Operation and control of DC microgrids with integration of renewable energy sources and energy storages

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**Operation and Control of DC Microgrids with
Integration of Renewable Energy Sources and
Energy Storages**

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**SCHOOL OF ELECTRICAL AND ELECTRONIC
ENGINEERING**

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Summary

With high penetration of DC-compatible energy sources, storages and loads, DC microgrids with minimized number of DC/AC/DC power conversions are becoming more popularized. Proper control algorithm for autonomous operation of system interfacing various system units stands as a challenge. Centralized energy management system with communication link between the central controller and individual system unit is usually implemented to realize systematic coordination. However, low system reliability due to the need for communication link and long response time due to communication delay are the main disadvantages of the centralized control.

DC bus signaling, in which DC bus voltage is regarded as the global indicator for system power balance, is implemented for distributed control to enhance system reliability. Therefore, system units can schedule their operating modes and output power based on local bus voltage variations in distributed manner so that to eliminate the communication link. In multiple modes DC microgrid control, the allowable bus voltage range is divided into several regions. The operating modes of system units in different regions are assigned based on their utilization priorities. However, lacking of active power sharing among slack terminals and significant bus voltage variation during operating region transitions are the main drawbacks of multiple mode operation.

Combination of multiple modes operation and voltage/power (V/P) droop control is proposed in multiple-slack-terminal DC microgrid control. Droop relationships are imposed for system units operating in voltage regulation mode to generate the reference voltage based on actual output power. It helps active power sharing among slack terminals based on their power capacities and reducing the bus voltage fluctuations during the voltage region transitions. To equalize system bus voltage/load power droop relationship in different regions, capacity based bus voltage partition is proposed to determine the threshold voltages. Online droop

coefficient tuning in distributed manner is also implemented to prevent bus voltage discontinuity due to reduction of system units' power capacities.

Due to the transmission line impedance and droop relationships imposed, power tracking errors and bus voltage deviation exist in multiple-slack-terminal DC microgrid. To enhance system control accuracy while retaining the reliability, multi-level energy management system is proposed. Multiple-slack-terminal DC microgrid distributed operation for bus voltage regulation and power sharing is scheduled as the primary control. Bus voltage restoration is implemented in secondary control to eliminate the steady state bus voltage deviations. In tertiary control, the power references of slack terminals are generated based on the comparison of their marginal costs. The power tracking errors are minimized with power sharing compensation. In case of communication failure, system operation can still be retained with distributed control, but the control accuracy is degraded.

Energy storages (ESs) are widely installed to compensate the intermittency of renewable energy generation and uncertainty of load consumption. ESs be categorized based on their energy density, power density, ramp rates, *etc.* Hybridization of ESs with difference characteristics is an effective and economic solution to comply with system design specifications. Hybrid energy storage system (HESS) with centralized control for system net power decomposition and ESs power dispatch is normally implemented. Low speed of response and low system reliability limit its effectiveness for real-time operation. Hierarchical control of HESS, comprised of both centralized and distributed controls, is proposed to ensure both system reliability and control accuracy. System operates with HESS centralized control in which iteration based power dispatch is applied to maximize the utilization of ESs ramp rates. In case of communication failure, system net power decomposition and ESs power dispatch are realized with localized low pass filters in distributed control.

Reassignment of slack terminal in case of slack terminal outage and ESs operating mode change in case of communication failure are the main disadvantages of HESS hierarchical control. Multi-level energy management system is thus

proposed for HESS control. In primary control, all ESs are scheduled to operate in voltage regulation mode with droop control. System net power decomposition and ESs power dispatch are realized with localized low pass filters applied to ESs with low ramp rate so that they only respond to low frequency net power changes. Bus voltage restoration and power sharing compensation are implemented in secondary control to enhance system control accuracy. Autonomous state of charge recovery of ESs with high ramp rates is applied to generate their voltage references based on the real-time stored energy. In case of communication failure, system operation can still be retained without ESs operating mode change.

In grid-tied DC microgrid with bidirectional interlinking converter (BIC) for power exchange between the utility grid and DC microgrid, the BIC is usually scheduled to regulate DC bus voltage in grid-tied state. The rest of system units are configured as power terminals to track respective power reference based on systematic optimization. In case of utility grid outage, DC microgrid islanded state will be activated by disabling BIC power electronic switches to isolate the utility grid disturbance. At the same time, localized energy storage is scheduled to regulate system bus voltage. Operating mode changes of system units during the transitions induces significant bus voltage fluctuations. Multiple-slack-terminal DC microgrid, in which both BIC and localized ESs operate in voltage regulation mode, is applied to eliminate the operating mode changes of system units. Bus voltage restoration and power sharing compensation are implemented in multi-level energy management system to enhance system control accuracy. Detailed procedures for transitions between grid-tied and islanded states are proposed to minimize bus voltage fluctuations and inrush current during the transitions.

Various system control algorithms for operations of DC microgrid and HESS have been verified with MATLAB simulation. Besides, a lab-scale DC microgrid with integration of various energy sources, storages and loads has been developed in the Water and Energy Research Laboratory (WERL), School of Electrical and Electronic Engineering, Nanyang Technological University. Experimental case

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List of Abbreviations

AC	Alternating Current
BES	Battery Energy Storage
BIC	Bidirectional Interlinking Converter
BMS	Battery Management System
CC-CV	Constant Current-Constant Voltage
DBS	DC Bus Signaling
DC	Direct Current
DoD	Depth of Discharge
EMS	Energy Management System
ES	Energy Storage
EV	Electrical Vehicle
HESS	Hybrid Energy Storage System
HEV	Hybrid Electrical Vehicle
HPF	High Pass Filter
HRES	High Ramp Rate Energy Storage
HVDC	High Voltage Direct Current
IC	Incremental Conductance
LPF	Low Pass Filter
LRES	Low Ramp Rate Energy Storage
LVDC	Low Voltage DC
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
NRES	Non-Renewable Energy Source
NRS	Nonrenewable Energy Source
P&O	Perturb and Observe
PCC	Point of Common Coupling
PCM	Power Control Mode
PI	Proportional-Integral
PLC	Programmable Logic Units

PLL	Phase Lock Loop
PR	Proportional-Resonant
PV	Photovoltaic
PWM	Pulse-Width-Modulation
RES	Renewable Energy Source
RTU	Remote Terminal Unit
SAS	Solar Array Simulator
SCADA	Supervisory Control And Data Acquisition
SoC	State of Charge
SSTS	Solid State Transfer Switch
UC	Ultra-Capacitor
VRM	Voltage Regulation Mode

List of Symbols

A	Ideality factor for solar cell
C	Equivalent capacitance of DC microgrid
C_A	Actual capacity at actual discharging rate
C_{AiK}	Actual capacity of BESi in iteration cycle K
C_R	Battery rated amp-hour capacity at rated discharging current
D_A	Actual Depth of discharge
D_{AiK}	Actual Depth of discharge of BESi in iteration K
d_A	Actual ampere-hour discharge
d_{AiK}	Actual discharge of BESi in iteration cycle K
d_{BES}	Duty ratio for BES converter
d_{eff}	Effective ampere-hour discharge
d_{NRES}	Duty ratio for NRES converter
dP_{net}^{max}	Maximum change rate of system net power
d_{PV}	Duty ratio for PV converter
D_R	Rated depth of discharge
DoD_i	Depth of Discharge of the i^{th} battery energy storage
E_{gap}	Gap energy
E_{iK}	BESi cost during iteration K
f_{ESi}	Cut-off frequency of ESi
f_{ESi}^{max}	The maximum cut-off frequency of ESi
G_{BES}	Switch signal for BES converter
G_{BIC}	Switch signal for BIC
G_{BVR}	PI gain for bus voltage restoration
G_{NRES}	Switch signal for NRES converter
G_{PSCI}	PI gain for i^{th} slack terminal in power sharing compensation
G_{PV}	Switch signal for PV converter
I_d	Inductor current in direct axis
I_d^*	Reference inductor current in direct axis
I_L	Inductor current

I_L^*	Reference inductor current
I_{mp}	PV output current at the maximum power point
I_{ph}	Photocurrent
I_{PV}	Solar PV output current
I_q	Inductor current in quadrature axis
I_d^*	Reference inductor current in quadrature axis
I_{rr}	Reverse saturation current at T_r
I_{sat}	Saturation current
I_{sc}	Short-circuit current of solar PV
I_{sso}	Short-circuit current
k	Boltzman constant
K_{Ic}	SoC recovery coefficient of ES1 in centralized control
K_{Id}	SoC recovery coefficient of ES1 in distributed control
K_i	Short-circuit current temperature coefficient
K_o	Coefficient for fractional open-circuit voltage method
L_R	Rated life cycle of battery energy storage
M	Number of voltage sensitive loads
M_{BIC}	Droop coefficient of BIC
m_{eq}	Equivalent droop coefficient
m_i	Droop coefficient of the i^{th} slack terminal
MC_{BESi}	Marginal cost of BESi
MC_{NRES}	Marginal cost of NRES
MC_{RES}	Marginal cost of RES
MC_{Ut}	Marginal cost of utility grid
n_p	Number of parallel solar cells
n_s	number of series solar cells
V	System bus voltage
$\bar{V}$	Average bus voltage
V_{BES}	Output voltage of BES
V_{BES}^*	Reference BES converter output voltage

V_{H1}	Threshold voltage for bus voltage region H1
V_i	Output voltage of the i^{th} slack terminal
V_i^*	Reference voltage of the i^{th} slack terminal
V_{iK}	Terminal voltage of the i^{th} BES in iteration cycle K
V_{L1}	Threshold voltage for bus voltage region L1
V_{max}	Maximum allowable bus voltage
V_{min}	Minimum allowable bus voltage
V_{mp}	PV terminal voltage at the maximum power point
V_n	Nominal bus voltage
V_{NRES}	Output voltage of NRES
V_{NRES}^*	Reference NRES converter output voltage
V_{oc}	Open-circuit voltage of PV
V_{oi}	Threshold voltage of the i^{th} slack terminal
V_{PV}	Solar PV terminal voltage
V_{PV}^*	Reference PV terminal voltage
V_{PV}^{max}	Maximum PV terminal voltage
V_{PV}^{min}	Minimum PV terminal voltage
V_{PVo}	PV converter output voltage
V_{PVo}^*	Reference PV converter output voltage
V_{Si}	Bus voltage measured at the i^{th} sensitive load
P_{BES}	Output power of battery energy storage
P_{BES}^{max}	Maximum discharging power of battery energy storage
P_{BES}^{min}	Maximum charging power of battery energy storage
P_{BIC}	Output power of bidirectional interlink converter
P_{BIC}^{max}	Maximum output power of bidirectional interlink converter
P_{BIC}^{min}	Manimum output power of bidirectional interlink converter
P_{BIC}^*	Reference output power of bidirectional interlink converter
P_{Con}	Power consumption
P_{DG}	Output power of diesel generator

P_{ES}	Output power of energy storage
$P_{ES}^{\max}$	Maximum discharging power of ES
$P_{ES}^{\min}$	Maximum charging power of ES
P_{Gen}	Power generation
P_i	Output power of the i^{th} slack terminal
P_{iK}	Output power of the i^{th} slack terminal in iteration cycle K
P_{LAC}	AC load power consumption
P_{LDC}	DC load power consumption
P_{Loads}	Load power consumption
P_{net}	System net power
P_{NRES}	Output power of nonrenewable energy source
$P_{NRES}^{\max}$	Maximum output power of NRES
P_{PV}	Output power of solar PV
P_{RES}	Renewable energy source generation
$P_{RES}^{\max}$	Maximum output power of RESs
P_{WT}	Output power of wind turbine
q	Electron charge
R_s	Series resistance
RC_i	Replacement cost of BESi
r_{ESi}	Ramp rate of ESi
$r_{ESi}^{\max}$	<i>Maximum ramp up rate of ESi</i>
$r_{ESi}^{\min}$	<i>Maximum ramp down rate of ESi</i>
S	Solar irradiation level
SoC_{nom}	Nominal state of charge
SoC_{max}	Maximum state of charge
SoC_{min}	Minimum state of charge
T_J	Junction temperature
T	Iteration duration
T_{ESi}	Time constant for the LPF of ESi
T_r	Reference temperature

ΔP_i	Output power change of the i^{th} slack terminal
ΔP_{ES1}	Modified output power of ES1
ΔV	Change of system bus voltage
ΔV_i	Output voltage change of the i^{th} slack terminal
ΔV_{iP}	Power sharing voltage compensator for the i^{th} slack terminal
ΔV_V	Voltage compensator for bus voltage restoration
δV	Change in threshold voltage due to line impedance
δm	Change in droop coefficient due to line impedance

Chapter I. Introduction

1.1 Background

Alternating current (AC) supported by Nikola Tesla and George Westinghouse has won over the direct current (DC) promoted by Thomas Edison more than one hundred years ago [1, 2]. It was mainly due to the ease of voltage regulation with transformers which helps voltage regulation of AC power effectively and efficiently. With the development of electricity industry, centralized power generation has stood out because of the low unit cost of electricity. However, those central power generation stations are usually located far away from the user point and long distance power transmission is needed. To enhance the efficiency of the transmission system, high voltage power transmission, which requires frequent voltage regulation, is normally implemented. Compared with AC voltage regulation with transformer, DC voltage regulation was very difficult, inefficient and costly at that time. As a result, AC appeared to be a better choice and has been standardized for electricity transmission and distribution ever since [3].

The development of semiconductor technology, power electronic converters, which appeared since 1970s [4], facilitated DC power conversions. Power converters are so efficient, versatile and reliable nowadays that they are widely used in areas including power transmission, distributed generation, automobile, robot, consumer electronics, *etc.* Except for the development of power electronic converters, following changes are also affecting the dominance of AC grid:

DC-compatible Loads

Semiconductors which are inherently DC start to dominate the electrical loads in commercial, residential and industrial buildings [5]. DC-compatible load includes the LED lighting, LCD display, computer and communication devices, *etc.* Motors with variable speed drives, like washing machine and air conditioner, are also

categorized as DC compatible loads. In current power distribution network, all electric loads are connected to AC power supply. Dedicated AC/DC rectifiers are needed to convert utility AC power to DC power. Power consumed by DC-compatible loads takes up nearly 30% of the total consumption and is predicted to increase to 80% within 10-15 years [4, 5]. Popularity of electric vehicle (EV) which requires DC power charge brings in another hotspot for DC loads [6].

Compared with centralized power conversion, localized AC/DC conversions are always of relatively low efficiency. Besides, most of the AC/DC adapters don't have active voltage regulation capability and thus DC power quality might be not as satisfactory. Thus with increase in the penetration of DC-compatible loads, tying the loads directly to DC distribution network appears to be more beneficial due to its higher efficiency, more enhanced reliability, better compatibility and power quality.

Distributed Generation

With the global concern over depletion of conventional fossil fuel and the consequential environmental impacts, clean and renewable energy sources (RESs) like solar photovoltaic (PV) and wind, which are abundant and easy to acquire, are well accepted. Both centralized RES power plants and distributed house-hold RES systems are installed to reduce carbon emission and dependence of fossil fuels. Household distributed generation has the advantage of geometrical closer location to the load center to eliminate the long distance transmission which would otherwise induce power loss of about 6.5% [7]. Zero-net-energy buildings were constructed around the world to demonstrate the possibility of "clean" generation of localized RESs to completely fulfill the building power consumption [8]. Rooftop solar PV systems which require no additional installation space and are of low noise level compared with wind turbines appear to be a better choice for household applications [9].

Government regulations for the integration stand as a barrier for the development of RESs, but the situation changed dramatically nowadays when government

allows integration of RESs to the utility power grid and provides respective incentives in countries like Germany, Australia, China, *etc.* [10]. Participation of household distributed generation changes the conventional single direction power transmission from centralized power plant to users. Electricity fed back from users to utility is also possible in case of load peak to reduce power system generation capacity and spinning reserve required.

The outputs of RESs like solar PV, fuel cell, *etc.* are DC-inherent. DC/AC power conversions are needed to connect the RESs to the conventional AC distribution system.

Distributed Energy Storage

RESs are usually controlled to operate in maximum power point tracking mode (MPPT) to maximize their utilizations. Unlike the conventional fossil fuel based generation, RESs generation is determined based on the weather condition including solar irradiation, wind speed, temperature, *etc.* Intermittence of renewable sources induces significant variations of RESs power generation. Therefore, sufficient spinning reserves with fast ramping up rate should be installed to cope with generation variation which further increases utility grid installation and operation costs. With the increase of RESs penetration, the effect becomes more crucial [10]. Localized energy storages (ESs) are proposed to smoothen the generation variations of RESs by charging during load valley and discharging in case of load peak to reduce the spinning reserves needed [11-15]. Distributed generation together with distributed energy storage create “virtual generator” which can be dispatched to replace conventional generator to commit relatively stable power output.

Most of the distributed energy storages like battery, ultra-capacitor (UC), flow battery, *etc.* are inherently DC. DC/AC bidirectional inverters are required for integration of ESs in conventional AC grid.

Multiple DC/AC/DC power conversions are needed for integration of DC-compatible load, energy sources and storages mentioned foregoing in the

conventional AC distribution system. Therefore, DC grid is becoming more beneficial for system with high penetration of DC-compatible system units [16]:

- Reduced number of DC/AC/DC power conversions
- Lower system installation and operation cost
- Enhanced energy efficiency and system reliability
- Enhanced DC power quality

DC grids are gaining its popularity with the advantages mentioned forehead [3, 4, 8, 17, 18]. High voltage DC (HVDC) transmission [19-24] is a good example for DC grid application. Compared with AC transmission system, DC power transmission has been proven to have higher transmission capacity, better stability with transmission loss reduction of up to 30%-50% [20]. HVDC is suitable for long distance high power transmission. Numbers of HVDC projects have been carried out all over the world including China, Europe, *etc.* with voltage of up to ± 800 kV [25].

