Voltage profiles with droop based method.

Figure 3.20 Power curtailed with constant droop based method.

3.4.2 Case Study: 13-Bus Distribution Network

In this section, the performance of the proposed control method is demonstrated in a residential distribution network with multiple laterals. The configuration of the test system is a 13-bus distribution network which is a part of IEEE 34-bus system [11] as shown in Figure 3.21. The overhead residential feeder supplies electricity to twelve customers by a 22/0.4kV transformer, with seven households installed PV and ESS integrated DG units. The distance between each bus is 50m. The PV profile is the same as that in Figure 3.14. The load demand profile is 50% of that in Figure 3.14. The initial SoCs of ESSs at buses 2, 3, 6 and 7 are 20%, and the initial SoCs of ESSs at buses 4, 10 and 12 are 30%, 40% and 50% respectively.

As shown in Figure 3.21, the distribution network has three laterals. Buses 4, 10 and 12 are at the end of each lateral and have the highest/lowest voltage in each lateral. So they are chosen as virtual leaders for distributed control. It is also assumed that each bus can communicate with its adjacent buses. The communication graph for the

13-bus distribution network is presented using state transitions diagram as shown in Figure 3.22.

Figure 3.21 Configuration of the 13-bus residential distribution network.

Figure 3.22 Communication graph for the 13-bus distribution feeder.

Figures 3.23 and 3.24 show the voltage profiles of each bus without and with ESSs respectively in this case study. In Figure 3.23, the overvoltage and undervoltage are even severe than in Figure 3.15. The voltages at most buses will violate the voltage limits during peak generation/load periods. Bus 10 has the longest distance to the

secondary transformer, so the voltage at bus 10 is the highest/lowest in the network. As shown in Figure 3.24, with the proposed control method adopted by ESSs, voltages in the network are regulated within the voltage references. The corresponding power outputs and SoC profiles of ESSs are shown in Figure 3.25 and Figure 3.26 respectively. ESSs 2, 3, 6 and 7 have the same power outputs and SoC profiles, so only the profile of ESS 7 is shown here.

Figure 3.23 24-hr voltage profiles without ESSs.

Figure 3.24 24-hr voltage profiles with ESSs and proposed method.

Figure 3.25 Power outputs of ESSs 4, 7, 10 and 12.

Figure 3.26 SoC profiles of ESSs 4, 7, 10 and 12.

The time sequences of the operation are detailed as follows:

- 1) At 9:30h, ESSs 2, 3, 6 and 7 start to charge. The power output of ESS 10 remains 0 until 10:30 h and the power output of ESS 12 remains 0 until 11:30 h.
- 2) At 12:10h, due to the large variation of solar irradiation, there is a sudden drop of charging power of each ESS.
- 3) From 13:10h to 15:30h, ESSs 2, 3, 6 and 7 have more charging power than ESSs 4, 10 and 12.

- 4) From 15:30h to 17:00h, the charging speed of each ESS slows down quickly.
- 5) At 17:00h, the SoC control changes from charging mode to discharging mode.
- 6) From 17:00h to 24:00h, each ESS starts to discharge at 17:30h. The SoC of each ESS reduces during the discharging process.

3.5 Conclusion

In this chapter, distributed ESSs have been utilized to regulate the voltages in LV distribution networks with high PV penetration. The impact of ESS integrated with PV source on feeder voltages has been investigated. A coordinated control method has been proposed for voltage regulation while effectively utilizing storage capacities of ESSs during daily operation. The power outputs of ESSs are determined by both distributed control and localized SoC control. Real-time SoC of each ESS is estimated for the proposed control method. A simulation platform has been implemented in Matlab/Simulink to validate the performance of the proposed control method under various operation conditions. The simulation results have demonstrated that the proposed control method ensures the voltages in the networks within the voltage limits during the daily operation. Based on the SoC condition of each ESS, the power sharing among each ESS for voltage regulation is automatically determined. So the SoC of each ESS is regulated within desired SoC range during the operation. The proposed method can also be implemented to distribution networks with multiple laterals as shown by the case study conducted in 13-bus distribution network.

However, there are several limitations of the research work in this chapter. First, the control parameters V^{up} , V^{low} and the SoC references of the proposed control method are chosen according to the author's experience. For future applications, upper level controller should be designed to optimize these parameters according to the PV and

load prediction. Second, the power conversion efficiency of VRB model and power inverter model is not considered. Besides, the total capacity of ESSs is considered to be enough for voltage regulation in the distribution network. However, the ESS capacity may not be enough in practical situation. Therefore, the coordination between ESSs and other voltage regulation methods such as OLTCs, voltage regulators and demand response should be further investigated.

References

- [1] M. B. Delghavi and A. Yazdani, "A unified control strategy for electronically interfaced distributed energy resources," *IEEE Trans. Power Delivery*, vol. 27, no. 2, pp. 803-812, Feb. 2012.
- [2] R. Tonkoski, L. A. C. Lopes, and T. H. M. El-Fouly, "Coordinated active power curtailment of grid connected PV inverters for overvoltage prevention," *IEEE Trans. Sustainable Energy*, vol. 2, no. 2, pp. 139-147, Apr. 2011.
- [3] F. Viawan and A. Sannino, "Voltage control with distributed generation and its impact on losses in LV distribution systems," *IEEE Power Tech, Russia*, 2005, pp.1-7.
- [4] Q. Xin, T. A. Nguyen, J. D. Guggenberger, M. L. Crow, and A. C. Elmore, "A field validated model of a vanadium redox flow battery for microgrids" *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1592-1601, Jul. 2014.
- [5] L. Barote, C. Marinescu, and M. Georgescu, "VRB modeling for storage in stand-alone wind energy systems," *IEEE PowerTech, Bucharest, 2009*, pp. 1-6.
- [6] A. Maknouninejad and Q. Zhihua, "Realizing unified microgrid voltage profile and loss minimization: a cooperative distributed optimization and control approach," *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1621-1630, Apr. 2014.

- [7] G. Mokhtari, A. Ghosh, G. Nourbakhsh, and G. Ledwich, "Smart robust resources control in LV network to deal with voltage rise issue," *IEEE Trans. Sustainable Energy*, vol. 4, no. 4, pp. 1043-1050, Oct. 2013.
- [8] Y. Ru, J. Kleissl, and S. Martinez, "Storage size determination for grid-connected photovoltaic systems," *IEEE Trans. Sustainable Energy*, vol. 4, no. 1, pp. 68-81, Jan. 2013.
- [9] J. A. Jardini, C. M. V. Tahan, M. R. Gouvea, S. U. Ahn, *et al.*, "Daily load profiles for residential, commercial and industrial low voltage consumers," *IEEE Trans. Power Delivery*, vol. 15, no. 1, pp. 375-380, Jan. 2000.
- [10] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, "Mitigation of rooftop solar PV impacts and evening peak support by managing available capacity of distributed energy storage systems," *IEEE Trans. Sustainable Energy*, vol. 28, no. 4, pp. 3874-3884, May 2013.
- [11] IEEE PES, Distribution Test Feeders, Sep. 2010. [Online]. Available: <http://www.ewh.ieee.org/soc/pes/dsacom/testfeeders/>.

Chapter 4

Two-stage Coordination of Distributed Electrical Vehicle Chargers for Voltage Regulation in Distribution Networks

In this chapter, distributed EVCs are proposed to solve the voltage rise/drop issues in LV distribution networks with a high penetration of rooftop PVs and EVs. A two-stage voltage regulation method is proposed to coordinate the operation of distributed EVCs.

4.1 Introduction

Nowadays, increasing amount of EVs are plugged in the home EVCs in distribution networks, which will cause serve voltage problems with poor coordinated charging. Due to the concept of V2G, EVs with proper control strategy can be served as energy storage devices and utilized for voltage regulation. The availability of EVs for V2G application will vary according to the owner's preference, which can be obtained from the travelling preference of different types of EVs. The travelling preference usually includes the daily travel distance and the parking/charging time of the EV users. In Singapore, the daily average travel distances of EVs are 55km, which are within the typical EV travelling ranges between 90km to 160km [1]. The time during which the EVs are parked is available to be used for V2G application. The majority of the EVs are generally used for transportation to and from workplace between 08:00 to 10:00 hours and 16:00 to 20:00 hours respectively. These are the time periods when the availability of EVs for grid ancillary services are low. However, during other periods (i.e., between 10:00 to 14:00 hours and 22:00 and 05:00 hours) the EVs are usually not used or immobile as they are typically plugged in for charging at the workplace and home respectively. These are the time periods when the availability of EVs for grid ancillary services are high. Besides, the EV charging manner could be quite different from commercial areas to residential areas. In high density commercial and residential areas, EVs are aggregated in EV charging stations and charged together in a centralized way. While in low density residential areas, EVs are usually charged by home charging outlets in a distributed way. In this chapter, the voltage regulation problem in LV distribution networks with high PV penetration and typical residential EV charging is considered.

To delineate the behaviors of storage devices on EVs, a lithium-ion battery model based on data fitting is derived to estimate SoC for the proposed control method in

this chapter. A novel two-stage coordination method of distributed EVCs is proposed. The first control stage obtains the voltage regulation target by measuring voltage of critical bus and distributes the control signal to each EVC through communication links. The second control stage determines the amount of real and reactive power which can be provided by each EVC, considering the constraints and charging objectives of the EVC and its charging EV. Different types of PV and load profiles are applied to evaluate the performance of the proposed method in a practical distribution network.

4.2 Modeling and Assumptions

4.2.1 Lithium-ion Battery Model

An electrical circuit model consists of a controlled voltage source in series with a variable resistance is used to characterize the lithium-ion battery, as shown in Figure 4.1 [2]. In Figure 4.1, the open circuit voltage V_{oc} is modeled as a cubic function of SoC, while the internal resistance R_b is modeled as a linear function of SoC. Through fitting the experimental data of the lithium-ion battery in [3], the following equations can be derived:

$$V_{oc} = a_1 SoC^3 + a_2 SoC^2 + a_3 SoC + a_4 \quad (4.1)$$

$$R_b = \begin{cases} R_{ch} = b_1 SoC + b_2 \\ R_{dis} = b_3 SoC + b_4 \end{cases} \quad (4.2)$$

where the coefficients a_1 - a_4 and b_1 - b_4 are shown in Table 4.1, R_{ch} and R_{dis} are the charging and discharging internal resistance respectively. According to Figure 4.1, the battery output voltage V_b can be derived as follows:

$$V_b = V_{oc} + R_b I_b \quad (4.3)$$

where I_b is the charging/discharging current of the battery.