Data center is another application for DC microgrids [3, 24]. Servers, which are inherently DC, are the most significant and critical load in data center. DC microgrid with nominal bus voltage of 380V has already been proposed and standardized by Emerge Alliance [3]. DC microgrids are also applied in residential complex [9, 26, 27], vehicle [28-30], renewable energy source integration [31], *etc.*

1.2 DC Microgrid

The schematic diagram of a generic DC microgrid is as shown in Figure 1-1. All system units including the energy sources, loads and storages are connected to the DC bus. DC/DC power electronic converter is used to control the output of solar PV which is DC inherent. PV converter normally operates in MPPT mode with output power of P_{PV} . Wind turbine is also an important type of RES which is widely installed. AC/DC power electronic converter is used for integration of wind turbine to DC microgrid with output power is P_{WT} . DC load is connected to system

bus directly. For some AC loads with high power quality requirement, dedicated DC/AC conversion is needed.

Figure 1- 1. Schematic layout of a generic DC microgrid.

DC microgrid can be configured to operate in grid-tied or islanded states. A bidirectional interlinking converter (BIC) is always used for power exchange between the utility grid and DC microgrid in grid-tied state [32]. In case of utility grid disturbance, including bus voltage fluctuation, frequency range violation, *etc.* system changes to operate in islanded state to isolate the utility disturbance. To compensate for the intermittence of RESs generation and uncertainty of load consumption, which induces significant variations of BIC output power P_{BIC} in grid-tied state, localized energy storages (ESs) are usually implemented to reduce the spinning reserves needed for utility grid. Battery banks are integrated to DC microgrid through a bidirectional DC/DC converter as shown in Figure 1-1. Diesel generator serves as the backup generation and AC/DC power conversion is needed when the output of diesel generator is connected to the DC bus.

Functionalities of energy sources and storages, controlled with respective power electronics, are versatile in the sense that the converters can be controlled to operate in different operating modes and with different operating references [33]. For DC microgrid operation, system power balance and bus voltage regulation are

the basic control objectives to ensure system stability. Besides, system operation cost, battery lifetime, load management, *etc.* should also be taken into consideration. Therefore, proper control algorithms should be implemented to coordinate all system units to realize system-wide optimization.

1.3 Barriers for Development of DC Microgrid

DC microgrid has advantages including reduced power conversion, lower system cost, higher energy efficiency and system reliability. However, there are also some barriers for the development of DC microgrids [34].

a. Robust control algorithm

For DC microgrid with integration of various energy sources, storages and loads, robust control algorithm to coordinate all system units is needed. System operation in grid-tied and islanded states, with/without communication link, *etc.* should be investigated.

b. Standards for distribution network

Well-accepted industrial standard, which regulates system power quality requirement of DC microgrid, is necessary. International Electrotechnical Commission (IEC) has mentioned about the bus voltage requirement in the publicized standard [35] One of the most active organizations for low voltage DC (LVDC) standardization is the Emerge Alliance which has published 380 VDC for data/telecom centers and 24 VDC for LED lighting system [3]. Rebus Alliance has also published a draft version of regulation for household DC microgrid with integration of RESs [36].

c. Protection device and appliance

Commercial protection device and household appliance available in the market is based on the conventional AC distribution system. Dedicated protection devices and appliances for DC microgrid applications are rare and costly. It is due to the modification of design needed and limited production volume.

d. Ecosystem to drive momentum

The ecosystem for DC microgrid includes suppliers, customers and governor. Suppliers should provide qualified products including DC-compatible utilities, protection devices and other necessary auxiliary components like connectors, plugs, *etc.* Customers are expected to fully understand the significance and are willing to play their roles for the promotion of DC system. Government is supposed to provide respective incentives and regulate the market to facilitate the development of DC microgrid.

1.4 Objectives

The focus of the Ph.D. work is to develop robust control algorithms for DC microgrid to ensure system stability, efficiency and reliability. Main objectives of this research work include:

- 1) Compare different types of microgrids including AC, DC and hybrid AC/DC distributed systems.
- 2) Analyze the feasibility of DC microgrid with high penetration of renewable energy sources and energy storages.
- 3) Conduct comprehensive review regarding the existing control methods for DC microgrid operation.
- 4) Propose reliable control algorithms for DC microgrid operation to ensure system stability and minimize bus voltage variation.
- 5) Discuss system operation in grid-tied and islanded states and the transition between them.
- 6) Realize the economic dispatch to minimize system cost for real-time operation.
- 7) Investigate different types of energy storages and propose hybrid energy storage system to enhance system performance.

- 8) Propose energy management system (EMS) based on centralized control to realize system optimization.
- 9) Develop lab-scale DC microgrid for experimental verifications of the proposed control methods.

1.5 Contributions

The main contributions of the Ph.D. work include:

a. Multiple-slack-terminal DC microgrid for distributed control

DC microgrid distributed control has exhibited higher system reliability in case of communication failure. The bus voltage is regarded as the global information carrier to indicate system power balance. The voltage range, in which system bus voltage is allowed to vary, is divided into several sub-regions. System units, including RESs, ESs, loads, BIC and DGs, are prioritized based on their utilization costs. The operating modes of all system units are scheduled based on the comparison between the threshold voltages and local bus voltage in real-time operation to realize system control in distributed manner. At least one type of system units is scheduled as the slack terminal to compensate system power balance and regulate bus voltage. To prevent uncontrollable circulating current, droop relationships are imposed when system units operate in voltage regulation mode (VRM). It helps active power sharing among slack terminals and ensures smooth transition between different bus voltage regions. Power capacity based bus voltage region partition is proposed to equalize the droop coefficient in all voltage regions. To prevent system bus voltage discontinuity due to power capacity reduction during voltage region transitions, online bus droop coefficient tuning based on estimation of the real-time power capacity is proposed.

b. Multi-level EMS for DC microgrid real-time operation

Distributed control of DC microgrid has exhibited higher reliability and faster system response by eliminating the communication link. However, due to the transmission line impedance and droop relationship imposed in actual

implementation, bus voltage deviation from the nominal value and power tracking errors are the main drawback of DC microgrid distributed control. Multi-level EMS is thus proposed to enhance system control accuracy while retaining system reliability. Distributed control of DC microgrid with implementations of DC bus signaling (DBS) and droop control is scheduled as the primary control. Bus voltage restoration is implemented in secondary control to minimize the bus voltage deviations so that system power quality can be ensured. In tertiary control, economic dispatch is proposed to minimize system operation cost. Slack terminal power references are generated by comparing the marginal costs of all system units. Power sharing compensation is implemented to minimize the power tracking errors. In case of communication failure, in which higher level coordination algorithms cannot be implemented, system operation can still be retained with primary control. However, the control accuracy is degraded.

c. Hybrid energy storages system

For DC microgrid with high penetration of RESs, energy storages are needed to compensate the intermittence of RESs generation and uncertainty of load consumption [37]. Variations of RESs generation and load consumption can be decomposed into high and low frequency components. Hybridization of energy storages with different ramp rates (kW/min) is an effective and economic solution to mitigate bus voltage variation due to system power imbalance. Hybrid energy storage system (HESS) control is normally realized with supervisory EMS. In case of communication failure, system operation cannot be retained. Hierarchical HESS comprised of both centralized and distributed control is proposed to enhance system reliability. System operates in centralized control with high ramp rate energy storages (HRES) in VRM and low ramp rate energy storages (LRES) in power control mode (PCM) in normal state. The power reference of LRES is generated based on the real-time system net power to maximize the ramp rate of LRES. HRES compensates the power deficiency which is the high frequency component. In case of communication failure, system changes to operate in distributed control to enhance system reliability. HRES operates in VRM with

droop control and the power reference of LRES is generated based on local bus voltage variations. State of charge (SoC) recovery for ESs in both centralized and distributed control has been proposed to prevent over-charged/discharged damage.

Operating mode change of HRES and LRES in hierarchical HESS induces system bus voltage fluctuation. Therefore, multi-level EMS based HESS is proposed. Both LRES and HRES operate in VRM with droop control. System net power decomposition and ESs power scheduling are realized with low pass filter (LPF) applied at the feedback voltage of LRES. The relationship between the cut-off frequency of LPF and the ramp rate of LRES has been elaborated in detail to maximize the utilization of LRES ramp rate. Multi-level EMS is implemented to enhance system control accuracy while retaining the reliability.

d. Transitions between grid-tied and islanded states

DC microgrid operation transitions between grid-tied and islanded states are commonly encountered in case of utility grid disturbance. However, the transition procedures for islanding and reconnection have seldom been discussed in detail. BIC is usually scheduled to regulate DC bus voltage in grid-tied state. In case of utility grid fault, operating mode change of BIC from VRM to idle is activated to isolate the disturbance. Localized battery energy storage (BES) operating mode change from PCM to VRM to maintain system power balance is needed. Due to the operating mode change of BIC and BES, significant bus voltage fluctuation and inrush current usually appear during the transitions. Multiple-slack-terminal DC microgrid, in which both BIC and BESs operate in DC VRM, is proposed to ensure smooth transitions. The operating mode change of BESs is eliminated and thus system bus voltage is regulated actively throughout the transitions. Implementation of contactor helps decoupling the BIC operating mode change and grid connection during the transition from islanded to grid-tied state. A counter is used to ensure bus voltages at both sides of the contactor are matched stably to minimize the inrush current.

1.6 Organization

This report is organized as follows:

Chapter I introduces the background information. Changes of the power system including higher penetration of DC-compatible loads, energy storages and sources are explained. The significance and barriers for the development of DC microgrid are discussed. The main contributions of the PhD work have been concluded.

In Chapter II, literature review of current control algorithms for DC microgrid operation has been conducted. Techniques for DC microgrid control in distributed manner like DC bus signaling (DBS), multiple voltage level control, *etc.* are explained. Detailed experimental setups of the lab-scale DC microgrid are introduced.

Multiple-slack-terminal DC microgrid, which enables system units with plug-and-play capability, is presented in Chapter III. Power capacity based bus voltage region partition is proposed to equalize the equivalent droop coefficients in different bus voltage regions. Online droop coefficient tuning is also proposed to prevent bus voltage discontinuity during voltage region transitions.

Multi-level EMS for DC microgrid control is proposed in Chapter IV. Distributed control of the multiple-slack-terminal DC microgrid is scheduled as the primary control. Bus voltage restoration is implemented in secondary control to enhance system power quality. Power sharing compensation is implemented in tertiary control to eliminate the power tracking errors.

Two methods for hybridization of energy storages, including hierarchical HESS and multi-level EMS, are proposed in Chapter V. Distributed algorithm for system net power decomposition and ESs power scheduling are proposed to enhance system reliability. Central EMS is implemented to enhance system control accuracy.

Multiple-slack-terminal DC microgrid is proposed to smooth DC microgrid transitions between grid-tied and islanded states in Chapter VI. Detailed procedures

for islanding and reconnection are designed to minimize the bus voltage fluctuations and inrush current.

Chapter VII concludes the Ph.D. work. Future works have also been explained in this chapter.

Chapter II. Multiple Modes Control of DC Microgrids

2.1. DC Microgrid Distributed Control

Multi-level supervisory energy management system (EMS) is usually implemented for DC microgrid system-wide control [38-41]. System operating statuses including bus voltage, RESs generation, load consumption, system power flow, ESs stored energy, *etc.* are acquired by the central controller through the communication link [42]. Upon data acquisition, the operating references for all system units are generated based on control objectives to realize global optimization. The operating references are assigned to respective system units through the communication link.

Master-slave has been implemented to realize system bus voltage regulation and power sharing in [43]. Salomonsson *et al.* [24] has shown the effectiveness of operation by defining eight modes, each of which configures system units based on the loading condition and RESs generation, for DC microgrid application. Smart artificial intelligent methods like neural network and fuzzy control are also implemented in the central controller to achieve better system performance [27]. Secondary voltage compensation which minimizes bus voltage deviation from nominal value was introduced in [44, 45].

With centralized coordination, system-wide optimization can be realized and system power quality can be ensured. However, it has mainly three drawbacks [9, 29, 46]:

- Higher installation cost due to the necessity for the central controller and transmission link.
- Lower reliability in case of communication link failure which might lead to malfunction of the whole system.
- Slower speed of response due to the time needed for information transmission between the central controller and system units [47].

DC bus signaling

Distributed control of DC microgrid, in which the bus voltage is regarded as the global indicator for system power balance, has been proposed to enhance system reliability in literatures [32]. DC microgrid bus is naturally capacitive due to the cumulated capacitance of output capacitors attached with every power electronic converters. The equivalent circuit for the capacitive DC microgrid is as shown in Figure 2-1. P_{Gen} and P_{Con} are system power generation and consumption, respectively. C is the equivalent system capacitance and V is system bus voltage.

Figure 2-1. Equivalent circuit for capacitive DC microgrid.

The relationship between system bus voltage and power balance in real time is:

$$V(t) \frac{dV(t)}{dt} = \frac{1}{C} (P_{Gen}(t) - P_{Con}(t)) \quad (2-1)$$

When power generation is lower than load consumption, system power deficiency appears and thus bus voltage reduction will be induced. On the other hand, when system power generation is higher than consumption, bus voltage increment due to system power surplus will be induced. System bus voltage is available locally for all power electronic converters connected to the DC bus. Increase in system bus voltage indicates system power surplus and bus voltage drop indicates system power deficiency. This explains why bus voltage can be used as global indicator for system power balance. This technique is termed as DC bus signaling (DBS) [32, 48-51].

Bus voltage range partition

In order to schedule the operating mode of different system units in distributed manner, system bus voltage range partition is necessary. The nominal bus voltage and allowable bus voltage range is determined by industrial standards and government regulations [36, 52]. Threshold voltages are set to divide the allowable bus voltage range into several regions as shown in Figure 2-2. V_n , V_{min} and V_{max} are the nominal bus voltage, minimum and maximum allowable bus voltage, respectively. V_{L1} and V_{H1} are the threshold voltages for region L1 and H1 respectively as shown in the figure [53]. The threshold voltages are usually set to partition the voltage regions equally. Therefore, V_{L1} is the average value of V_n and V_{min} ; V_{H1} is the average value of V_n and V_{max} .

Figure 2-2. Bus voltage range partition.

2.2. Multiple Modes Control of DC Microgrids

2.2.1. Operating mode configuration

For an islanded DC microgrid with integration of renewable energy source (RES), energy storage and backup diesel generator, prioritization of system units for distributed control is needed [54]. In order to minimize system operation cost, system units are prioritized based on the marginal utilization cost [55]. The marginal utilization cost refers to the additional cost that will be induced for energy output of 1 kWh. The marginal cost of RES is the lowest as the renewable source is free. Therefore, RESs are normally controlled to operate in maximum power point tracking (MPPT) mode to maximize the utilization of renewable source. Diesel

generator is considered as the nonrenewable energy source (NRES) whose marginal cost is equivalent to the fuel cost needed. ES is regarded as the energy buffer in this case. The marginal cost is indicated with the power losses induced during charge and discharge. Therefore, the utilization priority of ES is set to be lower than RES, but higher than NRES [53].

System units can be controlled to operate as a power terminal or slack terminal based on the operating mode configuration of respective power electronic converter. Power terminal operates in power control mode (PCM) to track power reference regardless of the bus voltage variation. Slack terminal operates in voltage regulation mode (VRM) to follow voltage reference and maintain system power balance autonomously. In order to ensure stable system bus voltage, at least one slack terminal should be online at all time [56]. System bus voltage range is divided into 4 regions, namely region H2, H1, L1 and L2 with threshold voltages V_{H1} and V_{L1} . The relationship between the threshold bus voltages is:

$$V_{\min} < V_{L1} < V_n < V_{H1} < V_{\max} \quad (2-2)$$

Different operating modes of system units are assigned when they operate in different voltage regions. The operating mode of system units are determined based on the comparison of the local bus voltage with the threshold bus voltage values [57]. Detailed operating mode configurations are as shown in Table 2.1.

Table 2.1. Operating mode configurations of system units in distributed control.

Region\System Unit	<i>ES</i>	<i>RES</i>	<i>NRES</i>
<i>H2</i>	PCM charge	VRM	IDLE
<i>H1</i>	VRM charge	MPPT	IDLE
<i>L1</i>	VRM discharge	MPPT	IDLE
<i>L2</i>	PCM discharge	MPPT	VRM

In region H1 and L1, ES operates in VRM to regulate system bus voltage and RES operates in MPPT mode. When RES power generation P_{RES} is higher than the combined load consumption, ES operates in charging stage in region H1. ES changes to operate in discharging stage to maintain system power balance when

system RES generation is lower than load consumption. System changes to operate in region L1.

The charging/discharging power of ES is limited by its power capacity. When ES reaches the maximum charging power, ES changes to operate in PCM with the maximum charging power as the power reference to prevent over-current charge which deteriorates ES lifetime operation [58]. System bus voltage increment will be induced due to system power surplus and system changes to operate in region H2. RES VRM operating will thus be activated to prevent over-voltage damage. Operating mode of NRES remains the same.

Similarly, when ES reaches the maximum discharging power, ES changes to PCM operation to prevent over-current discharge. The maximum discharging power is set as the power reference. System power deficiency induces bus voltage reduction. NRES operating mode change from idle to VRM will thus be activated to retain system power balance.

2.2.2. System voltage-power characteristic

Figure 2-3. Voltage-power characteristic curves of system units.

With the operating mode configuration of system units as in Table 2-1, the voltage/output power (V/P) characteristic curves of RES, ES and NRES are as shown in Figure 2-3. RES operates in MPPT mode in regions H1, L1 and L2. Therefore, the output power remained at the maximum value regardless of bus voltage variation in these regions. RES changes to operate in VRM in region H2.

The output power is determined by system power balance. ES operates in VRM with reference voltage of V_n in regions H1 and L1. In region H2 and L2, ES output power is remained to be constant at the maximum charging and discharging power, respectively. NRES operates in idle mode with output power of zero in regions L1, H1 and H2. NRES is the backup energy source which will be activated to operate in VRM in region L2. NRES actual output power is determined by the real-time power generation and load consumption to maintain system power balance.

ES output power P_{ES} is positive in discharging stage and negative in charging stage. The relationship between load consumption P_{Load} and output powers of system units is:

$$P_{Load} = P_{RES} + P_{ES} + P_{NRES} \quad (2-3)$$

Therefore, the relationship between system bus voltage and load consumption (V/P_{Load}) can be obtained with superposition of system units' V/P characteristic curves as shown in Figure 2-4. With the relationship between system bus voltage and load power as in the figure, operating region and system bus voltage can be generated in different loading conditions intuitively.

Figure 2-4. System voltage-load power characteristic.