Figure 4.1 The equivalent circuit model of the lithium-ion battery.

Table 4.1 Data fitting results of the lithium-ion battery

V_{oc} (V)			
a_1 (V)	a_2 (V)	a_3 (V)	a_4 (V)
1.729	-2.3	1.457	3.24
R_{ch} (m Ω)		R_{dis} (m Ω)	
b_1 (m Ω)	b_2 (m Ω)	b_3 (m Ω)	b_4 (m Ω)
-0.7357	3.957	-1.782	5.191

Based on (4.1)-(4.3), the charging and discharging characteristics of the proposed lithium-ion battery can be obtained as shown in Figures 4.2 and 4.3 respectively. It can be observed that the battery output voltage V_b is a function of SoC at a given charging/discharging current I_b . Furthermore, for a certain SoC, V_b is proportional to the charging current, while V_b is inversely proportional to the discharging current. The SoC of the lithium-ion battery model is estimated using the ampere-hour counting method as

$$\text{SoC}(k) = \text{SoC}(k-1) + \frac{I_b(k)\Delta t}{C_B} \quad (4.4)$$

where C_B is the capacity of the lithium-ion battery and Δt is the time interval.

Figure 4.2 The charging characteristic of the lithium-ion battery.

Figure 4.3 The discharging characteristic of the lithium-ion battery.

4.2.2 Assumptions

The EV is modeled as Nissan Leaf with storage capacity of 24 kWh, which has a battery pack consisting of 120 lithium-ion battery cells connected in series. The EVC is 230V/16A Level II battery charger with 3.6 kVA charging power rating [4]. The same power rating is assumed to be valid for the discharging operation in V2G mode.

All EVs are charged in a distributed way at the home charging outlets (i.e., EVCs) in the community-scale residential network. Once an EV is plugged in the EVC, the EV user's individual information including arrive time, estimated departure time and SoC is recorded. Then the power allocator judges whether the EV is in V2G mode or maximum power charging mode. If the EV is in V2G mode, the EV will participate in the voltage regulation once there is a voltage violation at critical buses. Otherwise, the EV is charged with the maximum power allowed by the EVC. All EV users will be kept above a desired SoC of 80% by departure. This is preferable from the EV users' point of view that the EV will have sufficient energy for the next trip. Besides, the EV will operate at linear operating range of lithium-ion battery, which is between 10% and 90% of SoC, to avoid depletion or saturation of EV's battery pack.

4.3 Proposed Voltage Regulation Method

In order to coordinate distributed EVCs for voltage regulation in distribution networks, this research proposes a new efficient approach to control the real and reactive power outputs of EVCs. The proposed control method includes two control stages which are distributed voltage control and localized power allocator. The entire control structure of the proposed voltage regulation method is shown in Figure 4.4. In Figure 4.4, the voltages of the critical buses are measured by virtual leader to initiate the voltage regulation. In the stage one, utilization ratio u of each EVC is updated with the signals received from adjacent EVCs. Then the power allocator determines how much real and reactive power will be provided by each EVC in the stage two. The details of the proposed voltage regulation method are explained in the following subsections.

Figure 4.4 Entire control structure of the proposed voltage regulation method.

4.3.1 Stage One: Distributed Voltage Control

The stage one of the proposed control method is to coordinate EVCs for voltage regulation using distributed voltage control. The distributed control can be achieved by the consensus algorithm which shares the information state among all available units through communication links between them. The information state is initiated by the virtual leader which measures the information of the critical points [5]. With the information state provided by the virtual leader, the distributed control will determine the utilization ratio u for each EVC. The number of EVCs is represented by $i=1, 2, \dots, N$. For radial distribution feeders with only one lateral, the last bus has the highest/lowest voltage in this feeder, which is defined as a critical bus. For

distribution networks with multiple laterals, the last bus of each lateral may have the highest/lowest voltage in the whole system. Therefore, there will be several critical buses in this condition, and they will be chosen as virtual leaders to initiate the distributed control. The information state of the virtual leader u^{ref} at a critical bus is updated as follows:

$$u^{ref}(t) = \begin{cases} u^{ref}(t-t_s) + k_1(V_c(t) - 1.05V_0) & V_c(k) > 1.05V_0 \\ u^{ref}(t-t_s) & 1.05V_0 > V_c(k) > 1.03V_0 \\ 0 & 1.03V_0 > V_c(k) > 0.97V_0 \\ u^{ref}(t-t_s) & 0.97V_0 > V_c(k) > 0.95V_0 \\ u^{ref}(t-t_s) + k_2(V_c(t) - 0.95V_0) & V_c(k) < 0.95V_0 \end{cases} \quad (4.5)$$

where V_c is the voltage of the critical bus, V_0 is the voltage of the transformer bus, which is set to 1.0p.u. in this thesis. Parameters k_1 and k_2 are the control gains, which affect the convergence speed and control accuracy of the distributed control, and t_s is the sampling interval.

The distribution systems are normally allowed a maximum voltage deviation of 5%-10% (depending on national standards) from the secondary of the transformer to the customer end. In this chapter, the upper and lower voltage references in (4.5) are chosen as $1.05V_0$ and $0.95V_0$ respectively. So the proposed method can regulate the voltage of the critical bus within the allowable range if EVCs can provide enough real and reactive power. According to (4.5), if the voltage of the critical bus V_c goes beyond $1.05V_0$, u^{ref} will start to increase. If the voltage of the critical bus V_c reduces below $0.95V_0$, u^{ref} will start to decrease. If V_c is between $1.03V_0$ and $0.97V_0$, u^{ref} will become 0. Otherwise, u^{ref} will keep the value of previous step.

The information state u^{ref} of the virtual leader is then communicated to each EVC through communication links. The instantaneous communication graph can be

represented by the following matrix:

$$S(t) = \begin{bmatrix} s_{11}(t) & s_{12}(t) & \cdots & s_{1N}(t) \\ s_{21}(t) & s_{22}(t) & \cdots & s_{2N}(t) \\ \vdots & \vdots & \ddots & \vdots \\ s_{N1}(t) & s_{N2}(t) & \cdots & s_{NN}(t) \end{bmatrix} \quad (4.6)$$

where s_{ij} denotes the communication link between the i th and j th EVCs. $s_{ii} = 1$ for all i , $s_{ij} = 1$ if the information state of the j th bus is received by the i th bus at time t , and $s_{ij} = 0$ if otherwise. In this thesis, it is assumed that all EVCs only communicate with their neighbours, which means all $s_{i(i-1)} = 1$ and $s_{i(i+1)} = 1$.

The communication graph can be known by each EVC as a prior knowledge. However, this restricts the application when there is a communication failure or new EVCs participate for voltage regulation. Under these conditions, global communication graph will change due to the addition and removal of certain EVCs. Hence, a graph discovery algorithm is proposed to determine the matrix S and the number of EVCs N participated in the voltage regulation in a distributed way.

It is assumed that each EVC i is assigned a unique identifier $ID(i)$, and $G_i(k)$ denotes the neighbor set obtained by EVC i . The graph discovery algorithm is designed as follows:

- 1) At $k=0$, each EVC i initializes the set $G_i(k)$ as $G_i(k) = \{ID(i) [ID(j)]\}$, where $ID(j)$ is identifier of the EVC j which has communication link with EVC i . $G_i(0)$ will be sent to all its neighbors EVC j .
- 2) For each step $k \geq 1$, EVC i updates its set $G_i(k)$ as $G_i(k) = G_i(k-1) \cup G_j(k-1)$.
- 3) If $G_i(k) = G_i(k-1)$, then EVC i stops exchanging information with its neighbors, and this time instant is recorded as K . Otherwise, go to step 2.
- 4) Finally, the total EVC number N can be extracted by counting the number of

elements in set $G_i(K)$, which is also the dimension of matrix S . The identifier of EVC which participates in the voltage regulation will be known by each EVC.

With information state of virtual leader u^{ref} and communication graph S obtained above, the utilization ratio for the EVC i is updated as follows:

For EVC i at critical bus,

$$u_i(t) = \sum_{j \neq i}^N d_{ij}(t)u_j(t-t_s) + d_{ii}(t)u^{ref}(t) \quad (4.7)$$

For EVC i at non-critical bus,

$$u_i(t) = \sum_{j=1}^N d_{ij}(t)u_j(t-t_s) \quad (4.8)$$

where $d_{ij}(t)$ is the (i,j) entry of a row stochastic matrix (i.e., row sum of 1) $D(t)$ which can be found in each discrete time data exchange as follows:

$$d_{ij}(t) = \frac{\omega_{ij}s_{ij}(t-t_s)}{\sum_{j=1}^N \omega_{ij}s_{ij}(t-t_s)} \quad (4.9)$$

where the weights ω_{ij} are set to 1 in this thesis to share the required power equally among distributed EVCs and s_{ij} are the entries of the communication matrix, given in (4.6).

4.3.2 Stage Two: Localized Power Allocator

The stage two of the proposed voltage regulation method is to determine the active and reactive power outputs of each EVC by power allocator. There are two requirements for designing the power allocator of each EVC. Firstly, the voltage regulation target required by the first control stage must be achieved within the SoC

limits of each EV and the power limits of each EVC. As mentioned before, the power capacity of the EVC S^{max} is 3.6kVA. So the maximum charging/discharging power output of the EVC P^{max} is 3.6kW. SoC^{max} and SoC^{min} are the maximum and minimum SoC limits of the EV's battery pack, which is 90% and 10% respectively.

The second requirement is that the EV needs to be charged to a desired SoC level of 80% before leaving. Therefore, the power allocator needs to determine the mode of operation of the EV plugged in the EVC. In V2G mode, the EV can participate in the voltage regulation and work as an energy storage device. The real power of the EV can be utilized dependent on the utilization ratio and real-time SoC. While in maximum power charging mode, the EV cannot participate in the voltage regulation and work as a constant power load in the system.

The following algorithm is developed to judge whether the EV plugged in EVC i will work as V2G mode or maximum power charging mode.

- 1) At $k=1$, the EV's current SoC value $SoC(1)$ and estimated departure time t_d are recorded.
- 2) For each step $k \geq 1$, with SoC information $SoC(k)$ and (4.1)-(4.3) of battery model, the maximum charging current I^{max} at time instant k is derived as follows:

$$I^{max}(k) = \frac{1}{2R(k)} (V_{oc}(k) - \sqrt{V_{oc}(k)^2 - 4R(k)P^{max}}) \quad (4.10)$$

where V_{oc} and R can be obtained by substituting $SoC(k)$ into (1) and (2).

- 3) With maximum charging current calculated by (4.10), $SoC(k+1)$ of the next step can be as estimated as follows:

$$SoC(k+1) = SoC(k) - \frac{I^{max}(k)\Delta t}{C_B} \quad (4.11)$$

- 4) If $SoC(k) \geq 80\%$, this time instant is recorded as K , and go to the next step. Otherwise, go back to step 2. $K\Delta t$ is the charging time required in which the EV

is charged from $SoC(1)$ to 80% with maximum charging power.

5) Compare $K\Delta t$ with the time left for the EV before leaving ($t_d - t$).

If $K\Delta t \geq (t_d - t)$, the EV will work in maximum power charging mode.

If $K\Delta t < (t_d - t)$, the EV will work in V2G mode.

In the above algorithm, the minimum charging time of the EV (i.e., the charging time with the maximum charging power) is estimated through steps 1-4. The EV's minimum charging time is compared with the time left before leaving to determine the mode of operation in step 5. When the EV operates in V2G mode, real power output of the EVC can be controlled by the utilization ratio u considering the power limits and SoC limits of the first requirements as follows:

$$P_i^{ref}(t) = \begin{cases} P^{\max} & u_i(t) \geq 1 \& SoC_i(t) > 0.1 \\ u_i(t)P^{\max} & 0 \leq u_i(t) < 1 \& SoC_i(t) > 0.1 \\ u_i(t)P^{\max} & -1 \leq u_i(t) < 0 \& SoC_i(t) < 0.9 \\ -P^{\max} & u_i(t) < -1 \& SoC_i(t) < 0.9 \\ 0 & otherwise \end{cases} \quad (4.12)$$

When the EV operates in maximum power charging mode, the EV must be charged with maximum charging power $P^{\max}$.

The reactive power output of each EVC is a supplement for real power output when there is no EV plugged in the EVC or the remaining capacity of the EV is not enough for the voltage regulation. The reactive power output of each EVC is determined by the utilization ratio u and reactive power limits as follows:

$$Q_i^{ref}(t) = \begin{cases} Q^{\max}(t) & u_i(t) \geq 2 \\ (u_i(t) - 1)Q^{\max}(t) & 1 \leq u_i(t) < 2 \\ 0 & -1 \leq u_i(t) < 1 \\ (u_i(t) + 1)Q^{\max}(t) & -2 \leq u_i(t) < -1 \\ -Q^{\max}(t) & u_i(t) < -2 \end{cases} \quad (4.13)$$

The maximum reactive power which can be provided by each EVC is determined by the power capacity and real power output of the EVC.

$$Q^{\max}(t) = \sqrt{(S^{\max})^2 - P_i^{\text{ref}}(t)^2} \quad (4.14)$$

Finally, the power output of each EVC will be provided according to P_i^{ref} and Q_i^{ref} at each time instant.

4.4 Results and Discussions

A 17-bus distribution network is implemented in Matlab/Simulink to evaluate the performance of the proposed voltage regulation method. The configuration of the test distribution network is shown in Figure 4.5. It is assumed that there are both PV generation and load demand at each bus, and totally 10 buses installed the EVCs in the distribution system, as shown in Figure 4.5. The residential distribution network is connected to the utility grid through a 100kVA, 22/0.4kV transformer. The voltage at the secondary of the transformer is set as 230 V (1.0 p.u.). The distribution network has one main feeder and three laterals. The bus to bus distances of the main feeder, laterals 1, 2 and 3 are 50m, 100m, 40m and 30m respectively. Buses 6, 12 and 16 are the critical buses which potentially have the highest voltage in the system. The parameters of the simulation system are given in Table 4.2.

To evaluate the proposed control method in a realistic environment, real PV penal and residential load profiles are used in the simulation. The PV output data are collected every 5 minutes using the GL 130 PV module in the summer 2014 at Clean Energy Research Laboratory, Nanyang Technological University, Singapore. The load profiles are typical residential load profiles, which is presented in [6]. The PV and load data are scaled up for this study, which is shown in Figure 4.6. In addition, this study focuses a distribution network in a community-scaled area. Therefore,

identical PV and load profiles can be applied for each bus. Two test cases are conducted and discussed in the following subsections. Table 4.3 shows the usage data of distributed EVCs for two test scenarios.

Figure 4.5 Configuration of the 17-bus residential distribution network.

Table 4.2 Parameters of the simulation system

Parameter	Value
System Frequency	50Hz
MV/LV Transformer Size	100kVA, 22/0.4kV
Conductor Size	$0.549 + j0.072 \Omega/\text{km}$
EVC Rating	3.6kVA
Nissan Leaf EV capacity	24kWh
Distributed control (k_1, k_2)	0.01,0.01

Table 4.3 Usage data of distributed EVCs

EVC ID (i)	EV Data		
	Initial SoC (%)	Arrival Time (h)	Departure Time (h)
EVC 1	50	16:00	06:00
EVC 2	45	17:00	07:00
EVC 3	40	18:00	08:00
EVC 4	35	19:00	08:30
EVC 5	30	20:00	07:30
EVC 6	25	21:00	06:30
EVC 7	20	10:00	18:00
EVC 8	30	12:00	20:00
EVC 9	40	14:00	22:00
EVC 10	40	08:00	07:59

Figure 4.6 PV generation and load profiles for simulation study.

4.4.1 Test Case 1: Sunny PV and Light Load Condition

The first test case demonstrates the proposed method under sunny PV generation and light load condition. The voltage profile of each bus with uncoordinated charging (i.e., charging with maximum power once plugged in) is shown in Figure 4.7. The voltage profiles with the proposed voltage regulation method are shown in Figure 4.8. As shown in Figure 4.7, there are voltage rise and drop beyond the allowable voltage range [0.95p.u., 1.05p.u.] in this distribution network. From 10.2h to 15.1h in the daytime, buses 8-16 violate the voltage upper reference 1.05p.u. and the highest voltage is 1.067p.u. at bus 16 at 14h. From 18.5h to 22.5h in the evening, buses 8-16 violate the voltage lower reference 0.95p.u. and the lowest voltage is 0.941p.u. at bus 16 at 20h. As shown in Figure 4.8, with the proposed method applied for each EVC, the voltages can be regulated within the allowable voltage range for both peak PV generations in the daytime and peak load generation in the evening. The real and reactive power absorption and the SoC profile of each EVC during the operation period are shown in Figure 4.9, where the operation of each EVC at each time is clearly demonstrated. In addition, in Figure 4.9, positive value means absorption of power by the EVC, while negative value means injection of power by the EVC.

Figure 4.7 Voltage profiles with uncoordinated EV charging for test case 1.

Figure 4.8 Voltage profiles with the proposed method for test case 1.

Figure 4.9 Real and reactive power absorption and SoC profile of each EVC for test case 1.

The simulation results shown in Figures 4.7-4.9 for test case 1 are further illustrated in time sequences as follows:

- 1) $8h \leq t < 10.3h$. Although PV generation is larger than the load demand in this period, the voltages of all buses are still below 1.05p.u. as shown in Figure 4.8. Therefore, no voltage regulation is needed during this period. As shown in Figure 4.9, the real and reactive power outputs of each EVC remain 0.
- 2) $10.3h \leq t < 13.2h$. The PV generation increases significantly during the midday and becomes much larger than the load demand. The voltages of critical buses exceed 1.05p.u., which initiates the distributed voltage control at 10.3 h. The utilization ratio u is between 0 and 1 in this period and the real power of EVCs 7, 8 and 10 is enough for voltage regulation.
- 3) $13.2h \leq t < 15.3h$. As PV generation increases further, the real power absorbed by each EVC is not enough for voltage regulation. The utilization ratio u is between 1 and 2 and EVCs 1-6 which cannot absorb real power start to absorb reactive power for voltage regulation. Besides, as shown in Table 4.3, an EV begins charging at 14h at EVC 9. Therefore, real power instead of reactive power is absorbed at EVC 9 for voltage regulation from 14h as shown in Figure 4.9.
- 4) $15.3h \leq t < 18.7h$. Although PV generation decreases significantly, the voltages of critical buses drop below 1.03p.u. but still above the voltage lower reference 0.95p.u. as shown in Figure 4.8. Therefore, voltage regulation is not needed during this period. In addition, as the SoC of the EV plugged in EVC 7 is above 80%, mode change is not needed before its leaving at 18h.
- 5) $18.7h \leq t < 23.1h$. As the load demand increases further in the evening, the voltages of critical buses drop below 0.95p.u. at 18.7h. The utilization ratio u decreases between -1 and 0 in this period and the real power outputs of all available EVCs are enough for voltage regulation. As EVs plugged in EVC 8 and EVC 9 will leave in this period, they need to be charged with maximum

charging power until their SoCs reaching 80% before their leaving, as shown in Figure 4.9.

- 6) $23.1h \leq t \leq 24h$. As the load demand decreases in this period, the voltages of critical buses increase above 0.97p.u. as shown in Figure 4.8. Therefore, no voltage regulation is required during this period.