2.3. Control of Power Electronic Converters

Operating mode configurations and output control of RES, ES and NRES are realized with respective power electronic converters.

2.3.1. Solar PV system

Figure 2-5. Modeling of solar PV.

Solar PV cell is usually simulated as a current source with a parallel reverse diode and shunt resistor R_P and in series with resistor R_S is as shown in Figure 2-5 [59].

The output current of solar PV array is:

$$I_{PV} = n_p I_{ph} - n_p I_{sat} \times \left[\exp\left(\frac{q}{AkT} \left(\frac{V_{PV}}{n_s} + I_{PV} R_s\right)\right) - 1 \right] \quad (2-4)$$

$$I_{ph} = (I_{sso} + k_i(T_J - T_r)) \cdot \frac{S}{1000} \quad (2-5)$$

$$I_{sat} = I_{rr} \left(\frac{T}{T_r}\right)^3 \exp\left(\left(\frac{qE_{gap}}{kA}\right) \cdot \left(\frac{1}{T_r} - \frac{1}{T_J}\right)\right) \quad (2-6)$$

Where:

- I_{PV} Solar PV output current
- V_{PV} Solar PV terminal voltage
- I_{ph} Photocurrent
- I_{sat} Saturation current
- q Electron charge
- A Ideality factor
- k Boltzman constant
- R_s Series resistance
- I_{sso} Short-circuit current
- K_i Short-circuit current temperature coefficient
- T_r Reference temperature
- I_{rr} Reverse saturation current at T_r
- E_{gap} Gap energy
- n_p Number of parallel solar cells
- n_s number of series solar cells

S Solar irradiation level
 T_j Junction temperature

With solar PV model described with (2-4) – (2-5), the output current-terminal voltage (I-V) characteristic curve of solar PV array is as shown in Figure 2-6 [60]. PV output current decreases with the increase in with terminal voltage. When PV terminal voltage is zero, the output current is the highest, which is termed short-circuit current I_{SC} . PV terminal voltage V_{PV} is the highest when the output current is zero. The voltage is termed open-circuit voltage V_{OC} . The output power of solar PV P_{PV} can thus be obtained by multiplication of the terminal voltage and output current. The relationship between P_{PV} and V_{PV} are as shown in Figure 2-6. A maximum power point (MPP) exists with terminal voltage of V_{mp} and output current of I_{mp} . The output power is positively related with the terminal voltage when V_{PV} is lower than V_{mp} [48]. When V_{PV} is higher than V_{mp} , P_{PV} decreases with the increase of V_{PV} .

Figure 2-6. I-V characteristic curve of solar PV.

A unidirectional DC/DC booster is implemented in this case for integration of solar PV in DC microgrid as shown in Figure 2-7. When PV converter operates in MPPT mode, the reference terminal voltage V_{pv}^* is generated in MPPT function block. Conventional double-loop proportional-integral (PI) control is implemented to track the reference terminal voltage. In the outer voltage loop, the difference between the reference and actual terminal voltage is processed with a PI controller to generate the reference inductor current I_L^* . Another PI controller is used in the inner current loop to minimize the inductor current tracking error and obtain the

duty ratio for PV converter d_{PV} . Pulse-width-modulation (PWM) generator is used to generate the switching signal (G_{PV}) for the power electronic switch.

Figure 2- 7. Control schematic diagram of solar PV converter.

When PV converter operates in VRM, double-loop PI controller is used to track the reference output voltage V_{PVo}^* . The different between V_{PVo}^* and actual out capacitor voltage is processed with a PI controller to generate the reference inductor current in outer voltage loop. The inductor current tracking in VRM is the same as that in MPPT mode. The operating mode selection is based on the comparison of actual bus voltage with the threshold value V_{H1} . The relationship between the output voltage and terminal voltage is:

$$V_{PVo} = \frac{1}{1-d_{PV}} V_{PV} \quad (2-7)$$

MPPT algorithms

Various solar PV MPPT algorithms including perturbation & observe (P&O), incremental conductance (IC), fractional open-circuit voltage/short-circuit current, *etc.* have been analyzed and compared [61, 62]. In P&O, PV terminal voltage is designed to perturb with a small step in certain direction to obtain the corresponding output PV output power. Comparison of newly obtained output power and previous power determines whether the perturbation is directed correctly towards the MPP. If the newly obtained power is higher than the previous

value, the direction of perturbation in next step remains the same. Otherwise, the direction of perturbation should be reversed. Detailed mechanism is as described in Table 2.2.

Table 2.2. P&O Mechanism.

<i>Perturbation Direction</i>	<i>Change of Output Power</i>	<i>Next Perturbation Direction</i>
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

Simplicity and ease of implementation is the most significant advantage of P&O. However, continuous oscillation around MPP in steady state and slow response during rapid solar irradiation change due to step limitation are the main drawbacks [63]. Nowadays, the processors of embedded systems, which are used for the operation of PV converters, are so powerful that their computational capabilities are good enough to control converters with higher switching frequency and smaller step change. Thus oscillation at the MPP in steady state could also be minimized with smaller step change implemented. The computation cycle can be finished within several or tens of microseconds. Therefore, the tracking speed can be fast enough to cope with weather condition change.

For single stage DC/DC converter, the boost ratio is limited in actual implementation. Converter instability will be induced when the boost ratio exceeds certain range. Therefore, hybrid MPPT mechanism, which combines P&O and fractional open-circuit voltage, is proposed [53]. The approximated relationship between V_{mp} and open-circuit voltage V_{oc} is:

$$V_{mp} \approx k_o V_{oc} \quad (2-8)$$

where coefficient k_o is the value between 71% and 78% [61]. As the variation of V_{oc} due to solar irradiation change is very limited, fractional open-circuit voltage is used to limit the range variation of PV terminal voltage as shown in Figure 2-8.

$V_{PV}^{\max}$ and $V_{PV}^{\min}$ are set as the upper and lower boundary of V_{PV} variation. Whenever

the terminal voltage reaches upper boundary value $V_{PV}^{\max}$, the reference terminal voltage is reduced, and vice versa.

Figure 2-8. Combined P&O and fractional open-circuit voltage for MPPT.

The experimental setup of the multi-channel PV converter is as shown in Figure 2-9. The main components include input capacitor, output capacitor, inductors, controller and the main circuit board where MOSFETs together with their drivers are installed. Modular voltage and current sensors are installed to measure the input/output voltage and current. It integrates 3 channels of PV input to operate in parallel. Microcontroller C8051f930DK enables the converter to operate with frequency of up to 100 KHz which helps minimizing inductor size and converter weight. Detailed specifications of converter setups are as shown in Table 2.3.

Table 2.3. Experimental setups for PV converter.

<i>Component parameters</i>	<i>Unit</i>	<i>Value</i>
Output capacitance	μF	2200
Input capacitance	μF	30
Inductance	mH	3
Switching frequency	kHz	100

Figure 2-9. Experimental setups for PV converter.

2.3.2. Battery energy storage system

Figure 2-10. Control schematic diagram of battery converter.

Battery banks are the most common energy storage installed for household applications due to its safety, operation quietness, ease of installation and maintenance, low cost, low space occupation, *etc.* Battery bank together with the power electronic converter is termed battery energy storage (BES). The schematic layout and control diagram of battery converter is as shown in Figure 2-10. BES can be controlled to operate in two modes, namely VRM and PCM. Same as PV converter, the conventional double-loop PI controller, which is comprised of outer voltage and inner current loop, is implemented for BES VRM operation. When BES operates in PCM, the reference inductor current I_L^* is generated by dividing the reference BES output power P_{BES}^* with battery bank terminal voltage V_{bat} . A PI controller is implemented in the inner current loop to track I_L^* .

Converter operates as boost converter in discharging stage and buck converter in charging stage. The upper and lower switches are controlled in complementary manner. In actual implementation, turning off of the power switches (IGBT in this case) takes time, thus a dead time when both switches are off is designed to compensate for the turn on/off delay to prevent short circuit damage.

Figure 2-11. Experimental setups of BES converter.

The experimental setup of PV converter, comprised of main circuit board, sensor board, inductor, output capacity and central controller, is as shown in Figure 2-11. C8051f120 development kit is used as the central controller to accelerate converter construction. ISGT module is used as the power switch which has been proven with better noise resistance. Detailed specifications of converter setups are as shown in Table 2.4.

Table 2.4. Experimental setups for BES converter.

<i>Component parameters</i>	<i>Unit</i>	<i>Value</i>
Output capacitance	μF	2200
Inductance	mH	10
Switching frequency	kHz	10

2.3.3. NRES converter

The output of fossil fuel based NRES are usually of AC. AC/DC power conversion is needed for integration of NRES in DC microgrid. The schematic layout and control diagram of NRES converter is as shown in Figure 2-12. NRES converter operates in two modes, namely Idle and VRM. In VRM, the output voltage V_{NRES} is compared with the reference value V_{NRES}^* . The difference is processed with a PI controller to generate the direct component of the reference inductor current I_d^* . The direct component of reference inductor current is zero in Idle mode. As no reactive power is considered in DC microgrid, the quadrature component of reference inductor current I_q^* is set to be zero. Phase angle θ is generated with phase lock loop (PLL). Reference inductor current of three phases are obtained with dq/abc conversion. The difference between the reference and actual inductor current is processed with a proportional-resonant (PR) controller to generate the duty ratio for three phases. The switching signals G_{NRES} is obtained with the PWM generator.

Figure 2-12. Control schematic diagram of NRES.

2.4. Experimental Verifications

To verify the effectiveness of the proposed multiple bus voltage level control for DC microgrid operation, a lab-scale DC microgrid has been developed in Water and Energy Research Laboratory (WERL), School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, as shown in Figure 2-13. System bus is comprised of 8 circuit panels connected in a loop. The circuit panel serves as remote terminal unit (RTU) in which sockets are installed for integration of various system components.

Two Agilent E4360A Modular Solar Array Simulators (SAS) with combined power capacity of 2.4kW are installed as the renewable energy source. SAS is capable of emulate the output of PV arrays to control the output current based on the terminal voltage. The I-V characteristic curve is defined based on the open-circuit voltage V_{oc} , short-circuit current I_{sc} , maximum power voltage V_{mp} and current I_{mp} . Solar irradiation changes can also be simulated by switching between

difference I-V curves. PV converter as described in Figure 2-9 is used to integrate the PV array output power into the DC microgrid.

Figure 2-13. Schematic layout of the lab-scale DC microgrid.

Lead-acid battery bank, which is comprised of 16 battery cells connected in series, serves as energy storage in this case. The nominal terminal voltage and capacity of each battery cell is 12 V and 200Ah, respectively. Therefore, the nominal open-circuit voltage of the battery bank is 192 V. Battery management system (BMS) with functionalities including state of charge (SoC) estimation, cell SoC equalization, *etc.* is installed to optimize the utilization of the battery bank. Power electronic converter as in Figure 2-11 is used to control the output of BES. BES power capacity is limited by the maximum inductor current of 10A in this case. Thus to ensure safe operation, the maximum power capacity of the lead-acid BES is set as 1.6 kW.

Both resistive load bank and Chroma programmable load are used to simulate different loading profiles. The programmable load can be configured to operate in constant resistance, constant current and constant power modes to emulate different types of loads. NRES is emulated by Chroma DC power supply in this case. NRES

operates in idle mode in normal state and can be activated autonomously when system bus voltage is lower than its reference output voltage.

Lacking of well-accepted industrial standard and government regulation for LVDC microgrid application is one of the major barriers for the development of DC microgrid. Nominal bus voltage of 380 V is specified in microgrid specifications draft V. 0.14 published by REbus Alliance in 2011 [3, 36]. 380 VDC has also been implemented for application of data center. Therefore, the nominal bus voltage for DC microgrid operation is set to be 380 V throughout the thesis. The allowable bus voltage range is set to be ± 20 V (about $\pm 5\%$ of the nominal voltage). Therefore, the reference output voltage of RES, BES and NRES in VRM are set to be 400 V, 380 V and 360 V, respectively. Two experimental case studies have been carried out for verification.

Case 1

System transition between voltage regions H1 and L1 is verified in case 1. The resistor bank is set with resistance of 144.4Ω and programmable load is configured with constant power consumption of 1 kW. The experimental results are acquired with LeCroy oscilloscope as shown in Figure 2-14. V_{BES} , I_{BES} , V_{bat} , I_L and P_{BES} refer to BES output voltage, BES output current, battery bank terminal voltage, inductor current and output power of BES, respectively. Negative BES output current and power indicate BES operating in charging stage, and vice versa.

In the beginning, only the resistive load bank was turned on. System bus voltage was regulated by BES at 380 V. PV converter operated in MPPT mode with output power of 1.6 kW which was higher than the load consumption of 1 kW. BES operated in charging stage with power magnitude of 0.6 kW. System bus voltage was regulated at the nominal value steadily. The wide band of inductor current was due to the saw-wise switching ripple caused by periodic inductor charging and discharging.

When the programmable load was turned at 6s, BES output power has increased by 1 kW instantly to maintain system power balance. Due to BES response lag,

fluctuations of BES output current appeared. RES operating mode remained unchanged. System bus voltage sag was observed due to instant power deficiency during the transition. The duration of the transition was 0.17s. System was stabilized with BES discharging power of 0.4 kW. System bus voltage was remained at the nominal value.

Figure 2-14. Experimental results for case 1: BES charge and discharge.

When load 2 was switched off at 14.2s, BES changed back to charging stage instantly to maintain system power balance. Bus voltage surge has appeared due to instant system power surplus during the transition. Bus voltage was maintained at the nominal value in steady state.

Case 2

Operating mode changes of system units in different bus voltage regions was verified in experimental case 2. The experimental results are as shown in Figure 2-15. RES power capacity was increased to 2.2 kW. Resistance of load bank and power rating of programmable load were changed to 240 Ω and 0.3 kW, respectively.

In the beginning, both the programmable load and resistive load are connected to

system bus. System net power, which is the difference between load consumption and PV generation, was negative and lower than the charging capacity of BES. Therefore, BES operated in VRM with charging power of 1.3 kW. System bus voltage was regulated at the nominal value.

When the programmable load was turned off at 9.6s, BES charging power was increased instantly as it was regulating system bus voltage. When the charging power exceeded the threshold value of 1.6 kW, BES changed to PCM operation with the maximum discharging power (1.6 kW) as the power reference. To prevent undesired operating mode change of BES due to power fluctuations, the threshold power of mode change was set to be 10% higher than the maximum discharging power. This explains the reason for BES output power curve during the transition.

Figure 2-15. Experimental results for case 2: operating mode change.

All system units operated as power terminals when BES changed to PCM. System bus voltage increase due to power surplus was induced in this case. When system bus voltage exceeded the threshold value for PV converter operating mode change, PV changes to operate in VRM with reference voltage of 400 V. System was stabilized at 9.7s with bus voltage of 400 V. PV converter operated in VRM and BES operated in PCM in steady state.

Experimental cases have demonstrated the effectiveness of the multiple mode operation. Operating mode configuration of system unit with the comparison of local bus voltage with respective threshold voltages can be realized effectively. Transitions of system bus voltage regions are realized autonomously.

2.5. Conclusion

DC microgrid operation with centralized EMS is normally implemented. However, higher installation cost and lower system reliability due to the necessity for the communication link are the main drawbacks of centralized control. Multiple modes DC microgrid control, which is independent of the communication link, is implemented to enhance system reliability. System bus voltage range is divided into several regions and system units are prioritized based on their marginal utilization costs. The operating mode of system units are scheduled by comparison of the local bus voltage and threshold voltages.

Effectiveness of the multiple modes DC microgrid control has been verified with a lab-scale DC microgrid. Operating mode change of system units have been realized with localized bus voltage variations. Transitions between different bus voltage regions in different loading conditions have been realized effectively. System bus voltage was regulated steadily in each bus voltage region. However, there are also some disadvantages:

- Lower system power quality due to the variation of system bus voltage in different voltage regions.
- Significant bus voltage fluctuations during the voltage region transitions due to the reference bus voltage change and operating mode change of system units.
- Lacking of active power sharing scheme in case of multiple slack terminals operating in parallel.
- Systematic optimization can hardly be realized.

Chapter III. Multiple-Slack-Terminal DC Microgrids

3.1. Droop Control

With the multiple modes DC microgrid control as described in Chapter II, system units operating mode configuration can be realized effectively by comparison of the threshold voltages with the real-time local bus voltage. However, the reference bus voltage in different bus voltage regions is discretized. Significant bus voltage variations will be induced during bus voltage region transitions due to bus voltage discontinuity and operating mode changes of system units. System units operating in CRM are termed slack terminal and system units in PCM are termed power terminal. With the multiple modes operation, the power sharing among them is random in case of multiple slack terminals in VRM operating in parallel.

Bus voltage/output power (V/P) power droop control is implemented for active power sharing among slack terminals in DC microgrid [64-70]. The concept of V/P droop control in DC microgrid is similar to that of frequency regulation in conventional AC utility grid. The rotating speed of governor, which determines system power frequency, reduces with the increase in output power. Frequency/output power (f/P) and AC voltage/reactive power (V/Q) droop relationships are imposed for active and reactive power sharing for AC microgrid operations [65, 71-73]. The advantages of droop control include:

- Realizes active power sharing among slack terminals
- Enables DC microgrid plug-and-play capability
- Introduces limited bus voltage variation which can be used as global indicator for system power balance

The relationship between the output power and voltage with droop control is:

$$V_i = V_{oi} - m_i P_i \quad (3-1)$$

Where V_i , V_{oi} , m_i and P_i are the output voltage, threshold voltage, droop coefficient and output power of the i^{th} slack terminal [74]. To reduce system bus voltage deviation, the nominal bus voltage V_n is usually set as the threshold voltage. The output voltage decreases with the increase of output power. To maximize the utilization of the bus voltage range, droop coefficient of slack terminals is determined based on the maximum allowable voltage variation ΔV_{max} and the power capacity P_i^{max} .

$$m_i = \frac{\Delta V_{max}}{P_i^{max}} \quad (3-2)$$

The relationship between the output voltage change ΔV_i and the change in output power ΔP_i is:

$$\Delta V_i = -m_i \Delta P_i \quad (3-3)$$

The magnitude of output voltage change is proportional to that of output power change. The output voltages for slack terminals connected in parallel are assumed to be the same, thus output voltage change is denoted as system bus voltage change ΔV .

$$\Delta V = -m_1 \Delta P_1 = -m_2 \Delta P_2 = -m_i \Delta P_i \quad (3-4)$$

The output power change in steady state is:

$$\Delta P_i = -\frac{\Delta V}{m_i} \quad (3-5)$$

The output power change of the combined slack terminals ΔP is:

$$\Delta P = \sum \Delta P_i = \sum -\frac{\Delta V}{m_i} = \Delta V \sum \frac{-1}{m_i} \quad (3-6)$$

The equivalent droop coefficient of the combined slack terminals m_{eq} is:

$$m_{eq} = \frac{\Delta V}{\Delta P} = \frac{1}{\sum \frac{-1}{m_i}} \quad (3-7)$$

The relationship between system bus voltage and slack terminal combined output power P is:

$$V = V_n - m_{eq} P \quad (3-8)$$

Replace system bus voltage with the combined output power in Eqn. (3-1), the shared power of the i^{th} slack terminal is:

$$P_i = \frac{m_{eq}}{m_i} P \quad (3-9)$$

Substitute the droop coefficient with Eqn. (3-2):

$$P_i = \frac{m_{eq} P_i^{\max}}{\Delta V_{\max}} P \quad (3-10)$$

It can be concluded based on the Eqn. (3-10) that the power sharing among slack terminals according to droop control is proportional to their installed power capacities $P_i^{\max}$ [47].

The V - P characteristic curves of two battery energy storages are as shown in Figure 3-1. BES1 and BES2 operate in VRM voltage regions H1 and L1. The droop coefficients can be obtained according to Eqn. (3-2). As the voltage range in region L1 is the same as in region H1 and the magnitudes of charging and discharging power capacities are the same, the droop coefficients of BESs in charging and discharging stage are the same.

$$m_1 = \frac{V_{H1} - V_{L1}}{P_{BES1}^{\max} - P_{BES1}^{\min}} \quad (3-11)$$

$$m_2 = \frac{V_{H1} - V_{L1}}{P_{BES2}^{\max} - P_{BES2}^{\min}} \quad (3-12)$$

Where $P_{BES1}^{\max}$ and $P_{BES2}^{\max}$ are the maximum discharging powers of BES1 and BES2, respectively; $P_{BES1}^{\min}$ and $P_{BES2}^{\min}$ are the maximum charging powers of BES1 and BES2, respectively. With a given system bus voltage, the respective output powers of BES1 and BES2 can be obtained with their V - P characteristic curves intuitively. The combined output power of BESs can thus be generated with summation of output powers of BES1 and BES2. Therefore, the V - P characteristic curves of BESs in charging and discharging stages are generated as the dash curves in Figure 3-1. With the combined output power of P_{BESs} , system bus voltage will be regulated at V with corresponding BES1 and BES2 output powers of P_{BES1} and P_{BES2} , respectively.

Figure 3-1. V - P characteristic curve of BESs.

Droop control enables active power sharing among slack terminals. The shared power of a slack terminal is inversely proportional to the droop coefficient assigned. With droop control, system bus voltage is continuous throughout the voltage regions H1 and L1. Unlike the discretized bus voltage in multiple modes operating in chapter II, system bus voltage can be scheduled to be continuous so that voltage variation can be reduced significantly during the voltage region transitions.

With linear droop control, BESs power sharing is scheduled without considering their state of charge (SoC). BES stored energy should be limited within certain range to prevent over-charge/discharge. Gain-scheduling is proposed to equalize the SoC of BESs in distributed manner [27, 67]. It is realized by modification of BESs droop coefficients based on the real-time SoC:

$$m'_{BESi} = \begin{cases} m_{BESi} SOC_i^n, & P_{BESi} < 0 \\ m_{BESi} / SOC_i^n, & P_{BESi} > 0 \end{cases} \quad (3-13)$$

where m'_{BESi} is the newly obtained droop coefficient of BES_i; n is the power exponent of SOC [27]. When BES operates in discharging stage, droop coefficient will be higher than initial value. The shared power of BES with higher SoC will be increased compared with the linear droop control. On the other hand, BESs droop coefficients decreases in charging stage. The charging power of BES with low SoC increases. Therefore, the SoC values of BES1 and BES2 can be equalized in steady state. It has been verified through simulation and experimental case studies that the larger the higher n value could induce faster SOC balance [67]. The effectiveness of gain-scheduling with $n=1$ is illustrated as in Figure 3-2.

Figure 3-2. BESs output voltage power characteristic curves with SOC-based droop.

The V - P characteristic curve of the combined BESs is obtained based on BES1 and BES2. With higher droop coefficient in discharge stage, system bus voltage reaches the threshold voltage V_{L1} before the maximum discharging capacities are reached. BESs operate with constant bus voltage reference of V_{L1} with further increase in load power consumption till reaching the rated capacities. As a result, randomness of power sharing among BESs as highlighted in the figure will be induced. Similarly, the modified droop coefficients are smaller than initial values, so BESs reach the maximum charging capacities at voltage lower than V_{H1} . Therefore, bus voltage discontinuity during the voltage region transitions would be induced.

3.2. Multiple-slack-terminal DC Microgrid Control

Combination of multiple modes control discussed in chapter II and droop control is proposed to enhance DC microgrid operation in distributed manner [33, 75, 76]. For a generic DC MG with integration of various RESs, BESs, NRESs and utility grid as shown in Figure 1-1, the bus voltage range is divided into 6 regions, namely L3, L2, L1, H1, H2 and H3, as shown in Figure 3-3. The relationship between the threshold voltages is:

$$V_{\max} > V_{H2} > V_{H1} > V_n > V_{L1} > V_{L2} > V_{\min} \quad (3-14)$$

Figure 3-3. V - P characteristic curves of system units.

Same as multiple modes DC microgrid control, prioritization of system units is needed to schedule their operating modes in different bus voltage regions. NRES is

prioritized lowest due to the fossil fuel needed and RESs is prioritized the highest as the incremental cost is zero. The utilization priority of RESs and NRES should be prioritized as the highest and lowest, respectively. The power difference between combined load consumption P_{Loads} and RESs generation P_{RESs} is defined as system net power P_{net} .

$$P_{net} = P_{Loads} - P_{RESs} \quad (3-15)$$

As both utility grid and localized BESs can be regarded as energy buffer to mitigate the power mismatch between generation and consumption, the prioritization of BIC and BESs is much more complicated.

BESs maintain system power balance through charge and discharge. Battery life cycle degradation is considered as the major cost of BESs. At the same time, the operation of BESs is limited by the power and energy capacities. For BIC, the utility grid can be regarded as the energy buffer with infinite energy capacity, but the power capacity is limited by the power rating of BIC. The output power of BIC is limited by the power ratings of the power electronic converter in both directions of $P_{BIC}^{\max}$ and $P_{BIC}^{\min}$, respectively. When BIC injects power into DC microgrid, the cost will be reflected on the electricity bill. In contrast, government incentive applies when BIC transfers power from DC microgrid to utility grid. As the government incentive is usually lower than the electricity price, localized BESs is assigned with higher priority when system net power is negative. While in case of positive system net power, the utilization priority of BIC should be higher than that of BESs. Therefore, the operating mode configurations of system units in different bus voltage regions are as shown in Table 3.1 [75].

Table 3.1. Operating mode configurations of system units.

<i>Region</i>	<i>RESs</i>	<i>BESs</i>	<i>BIC</i>	<i>NRES</i>
<i>H3</i>	VRM	PCM charge	PCM Inversion	Idle
<i>H2</i>	MPPT	PCM charge	VRM Inversion	Idle
<i>H1</i>	MPPT	VRM charge	Idle	Idle

<i>L1</i>	MPPT	Idle	VRM Rectification	Idle
<i>L2</i>	MPPT	VRM discharge	PCM Rectification	Idle
<i>L3</i>	MPPT	PCM discharge	PCM Rectification	VRM

RESs operate in VRM in region H3. The control diagram is the same as that in Figure 2-7 except that the reference bus voltage in VRM is generated with droop control based on the real-time output power as Eqn. (3-1). RESs operate in MPPT mode to harvest the maximum renewable source in rest bus voltage regions. V_{H2} is the threshold voltage for operating mode transitions. Therefore, with fixed solar irradiation, RESs output power P_{RES} decreases with the increase in system bus voltage in region H3. The output power remained constant regardless of bus voltage variation in rest regions as shown in the V - P characteristic curve in Figure 3-3.

Figure 3-4. Control schematic diagram of BES.

BESs operate in PCM with the maximum charging power as the reference power in regions H2 and H3. The output power is constant regardless of bus voltage

variation in these two regions as shown in Figure 3-3. In regions H1 and L2, BESs operate in VRM mode with droop control for obtainment of the reference voltage. The control schematic diagram of BES in VRM is as shown in Figure 3-4. The droop voltage compensator is generated with multiplication of the real-time output power and droop coefficient. The reference output voltage is obtained by taking the difference between the nominal bus voltage and droop voltage compensator. Conventional double-loop PI controller is used to track the reference voltage and generate the switching signal for power switches.

Figure 3-5. Control schematic diagram of BIC.

In region L1, BESs are controlled to operate in Idle mode with output power of zero. Therefore, the control schematic is similar to that of PCM, but the reference inductor current is set to be 0 as shown in Figure 3-4. In region L3, BESs operate in PCM with the maximum discharging power $P_{BES}^{\min}$ as the power reference. The resultant V - P characteristic curve of BESs is as shown in Figure 3-3. The output

power remained constant in regions L3, L1, H2 and H3, while the output power changes with real-time bus voltage in regions H1 and L2.

Bidirectional AC/DC converter is implemented as the BIC for power exchange between the utility grid and DC microgrid as shown in Figure 3-5. When BIC injects power from DC microgrid to utility grid, BIC operates in inversion stage. On the other hand, BIC operates in rectification stage when power flow is from utility grid to DC microgrid. BIC operates in PCM in regions H3, L2 and L3 as shown in Table 3.1. The reference inductor current in direct axis is generated with the reference power P_{BIC}^* and AC side bus voltage V_{abc} . Conventional PR controller as described in chapter II is used to track the inductor current and generate switching signals G_{BIC} . The reference inductor current is set to be zero when BIC operates in Idle mode in region H1. When BIC operates in VRM in regions H2 and L1, the reference output voltage V_{BIC}^* is generated by taking the difference between the nominal bus voltage and voltage compensator obtained in droop control. PI+PR controller is used to minimize the voltage tracking error. The V - P characteristic curve of BIC is as shown in Figure 3-3. The output power is constant in regions H3, H1, L2 and L3. In regions H2 and L1, the output power increases with decrease of system bus voltage.

The control of NRES in multiple-slack-terminal DC microgrid is similar to that of multiple modes operation as shown in Figure 2-2. In VRM operation, the reference output power is generated with droop control. Therefore, the output power of NRES in regions L2, L1, H1, H2 and H3 is zero. When system operates in region L3, NRES will be activated to operate in VRM. The output power increases with reduction of system bus voltage.

With the operating mode configurations of system units in different voltage regions as in Table 3.1, system bus voltage regulated actively in all regions and bus voltage is continuous during the voltage region transitions. System power balance is ensured with slack terminals at all time. The relationship between load power consumption P_{Loads} and the output powers of other system units is:

$$P_{Loads} = P_{BESs} + P_{BIC} + P_{NRES} + P_{RESs} \quad (3-16)$$

Therefore, the relationship between the load consumption and system bus voltage can be obtained with superposition of V - P characteristics of NRES, RESs, BESs and BIC. The relationship between load consumption and system bus voltage is as shown in Figure 3-6. System operation voltage region and the exact bus voltage can be obtained intuitively with the V - P_{Loads} curve in different loading conditions.

Figure 3-6. Relationship between system load consumption and bus voltage.

Compared with the V - P_{loads} characteristic curve as in Figure 2-4, system bus voltage is continuous throughout the bus voltage range and thus bus voltage fluctuation during voltage region transitions can be minimized. In region H3, BESs operates in PCM with the maximum charging power $P_{BESs}^{\min}$ as the reference power. NRES operates in idle mode with output power of zero. BIC operates in PCM with $P_{BIC}^{\min}$ as the power reference. RESs operate in VRM to maintain system power balance.

$$P_{RESs} = P_{Loads} - P_{BESs}^{\min} - P_{BIC}^{\min} \quad (3-17)$$

Therefore, at the intersection point of the V - P_{Loads} curve with the voltage axis, RESs output power is:

$$P_{RESs} = -P_{BESs}^{\min} - P_{BIC}^{\min} \quad (3-18)$$

Based on the droop relationship imposed for RESs in region H3:

$$V = V_{\max} - \frac{V_{\max} - V_{H2}}{P_{RESs}^{\max}} P_{RESs} \quad (3-19)$$

The V - P_{Loads} curve intersects with the voltage axis at the voltage value of:

$$V = V_{\max} + \frac{V_{\max} - V_{H2}}{P_{RESs}^{\max}} (P_{BESs}^{\min} + P_{BIC}^{\min}) \quad (3-20)$$

As the signs of minimum BESs and BIC power are negative, the intersection point is lower than the maximum allowable voltage $V_{\max}$.

In region L3, BIC and BESs operate in PCM with the maximum output power. RESs operate in MPPT mode and NRES is activated to regulate system bus voltage. NRES output power is:

$$P_{NRES} = P_{Loads} + P_{BESs}^{\max} + P_{BIC}^{\max} + P_{RESs}^{\max} \quad (3-21)$$

The maximum load consumption is limited by the power capacities of all other system units.

$$P_{Loads}^{\max} = P_{NRES}^{\max} + P_{BESs}^{\max} + P_{BIC}^{\max} + P_{RESs}^{\max} \quad (3-22)$$

System bus voltage is regulated at $V_{\min}$ with the maximum load consumption.

The advantages of multiple-slack-terminal DC microgrid control compared with multiple modes operation include:

- Continuous system bus voltage in different loading conditions so that to minimize bus voltage fluctuation during the transitions of bus voltage regions.
- Active power sharing among slack terminals when multiple slack terminals operate in parallel.

3.3. Power Capacity Based Bus Voltage Region Partition

In the multiple-slack-terminal DC microgrid control discussed foregoing, system bus voltage regions are defined by the maximum bus voltage V_{max} , minimum bus voltage V_{min} , nominal bus voltage V_n and threshold bus voltages. V_{max} , V_{min} and V_n are determined by industrial standards. Therefore, the actual bus voltage regions are defined with the threshold voltages. Threshold bus voltages are usually determined with certain percentage of bus voltage variation of the nominal value [48, 49, 51, 57, 77]. For example, threshold voltage V_{H1} and V_{L1} are set with 2% higher and lower than the nominal bus voltage, respectively. As a result, system equivalent droop coefficient might vary in different regions.

Figure 3-7. Effect of threshold voltage value selection.

For islanded DC microgrid with integration of RESs, BESs and NRES, system bus voltage band is divided into four regions as in Figure 2-3. The regions H1 and H2 are partitioned with threshold voltage V_{H1} . RESs operate in VRM in region H2 and MPPT mode in region H1. The operating mode of BESs in regions H1 and H2 are VRM and PCM, respectively. To illustrate the effect of different V_{H1} settings, two threshold voltage values (V'_{H1} and V''_{H1}) are compared as shown in Figure 3-7. Droop coefficients of RESs in region H2 and BESs in region H1 are obtained accordingly. V - P characteristic curves of the i^{th} RES and combined BESs with different

threshold voltages settings are as shown in the figure. The curves based on V_{H1}' and V_{H1}'' are described with the dashed and solid curves, respectively.

System bus voltage is assumed to be uniform along system bus and capacity-based proportional power sharing among slack terminals can be realized precisely. However, in actual implementation, the local voltage values measured by all system units are different due to transmission line impedance, measurement errors, *etc.* Power sharing error will thus be induced. With bus voltage difference of ΔV as in the figure, the power sharing error of RES_{*i*} in region H2 is:

$$\Delta P_{RESi} = \frac{\Delta V}{-m_{RESi}} = -\frac{\Delta V \times P_{RESi}^{\max}}{V_{\max} - V_{H1}} \quad (3-23)$$

where ΔP_{RESi} is the power sharing error; $P_{RESi}^{\max}$ is the maximum power of RES_{*i*}. The magnitude of power sharing error is inversely related to the width of voltage region H2. With narrower band of the voltage region, the magnitude of $\Delta P_{RESi}'$ is much larger compared with $\Delta P_{RESi}''$ as shown in the figure. It results in more significant deviation from the proportional power capacity-based power sharing as indicated in Eqn. (3-10) if V_{H1}' is selected.

On the other hand, the droop gradient of BESs V - P characteristic curve in region H1 is equivalent to that of system V - P_{Loads} curve. System bus voltage change due to load power variation ΔP_{Loads} is proportional to the droop coefficients.

$$\Delta V = -\Delta P m_{BESs} = \Delta P_{Loads} \frac{V_{H1} - V_n}{P_{BES}^{\min}} \quad (3-24)$$

With larger voltage region band, $\Delta V'$ is much larger compared with $\Delta V''$ as shown in the figure. In conclusion, with narrow voltage region band, more significant power sharing error will be induced. While, significant system voltage variation will appear if the voltage band is large.

To prevent both too significant bus voltage variation due to load change and slack terminal power sharing error due to transmission line impedance, power capacity

based voltage region partition is proposed. The threshold voltages V_{H1} and V_{L1} are determined so that to equalize the droop coefficients in different regions. The equivalent droop coefficient of system V - P_{Loads} curve m_{eq} in all bus voltage regions is:

$$m_{eq} = \begin{cases} \frac{V_{\max} - V_{H1}}{P_{RESs}^{\max}} & (V_{H1} < V \leq V_{\max}) \\ \frac{V_n - V_{H1}}{P_{BES}^{\min}} & (V_n < V \leq V_{H1}) \\ \frac{V_n - V_{L1}}{P_{BESs}^{\max}} & (V_{L1} \leq V \leq V_n) \\ \frac{V_{L1} - V_{\min}}{P_{NRES}^{\max}} & (V_{\min} \leq V < V_{L1}) \end{cases} \quad (3-25)$$

Capacity-based bus voltage region partition is proposed in this paper to determine V_{H1} and V_{L1} so that system equivalent droop coefficients in different regions are equalized. The V_{H1} can be obtained by equalizing the droop coefficients in H1 and H2 as:

$$V_{H1} = V_n + \frac{(V_n - V_{\max})P_{BESs}^{\min}}{P_{RESs}^{\max} - P_{BESs}^{\min}} \quad (3-26)$$

Similarly, V_{L1} is obtained by equalizing the droop coefficients in L1 and L2:

$$V_{L1} = V_n - \frac{(V_n - V_{\min})P_{BESs}^{\max}}{(P_{BESs}^{\max} + P_{NRES}^{\max})} \quad (3-27)$$

With capacity-based system bus voltage region partition, the newly obtained V - P characteristic curves of system units and system V - P_{Loads} curve are as shown in Figure 3-8. Power capacity based bus voltage region partition ensures equalized droop coefficients in regions H1 and H2 as well as in regions L1 and L2. However, the coefficients in regions H1 and L1 are the same only if the voltage ranges in these two regions are the same.