4.4.2 Test Case 2: Cloudy PV and Heavy Load Condition

The second test case demonstrates the proposed method under cloudy PV generation and heavy load condition. The voltage profile of each bus with uncoordinated charging for test case 2 is shown in Figure 4.10. The voltage profiles with the proposed voltage regulation method for test case 2 are shown in Figure 4.11. As shown in Figure 4.10, there are still bus voltage rise and drop beyond the allowable voltage range [0.95p.u., 1.05p.u.] in the distribution networks under this condition. Due to the cloudy weather condition in the daytime, there are several large voltage variations along the distribution feeder. In the daytime, the voltage rise problem becomes less severe than test case 1 due to the lower PV generation. While in the evening, the voltage drop problem becomes more severe than test case 1 due to the heavy load demand, and the lowest voltage is 0.93p.u. at bus 16 at 20h. As shown in Figure 4.11, with the proposed method applied for each EVC, the voltages can be regulated within the allowable voltage range. The real and reactive power absorption by each EVC and the SoC profile of each EV user during the operation period are shown in Figure 4.12.

Figure 4.10 Voltage profiles with uncoordinated EV charging for test case 2.

Figure 4.11 Voltage profiles with the proposed method for test case 2.

Figure 4.12 Real and reactive power absorption and SoC profile of each EVC for test case 2.

The simulation results shown in Figures 4.10-4.12 for test case 2 are further illustrated in time sequences as follows:

- 1) $8h \leq t < 11.2h$. Although PV generation is larger than the load demand, the voltages of all buses are below 1.05p.u. as shown in Figure 4.11. Therefore, no voltage regulation is needed during this period.
- 2) $11.2h \leq t < 14.7h$. As PV generation increases in the midday, the voltages of critical buses are beyond 1.05p.u. at 11.2h. The real power outputs of EVCs 7, 8, 9 and 10 are utilized for voltage regulation if available during this period, as shown in Figure 4.12. The voltage regulation stops working due to the large PV variation from 12h to 13.1h.
- 3) $14.7h \leq t < 18.4h$. The voltages of critical buses drop below 1.03p.u. but still above the voltage lower reference 0.95p.u. as shown in Figure 4.11. The voltage regulation is not needed in this period. In addition, the SoC of the EV plugged in EVC 7 is not fully charged during the daytime, so the EV changes to maximum power charging mode at 15.4h and is charged to 80% of the SoC at 18h before leaving as shown in Figure 4.12.
- 4) $18.4h \leq t < 19.8h$. The voltages of critical buses drop below 0.95p.u. at 18.4h. EVCs 1, 2, 3, 4, 9 and 10 start to inject real power for voltage regulation as shown in Figure 4.12. The real power outputs of all available EVCs are enough for voltage regulation in this period.
- 5) $19.8h \leq t < 22.8h$. As the load demand increases further, the real power discharged by each EVC is not enough for voltage regulation. The utilization ratio u decreases between -1 and -2 during this period. EVCs which cannot inject real power start to inject reactive power as shown in Figure 4. 12.
- 6) $22.8h \leq t \leq 24h$. As the load demand decreases significantly in this period, the voltages of critical buses increase above 0.97p.u. as shown in Figure 4.11. Therefore, voltage regulation is no longer needed in this period.

4.5 Conclusion

In this chapter, distributed EVCs have been utilized to regulate the voltages in a LV distribution network. A lithium-ion battery model has been developed for SoC estimation. A two-stage voltage control method has been proposed to coordinate the power outputs of distributed EVCs during daily operation. The power outputs of the EVCs are determined by both distributed voltage control and localized power allocator. A 17-bus distribution network has been implemented in Matlab/Simulink to validate the performance of the proposed method. Based on the utilization ratio generated by distributed voltage control, the power allocator of each EVC can determine the real and reactive power outputs to realize voltage regulation. The simulation results have demonstrated that the proposed control method can ensure the voltages along the distribution network within allowable voltage range under various operation conditions.

There are still several limitations of the research work in this chapter. First, the state-of-health (SoH) is not considered in the lithium-ion battery modelling in this research. However, due to the limited life cycle of lithium-ion battery, the SoH and capacity fading are important issues to be considered for long time operation. Second, the EV user data is considered as a given information in this research. In future research, probability based model can be built to estimate the SoCs of the EVs and the parking/charging time of the EV users. Furthermore, the research scope is limited to the voltage regulation and EV charging problem in a low density residential area. While for different areas (commercial or residential), the time and amount of EV charging could be quite different. The real-time voltage regulation through V2G should also consider EV management strategies.

References

- [1] Land Transport Authority of Singapore, Singapore Land Transport Statistics in Brief [Online]. Available: <http://www.lta.gov.sg/>.
- [2] X. J. Li, D. Hui, and X. K. Lai, "Battery energy storage station (BESS)-based smoothing control of photovoltaic (PV) and wind power generation fluctuations," *IEEE Trans. Sustainable Energy*, vol. 4, no. 2, pp. 464-473, Mar. 2013.
- [3] A. Rahmoun and H. Biechl, "Modelling of Li-ion batteries using equivalent circuit diagrams," *Przegląd. Elektrotechniczny (Electrical Review)* 88 (7b/2012) 152-156, 2012.
- [4] J. G. Pinto, V. Monteiro, H. Goncalves, and J. L. Afonso, "Onboard reconfigurable battery charger for electric vehicles with traction-to-auxiliary mode," *IEEE Trans. Vehicular Technology*, vol. 63, no. 3, pp. 1104-1116, Sep. 2013.
- [5] A. Maknouninejad and Q. Zhihua, "Realizing unified microgrid voltage profile and loss minimization: a cooperative distributed optimization and control approach," *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1621-1630, Apr. 2014.
- [6] J. A. Jardini, C. M. V. Tahan, M. R. Gouvea, S. U. Ahn, *et al.*, "Daily load profiles for residential, commercial and industrial low voltage consumers," *IEEE Trans. Power Delivery*, vol. 15, no. 1, pp. 375-380, Jan. 2000.

Chapter 5

Hierarchical Control and Power Management of Islanded Microgrids with Energy Storage Systems and Renewable Energy Sources

In this chapter, a hierarchical control scheme is presented for an islanded AC microgrid formed by PVs, ESSs and multiple loads. Both the short-term and long-term power imbalance in the microgrid is solved by the proposed control scheme.

5.1 Introduction

It is of great importance to ensure efficient utilization of RESs while avoiding depletion or saturation of the ESSs in the microgrids under various operation conditions. In this chapter, a hierarchical control scheme is presented for PV systems, ESSs and loads in an islanded AC microgrid to deal with both the short-term and long-term power imbalance. ESSs will function as UPS to make the microgrid continue working at islanded condition. To achieve fast dynamic response and small steady-state error of VSIs, a novel N-step MPC is developed for the primary control. Depending on different cost functions of MPC method, the VSIs of each unit can operate in CCM or VCM. The secondary control is taken effect when the primary control cannot handle the power imbalance in the microgrid. The secondary control is achieved through communication links between each agent using the consensus algorithm. This control scheme ensures the power balancing and power management can be achieved hierarchically under different operation conditions in the microgrid.

5.2 System Description

5.2.1 System Configuration

The configuration of an ac microgrid with multiple communication agents is shown in Figure 5.1. The microgrid consists of two EESs, two PV systems and four distributed loads which is interfaced to the utility grid through a 1MVA, 22/0.4kV transformer. The ESSs and PVs are connected to each bus through VSIs. It assumes that there is communication agent at each bus, which can communicate with other agents through low bandwidth communication links [1]. The distributed control signal of each agent will be executed by the local ESS/PV and load.

Figure 5.1 The configuration of an ac microgrid with communication agents.

In grid-connected condition, the utility grid can support any shortage or surplus of power in the microgrid. In this condition, the primary control of all VSIs will operate in CCM. The charging/discharging of the ESSs can be controlled by secondary control for peak shaving [2]. While in islanded condition, which is the focus of this research, the circuit breaker (CB) of the microgrid shown in Figure 5.1 will be open. The ESSs will function as UPS and coordinate with PV systems and loads to supply power imbalance within the microgrid. For primary control, ESS-1 operates in VCM to control the voltage and frequency of the islanded microgrid, and ESS-2, PV-1 and PV-2 operate in CCM to supply the required power. ESS-1 will work as a master unit while ESS-2 and PVs will work as slave units. For secondary control, if the master unit is not able to balance the power in the microgrid, the slave units will be coordinated for power balancing. In this research, ESS-1 has large power rating and capacity than ESS-2, so it is more suitable to be chosen as a master unit, which will provide more stable voltage support for other devices in the islanded microgrid. If all ESSs are not enough to supply the power imbalance, PV curtailment or load shedding will be conducted. For practical applications, in order to balance the total load demand for a long time, backup generators can be started up during the operation of ESSs. After that, the backup generators will play the role of UPS to

continue supplying the load demand in the islanded microgrid.

5.2.2 Structure and Control Scheme of ESS/PV

Figure 5.2 shows the structure of each ESS/PV and its control scheme. The configuration of each ESS/PV consists of two parts: the dc source and power conversion stage (PCS). The dc source of ESS refers to battery management system (BMS) of battery bank. The function of the BMS is to balance the SoC and the output voltage of each cell in the battery bank [3]. The dc source of PV system refers to the PV panels and the dc/dc boost converter, which is controlled by maximum power point tracking algorithm (MPPT) to obtain the maximum power output [4]. As this research is focused on the control of PCS, the dc part will be simplified into dc voltage source, which provides constant dc link voltage.

Figure 5.2 Structure and hierarchical control scheme of each ESS/PV unit.