Figure 3-8. Characteristic curves with capacity-based bus voltage region partition: (a) V - P character of system units; (b) system V - P_{Loads} characteristic curve.

3.4. Bus Voltage Discontinuity and Online Droop Coefficient Tuning

3.4.1. Bus voltage discontinuity

The threshold voltages V_{H1} and V_{L1} are generated to partition the voltage regions in proportional to the rated power capacities of system units. In actual implementation, the power capacity of RESs varies with the real-time weather condition including solar irradiation and wind speed. Assume that the real-time RESs power capacity $P_{RESs}^{\max}(t)$ is lower than the rated value. When RESs operate in VRM in region H2, the droop relationship remained unchanged:

$$V = V_{\max} - \frac{V_{\max} - V_{H1}}{P_{RESs}^{\max}(t)} P_{RESs}(t) \quad (3-28)$$

RESs reaches the maximum bus output power $P_{RESs}^{\max}(t)$ at bus voltage V_x as illustrated in Figure 3-9.

$$V_x = V_{\max} - \frac{V_{\max} - V_{H1}}{P_{RESs}^{rated}} P_{RESs}^{\max}(t) \quad (3-29)$$

System bus voltage jumps from V_x to V_{H1} during the voltage region transition from H2 to H1 and thus voltage discontinuity appears. The voltage gap between V_x and V_{H1} is:

$$V_{gap} = V_x - V_{H1} = \frac{(V_{\max} - V_{H1})(P_{RESs}^{rated} - P_{RESs}^{\max}(t))}{P_{RESs}^{rated}} \quad (3-30)$$

Similarly, during the region transition from H1 to H2 with load power increase, RESs operating mode change from MPPT to VRM is activated when system bus voltage has reached V_{H1} . The minimum reference bus voltage when RESs operates in VRM is V_x . Therefore, system bus voltage is not regulated actively in the region from V_{H1} to V_x .

Figure 3-9. Bus voltage discontinuity due to reduction of RESs power capacity.

Online droop coefficient tuning based on real-time RESs power capacity is thus proposed to eliminate the bus voltage discontinuity. The droop coefficient of RESs is updated with the real-time power capacity as:

$$m_{RESi}(t) = \frac{V_{\max} - V_{H1}}{P_{RESi}^{\max}(t)} \quad (3-31)$$

The updated droop relationship of RESi, the V - P characteristic curve of RESs in region H2 is as shown as the dashed curve 1 in Figure 3-9. Continuous bus voltage during region transition can be ensured.

Similarly, BESs power capacities in both charging and discharging stage also vary with the real-time state of charge (SoC). Therefore, the droop coefficients of BESs in region H1 and L1 should be updated in similar way as the RESs as Eqn. (3-29). Power capacity of NRES is considered constant and the droop coefficient remains unchanged.

3.4.2. Real-time Power Capacity Estimation

The real-time power capacities of system units are necessary for online droop coefficient tuning. However, they are not available directly and accurately. Estimation of the real-time power capacities is necessary.

Estimation of solar PV power capacity

When PV converter operates with MPPT mode in regions H1, L1 and L2, the instant output power can be used as the real-time power capacity. However, when PV converter operates in VRM in region H2 with constraint generation, the power capacity cannot be obtained easily. A novel method is proposed to estimate $P_{PVi}^{\max}(t)$ based on the PV output power-terminal voltage (P_{PV} - V_{PV}) characteristic curve as shown in Figure 3-10.

Figure 3- 10. Real-time PV power capacity estimation.

Solar PV P_{PV} - V_{PV} characteristic curves in different solar irradiation conditions are as shown in the figure. When PV converter operates in VRM, the instant terminal voltage and output power are $V_{PV}(t)$ and $P_{PV}(t)$, respectively. Curves k and k+1 represent PV output characteristics in solar irradiation levels of k and k+1 with respective power capacities of $P_k^{\max}$ and $P_{k+1}^{\max}$. When the terminal voltage is $V_{PV}(t)$, the output powers are P_k and P_{k+1} , respectively.

$$P_k \leq P_{PV}(t) \leq P_{k+1} \quad (3-32)$$

Linear interpolation is implemented for estimation of power capacity. The real-time power capacity could be estimated as:

$$P_{PV}^{\max}(t) = P_{k+1}^{\max} - \frac{P_{k+1} - P_{PV}(t)}{P_{k+1} - P_k} (P_{k+1}^{\max} - P_k^{\max}) \quad (3-33)$$

The more P_{PV} - V_{PV} characteristic curves with different solar irradiation levels used for comparison, the more accurate the estimation results will be. With the estimated solar PV power capacities, the droop coefficients in region H2 are updated accordingly.

Estimation of BES power capacity

Figure 3- 11. BES two-stage charge

The real-time power capacity of BES varies with its stored energy, which is normally indicated with SoC [78]. The SoC of battery can be estimated based on combination of Coulomb counting and terminal voltage methods [79]. Constant current–constant voltage (CC-CV) two stage charging scheme is usually implemented for BES constant power charging as shown in Figure 3-11 [33, 80, 81].

The battery is controlled to charge with constant current in the first stage and battery terminal voltage increases with the SoC. Battery constant voltage charging is activated when the terminal voltage has reached a threshold value. During constant voltage charging, the charging current reduces with the increase of SoC. The transition between constant current and constant voltage occurs at the SoC of 70-80%. Battery is considered fully charged when the charging current is lower than a predefined cutoff current in constant voltage charging stage. Therefore, the relationship between BES power capacity and SoC could be obtained with multiplication of charging current and terminal voltage as indicated by the dashed curve in the figure.

3.4.3. Effect of system units' power capacities reduction

With online droop coefficient tuning, the droop coefficients of the slack terminals in different voltage regions are updated with the real-time power capacities. The relationship between system load consumption and bus voltage is:

$$P_{Loads} = \begin{cases} \frac{V_{\max} - V}{V_{\max} - V_{H1}} P_{RESs}^{\max}(t) - P_{BESs}^{\min}(t) & (V_{\max} \geq V > V_{H1}) \\ P_{RESs}^{\max}(t) - \frac{V - V_n}{V_{H1} - V_n} P_{BESs}^{\min}(t) & (V_n < V \leq V_{H1}) \\ \frac{V_n - V}{V_n - V_{L1}} P_{BESs}^{\max}(t) + P_{RESs}^{\max}(t) & (V_{L1} \leq V \leq V_n) \\ P_{BESs}^{\max}(t) + P_{RESs}^{\max}(t) + \frac{(V_{L1} - V)}{V_{L1} - V_{\min}} P_{NRES}^{\max} & (V_{\min} \leq V < V_{L1}) \end{cases} \quad (3-34)$$

The effect of power capacities change of RESs and BESs on system V - P_{Load} characteristic curve is as shown in Figure 3-12. System V - P_{Loads} characteristic

curve with system units' rated power capacities is indicated with the red solid curve. The left plane, where P_{Loads} is negative, does not have physical meaning. Thus dashed lines are used to indicate the characteristic curve. RESs operate in MPPT mode in regions H1, L1 and L2, therefore, when RESs power capacity reduces, with the same system bus voltage, system load consumption reduces accordingly. It is equivalent to shift the $V-P_{Loads}$ characteristic curve leftwards in regions H1, L1 and L2 as indicated with the arrow 1. In region H2, the gradient of droop curve, which is inversely proportional to $P_{RESs}^{max}(t)$, will increase with reduction of PVs power capacity. The point, where PV generation is zero can be expressed as coordinate $(P_{BESs}^{min}, V_{max})$, remains unchanged. Arrow 2 shows the curve change due to RESs power capacity reduction in H2. Curve a shows the extreme case when RESs generation reduces to zero. System only operates in regions L1 and L2 where BESs operates in discharging stage.

Figure 3-12. System $V-P_{Loads}$ characteristic curve change.

Similarly, when BESs discharging power capacity P_{BESs}^{max} reduces, the curve in region L2 is equivalently shifted leftwards as indicated by arrows 3. The gradient of curve in region L1 which is inversely proportional to BESs real-time discharging power capacity increases. The point where BESs discharging power is zero $(P_{RESs}^{max}(t), V_n)$ remains the same if RESs combined power capacity remained unchanged. Arrow 4 indicates the droop curve change in region L1. The dashed curve *b* shows the case

when the BESs are fully discharged. The discharging power capacity in region L1 is zero and bus voltage region jumps directly between L2 to H1, which induces bus voltage discontinuity during voltage region transitions. System droop curve changes in regions H2 and H1 due to change of BESs charging capacities reductions are described with the arrows 5 and 6, respectively. The dashed line *c* shows the case when BESs are fully charged.

3.5. Experimental Verifications

To verify the effectiveness of the proposed control methods, the lab-scale DC microgrid as shown in Figure 2-13 is used for experimental verifications. The experimental setups are as shown in Table 3.2.

Table 3. 2. Experimental Setups.

<i>Parameter</i>	<i>Unit</i>	<i>Setting</i>
Nominal Bus Voltage	V	380
Allowable Voltage Variation	V	± 20
BES Rated Power Capacity	kW	1
BES Energy Capacity	kWh	10
PVs Rated Power Capacity	kW	2
NRES Rated Power Capacity	kW	2
System Bus Equivalent Capacitance	μF	4000

Case 1:

System responses based on the conventional and proposed power capacity based bus voltage partition are compared in case 1. Due to the limited number of measurement channels and duration of data acquisition of the oscilloscope, data from the DC meters installed at the circuit panel outlets are used to showcase the experimental results. The allowable bus voltage range is 380 ± 20 V. The power capacities of RESs and BESs are set to be 2 and 1 kW, respectively. With the conventional partition, the threshold voltage V_{HI} and V_{LI} are set to be 390 V and 370 V, respectively, to equalize the widths of all voltage regions. System units operate with their rated power capacities. Thus the droop coefficients in H2 and H1 can be obtained to be 5 V/kW and 10 V/kW according to (2). The experimental results including bus voltage, load consumption, output power of PV and battery

are as shown in Figure 3-13. Initially, the resistive load and programmable load with respective power consumption of 0.5 kW and 2 kW were tuned on. PV converter operated in MPPT mode and the power generation was 2 kW. Therefore, battery converter regulated bus voltage with discharging power of 0.5 kW. System operated in L1 and the bus voltage V was regulated at 375 V.

Figure 3- 13. Experimental result for case 1.

At 2 min, the programmable load power consumption was reduced to 1 kW. Battery converter rebalanced system power by changing to charging stage with power rate of 0.5 kW. The operating mode of PV converter remained unchanged. Due to the response delay of battery converter, a voltage surge with insignificant magnitude and duration was observed. System bus voltage was stabilized at 385 V with voltage increment 10 V after the load reduction.

At 4 min, the programmable load was turned off and thus system load was decreased to 0.5 kW. Battery charging power increased instantly till reaching the maximum value. The converter changed from VRM to CPC mode operation with charging power reference of 1 kW to prevent over-current charge. System bus voltage was not regulated actively and has exceeded the threshold value V_{HI} due to

system power surplus. PV converter operating mode change from MPPT mode to VRM is thus activated. The output power of PV was reduced to 1.5 kW to rebalance system power. The duration of transition was longer than that at 2 min due to the response time need for battery and PV converter operating mode change. System was stabilized at 392.5 V and the voltage increment was 7.5 V.

In comparison, power capacity-based bus voltage region partition was implemented to obtain the threshold voltages V_{HI} and V_{LI} to be 386.7 V and 373.3 V, respectively, according to equations (3-26) and (3-27). The droop coefficients in all regions were uniform to be 6.67 V/kW. The experiment was repeated with the same generation and loading profiles. System bus voltage with power capacity based partition is indicated with curve V' .

System units operating modes and output power remained the same as that with the conventional partition method. In the beginning, system bus voltage was regulated by the battery converter at 376.7 in discharging stage. When load power was reduced to 1 kW at 2 min, BES changed to charging stage and system bus voltage was stabilized at 383.3 V. The bus voltage increment with load reduction of 1 kW was 6.7 V which is smaller compared with the conventional partition. System bus voltage was increased to 390 V at 4 min after load power reduction of 1 kW was triggered. The voltage increments during both transitions due to load variations were the same. It has coincided with the equalized droop coefficients in region H1 and H2 described forehead.

Experimental case studies conducted has shown that all system units can response based on local information to schedule their operating modes and output power autonomously. The bus voltage could be regulated in different voltage regions effectively. Compared with the conventional bus voltage regions partition, the capacity-based partition ensures equalized droop coefficients in all regions to prevent too significant bus voltage variation due to load power change and power sharing errors due to transmission line impedance.

Case 2:

Effect of online droop coefficient tuning in case of system unit power capacity variation was verified in case 2. PV power capacity was reduced to 1.5 kW due to solar irradiation change. To compare the effect with and without online droop coefficient tuning, the droop relationships of PV and battery were kept the same as that in case 1 firstly. The results are as shown in Figure 3-14. In the beginning, resistive load was turned on with power consumption of 0.75 kW. System bus voltage was regulated by BES with charging power of 0.75 kW at 385 V.

Figure 3-14. Experimental result for case 2.

To demonstrate system response during operating mode transition from H1 to H2, continuous reduction of load power consumption from 0.75 to 0.45 kW was triggered at 3 min. BES charging power increased accordingly till reaching the maximum charging power. BES changed from VRM to PCM with reference power of 1kW. At the same time, system bus voltage has increased gradually till 386.7 V which is the threshold voltage for activation of PV operation mode change. A bus voltage jump with magnitude of 3.3 V was observed due to bus voltage discontinuity as shown in the figure. Same as case 1, voltage surge was observed

during the operating region transition due to PV converter response delay. System was stabilized at 390.3 V with PV output power of 1.45 kW.

In contrast, the droop coefficient of PV in H2 was updated with real-time power capacity to be 8.89 V/kW based on estimation of the real-time PV power capacity as discussed in Section 3.4.2. When PV converter operating mode change from MPPT to VRM was activated, the reference bus voltage was 387 based on the newly obtained droop relationship. Therefore, with online droop coefficient tuning, seamless voltage region transition was ensured with continuous bus voltage change during the transition. Experimental case 2 has demonstrated the effectiveness of online droop coefficient tuning which helped elimination of bus voltage discontinuity to reduce bus voltage variations.

Case 3

To showcase the droop based power sharing among slack terminals, additional Li-ion battery bank was installed. The power capacities of BES1 and BES2 were 1 and 2 kW, respectively. Therefore, the droop coefficient can be obtained based on (3-2) to be 10 and 5 V/kW. Rooftop solar PV arrays with combined power capacity of 2.7 kW were integrated as the RESs. Different with the solar array simulated used for previous experimental studies, the output power of solar PV changed with the real-time weather condition in this case.

Experimental results including system bus voltage V , combined PVs generation P_{PVs} , combined load consumption and BESs output powers are as shown in Figure 3-15. In the beginning, only resistive load bank with resistance of 290 Ω was connected. The load consumption and PVs generation were 0.5 kW and 1.61 kW, respectively. Therefore, BESs operated in charging stage and the bus voltage was stabilized at 384.4 V. The theoretical shared powers of BES1 and BES2 are 0.37 and 0.74 kW, respectively. However, due to the transmission line impedance, power sharing error existed.

When the programmable load with power consumption of 1 kW was turned on at 5 min, BESs charging power decreased instantly to rebalance system power. System

bus voltage was stabilized at 379.2 V after the transition. When the programmable load consumption increased to 2 kW at 10 min, BESs changed to discharging stage to rebalance system power. System bus voltage has been reduced to 374 V with deviation of 6 V from the nominal value. BES1 and BES2 shared power are 0.25 and 0.57 kW, respectively, in steady state.

Figure 3-15. Experimental result for case 3.

The programmable load power consumption was reduced to 1 kW at 15 min. BESs changed to operate in charging stage and the bus voltage was regulated at 379.6 V. System bus voltage was increased to 384 V when the load consumption was reduced to 0.5 kW at 20 min. Significant PV power variations were observed during 20-25 min due to solar irradiation change. BESs output power and bus voltage have followed the variations of system net power P_{net} accordingly. Power sharing errors existed in both transient and steady states. The most significant steady state errors occurred during 2.4-5 min and 21.4-25 min with magnitude of 0.07 kW.

3.6. Conclusion

Multiple-slack-terminal DC microgrid, with combination of multiple voltage level control and droop control, is an effective solution for DC microgrid operation in distributed manner. Seamless system bus voltage during the transitions of bus voltage regions is ensured and active power sharing among the multiple slack terminals can be realized effectively.

Capacity-based bus voltage region partition ensures equalized droop coefficients in different bus voltage regions to prevent too significant bus voltage variation due to load change and power sharing error due to transmission impedance. Online droop coefficient tuning based on the estimation of system units' power capacities in real time helps eliminating of the bus voltage discontinuity. The effectiveness of the control methods have been verified with a lab-scale DC microgrid. Disadvantages of DC microgrid distributed control include:

- Steady state bus voltage deviations which degrades system power quality
- Power sharing error
- Lacking of observability over system operating status, systematic optimization, including the minimization of system operation cost, can hardly be realized.

Chapter IV. Multi-level EMS for DC Microgrid Control

4.1. Multi-level Energy Management System

For DC microgrid with integration of various RESs, BESSs, fossil fuel based NRES and BIC as shown in Figure 1-1, centralized supervisory EMS is usually implemented for system operation [9, 39, 82-84]. Systematic optimization with control objectives including minimization of bus voltage variation, minimization of operation cost, equalization of BESSs stored energy, *etc.* can be realized effectively [14, 82, 85, 86]. For centralized EMS-based DC microgrid control, supervisory control and data acquisition (SCADA) system is needed. System operation statuses, including RESs generation, load consumption, system power flow, ESs SoC, *etc.*, are acquired through the communication link. Operating commands of system units are generated based on system control objectives in the central controller. The operating commands are assigned to respective system units through the communication link again. Therefore, system performance depends on the fluency of the communication link. In case of communication failure, system operation cannot be retained. Besides, system operation depends heavily on the performance of the slack terminal which regulates system bus voltage and maintains system power balance. When slack terminal outage occurs, reassignment of slack terminal is needed. During the transition, system bus voltage fluctuation might occur.

The effects of slack terminal outage and communication link failure can be minimized with distributed control of the multiple-slack-terminal DC microgrid as discussed in Chapter III [69, 75, 87]. System bus voltage is regarded as the global information carrier to schedule the operation of system units [49, 88]. System bus voltage range is divided into several regions and the operating mode configuration of system units are defined based on their utilization priority settings. V - P droop relationships are imposed for power sharing among slack terminals based on localized information. The power sharing among the slack terminals is inversely

proportional to the droop coefficients assigned [27]. Therefore, system operation is independent of the communication link and the speed of response is enhanced. Multiple-slack-terminal DC microgrid discussed in Chapter III has been widely implemented for system operation [69, 75].

Figure 4-1. Schematic diagram for multi-level EMS-based DC microgrid control.

The theoretical shared power of slack terminal is inversely proportional to the assigned droop coefficient. In actual implementation, difference in the bus voltages measured at slack terminal local controllers exists due to the transmission line impedance. As a result, system bus voltage variation and power tracking errors among slack terminals appear [47, 65]. Besides, with the imposed droop relationships, system bus voltage changes with the instant output power. Therefore, droop control exacerbates the bus voltage deviation, which degrades lifetime operation of the voltage sensitive loads [89, 90]. Voltage deviation, which indicates the difference between system bus voltage and the nominal value, is unpredictable due to the randomness of system power flow especially for distribution network with generic layout. In conclusion, system bus voltage variation and power sharing

errors among slack terminals are the main drawbacks of DC microgrid with multiple slack terminals [47, 65].

Secondary control has been proposed to reduce the bus voltage deviation and power sharing errors [47, 64, 70, 91]. System bus voltage and slack terminal power flow are modified by tuning the droop relationships of slack terminals. Slack terminals are usually assigned with the same utilization priority. The power sharing among them is proportional to their installed power capacities, which is not a cost-effective solution [70, 91]. Therefore, slack terminals' power references should be scheduled based on the real-time system status to minimize system operation cost. Multi-level EMS is proposed to enhance system control accuracy while retaining the reliability [92]. The control schematic diagram of the multi-level EMS is as shown in Figure 4-1.

4.1.1. Primary Control

Distributed control of multiple-slack-terminal DC microgrid slack terminal described in Chapter III is scheduled as the primary control. Several system units are configured to operate in voltage regulation mode. Droop relationships are imposed for active power sharing among them and to prevent circulating current. As shown in the figure, the real-time output power of the i^{th} slack terminal P_i is multiplied with the droop coefficient m_i to generate the droop voltage compensator ΔV_{iD} in the droop control block. The reference output voltage of the i^{th} slack terminal V_i^* is obtained by taking the difference between the threshold voltage V_{oi} and droop voltage compensator. Conventional double-loop PI controller is used to track the reference output voltage and generate the duty ratio d_i for converter power switches [53]. The resultant duty ratio is processed with a PWM generator to generate the switching signals for respective power electronic switches.

With distributed control, slack terminals schedule their output powers and regulate bus voltage autonomously. Compared with operation with EMS, distributed control has following advantages:

- Better scalability for integration of additional slack terminals.
- Higher system reliability in case of slack terminal failure as no slack terminal reassignment is needed.
- Higher voltage regulation capacity as the combined power capacity of slack terminals is higher.
- Faster system speed of response as centralized coordination with communication link is not necessary. System operation can be retained without the communication link.

4.1.2. Secondary Control

Steady state bus voltage deviation from the nominal bus voltage exists for multiple-slack-terminal DC microgrid distributed control due to transmission line impedance and droop relationships imposed [70]. For an islanded DC microgrid with BESs operating in VRM in bus voltage regions L1 and H1, the relationship between system bus voltage and system net power P_{net} in steady state is:

$$V = V_n - m_{eq} P_{net} \quad (4-1)$$

where m_{eq} is the equivalent droop coefficient of slack terminals.

The theoretical V - P characteristic curve is as indicated with the curve 1 in Figure 4-2. System bus voltage decreases with the increase in net power. With system net power of P_{net} , the theoretical bus voltage is V_1 . In actual implementation, transmission line impedance induces the droop coefficient change and voltage drop results in threshold voltage variation. The relationship between bus voltage and system net power changes to:

$$V = (V_n + \delta V) - (m_{eq} + \delta m) P_{net} \quad (4-2)$$

where δV and δm indicate the changes in threshold voltage and droop coefficient, respectively [47]. δV is the vertical shift of the characteristic curve and δm results in the change of the curve gradient. The actual system characteristic curve is

indicated with the dashed curve 2. With the same system net power of P_{net} , the newly obtained bus voltage is changed to V_2 . System bus voltage deviation, which is indicated with the difference between the actual bus voltage and the nominal value, varies with system net power in real time. The sign and magnitude of the voltage deviation is unpredictable due to the randomness of system power flow. It degrades system power quality and affects the lifetime operation of system units.

Figure 4-2. System characteristic curve change with bus voltage restoration.

To eliminate the system bus voltage deviation systematically, bus voltage restoration is implemented in secondary control as in Figure 4-3 [47, 65, 93]. The bus voltage V is compared with the nominal value and the difference is processed with a PI controller to generate the voltage compensator ΔV_V [91]:

$$\Delta V_V = G_{BVR}(V - V_n) \quad (4-3)$$

where G_{BVR} is the gain of the PI controller in bus voltage restoration.

For a generic DC microgrid as in Figure 1-1, all system units are connected in parallel. Unlike the point of common coupling (PCC) in conventional AC microgrid, there is no single point bus voltage measurement can be used to indicate

the system bus voltage. Therefore, the average value of the voltages measured at the voltage sensitive loads is used to indicate system bus voltage.

$$\bar{V} = \frac{1}{M} \sum V_{Si} \quad (4-4)$$

where V_{Si} is the measurement at the i^{th} voltage sensitive load; M is the total number of voltage measurements; $\bar{V}$ is the average voltage.

Figure 4-3. Bus voltage restoration in secondary control.

The voltage compensator ΔV_V is generated in the central controller. The threshold voltages of all slack terminals are updated with ΔV_V through the communication link.

$$V_{oi} = V_{oi} + \Delta V_V \quad (4-5)$$

With bus voltage restoration, the threshold voltage of system V - P characteristic curve indicated with Eqn. (4-3) is increased by ΔV_V . It is equivalent to shift the V - P characteristic curve vertically from the dashed curve 2 in Figure 4-2. The magnitude and direction of shifting is determined by the magnitude and sign of ΔV_V , respectively. The dashed line 3 indicates the updated system characteristic curve in steady state. The bus voltage is thus maintained at the nominal value V_n with zero voltage deviation. The voltage compensator changes with the real-time net power variation to ensure system bus voltage deviation is eliminated at all time.

The primary control is implemented at the frequency which is equivalent to the switching frequency of converters to track respective reference output voltage. Bus voltage regulation is applied to generate the voltage compensator to tune threshold voltage to ensure minimized system voltage deviation in steady state. Therefore,

the updating frequency of the bus voltage compensation can be lower than that of the primary control.

4.1.3. Tertiary Control

The power sharing among slack terminals based on primary control is inversely proportional to the droop coefficient assigned. Yet system bus voltage varies at different measurement points due to the transmission line impedance. Power tracking errors are thus induced. To minimize the power tracking errors, power sharing compensation is implemented in tertiary control as shown in Figure 4-4 [70]. Slack terminal power reference is obtained with economic dispatch to minimize system operation cost. Details of the economic dispatch will be elaborated in Section 4.2.

Figure 4-4. Power sharing compensation in tertiary control.

Reference power of the i^{th} slack terminal P_i^* is compared with the real-time output power P_i to generate the power tracking error. The difference is processed with a PI controller to generate the power sharing voltage compensator ΔV_{iP} [70].

$$\Delta V_{iP} = G_{PSCi} (P_i - P_i^*) \quad (4-6)$$

where G_{PSCi} is the gain of the PI controller in power sharing compensation for the i^{th} slack terminal.

The power sharing voltage compensator ΔV_{iP} is generated in the central controller and used to tune the threshold voltage of respective slack terminals. The threshold voltage of the i^{th} slack terminal with multi-level EMS can be expressed as:

$$V_{oi} = V_n + \Delta V_V + \Delta V_{iP} \quad (4-7)$$

Slack terminal output voltage is reduced when the actual output power is higher than the reference value, and vice versa. With power sharing compensation, slack terminal can be controlled to track a power reference even though it operates in voltage regulation mode. However, the power reference is only effective in steady state. Same as the bus voltage restoration in secondary control, the updating frequency of the power sharing voltage compensator should be slower than the primary control.

Multi-level EMS based DC microgrid operation with primary, secondary and tertiary control ensures system control accuracy. System bus voltage deviation and power tracking errors can be eliminated effectively in steady state. In case of communication failure, secondary and tertiary controls, which require centralized coordination, cannot be retained. System operation can still be ensured with primary control but the control accuracy is degraded.

4.1.4. Load Shedding and Generation Curtailment

BESs are scheduled to operate in VRM and compensate system net power autonomously. BESs charging/discharging power in voltage region H1 and L1 are limited by their power capacities. Operating mode change from voltage regulation to power control will be activated in case of output power range violation to prevent over-current charge/discharge [33]. Therefore, load shedding/generation curtailment is implemented to limit the range of system net power [94]. When BESs charging power reaches the maximum value, generation curtailment should be activated to prevent bus voltage overshoot caused by system power surplus. Generation curtailment is realized by constraint solar PV generation [39]. Solar PV with lower installed power capacity is prioritized lower and to be disabled first when generation curtailment is activated. Similarly, load shedding is to be activated when BESs reaches threshold discharging power to prevent bus voltage from exceeding the lower boundary. All loads are prioritized and uncritical loads are to be disconnected first when load shedding is activated [95]. BESs stored energy range is another constraint for system operation. When BESs threshold

Depth of Discharge (DoD) values are reached, load shedding and generation curtailment are to be activated accordingly [88].

In case of sudden change of system net power, which is mainly induced by switch ON/OFF of big loads or solar irradiation variation, the response of the centralized coordination is relatively slow. As a result, significant bus voltage fluctuation might occur. Two-level generation curtailment/load shedding is implemented to ensure system response speed and control accuracy simultaneously. Upon detection of local bus voltage overshoot, PV converter changes operating mode instantly in generation curtailment. Solar PVs prioritized by assigning different threshold voltage values so that their operating mode changes are activated with predefined sequence. Same method applies for load shedding in case of bus voltage drop. The central controller reschedules system units' operating modes in steady state to prevent any maloperation.

4.2. Economic Dispatch

Conventionally, the power references in tertiary control are obtained based on proportional sharing of the system net power without considering the operation statuses of the other system units [91]. Economic dispatch is proposed in this report to minimize system operation cost. System operation cost includes the cost of BESs, NRESs, RESs and utility grid:

$$CT = \sum C_{BESi} + C_{NRES} + \sum C_{RESj} + C_{Ut} \quad (4-8)$$

where CT is system overall operation cost; C_{BESi} , C_{NRES} , C_{RESj} and C_{BIC} are the cost of $BESi$, $NRES$, $RESj$ and utility grid, respectively. Subject to constraints:

$$P_{Loads} = P_{RESs} + P_{NRES} + P_{BESs} + P_{BIC} \quad (4-9)$$

$$P_{BESi}^{\min} < P_{BESi} \leq P_{BESi}^{\max} \quad (4-10)$$

$$DoD_i^{\min} < DoD_i \leq DoD_i^{\max} \quad (4-11)$$

$$0 < P_{NRES} \leq P_{NRES}^{\max} \quad (4-12)$$

$$0 < P_{RESi} \leq P_{RESi}^{\max} \quad (4-13)$$

$$P_{BIC}^{\min} < P_{BIC} \leq P_{BIC}^{\max} \quad (4-14)$$

where $DoD_i^{\min}$ and $DoD_i^{\max}$ are BESi minimum and maximum depth of discharge, respectively; $P_{NRES}^{\max}$ is the maximum output power of NRES; $P_{RESi}^{\max}$ is the maximum power generation of RESi; $P_{BIC}^{\min}$ and $P_{BIC}^{\max}$ are the minimum and maximum output power of BIC, respectively.

Cost of system units can be categorized into fixed and variable costs. Fixed cost including the installation cost and annual maintenance cost which are constant regardless of the utilization. Fixed cost is regarded as sunk cost and is not considered for system operation [55]. Variable cost refers to the cost changes with cumulated output energy which includes fuel cost, battery lifetime degradation cost, utility electricity cost, *etc.*

Instead of implementing complicated optimization algorithm for minimization of system operation cost based on (4-8)-(4-14), economical dispatch based on comparison of their marginal costs is proposed in this report. Marginal cost (\$/kWh), which indicates the incremental costs induced for additional electricity generation of 1 kWh, is carried out for quantitative comparison of the variable costs. The advantages of economic dispatch with marginal cost comparison include:

- Converted different control objective into single objective optimization-minimization of system operation cost
- Simplified optimization process
- More intuitive power dispatch

The marginal cost of NRES (MC_{NRES}) is mainly due to the fossil fuel whose price is fixed. The marginal cost (MC_{PV}) of solar PV is assumed to be zero as the energy source is free. The marginal cost of utility grid (MC_{Ut}) is indicated with the

electricity price in BIC rectification stage. When BIC operates in conversion stage to inject power into the utility grid, government incentive, which is indicated with a negative MC_{Ut} value, applies. While the obtainment of BES marginal cost (MC_{BES}) is much more complicated [96].

Marginal cost of battery energy storages

Battery energy storage is assumed to have a finite life measured as the summation of effective ampere-hours (Ah) [97, 98]. Battery life Γ_R is affected by the actual DoD and the discharging rate [99].

$$\Gamma_R = L_R D_R C_R \quad (4-15)$$

where C_R is the rated amp-hour capacity at rated discharging current I_R ; D_R is the rated depth of discharge for which the rated cycle life is determined; L_R refers to the rated life cycle.

The cycle life decreases with the increase of DoD and the effect can be expressed as:

$$L = L_R \left(\frac{D_R}{D_A} \right)^{u_0} e^{u_1 \left(1 - \frac{D_A}{D_R} \right)} \quad (4-16)$$

where D_A is the actual depth of discharge. Coefficient u_0 and u_1 are determined based on curve fitting with experimental test. Battery cycle life also degrades with the increase of discharging rate. A simplified expression for the effective discharge of a discharge event is:

$$d_{eff} = \left(\frac{D_A}{D_R} \right)^{u_0} e^{u_1 \left(\frac{D_A}{D_R} - 1 \right)} \frac{C_R}{C_A} d_A \quad (4-17)$$

where d_{eff} and d_A are the effective and actual discharge, respectively; C_A is the actual capacity at actual discharging current obtained with the “amperes on discharge” table in battery specification sheets [98].

BES output power is assumed to be fixed in every iteration cycle. Thus the actual discharge of BES_i in iteration K d_{AiK} is:

$$d_{AiK} = \frac{P_{iK}}{V_{iK}} T \quad (4-18)$$

where T is the iteration cycle duration of the central controller; P_{iK} and V_{iK} are the discharging power and battery bank terminal voltage of BES_i at the K^{th} iteration, respectively. BES_i cost during iteration K E_{iK} is:

$$E_{iK} = \frac{RC_i}{\Gamma_R} d_{eff_iK} \quad (4-19)$$

where RC_i is the replacement cost of BES_i; d_{eff_iK} is the effective discharge of BES_i in the K^{th} iteration. Replace the effective discharge with actual discharge as in Eqn. (4-17) and (4-18):

$$E_{iK} = \frac{RC_i}{\Gamma_R} \left(\frac{D_{AiK}}{D_R} \right)^{u_0} e^{u_1 \left(\frac{D_{AiK}}{D_R} - 1 \right)} \frac{C_R}{C_{AiK}} \frac{P_{iK}}{V_{iK}} T \quad (4-20)$$

where D_{AiK} is BES_i actual depth of discharge in iteration K ; C_{AiK} is the actual capacity based on the real-time discharging current.

Therefore, the marginal cost of BES_i MC_{BESi} is generated by dividing the cost with the cumulated energy output:

$$MC_{BESi} = \left(\frac{D_{AiK}}{D_R} \right)^{u_0} e^{u_1 \left(\frac{D_{AiK}}{D_R} - 1 \right)} \frac{k}{C_{AiK}} \quad (4-21)$$

where k is a constant value in the K^{th} iteration.

$$k = \frac{RC_i C_R}{\Gamma_R V_{iK}} \quad (4-22)$$

BES DoD is also considered to be fixed in the K^{th} iteration due to the limited duration of the iteration cycle. The actual capacity C_{AiK} is inversely related to the output power [100]. Thus the marginal cost of BES_i is of DoD specific and

positively related to the discharging rate. Eqn. (4-21) shows the marginal cost of BESs in discharging stage. The marginal cost of BESs in charging stage is described with Figure 4-5. D is BES real-time DoD and D' is the DoD after the charging event. T_k and T_{k+1} are the time at the moment and after charging event, respectively.

Figure 4-5. Marginal cost of BES in charging stage.