The PCS of the ESS/PV contains a three-phase dc/ac VSI and a LC filter. The VSI of each unit is controlled with the proposed hierarchical control scheme to realize power balancing in islanded microgrid. As shown in Figure 5.2, there are two modes of operation for primary control, which can be changed according to the MPC cost function. For the microgrid in Figure 5.1, ESS-1 operates in VCM and ESS-2, PV-1 and PV-2 operate in CCM at primary control. In secondary control, the leader control is only for ESS-1, which measures the outputs to initiate the consensus algorithm. Other agents will update their distributed control signals u_i with the control signals received from neighbor agents. Then the distributed control signals will be allocated to the local controllable units of each agent (ESS, PV and load) to determine how to operate them. The detailed control scheme will be further illustrated in the following sections.

5.3 Model Predictive Control of Voltage Source Inverters

5.3.1 Modeling of Voltage Source Inverters

The state-space model of the inverter is used to predict the future behavior of the state variables, which will be used by the cost function to determine the switching signals for the inverter. Originated from the fact that the VSI can be modeled as a system with finite number of switching states, the implementation of MPC can be further simplified [5]. For the VSI shown in Figure 5.2, the switching states (S_1 - S_6) of the switches have only binary values “1” and “0” in a closed state and an open state respectively. The lower switches have the complementary values of their upper switches. Therefore, the switching signals of each phase are defined by

$$S_a = S_1 = \overline{S_4}, S_b = S_2 = \overline{S_5}, S_c = S_3 = \overline{S_6} \quad (5.1)$$

The output voltage of the VSI in vectorial form $v_{i(\alpha\beta)}$ can be expressed related to the switching signals by

$$v_{i(\alpha\beta)} = \frac{2}{3}(S_a + S_b e^{-j(2\pi/3)} + S_c e^{j(2\pi/3)})V_{dc} \quad (5.2)$$

Totally eight output voltage vectors can be obtained, considering eight possible combinations of the switching signals S_a , S_b and S_c , which is further interpreted in [5]. In order to simplify the modeling of three-phase VSI, all the parameters in abc frame are transformed to vectors in $\alpha\beta$ frame. The vector $u_{(\alpha\beta)}$ is a complex number, which can be obtained using the following transformation:

$$u_{(\alpha\beta)} = u_a + ju_\beta = \frac{2}{3} \begin{bmatrix} 1 & e^{-j(2\pi/3)} & e^{j(2\pi/3)} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \quad (5.3)$$

With the transformation (5.3), the filter current $i_{L(\alpha\beta)}$, the capacitor voltage $v_{C(\alpha\beta)}$, and the output current $i_{o(\alpha\beta)}$ can be expressed. Applying Kirchhoff's current and voltage laws to the LC filter of the VSI, the following equations are obtained

$$C \frac{dv_{C(\alpha\beta)}}{dt} = i_{L(\alpha\beta)} - i_{o(\alpha\beta)} \quad (5.4)$$

$$L \frac{di_{L(\alpha\beta)}}{dt} = v_{i(\alpha\beta)} - v_{C(\alpha\beta)} - Ri_{L(\alpha\beta)} \quad (5.5)$$

Compared to the high sampling frequency, the output current is changing very slowly. It can be assumed that

$$\frac{di_{o(\alpha\beta)}}{dt} = 0 \quad (5.6)$$

Discretize (5.2), (5.4), (5.5) and (5.6) using the forward Euler difference method, and define state variable as

$$x(k) = \begin{bmatrix} v_{C(\alpha\beta)}(k) & i_{L(\alpha\beta)}(k) & i_{o(\alpha\beta)}(k) \end{bmatrix}^T \quad (5.7)$$

The discrete time state-space model with a sampling time T_s can be obtained as follows:

$$\begin{aligned} x(k+1) &= Ax(k) + Bv_{i(\alpha\beta)} \\ y(k) &= Cx(k) \end{aligned} \quad (5.8)$$

where

$$A = \begin{bmatrix} 1 & \frac{T_s}{C} & -\frac{T_s}{C} \\ -\frac{T_s}{L} & -\frac{RT_s}{L} + 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ \frac{T_s}{L} \\ 0 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}.$$

5.3.2 Proposed Primary Model Predictive Control

The block diagram of the proposed MPC for primary control of VSI is shown in Figure 5.3. Using the state-space model (5.8), the measured state variable $x(k)$ is used to predict its value at next sampling instant for all the possible output voltage vectors of the VSI. Here, a N-step prediction is adopted to reduce the steady-state error of the controller.

Figure 5.3 Proposed model predictive controller for primary control.

The reference capacitor voltage $v_{C(\alpha\beta)}^*(k)$ is generated by

$$v_{C(\alpha\beta)}^*(k) = \frac{2}{3} \begin{bmatrix} 1 & e^{-j(2\pi/3)} & e^{j(2\pi/3)} \end{bmatrix} \begin{bmatrix} 230 \sin(2\pi f k T_s) \\ 230 \sin(2\pi f k T_s - 2\pi/3) \\ 230 \sin(2\pi f k T_s + 2\pi/3) \end{bmatrix} \quad (5.9)$$

With the values of $P(k)$ and $Q(k)$ at sampling instant k obtained from the secondary control, the reference output current $i_{o(\alpha\beta)}^*(k)$ can be obtained as follows:

$$i_{o(\alpha\beta)}^*(k) = \frac{P(k) + jQ(k)}{v_{C(\alpha\beta)}^*(k)} \quad (5.10)$$

Then the reference filter current $i_{L(\alpha\beta)}^*(k)$ can be derived from (5.5) as follows:

$$i_{L(\alpha\beta)}^*(k-1) = i_{o(\alpha\beta)}^*(k-1) - \frac{C_f}{T_s} (v_{C(\alpha\beta)}^*(k) - v_{C(\alpha\beta)}^*(k-1)) \quad (5.11)$$

As mentioned above, there are two modes of operation of VSI, which are VCM and CCM. The cost function of VCM is defined as the difference between the predicted capacitor voltage after N-step using the state-space model and its reference value as follows:

$$J_V = \left| v_{C(\alpha\beta)}^*(k) - v_{C(\alpha\beta)}(k+N) \right| \quad (5.12)$$

While the cost function of CCM is defined as the difference between the predicted inductor current after N -step using the state-space model and its reference value as follows:

$$J_I = \left| i_{L(\alpha\beta)}^*(k-1) - i_{L(\alpha\beta)}(k+N) \right| \quad (5.13)$$

where J_V and J_I are the cost functions of the proposed primary MPC in VCM and CCM respectively. N is number of the prediction steps which is set to 3 in this research.

To choose the optimal control signals, the voltage vector $v_{i(\alpha\beta)}$ that minimizes the cost function is selected, and the switching signals corresponding to this voltage vector are chosen as control signals of the VSI at next sampling instant.

5.4 Consensus Based Distributed Control

5.4.1 Communication Network and Consensus Algorithm

Consensus based distributed control offers interaction of control units in a dynamic multi-agent system. Each control agent exchanges data with some other agents on a communication network and processes the data to control its associated system. Graph theory is used for graphical representation of the communication network [6]. The communication network of a multi-agent system can be described by a graph, which is defined as $G = (V, E)$ with a set of N nodes $V = \{v_1, v_2, \dots, v_N\}$ and a set of edges $E = V \times V$. Each node is assigned with a agent in the system, and edges represent communication links for data exchange. If communication links are bidirectional, $(v_i, v_j) \in E \Rightarrow (v_j, v_i) \in E \forall i, j$, the graph is said to be undirected, otherwise it is directed. The set of neighbors of i th node is denoted N_i . Equivalently,

if $j \in N_i$, then v_i receives information from v_j . A matrix called adjacent matrix $\mathbf{S} = [s_{ij}]$ is associated to the edges. s_{ij} represents the weight for information exchanged between agents i and j , where $s_{ij} = 1$ if agents i and j are connected through an edge $(v_i, v_j) \in E$, otherwise, $s_{ij} = 0$.

In this chapter, the distributed control problem can be categorized as cooperative tracking problem, which is aimed to have consensus for each agent with a control objective provided by the leader [7]. The control objective is shared to each agent through the communication network to reach consensus. The node connected to the leader is called pinned node and the graph contains at least one pinned node.

The consensus algorithm updates the distributed control signals for both pinned and unpinned agents as

$$u_i(k+1) = \sum_{j \in N_i} d_{ij} u_j(k) + g_i u^{ref}(k) \quad (5.14)$$

where $u_j(k)$ is the local information discovered by agent j at iteration k , $u_i(k+1)$ is the update of $u_i(k)$ at iteration $k+1$, d_{ij} is the communication coefficient between agents i and j , g_i is the pinning gain of the agent i which is positive if there is a leader at this agent, and is zero otherwise, and $u^{ref}(k)$ is control objective function of the leader.

As discussed in [7], different methods for d_{ij} determination provide different converging speeds. The improved Metropolis method is adaptive to changes of communication network topology and is able to provide near optimal converging speed. The d_{ij} updating law is represented by

$$d_{ij} = \frac{s_{ij}}{\sum_{j=1}^N s_{ij}}, i = 1, 2, \dots, n. \quad (5.15)$$

where s_{ij} are the entries of adjacent matrix $\mathbf{S}$.

5.4.2 Proposed Secondary Distributed Control

For islanded microgrid with only proposed primary control scheme, the power is balanced by VCM-ESS. Any power imbalance in the microgrid will be supplied by the VCM-ESS. However, when there is large or long-term power imbalance which leads to rated power or SoC limit violation, the secondary control will be responsible for coordination of each available unit in the microgrid. It is noted that the operation of the ESS should also take into account the power and energy constraints. The power limits and SoC limits of the ESS can be described by (5.16) and (5.17) respectively.

$$-P_{ESS}^{rated} \leq P_{ESS}(k) < P_{ESS}^{rated} \quad (5.16)$$

$$SoC^{min} < SoC(k) < SoC^{max} \quad (5.17)$$

The SoC of the ESS can be simply estimated by the ampere-hour counting method as

$$SoC = SoC_{t=0} - \frac{1}{C_{ESS}} \int P_{ESS} dt \quad (5.18)$$

where $SoC_{t=0}$ is the initial value of SoC, C_{ESS} is the capacity of the ESS, and P_{ESS} is the power output of the ESS.