The effect of BES charging event is to increase the DoD for all discharging event occur afterwards. It is equivalent to replace the discharging event at DoD value of D_{max} (shaded area 2) with charging event with DoD of D (shaded area 1) as shown in the figure. The difference in effective discharge Δd_{eff} for future discharging event is:

$$\Delta d_{eff} = \left(\left(\frac{D_A}{D_R} \right)^{u_0} e^{u_1 \left(\frac{D_A}{D_R} - 1 \right)} - \left(\frac{D_{max}}{D_R} \right)^{u_0} e^{u_1 \left(\frac{D_{max}}{D_R} - 1 \right)} \right) \frac{P_{iK} T}{V_{iK}} \quad (4-23)$$

Replace the D_{max} with D_R .

$$\Delta d_{eff} = \left(\left(\frac{D_A}{D_R} \right)^{u_0} e^{u_1 \left(\frac{D_A}{D_R} - 1 \right)} - 1 \right) \frac{P_{iK} T}{V_{iK}} \quad (4-24)$$

Therefore, the marginal cost of BES_i in charging state, which is negative value, can be expressed as:

$$MC_{BESi} = \frac{\Delta d_{eff}}{\Gamma_R} RC_i = \frac{RC_i}{\Gamma_R V_{iK}} \left(\left(\frac{D_A}{D_R} \right)^{u_0} e^{u_1 \left(\frac{D_A}{D_R} - 1 \right)} - 1 \right) \quad (4-25)$$

The cost of ES_i in discharge stage is constant and determined by the real-time *DoD*. The marginal cost of combined BESs can thus be obtained.

Economic Dispatch

Figure 4-6. Comparison of system units' marginal costs.

The comparison between the marginal costs of NRES, utility grid and BES_i has been carried out as shown in Figure 4-6. The marginal costs of NRES, utility grid and BESs have been indicated in the figure, respectively. NRES only operates with positive output power and the marginal cost is determined by the fuel price. The marginal cost of utility grid is determined by the real-time electricity price in rectification stage. When BIC operates in inversion stage, the marginal cost MC_{Ut} is indicated with the government incentives for energy injection into the utility grid, whose magnitude is usually lower than that of electricity price. Normally, marginal cost of localized NRES generation is higher than the electricity price. Therefore, the utilization priority of NRES is assigned the lowest. The marginal cost of BESs

is affected by the real-time DoD and the magnitude of marginal cost is positively related to the output power in discharging stage.

System unit with lower utilization cost is assigned with higher utilization priority. RESs are assigned with the highest utilization priority and are scheduled to operate in MPPT mode at all time to maximize the utilization as long as the generation curtailment is not activated. MC_{BESs} curve interacts with the MC_{Ut} and MC_{NRES} at output power of P_o and P_l , respectively. Therefore, the marginal cost of BESi is lower than utility grid when output power is lower than P_o . Similarly, P_l should be set as the threshold power for activation of NRES. Therefore, the power scheduling of NRES, utility grid and BESs based on the real-time economic dispatch is:

$$P_{BESs} = \begin{cases} P_{net} & (P_{net} \leq P_o) \\ P_o & (P_o < P_{net} \leq P_o + P_{BIC}^{max}) \\ P_{net} - P_{BIC}^{max} & (P_o + P_{BIC}^{max} < P_{net}) \end{cases} \quad (4-26)$$

BESs power reference is also limited by the maximum charging and discharging power: $[P_{BESs}^{min}, P_{BESs}^{max}]$.

$$P_{BIC} = \begin{cases} P_{net} - P_{BESs}^{min} & (P_{net} \leq P_{BESs}^{min}) \\ P_{net} - P_o & (P_o < P_{net}) \end{cases} \quad (4-27)$$

BIC output power is limited by the power range: $[P_{BIC}^{min}, P_{BIC}^{max}]$.

$$P_{NRES} = \begin{cases} 0 & (P_{net} \leq P_l + P_{BIC}^{max}) \\ P_{net} - P_l - P_{BIC}^{max} & (P_l + P_{BIC}^{max} < P_{net}) \end{cases} \quad (4-28)$$

The output power of NRES is limited by the power capacity P_{NRES}^{max} . With the generated power references as described in Eqn. (4-26) – (4-28), power sharing compensation is implemented to minimize the power tracking errors in tertiary control.

The advantages of the proposed economic dispatch by comparing the marginal costs of NRES, RESs, BESs and utility grid include:

- Converted multiple control objectives into one objective—minimization of system operation cost.
- Instead of implementing complicated optimization for system operation cost, comparison of marginal cost is carried out to determine the utilization priority of system units.

4.3. MATLAB Simulation

Figure 4-7. Model for MATLAB simulation.

Simulation with MATLAB Simulink has been carried out to verify the proposed multi-level EMS based DC microgrid control. The simulation model is as shown in Figure 4-7. As the RESs and loads are power terminals, they are simplified as current sources with controllable output power and consumption, respectively. Two sets of BESs are used to mitigate the mismatch between generation and consumption. System layout is of generic as it can represent various grid types, including radial, loop-wise and parallel. Four nodes with respective bus voltages of V_1 , V_2 , V_3 and V_4 exist for integration of all system components. The line

impedances between grid nodes are indicated with r_{ij} , where i and j are the number of nodes. Disconnection between two nodes can be represented by taking the line impedance to infinite mathematically.

Table 4.1 Detailed MATLAB simulation setups.

<i>Parameters</i>	<i>Unit</i>	<i>Value</i>
Nominal Bus Voltage	V	400
Maximum Bus Voltage Variation	V	± 20
BES1 Power Capacity	kW	10
BES1 Droop Coefficient	V/kW	2
BES2 Power Capacity	kW	5
BES2 Droop Coefficient	V/kW	4
r_{12}	Ω	2
r_{13}	Ω	0.5
r_{14}	Ω	1
r_{23}	Ω	0.5
r_{24}	Ω	∞
r_{34}	Ω	0.2

Detailed parameters, including power capacities, bus voltage range and line impedance between different nodes, are as in Table 4.1. The transmission line impedances between different nodes were set randomly. Higher transmission line impedance indicates longer geographical distance between the nodes and thus induces more significant bus voltage variation between the node measurements. The resistance between node 2 and 4 r_{24} is set to be ∞ , which indicates that there is no physical connection between them. Nominal bus voltage and allowable bus voltage were chosen in accordance to different low voltage DC applications [3]. The droop coefficients of ESs are obtained with their power capacities and maximum allowable voltage variation accordingly.

Case 1:

Distributed control of the DC microgrid with multiple slack terminals was carried out in case 1. BESs operated in VRM with predefined droop relationships. System bus voltage measured at the loads together with load power, RESs generation and output powers of BESs are as shown in Figure 4-8. In the beginning, RES generation and load consumption were 5 kW and 2 kW, respectively. System bus

voltage was stabilized at 394.5 V with steady state voltage deviation of 5.5 V. With net power of 3 kW, the theoretical output power of ES1 and ES2 should be 2 kW and 1 kW, respectively. However, due to the transmission line impedance, the steady state output powers of ESs were 1.89 kW and 1.18 kW, respectively. The difference between the combined ESs output and system net power was due to the transmission line power losses.

System load power was increased to 10 kW at 50s and thus system net power has increased to 8 kW. BESs output power has increased instant to ensure system power balance. With larger magnitude of power flow, bus voltage variations due to droop control and line impedance both increase. The bus voltage was regulated at 385.3 V with voltage deviation of 14.7 V. At the same time, the power shared by BES1 and BES2 changed to 5.12 kW and 3.19 kW, respectively. The magnitudes of both bus voltage deviation and power sharing errors have increased with the system net power.

Figure 4-8. Simulation results for distributed control.

Case 2:

Multi-level EMS described in Section 4.2 was implemented in case 2 for verifications. Difference between the real-time system bus voltage and the nominal value is processed with bus voltage restoration in secondary control to tune the threshold voltages of BESs. The reference powers of BESs are set to share system

net power proportionally. Power sharing compensation implemented helps elimination of power tracking errors in tertiary control. The simulation results are as shown in Figure 4-9.

Figure 4-9. Simulation results for multi-level EMS based DC microgrid.

The difference between the reference and actual bus voltage was retrieved to zero in steady state with bus voltage restoration. The transient response during the transition is due to the response lag of the PI controller in the bus voltage restoration function block. The magnitude of transient response was 2.72 V and duration was 2.5s. Power tracking errors were also minimized with implementation of power sharing compensation. System control accuracy has been enhanced significantly with multi-level EMS. However, the transition duration is much longer due to the response lag of the ESs local converters.

Case 3:

System response in case of one slack terminal failure was verified in case 3 as shown in Figure 4-10. The relay, which controls the connection of BES2, was turned off at 50s to simulate BES2 outage. Load power remained constant to be 5 kW throughout the simulation. In the beginning, system bus voltage was regulated by BESs with zero bus voltage deviation. The power shared by BES1 and BES2 were 2.05 kW and 1.02 kW, respectively, which has coincided with the

proportional power sharing. When BES2 output power reduced to zero, system net power was compensated by BES1 instantly to rebalance system power. BES1 became the only slack terminal for system bus voltage regulation. The magnitude of bus voltage sag during the transition was 0.73 V. System operation was stabilized at the nominal value when BES2 is off.

Simulation case 1 has shown the effectiveness of the multiple-slack-terminal DC microgrid in distributed control. System bus voltage regulation and power sharing among slack terminals can be realized effectively in different loading conditions. However, bus voltage deviation and power sharing errors are the main drawbacks of distributed control. Multi-level EMS with implementations of bus voltage restoration and power sharing compensation has been carried out in simulation case 2. System control accuracy has been enhanced significantly. Simulation case 3 has demonstrated that system operation and bus voltage regulation can be retained in case of any slack terminal outage.

Figure 4-10. Simulation results in case of slack terminal outage.

4.4. Experimental verifications

Experimental verification has also been carried out to demonstrate the effectiveness of the multi-level EMS based DC microgrid control. The schematic diagram of the

lab-scale DC microgrid with integration of BESs, NRESs, solar PVs and various loads is as shown in Figure 4-11. System bus setups, system units and connection remained the same as in Chapter III.

Supervisory Control and Data Acquisition (SCADA) system is developed for centralized coordination. A programmable logic controller (PLC) serves as the central controller. Communication models are embedded for the power electronic converter for information sharing with the central controller. The communication system is based on the standard Modbus TCP/IP. Every circuit panel and power converter is assigned with a unique IP address. DC meters with data logging capability are installed at every panel outlet to record the operation information including bus voltage, power flow, *etc.* The I/O scanner is used to facilitate data acquisition and command sending. It acquires the operation statuses of all system units periodically by checking the IP addresses in sequence. The data is sent to the central controller for further analysis. Upon the generation of operation commands based on systematic optimization, the central controller sends the commands to system units accordingly through the I/O scanner.

Figure 4-11. Schematic diagram for lab-scale DC microgrid.

The frequency of the SCADA system is set to be 1 Hz in this case, which is much slower than the switching frequency of BES converters (10 kHz). Therefore, the

voltage compensators are updated every 1 second and the voltage compensators are considered as constant in primary control. The allowable bus voltage variation range was ± 10 V. BESs droop coefficients are determined based on (4-1) to be 5 V/kW and 10 V/kW, respectively. The experimental setups for BESs are as shown in Table 4.2.

Table 4.2. Experimental Setups for BESs.

<i>Parameters</i>	<i>BES1</i>	<i>BES2</i>
Power capacity (kW)	1	2
droop coefficient (V/kW)	10	5
L_R	2055	2055
D_R	1	1
C_R (Ah)	137	137
Terminal Voltage (V)	120	240
u_0	1.67	1.67
u_l	-0.52	-0.52
Replacement cost (\$)	18088.4	36172.8
Initial <i>DoD</i>	0.8	0.5

Case 1:

System operation in distributed manner is verified in case 1. Both BES1 and BES2 operated in voltage regulation mode and the reference voltages were generated based on the droop control. PV converters operated in MPPT mode to harvest the maximum solar power. NRES operated in idle mode and will only be activated when its local bus voltage has reached the lower voltage boundary of 370 V. Experimental results including system bus voltage, combined PVs generation, load consumption and BESs output powers are as shown in Fig. 4-12.

In the beginning, resistive load with resistance of 290Ω was connected to system bus. The combined solar PV output power was 1.6 kW. System bus voltage was stabilized at 384.4 V with deviation of 4.4 V from the nominal value. The theoretical shared power of BES1 and BES2 are proportional to their installed power capacities. However, power tracking error existed due to transmission line impedance in actual implementation. The difference between the theoretical and actual output power ΔP has been highlighted in the figure.

Figure 4-12. Experimental results for distributed control of multiple-slack-terminal DC microgrid.

When the programmable load with constant power consumption of 1 kW was turned on at 5 min, BESs charging power decreased instantly to rebalance system power. Bus voltage sag with magnitude of 2 V has appeared during the transition due to response delay of the BESs converters. System bus voltage was stabilized at 379.2 V after the transition. When the programmable load consumption was increased to 2 kW at 10 min, BESs changed to operate in discharging stage. System bus voltage was reduced to 374 V accordingly with deviation of 6 V.

The programmable load power consumption was reduced to 1 kW at 15 min. BESs changed to operate in charging stage and the bus voltage was regulated at 379.6 V. Bus voltage surge with magnitude of 2 V has appeared during the transition. System bus voltage was increased to 384 V when the programmable load was turned off at 20 min. Significant PV generation variations were observed during 20-25 min. BESs charging power and system bus voltage have followed the variations closely.

With the distributed DC microgrid control, the operation of all system units can be scheduled autonomously regardless of the net power variations. However, steady state bus voltage deviation, which degrades system power quality, existed. BESs power tracking errors has also been induced due to transmission line impedance.

Case 2:

In contrast, secondary control with implementations of bus voltage restoration and power sharing compensation was carried out in case 2. Upon detection of the bus voltage deviation from the nominal value, the voltage compensator generated as in Section 4.1 was used to tune the threshold voltages of BESs. At the same time, BESs power tracking errors were processed with PI controllers to generate the voltage compensators for power sharing compensation in the PLC. BESs threshold voltages are tuned based on (4-7) accordingly. To minimize the effect of threshold voltage tuning on system primary control, the magnitude of voltage compensators are limited to 0.1 V. The experimental setups and the loading profile remained the same as the case 1. BESs power references are generated based on proportional sharing. The experimental results are as shown in Figure 4-13.

In the beginning, BESs operated in charging stage with load consumption of 0.5 kW. System bus voltage was regulated by BESs based on droop control. The bus voltage deviation was retrieved to zero in steady state with bus voltage restoration. BESs power tracking error ΔP was maintained at zero with power sharing compensation as shown in the figure.

When system load consumption was increased to 1.5 kW at 5 min, BESs changed to discharging stage instantly to rebalance system power. System bus voltage sag with magnitude of 6.4 V was observed during the transition. The bus voltage deviation was sent to the voltage regulation block and generated voltage compensator to tune the BESs threshold voltages. Due to the limit of threshold voltage step change, the duration of the transition was 0.4 min before the bus voltage was restored to the nominal value. BESs power sharing error, which

appeared during the transition, was eliminated with power sharing compensation as indicated with curve ΔP .

Figure 4-13. Experimental results for multi-level EMS based DC microgrid.

Similarly, bus voltage sag was induced when system load consumption was increased to 2.5 kW at 10 min. BESs power tracking error has appeared during the transition but was eliminated in steady state. Significant variation of solar irradiation has occurred during the period of 10-15 min. As a result, high frequency variations of PV generation and BESs output power changes have been observed. With the proposed multi-level EMS, both system bus voltage regulation and power sharing were realized accurately.

Case 3:

Comparison of system units' marginal costs as discussed in Section 4.2 was carried out for economical dispatch. System unit with lower marginal cost is assigned with higher utilization priority to minimize system operation cost. System units power

references are thus generated according to (4-26) - (4-28). The experimental results are as shown in Figure 4-14.

Figure 4-14. Experimental results for economic dispatch.

In the beginning, load consumption and solar PV generation were 1.5 kW and 1.25 kW, respectively. With system net power of 0.25 kW, BESs operated in discharging stage to maintain system power balance. Bus voltage deviation was eliminated with bus voltage restoration in secondary control. NRES was scheduled to operate in idle mode as its marginal cost was much higher than that of BESs. The marginal costs of BES1 and BES2 were calculated based on (4-25). The cost curve of BES2 located beneath the curve of BES1 as the initial DoD was lower. Therefore, BES1 power reference was assigned to be zero and BES2 compensated the power deficiency. Power sharing compensation implemented in secondary control helped eliminating the power tracking errors.

When system load consumption increased to 2.5 kW at 10 min, both BES1 and BES2 output power has increased accordingly to maintain system power balance. Bus voltage reduction of 4.1 V has also occurred due to the droop relationship

imposed. Upon detection of bus voltage deviation, BESs threshold voltages were tuned with voltage compensator ΔV_V accordingly. Bus voltage was restored to the nominal value at 10.7 min. BES1 power reference generated remained the same based on the comparison of marginal costs. Therefore, BES1 output power was stabilized at 0 kW with the power sharing compensation after the transition. The resultant operation cost induced throughout the case study was 5.214 cents. In comparison, if proportional BESs power sharing were implemented, the resultant system operation cost will be 6.736 cents, which was 29.1% more than that with the proposed economic dispatch.

System bus voltage regulation and power sharing were realized effectively in case 1. However, bus voltage deviation and power tracking errors exist in steady state. Multi-level EMS ensures system control accuracy with implementations of bus voltage restoration and power sharing compensation in secondary control which has been demonstrated in case 2. Economic dispatch based on comparison of system units' marginal costs has been carried out in case 3. The overall system operation cost has reduced significantly compared with the conventional proportional sharing.

4.5. Conclusion

Multiple-slack-terminal DC microgrid is of high system scalability. System bus voltage regulation and power sharing in distributed manner can be realized effectively with combination of multiple mode operation and droop control. Therefore, system reliability is enhanced. However, due to the unpredictable transmission line impedance, system bus voltage deviation and power tracking errors become the main drawbacks. To enhance system control accuracy while retaining the reliability in case of communication failure, multi-level EMS is proposed.

Multi-level EMS for DC microgrid with multiple slack terminals has been verified with experimental cases. Bus voltage restoration helps minimization of bus voltage deviations in steady state. Economic dispatch is implemented in tertiary control to

generate power references for slack terminals to minimize system operation cost. Power tracking error is eliminated with power sharing compensation. The effectiveness of the multi-level EMS has been verified with both MATLAB simulation and lab-scale DC microgrid.

Comparison of DC microgrid control with centralized control, distributed control (multiple modes operation and multiple-slack-terminal control) and multi-level EMS based control has been conducted as shown in Table 4.3.