As mentioned above, the control objective determined by the leader is shared through communication network to each available agent. In this research, the leader is located at VCM-ESS. The objective function of the leader u^{ref} is updated at discrete time steps. If the measured charging power of the VCM-ESS goes beyond upper reference P^{up} , u^{ref} is increased. If P goes below lower reference P^{low} , u^{ref} is reduced. In between, u^{ref} is equal to the value of previous step. In general, the control objective of the leader is updated as follows:

$$u^{ref}(k) = \begin{cases} u^{ref}(k-1) + k_1(P(k) - P^{up}(k)) & \text{if } P(k) > P^{up}(k) \\ u^{ref}(k-1) & \text{if } P^{low}(k) < P(k) < P^{up}(k) \\ u^{ref}(k-1) + k_2(P(k) - P^{low}(k)) & \text{if } P(k) < P^{low}(k) \end{cases} \quad (5.19)$$

where parameters k_1 and k_2 are the control gains, which affect the convergence speed and control accuracy of the distributed control. Considering the operation limit of ESS, the upper and lower power reference is designed as follows:

$$P^{up}(k) = \frac{SoC^{max} - SoC_1(k)}{SoC^{max} - SoC^{min}} P_{ESS1}^{rated} \quad (5.20)$$

$$P^{low}(k) = -\frac{SoC_1(k) - SoC^{min}}{SoC^{max} - SoC^{min}} P_{ESS1}^{rated} \quad (5.21)$$

With the proposed secondary control, the power output of the VCM-ESS will be controlled within the upper and lower power references. According to (5.20), (5.21), the power references are functions of SoC, which will change according to the SoC of the VCM-ESS for each time instant. Both the upper and lower power references will increase during the ESS discharging condition. On the contrary, the upper and lower power references will decrease during the ESS charging condition. Thus this design restrains the overcharging when the SoC becomes high and the overdischarging when the SoC becomes low.

5.4.3 Distributed Signal Allocation

The distributed secondary control will initiate once there is power reference violation of (5.19) and each agent will update its distributed signal according to (5.14). Finally, each agent will have the same value which is equal to the control objective of the leader u^{ref} when they reach consensus (i.e., steady-state). The allocation of distributed signal is designed to determine how to utilize this control signal for power

balancing and SoC management of the entire microgrid. The detail is explained as follows:

If $u_i=0$, the VCM-ESS is enough to balance the power in the microgrid with only primary control, so secondary control will not work in this condition.

If $0 < u_i < 1$, the power output of the VCM-ESS is larger than the upper power reference. The CCM-ESS is charged to balance the power with the distributed signal of secondary control. Similarly, if $-1 < u_i < 0$, the power output of the VCM-ESS is smaller than the upper power reference and the CCM-ESS is discharged. The charging and discharging of CCM-ESS are determined by the following equations:

$$P_{ESS2}(k) = \begin{cases} \alpha(k)P_{ESS2}^{rated} & u_i(k) > 1 \\ u_i(k)\alpha(k)P_{ESS2}^{rated} & 0 < u_i(k) \leq 1 \\ -u_i(k)\beta(k)P_{ESS2}^{rated} & -1 < u_i(k) \leq 0 \\ -\beta(k)P_{ESS2}^{rated} & u_i(k) \leq -1 \end{cases} \quad (5.22)$$

$$\alpha(k) = \begin{cases} \frac{SoC^{max} - SoC_2(k)}{SoC^{max} - SoC^{up}} & SoC_2(k) > SoC^{up} \\ 1 & SoC_2(k) < SoC^{up} \end{cases} \quad (5.23)$$

$$\beta(k) = \begin{cases} 1 & SoC_2(k) > SoC^{low} \\ \frac{SoC_2(k) - SoC^{min}}{SoC^{low} - SoC^{min}} & SoC_2(k) < SoC^{low} \end{cases} \quad (5.24)$$

where SoC^{up} and SoC^{low} are the upper and lower SoC references to reduce the power output of the CCM-ESSs respectively. α and β are the utilization ratios of ESS-2 for the charging and discharging process respectively.

If $u_i > 1$, the CCM-ESS is already charging with the maximum power. PV generation curtailment will be conducted by the CCM-PV to reduce the PV generation. The curtailed power is defined by

$$P_{PV}^{max}(k) = (u_i - 1)P^{MPPT}(k) \quad (5.25)$$

where P^{MPPT} is the maximum power determined by MPPT.

If $u_i < -1$, the CCM-ESS is discharging with the maximum power. Load shedding will be conducted to shed the non-critical loads to reduce the total load demand. In order to avoid repetitive ON-OFF switch of loads, a relay control is used for load shedding and load recovering, as shown in Figure 5.4. The priority for load shedding from high to low is Load-3, Load-2 and Load-1. u_{L-ON} and u_{L-OFF} represent the thresholds to switch on and off each load respectively.

Figure 5.4 Thresholds of load shedding and load recovering.

5.5 Results and Discussions

The ac microgrid shown in Figure 5.1 is implemented in Matlab/Simulink as the platform of proposed hierarchical control scheme. The parameters of the simulation system are shown in Table 5.1 and the parameters of the proposed control scheme are shown in Table 5.2. To validate the performance of the proposed control scheme, both short-term and long-term test cases are demonstrated in this section. It is noted that small capacity of the ESS is chosen to make SoC change faster in this research. However, the proposed control scheme can also be applied to microgrids with larger ESS capacity. ESS-1 is controlled in VCM while ESS-2 and PVs are controlled in CCM at primary control. It is assumed that each agent can only communicate with its neighbors. The initial SoCs of ESS-1 and ESS-2 are set to 50% for all test cases.

Table 5.1 Parameters of the simulation system

Parameter	Value
Nominal Bus Frequency	50Hz
Nominal Bus Voltage	230V
Filter Capacitance	20 μ F
Filter Inductance	1.3mH
Load Ratings: Load-1 Load-2 Load-3 Critical Load-4	Real/ Reactive Power 3kW/0.7kVAr 4.2kW/0.9kVAr 4kW/ 1.2kVAr 6.8kW/ 1.5kVAr
PV Ratings: PV-1 PV-2	Maximum Power 7.8kW 9kW
ESS Ratings: ESS-1 ESS-2	Capacity/Rated Power 0.14kWh/5kW 0.07kWh/4kW

Table 5.2 Parameters of the proposed control scheme

Parameter	Value
Leader Control (k_1, k_2)	0.001, 0.001
Communication Speed	10ms
SoC Safety Range (SoC^{min}, SoC^{max})	0.1, 0.9
SoC Reference (SoC^{low}, SoC^{up})	0.3, 0.7
Load Shedding Thresholds ($u_{L1-OFF}, u_{L2-OFF}, u_{L3-OFF}$)	-1.2, -1.5, -2
Load Recovering Thresholds ($u_{L1-ON}, u_{L2-ON}, u_{L3-ON}$)	0, -0.25, -0.5

5.5.1 Test Case 1: Short-Term PV Generation and Load Demand Variation

The first test case demonstrates the performance of the proposed method under short-term large power variation condition. The microgrid with the proposed control method will be tested under large PV/load variation to evaluate the instant power balancing ability. Figure 5.5 shows the events of the simulation in test case 1. The initial state and switch on/off behaviors of PVs and loads during the simulation period are shown on the timeline. Figure 5.6 shows the real power output of each ESS in test case 1. The values are lined out at the end of each period. Figure 5.7 shows the corresponding real power output of each PV in this test case. The corresponding profiles of SoC and control objective of the leader during this period are shown in Figures 5.8 and 5.9 respectively. As shown in Figure 5.8, the SoC will change according to the real power outputs shown in Figure 5.6. Figure 5.9 shows that control objective of the leader u^{ref} is between -1 and 1 from 0 to 5s, and increases to 1.2 from 5s to 6s. According to the distributed signal allocation defined in this chapter, each agent will take measures properly.

Figure 5.5 Events of the simulation for test case 1.

Figure 5.6 Real power outputs of ESSs for test case 1.

Figure 5.7 Real power outputs of PVs for test case 1.

Figure 5.8 SoC profiles for test case 1.

Figure 5.9 Control objective of the leader for test case 1.

The results in Figures 5.6-5.9 are further explained in time sequences as follows:

- 1) $0 \leq t < 1s$. Initially, the power generation of PV-2 is larger than power consumption of Load-4 for 2.2kW. The surplus power is charged by ESS-1 as shown in Figure 5.6. The power output of ESS-1 is within the power reference calculated by (20) and (21), so only primary control is operated.
- 2) $1 \leq t < 2s$. As Load-1 is switched into the microgrid at $t=1s$, ESS-1 is discharged with 0.8 kW to match the power imbalance as shown in Figure 5.6. The power output of ESS-1 is still within the power reference, so the primary control responds fast to deal with the sudden load change.

- 3) $2 \leq t < 3s$. As Load-2 is switched into the microgrid at $t=2s$, the load demand is larger than PV generation for 5kW. The power output of ESS-1 increases larger than the upper power reference, so u^{ref} drops to -0.6 and the secondary control starts to work. Both ESS-1 and ESS-2 are discharged with 2.5kW to supply the power imbalance as shown in Figure 5.6.
- 4) $3 \leq t < 4s$. As PV-1 is switched into the microgrid at $t=3s$, the PV generation is larger than load demand for 2.8kW for this period. The power output of ESS-1 decreases smaller than the lower power reference, so ESS-1 and ESS-2 are charged with 2.5kW and 0.3kW respectively as shown in Figure 5.6.
- 5) $4 \leq t < 5s$. As Load-1 is switched off the microgrid at $t=4s$, the PV generation is large than load demand for 5.8kW for this period. ESS-1 and ESS-2 are charging with 2.5kW and 3.3kW respectively to match the power imbalance as shown in Figure 5.6.
- 6) $5 \leq t \leq 6s$. As Load-2 is switched off the microgrid at $t=5s$, the power imbalance increases further to 10 kW. ESS-1 and ESS-2 are charging with 2.5kW and 4kW respectively but still not enough to balance the power in the microgrid. u^{ref} increases further to 1.2 as shown in Figure 5.9. Therefore, the power output of PV-1 and PV-2 are curtailed to 6.4kW and 5.9kW as shown in Figure 5.7.

5.5.2 Test Case 2: Long-Term Power Imbalance and PV Curtailment

The second test case validates the performance of the proposed method under long-term power imbalance. In this condition, the PV generation is larger than the load demand and the power imbalance lasts long enough to test how of SoC changes influence the proposed control scheme. If the remaining capacity of the ESSs is not enough to absorb the surplus PV generation, PV curtailment will be conducted proportional to the power rating of the PV system. All the PVs and loads except Load-1 are connected into the microgrid in this test case. The real power outputs of

ESSs and PVs are shown in Figures 5.10 and 5.11 respectively. Figures 5.12 and 5.13 show the corresponding SoC profiles and power reference changes in test case 2 respectively.

Figure 5.10 Real power outputs of ESSs for test case 2.

Figure 5.11 Real power outputs of PVs for test case 2.

Figure 5.12 SoC profiles for test case 2.

Figure 5.13 Power reference changes for test case 2.

As shown in Figure 5.12, the SoC will change according to the real power outputs of ESS-1 and ESS-2 shown in Figure 5.10. The power references shown in Figure 5.13 will change according to SoC of ESS-1, as determined by (5.20) and (5.21). The results in Figures 5.10-5.13 are further explained in time sequences as follows:

- 1) $0 \leq t < 30s$. Initially, the surplus power generation is 1.8kW, which is within the power reference as shown in Figure 5.13. Therefore, only ESS-1 is operated with primary control to balance the power as shown in Figure 5.10.
- 2) $30 \leq t < 165s$. At $t=30s$, the charging power of ESS-1 (negative value of power output in Figure 5.10) reaches the upper power reference. The secondary

control starts to work and ESS-2 absorbs the remaining surplus power as shown in Figure 5.10.

- 3) $165 \leq t \leq 300s$. The charging power of ESS-2 starts to reduce due to the notably decrease of utilization ratio α in (5.23). As the total power of ESS-1 and ESS-2 is not enough to balance the power in the microgrid, PV curtailment will be conducted based on the distributed control signals. The power of PV-1 and PV-2 will be gradually reduced to 8kW and 7kW as shown in Figure 5.11.

5.5.3 Test Case 3: Long-Term Power Imbalance and Load Shedding

Similar to the second test case, the third test case validates the performance of the proposed method for long-term load demand larger than PV generation. Load shedding will be conducted when the remaining capacity of ESSs is not enough to supply the load demand in this condition. Initially, all the PVs and loads are connected into the microgrid in this test case. The real power outputs of ESSs and PVs are shown in Figures 5.14 and 5.15 respectively. It is assumed that all PV generation (PV-1 and PV-2) reduces to 80% of maximum power output at 400s as shown in Figure 5.15. Figure 5.16 shows the corresponding SoC profiles in test case 3. As shown in Figure 5.16, the SoC will change according to the real power outputs of ESS-1 and ESS-2 shown in Figure 5.14 for this test case.

Figure 5.14 Real power outputs of ESSs for test case 3.

Figure 5.15 Real power outputs of PVs for test case 3.

Figure 5.16 SoC profiles for test case 3.

The results in Figures 5.14-5.16 are further explained in time sequences as follows:

- 1) $0 \leq t < 95s$. As the power shortage is 1.2kW during this period, only ESS-1 is discharged for power balancing as shown in Figure 5.14.
- 2) $95 \leq t < 295s$. At $t=95s$, the discharging power of ESS-1 reaches the lower power reference. To balance the power in this condition, secondary control starts to work and ESS-2 will provide the remaining shortage power as shown in Figure 5.14.
- 3) $295 \leq t \leq 400s$. Due to the total discharging power of ESS-1 and ESS-2 are not able to support the power shortage, distributed control signals drop below -1.2 at 295s. Therefore, Load-1 will be shed due to the violation of load shedding threshold u_{L1-OFF} . After shedding of Load-1, the total PV generation becomes larger than the load demand for 1.8kW. ESS-1 changes back to charging mode during this period.
- 4) $400s \leq t < 470s$. As PV generation drops to 80% of maximum power output in Figure 5.15, the total power shortage becomes 1.56kW. ESS-1 changes to discharging mode to balance the power shortage as shown in Figure 5.14.
- 5) $470s \leq t < 500s$. As the distributed control signals drop to -1.5 at $t=470s$, which is load shedding threshold u_{L2-OFF} , Load-2 will be shed to deal with the power shortage in the microgrid. After the load shedding, ESS-1 is charged with 2.64kW for power balancing as shown in Figure 5.14

5.6 Conclusion

In this chapter, a hierarchical control scheme has been designed to achieve power balancing and power management in islanded microgrids. The primary control is performed by a novel MPC, providing fast dynamic response and small steady-state errors. The secondary control is initiated when the primary control is not enough to deal with the power imbalance in the microgrid. Then the distributed control signal

of each agent is updated autonomously through the signals received from neighbors. The allocation of the distributed control signal has been properly designed to effectively coordinate each available unit in the microgrid. A simulation platform has been implemented in Matlab/Simulink to evaluate the performance of the hierarchical control scheme under different test scenarios. The simulation results have validated the effectiveness of the proposed control scheme to deal with both short-term and long-term power imbalances in the microgrid. Proper actions such as PV curtailment and load shedding are conducted to ensure the safety operation of the ESSs. With the proposed control scheme, the power balancing and power management of the microgrid can be achieved hierarchically.

The limitations of the research work in this chapter are discussed as follows. First, the proposed hierarchical control method is only applied for a small scale islanded microgrid. The effectiveness of primary model predictive control and secondary distributed control need to be validated through hardware experiment. Furthermore, real-time control and operation of larger microgrid with more complex system structure is also needed. In addition, the reliability issues of the communication network are not considered in this research. In practical situation, there may be communication topology changes, communication failures and communication delays in the communication network. These problems related to communication layer are still needed to be investigated in future research.

References

- [1] H. Q. Li, G. Chen, T. W. Huang, and Z. Y. Dong, “High-performance consensus control in networked systems with limited bandwidth communication and time-varying directed topologies,” *IEEE Trans. Neural Networks and Learning Systems*, in Press.

- [2] Y. Z. Wang, X. Lin, and M. Pedram, "Adaptive control for energy storage systems in households with photovoltaic modules," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 992-1001, Feb. 2014.
- [3] C. H. Kim, M. Y. Kim, H. S. Park, and G. W. Moon, "A modularized two-stage charge equalizer with cell selection switches for series-connected lithium-ion battery string in an HEV," *IEEE Trans. Power Electronics*, vol. 27, no. 8, pp. 3764-3774, Jan. 2012.
- [4] A. Chikh and A. Chandra, "An optimal maximum power point tracking algorithm for PV systems with climatic parameters estimation," *IEEE Trans. Sustainable Energy*, vol. 6, no. 2, pp. 644-652, Mar. 2015.
- [5] J. Rodriguez, J. Pontt, C. A. Silva, P. Correa, et al., "Predictive current control of a voltage source inverter," *IEEE Trans. Industrial Electronics*, vol. 54, no. 1, pp. 495-503, Feb. 2007.
- [6] Z. Qu, *Cooperative Control of Dynamic Systems: Applications to Autonomous Vehicles*. New York, NY, USA: Springer-Verlag, 2009.
- [7] L. Xiao, S. Boyd, and S. J. Kim, "Distributed average consensus with least-mean-square deviation," in *Proc. 17th International Symposium Mathematical Theory of Networks and Systems*, Kyoto, Jul. 2006.

Chapter 6

Conclusions and Future Work

In this chapter, the summary and overall conclusions of this thesis are discussed. The performance of the proposed control methods has been verified through various test cases in this thesis. The research results have demonstrated that the proposed methods are effective to control energy storage systems for different applications in power systems. Moreover, areas for further research are presented as well, such as application of energy storage systems for voltage regulation in medium-voltage distribution networks, renewable intermittency mitigation and frequency regulation.

6.1 Conclusions

In the last few years, electric power systems have undergone many major transformations from centralized generation to distributed generation. To meet the world's rising energy demand, RESs together with ESSs and EVs have been largely penetrated into modern power systems, which can provide many economic and environmental benefits. The development of smart grid technologies provides approaches to realize the benefits of RESs as well as ESSs, and improve the power quality and system reliability. As the key elements in future smart grid, ESSs are of great importance for both grid-connected and islanded operations. Many research and development efforts which aim to provide efficient solutions have been conducted in this area.

The large penetration of RESs and EVs into the distribution networks or microgrids changes the voltage profiles dramatically and results in various power quality problems. Among them, voltage rise issue caused by large PV generation in the midday and voltage drop issue caused by the uncoordinated charging EVs require significant research attention. In this thesis, ESSs and EVCs have been utilized to overcome these voltage problems. Coordinated control methods have been proposed to control the operation of distributed ESSs and EVCs in the system, considering storage capacity and power limits of each device. Both upper level control and lower level control have been well designed to achieve the voltage regulation and effectively utilize the storage capacity. Besides, the utilization and control of ESSs in islanded microgrid has also been investigated.

In Chapter 3, distributed ESSs have been utilized to regulate the voltages in LV distribution networks with high PV penetration. The impact of ESS integrated with PV source on feeder voltages has been investigated in detail. After that, the VRB

model has been applied to simulate the characteristics of battery packs in ESS and real-time SoC of each ESS is estimated for the control system. A coordinated control method which consists of distributed control and localized control has been proposed for voltage regulation while effectively utilizing storage capacities of ESSs during daily operation. With consensus algorithm and communication links between each ESS, all available ESSs have been coordinated together to deal with the voltage rise/drop issues in the system. Based on the utilization ratio and availability ratio for each sampling interval, power outputs of each ESS have been determined.

The simulation platform in Matlab/Simulink has been built to study the performance of the proposed coordinated control method for distributed ESSs. The proposed control method has been tested in a 6-bus distribution feeder with different types of PV and load profiles. The simulation results have demonstrated that the proposed control method ensures the voltages in the distribution networks within the voltage limits during the daily operation. Based on the SoC condition of each ESS, the power sharing among each ESS for voltage regulation is automatically determined. Therefore, the SoC of each ESS is regulated within the desired SoC range during the daily operation. The advantage of the proposed method has been interpreted through comparison with droop based curtailment method. In addition, the proposed method has also been implemented in a 13-bus distribution network with random located ESSs. The results have further demonstrated the effectiveness of this method to solve voltage regulation problems in LV distribution networks.

To extend of the research work in Chapter 3, distributed EVCs have been proposed to regulate the voltages in LV distribution networks with high penetration of PVs and plug-in EVs in Chapter 4. To characterize the behaviors of storage devices on EVs, a lithium-ion battery model based on data fitting has been developed to estimate SoC for the proposed control method. Proper assumptions have been made to clarify the

control objective and constraints of the distributed EVCs and their plug-in EVs. A two-stage voltage control method has been proposed to coordinate the power outputs of distributed EVCs during daily operation. Based on the utilization ratio generated by distributed voltage control, the power allocator of each EVC determines the real and reactive power outputs to realize voltage regulation. Consensus algorithm has been used to design the distributed voltage control for both critical and non-critical nodes. The localized control determines the mode of operation of the plug-in EV as well as the real and reactive power outputs of each EVC.

A 17-bus distribution network has been implemented in Matlab/Simulink to validate the performance of the proposed method. Simulations of two test scenarios have been conducted under two different types of PV and load profiles. The voltage profiles with no voltage regulation and uncoordinated charging have shown that there are obvious voltage rise in the midday and voltage drop in the evening, while the voltage profiles with the proposed control method have demonstrated that the voltages along the distribution network are regulated within allowable voltage ranges. Besides, the simulation results have also shown that the proposed voltage control method can determine the real and reactive power outputs of each EVC based on utilization ratio of the EVC as well as the SoC and departure time of the plug-in EV automatically.

In Chapter 5, a hierarchical control scheme has been designed to achieve power balancing and power management in islanded microgrids. The primary control is performed by a novel MPC, providing fast dynamic response and small steady-state errors. Depending on different cost function, the primary MPC controller can operate in VCM to control the output voltage and in CCM to control the output current. The secondary control is initiated when the primary control is not able to deal with the power imbalance in the microgrid. Then the distributed control signal of each agent is updated autonomously through the signals received from its neighbors. In addition,

the allocation of the distributed control signal has been properly designed to effectively coordinate each available unit in the microgrid. Proper actions such as PV curtailment and load shedding should be conducted to ensure the safety operation of the microgrid.

The simulation platform has been implemented in Matlab/Simulink to validate the performance of the hierarchical control scheme under different test scenarios. The results of first test case have demonstrated that the proposed control scheme can deal with short-term power variation properly. The results of secondary test case have shown that PV generation is curtailed when the PV generation is larger than the load demand for a long time and the SoCs of ESSs are very high. Similarly, the loads in the microgrid have been shed according to their priority when the load demand is larger than the PV generation for a long time and the SoCs of ESSs are very low. The simulation results have validated the effectiveness of the proposed control scheme to deal with both short-term and long-term power imbalance in the microgrid. With the proposed control scheme, both power balancing and SoC management of the microgrid can be achieved hierarchically.

In summary, the previous proposed control methods and specific findings have been verified by favorable research results in this thesis. The simulation results have demonstrated that these control methods are effective and robust to coordinate ESSs for various applications in smart grids.

6.2 Future Work

With the rapid development of advanced control and communication technologies, the future smart grid will process different characteristics. There are many problems and challenges to be explored in this research field. The design of advanced control

systems requires extensive research on various aspects of the stability, reliability and power quality issues associated with the integration of various DERs. In this thesis, several control techniques for application of ESSs in smart grid have been proposed. But there are many assumptions and limitations of the modelling and control methods in this thesis, which still need to be considered and investigated in future research. The following are some recommendations for future research and development of control systems for ESSs in smart grid.

1. Although actual PV and load data have been used to validate the performance of the proposed control methods in simulation platform. The proposed control methods for ESSs still need to be further validated through experimental studies. The results obtained and the analysis carried out in this thesis serve as a preliminary step towards the design of control systems for future hardware implementation. The power and capacity levels of the distributed networks in this research can be scaled down and implemented in laboratory test bed. After that, real-time test of the proposed methods for voltage regulation could be conducted in existing power distribution networks.

2. This thesis mainly focuses on LV distribution networks with tens of buses. However, a real distribution network may contain thousands of buses with various electrical devices and different topologies. To deal with this problem, the network partition methods are to be investigated in order to realize zonal voltage control in a short control response time with the minimum amount of active and reactive power compensation. The voltage levels of distribution networks can also be classified into medium-voltage (MV) and low-voltage (e.g., 22kV/6.6kV for MV, 400V for LV in Singapore). In LV distribution networks, real power has larger impact than reactive power on feeder voltages. But in MV distribution networks, reactive power compensation is more effective for voltage regulation. The coordination of ESSs together with PVs, EVs and other voltage regulation devices (e.g., transformers and

switched capacitors) for different voltage levels is another important problem to be explored. In addition, the PVs, loads, EVs and ESSs in one residential feeder should be aggregated together for analysis and control in MV distribution networks. With aggregated PVs and loads for each LV feeder, the voltage profiles and compensation power required in MV distribution networks can be calculated and analyzed. Then the aggregated ESSs and EVs with the control methods proposed in this research can be applied for voltage regulation in MV distribution networks.

3. Although voltage regulation for LV distribution networks has been successfully achieved in this research, the voltage fluctuation issues still exist within the voltage limits. These voltage fluctuations are mainly caused by the intermittency of renewable energy generation. When a large number of PV panels are connected to the distribution networks, sudden changes in solar irradiance and temperature will cause the PV power outputs to vary which consequently result in voltage level fluctuations at the connecting buses. Therefore, the PV intermittency problem needs to be further studied for improving the power quality and voltage profiles in the distribution networks as well as increasing the efficiency of PV generation. The ramp-rate control method is suggested for reducing the ramp-rate of PV systems to a desired level, which is realized by controlling the power outputs of distributed ESSs. The ramp rates are typically specified by the utility operators in kilowatts per second (kW/s), and are common feature of new solar PV installation agreements between utility operators and independent power producers. Another issue which should be taken into consideration is the response time of ESSs for this application. The ramp-rate control requires ESSs provide large amount of power in few seconds. Hence, hybrid ESSs which contain batteries and ultracapacitors is very suitable for this application, where ultracapacitors are responsible for short-term PV intermittency with high ramp-rate while batteries are responsible for long-term PV

intermittency with low ramp-rate. The control algorithms for power allocation in the hybrid ESSs should be investigated in the future research as well.

4. The main focus of this thesis is on the voltage regulation issue, while frequency regulation using ESSs is another important issue to be explored. In power systems, frequency regulation reserves are usually categorized in three types: primary reserve (frequency-response reserve), secondary reserve (spinning reserve) and tertiary reserve (starting up backup generators). The primary reserve needs to be online within 8 seconds for at least 30 seconds. The secondary reserve should be online within 30 seconds for at least 10 minutes. The tertiary reserve should be online within 10 minutes for at least 30 minutes. Because of the fast response time of ESSs, they can be participated in primary reserve. Transfer functions based frequency regulation model needs to be built to analyze the impacts of ESSs to system frequency. The control algorithms to coordinate the operation of distributed ESSs are to be developed for frequency regulation purpose. In addition, because of the limited capacity of ESSs, the SoCs of ESSs should also be taken into account for control system design.

5. Last but not the least, various energy management functions such as load leveling, economic dispatch and optimal power flow can be incorporated into the control design considering the time-of-use (TOU) of electricity. This thesis mainly focuses on the power quality improvement of distribution networks. The future research could consider more on energy management and economic operation of ESSs in power systems. The cost functions to real-time optimize the operation of ESSs based on renewable generation forecasting, load demand forecasting, TOU of electricity and other factors should be developed to maximize the economic potential of ESSs.

List of Publications

Journal Publications

- [1] **Y. Wang**, K. T. Tan, and P. L. So, “Coordinated control of distributed energy storage systems for voltage regulation in distribution networks,” *IEEE Trans. Power Delivery*, vol. 31, no. 3, pp. 1132-1141, Jun. 2016.
- [2] **Y. Wang** and P. L. So, “Two-stage coordination of distributed electrical vehicle chargers for voltage regulation in distribution networks,” submitted to *IEEE Trans. Smart Grid*. (Under Review)
- [3] **Y. Wang**, T. John, and P. L. So, “Hierarchical control and power management of islanded microgrids with energy storage systems and renewable energy sources,” submitted to *IEEE Trans. Sustainable Energy*. (Under Review)
- [4] T. John, **Y. Wang**, P. L. So, and K. T. Tan, “A series-shunt network device for an interconnected microgrid system,” submitted to *IEEE Trans. Energy Conversion*. (Under Review)

Conference Publications

- [5] **Y. Wang**, K. T. Tan, and P. L. So, “Coordinated control of battery energy storage system in a microgrid,” in *Proc. IEEE PES Asia-Pacific Power and Energy Engineering Conference*, Hong Kong, Dec. 2013.
- [6] **Y. Wang**, B. F. Wang, and P. L. So, “A voltage regulation method using distributed energy storage systems in LV distribution networks,” in *Proc. IEEE International Energy Conference*, Leuven, Apr. 2016.
- [7] T. John, **Y. Wang**, K. T. Tan, and P. L. So, “Model predictive control of distributed generation inverter in a microgrid,” in *Proc. IEEE Asia Innovative Smart Grid Technology Conference*, Kuala Lumpur, May 2014, pp. 657-662.

- [8] T. John, **Y. Wang**, P. L. So, and K. T. Tan, “Coordinated operation of a microgrid with a distribution network device,” in *Proc. IEEE Asia Innovative Smart Grid Technology Conference*, Bangkok, Nov. 2015.