Table 4.3 Advantages and shortcomings of DC microgrid control algorithms.

<i>Control Algorithms</i>	<i>Advantages</i>	<i>Disadvantages</i>
Centralized Control	<ul style="list-style-type: none"> • High control accuracy • System operation cost optimization 	<ul style="list-style-type: none"> • High installation cost • Low reliability • Slow system respond
Multiple Modes Operation	<ul style="list-style-type: none"> • Fast system response • Low system cost • Simple control • High reliability 	<ul style="list-style-type: none"> • Discretized system bus voltage • Random power sharing among slack terminals • Voltage variation during mode transition
Multiple-slack-terminal Control	<ul style="list-style-type: none"> • Fast system response • High reliability • Seamless reference bus voltage • Slack terminal power sharing 	<ul style="list-style-type: none"> • Bus voltage deviation • Power sharing error • Lack of systematic optimization
Multi-level EMS based Control	<ul style="list-style-type: none"> • High reliability • High system control accuracy • Minimized system operation cost 	<ul style="list-style-type: none"> • High installation cost • Computational complexity

Chapter V. Hybrid Energy Storage System

5.1. Hybridization of Energy Storages

For DC microgrid with integration of various renewable energy sources, localized energy storages are usually needed to compensate the intermittency of RESs generation and uncertainty of load consumption [101]. ESs can be characterized based on energy density (kWh/kg), power density (kW/kg), ramp rate (kW/min), life cycle, *etc.* [102-105]. Unfortunately, none of ESs fulfills all expected features [106]. ES like ultra-capacitor has high power density and ramp rate but low energy density [107]. On the other hand, ES like flow battery has high energy density but limited ramp rate [12]. If only one type of ES is integrated as in [33, 53], it will result in high installation cost in order to meet all design specification of system including the power capacity, energy capacity and ramp rate.

Rather than simply increasing the number of ES cells, hybrid energy storage system (HESS), which makes the most of different ES characteristics, has been proven to be an effective and economic solution [84, 108-112]. HESS also helps ESs lifetime extension, because the stress of ESs with low ramp rates is released by limiting the output power change rate [83, 113, 114]. HESSs with coordination among various batteries, ultra-capacitor, compressed air, flywheel, *etc.* have been implemented [115-121]. Applications of HESS cover the hybrid electrical vehicles [122-124], buildings and offshore platforms [30, 124-126].

Coordination of ESs in HESS can be categorized as passive [113], semi-active [107] or active [116]. Schematic diagrams of different HESS coordination with UC and battery are as shown in Figure 5-1 [127]. In passive coordination, battery and UC are connected in parallel and tied to the bus directly. The power sharing between them is based on terminal voltage variations which is uncontrollable. Passive coordination is normally implemented in electrical vehicle (EV) and hybrid electrical vehicle (HEV). However, the nominal bus voltage should be matched with battery terminal voltage.

Figure 5-1. Schematic diagrams of different HESS coordination.

Two types of semi-active coordination are illustrated in the figure. A DC/DC converter is added at the common connection point in Semi-active (1). It helps active output power control of ESs and eliminates the necessity of voltage matching between system bus voltage and ES terminal voltage. UC could response to step load changes rapidly. While, UC terminal voltage variation is limited as the terminal voltage change of battery is insignificant. Therefore, UC energy capacity, which is positively related to its terminal voltage variations, cannot be fully utilized. In semi-active (2), the DC/DC converter is added at the output of UC so that the output power of UC could be controlled actively. But the battery terminal voltage still needs to be matched with the nominal bus voltage and the output power is uncontrollable.

In the active coordination as shown in the figure, DC/DC converters are added at the outputs of both battery and UC. The active coordination is the superior as it eliminates the match between ESs terminal voltages and system bus voltage [128]. Besides, ESs output power can be scheduled actively to fully utilize the power and energy capacities [129, 130]. Therefore, ESs active coordination is implemented for HESS control in this report.

The schematic layout of generic HESS system in DC microgrid is as shown in Figure 5-2. RESs operate in MPPT mode with output power of P_{RESs} . P_{Loads} refers to the combined load power consumption. The difference between system load

consumption and RESs generation is defined as system net power P_{net} . DC-compatible energy storages are integrated with respective bidirectional DC/DC converters. Detailed schematic layouts, operating modes and control methods of the converters can be found in Chapter II. P_{ESi} denotes the output power of the i^{th} ES and P_{HESS} is the combined output power of ESs.

Figure 5-2. Schematic diagram of a generic HESS in DC microgrid.

The relationship between the bus voltage and system power balance in real time is expressed as:

$$V(t)C \frac{dV(t)}{dt} = P_{HESS}(t) - P_{net}(t) \quad (5-1)$$

where C is the equivalent bus capacitance; $V(t)$, $P_{HESS}(t)$ and $P_{net}(t)$ are the real-time system bus voltage, ESs combined output power and system net power, respectively. Bus voltage variation diminishes only when the combined output power of ESs is equivalent to system net power. Therefore, HESS should be scheduled to follow system net power precisely to minimize bus voltage variations.

System power variations in DC microgrids are mainly due to the intermittence of RESs generation and uncertainty of load consumption [14, 85, 131]. System net power can be decomposed into high and low frequency components [30, 132]. Low frequency power variations for hours, whereas power variation for minutes, seconds or even miniseconds is considered as the high frequency component [115, 133, 134]. To compensate for the high frequency system net power, ESs with high

response is needed to ensure fast system net power tracking to minimize system bus voltage variation due to power imbalance[87, 107, 129, 132, 135].

ESs speed of response is limited by the chemical reaction, pump flow rate (for flow batteries), thermal constraints, *etc.* Ramp rate is normally used to indicate the dynamic response of energy sources like traditional generator and RESs. In this paper, ramp rate is used to quantify the output power change of ESs in unit time (kW/min). Detailed ramp rate, energy capacity, power capacity and respective application of typical ESs have been included as in Table 5.1.

Table 5. 1. Ramp rate, power capacity, energy capacity and application of typical energy storages.

<i>Energy Storage</i>	<i>Ramp Rate/Power Capacity</i>	<i>Power Capacity kW</i>	<i>Energy Capacity kWh</i>	<i>Application</i>
Lead Acid Battery	$> \frac{0.18\text{kW} / \text{ms}}{1.26\text{kW}}$ [130]	<1000	1-1000	Power quality; Renewable source integration
VRB	$\frac{31 \text{ MW} / \text{s}}{6\text{MW}}$ [136]	10-10 ⁷	<10 ⁶	Frequency regulation; Power quality
Fuel Cell with Electrolyzer	$\frac{0.25 \text{ kW} / \text{min}}{3\text{kW}}$ [137]	<1000	<2*10 ⁶	Vehicles; Time shifting
Ultra-capacitor	Considered infinite	1-100	<1	Frequency regulation; Transient stability
Compressed Air	$\frac{18 \text{ MW} / \text{min}}{110\text{MW}}$ [138]	10-10 ⁶	10-10 ⁶	Load shifting

In this report, energy storages are prioritized based on their ramp rates. For convenience, ES1 refers to the ES with highest priority and ES_n is prioritized the lowest, where *n* is the total number of ESs installed. ES with high ramp rate is termed high ramp rate energy storage (HRES) and ES with low ramp rate is termed low ramp rate energy storage (LRES) [139]. The main challenges for HESS control include system net power decomposition and ESs power dispatch based on their characteristics.

5.2. Distributed Control of HESS

System net power decomposition and ESs power dispatch in HESS are normally realized with centralized EMS [85, 116, 140, 141]. The central controller has full observability over system operation statuses. System net power is generated by taking the difference between load consumption and RESs generation in real time. System net power decomposition can be realized in the central controller with techniques including low pass filter/high pass filter (LPF/HPF) [116], fuzzy logic control [84], wavelet [142], *etc.* The resultant high and low frequency components of system net power are assigned as the power references for HRES and LRES, respectively [106, 142-146]. System net power decomposition and ESs power dispatch can be realized effectively in this case. However, data delay due to the time needed for system status acquisition and ESs operating references assignment degrades the accuracy of real-time system net power. As a result, significant bus voltage variations will be induced due to system power imbalance.

Mid-Eum *et al.* [83] and Mohamed *et al.* [115] have proposed forecasting techniques for estimation of system net power to compensate the time delay. Nevertheless, the forecasting time step is usually set as minutes or even hours, which is too long for real-time operation. Forecasting error also exists. Therefore, low time resolution and forecasting errors limit the effectiveness of forecasting techniques in DC microgrids real-time operation.

To minimize the effect of data delay, ES with the highest ramp rate is controlled to operate in voltage regulation mode (VRM) and the rest ESs operate in power control mode (PCM) in [116, 117]. The low frequency component of system net power is set as the power reference for LRESs. HRES operating in VRM is a slack terminal which regulates system bus voltage. System power deficiency, whose variations are of high frequency, is compensated by the HRES autonomously [30]. All control algorithms for HESS introduced forehead are of centralized control. System operation depends on the fluency of the communication link. In case of communication failure, system operation cannot be retained.

5.2.1. System net power decomposition

Distributed control of HESS, which is independent of the communication link, is proposed to enhance system reliability [147]. Same as multiple-slack-terminal DC microgrid discussed in Chapter III, system bus voltage is regarded as the global indicator for system power balance [48]. ESs operation is scheduled based on local bus voltage variations. ES1, which is of the highest ramp rate, is scheduled to operate in VRM with droop control [47, 66]:

$$V_{ES1}^* = V_n - m_{ES1} P_{ES1} \quad (5-2)$$

where m_{ES1} and V_{ES1}^* are the droop coefficient and reference voltage of ES1, respectively. The LRESs operate in PCM and the power references are obtained with reverse droop control (droop control generates reference voltage based on real-time output power while reverse droop control generates reference output power based on real-time bus voltage):

$$P_{ESi}^* = \frac{V_n - V}{m_{ESi}} \quad (5-3)$$

where m_{ESi} and P_{ESi}^* are the droop coefficient and power reference of ESi, respectively. ESs droop coefficients are determined with respective power capacity and the bus voltage range [53]. Same as the power sharing among slack terminals in Chapter III, ESi output power P_{ESi} in steady state is:

$$P_{ESi} = P_{net} / \left(m_{ESi} \sum_{j=1}^n \frac{1}{m_{ESj}} \right) \quad (5-4)$$

The relationship between bus voltage and system net power is:

$$V = V_n - \left(P_{net} / \sum_{j=1}^n \frac{1}{m_{ESj}} \right) \quad (5-5)$$

With droop control, system bus voltage can be used to indicate the net power variations. The control schematic diagram of the ESs with low ramp rates is as shown in Figure 5-3. ES1 operates in voltage regulation mode with droop control.

Conventional double-loop PI controller is used to track the reference voltage. The rest ESs operate in power control mode whose power references are generated based on reverse droop control. The reference inductor current is obtained by dividing the reference power with respectively terminal voltage V_{teri} . PI controller is implemented to track the reference inductor current.

Figure 5-3. Control schematic diagram of HESS operation in distributed manner: (a) ES1; (b) rest of the ESs.

The output powers of LRESs are determined based on the comparison between local bus voltages and the nominal value. To realize system net power decomposition, localized LPFs are added to the feedback bus voltage of LRESs. Low frequency component of local bus voltage is compared with V_n and the difference is amplified with the reciprocal of the droop coefficient to generate the power reference. Therefore, LRES only responses to low frequency net power variation.

The cut-off frequency of LPF is determined by the ramp rate of respective ES [114]. The relationship between ES $_i$ output power $P_{ESi}(t)$ and bus voltage $V(t)$ in real time can be expressed as:

$$\left(V_n - \frac{e^{(-t/T_{ESi})}}{T_{ESi}} V(t)\right) \frac{1}{m_{ESi}} = P_{ESi}(t) \quad (5-6)$$

where $e^{(-t/T_{ESi})} / (T_{ESi})$ is expression of the first order LPF of ESi in time domain; T_{ESi} is the reciprocal of the cut-off frequency f_{ESi} . Take the differentiation of (5-6) and combine with (5-1):

$$\left[\frac{1}{T_{ESi}^2} V(t) - \frac{1}{T_{ESi} CV(t)} \frac{dP_{net}(t)}{dt} \right] e^{(-t/T_{ESi})} = m_{ESi} \frac{dP_{ESi}(t)}{dt} \quad (5-7)$$

where system net power change $dP_{net}(t)/dt$ is obtained by taking the differentiation of system net power with respect to time t . Therefore, LRES output power changes with low frequency component of net power variation as indicated in (5-7). This explains how decomposition of net power and power dispatch among ESs are realized in distributed control. The output power change of ESi is limited by its ramp rate.

$$f_{ESi}^2 V(t) - \frac{f_{ESi}}{CV(t)} \frac{dP_{net}(t)}{dt} \leq \frac{m_{ESi} r_{ESi}}{e^{(-t/T)}} \quad (5-8)$$

where r_{ESi} is the ramp rate of ESi. The right hand side component is minimum when $t=0$.

$$f_{ESi}^2 V(t) - \frac{f_{ESi}}{CV(t)} \frac{dP_{net}(t)}{dt} - m_{ESi} r_{ESi} \leq 0 \quad (5-9)$$

The range of cut-off frequency is limited by (5-9). The maximum cut-off frequency $f_{ESi}^{\max}$ is normally implemented to maximize the utilization of ESs ramp rates.

$$f_{ESi}^{\max} = \frac{dP_{net}^{\max} + ((dP_{net}^{\max})^2 + 4V(t)^3 C^2 m_{ESi} r_{ESi})^{1/2}}{2V(t)^2 C} \quad (5-10)$$

where $dP_{net}^{\max}$ is the maximum net power change rate.

5.2.2. SoC Recovery in Distributed Control

ES1 is the sole slack terminal for system bus voltage regulation. Therefore, it is critical to ensure stable operation of ES1. The output power of ES1 obtained based

on (5-4) indicates that ES1 shares system net power with LRESs based on their droop coefficient setting. ES1 output power can never be zero as long as the RESs generation and load consumption are not balanced. What's worse, ES with high ramp rate, like UC, is usually of low energy density. As a result, the stored energy of ES1, which is indicated with SoC, varies significantly. In case of SoC range violation, ES1 should be scheduled to operate in PCM to retrieve the nominal SoC SoC_{nom} . At the same time, reassignment of slack terminal is needed to regulate system bus voltage. System bus voltage variation will be induced during the transition.

Figure 5-4. Control diagram of HESS in distributed control with autonomous SoC recovery: (a) ES1; (b) rest ESs

Therefore, autonomous SoC recovery is proposed for HESS distributed control to reduce the possibility of ES1 SoC range violation and the consequent system bus voltage variations due to slack terminal reassignment [128]. The control schematic diagram of HESS distributed control with SoC recovery is as shown in Figure 5-4. A LPF is added to the feedback voltage of LRESs to realize system net power decomposition and ESs power dispatch autonomously. A voltage compensator is used to tune the reference voltage of ES1 to realize SoC recovery.

$$V_{ES1}^* = V_n - k_{1d}(SoC_{nom} - SoC) - m_{ES1}P_{ES1} \quad (5-11)$$

where K_{1d} is the autonomous SoC recovery coefficient of ES1 in distributed control. Modified ESs power sharing with SoC recovery is:

$$P'_{ES1} = \frac{m_{ESs}P_{net} - K_{1d}(SoC_{nom} - SoC)}{m_{ESs} + m_{ES1}} \quad (5-12)$$

$$P'_{ESs} = \frac{m_{ES1}P_{net} + K_{1d}(SoC_{nom} - SoC)}{m_{ESs} + m_{ES1}} \quad (5-13)$$

where P'_{ES1} and P'_{ESs} are the modified output power of ES1 and rest ESs, respectively. m_{ESs} is the equivalent droop coefficient of the combined ESs (ES2 to ES_n):

$$m_{ESs} = 1 / \left(\sum_{i=2}^n \frac{1}{m_{ESi}} \right) \quad (5-14)$$

The coefficient K_{1d} is determined as:

$$K_{1d} = \frac{m_{ESs}(P_{net}^{\max} - P_{net}^{\min})}{SoC_{\max} - SoC_{\min}} \quad (5-15)$$

where $P_{net}^{\max}$ and $P_{net}^{\min}$ are the maximum and minimum system net power, respectively; $SoC_{\max}$ and $SoC_{\min}$ are the upper and lower boundaries of ES SoC range variations. When the ES1 SoC is higher than SoC_{nom} , the compensated power is positive, and vice versa. ES1 SoC stabilizes when P'_{ES1} is zero. The relationship between the bus voltage and system net power can be expressed as:

$$V = V_n - \frac{K_{1d}m_{ESs}(SoC_{nom} - SoC) + m_{ES1}m_{ESs}P_{net}}{m_{ESs} + m_{ES1}} \quad (5-16)$$

The advantages of the proposed SoC recovery include:

- Independent of communication link
- Easy implementation

5.3. Hierarchical Control of HESS

System net power decomposition and ESs power dispatch can be realized effectively with the proposed distributed control of HESS as in Section 5.2. System reliability and speed of response are enhanced as it is independent of the communication link. Autonomous SoC recovery implemented helps reducing the possibility of slack terminal SoC range violation. However, degraded control accuracy, including bus voltage deviation and ES1 SoC variation in steady state, is always the main drawback of distributed control.

Hierarchical control of HESS, which is comprised of both centralized and distributed controls, is proposed to ensure both system control accuracy and system reliability [147]. System operates with centralized EMS in normal state. In case of communication failure, distributed control of HESS will be activated to retain system operation even though the control accuracy is degraded.

Figure 5-5. Flowchart of iteration process in HESS centralized control.

In HESS centralized control, system operation status, including ESs SoC, RESs generation, load consumption, *etc.* are acquired through the SCADA system.

System net power decomposition in the central controller is normally realized with HPF/LPF [116]. The cut-off frequency is determined based on the maximum net power change rate and ES ramp rate. Therefore, ESs power capacities and ramp rates cannot be fully utilized at all time. A modified algorithm is proposed for HESS centralized control. The whole process, including system operation status acquisition, data analysis and operating reference assignment, is defined as an iteration cycle. The iteration process of HESS centralized control is as shown in Figure 5-5.

Slack Terminal Assignment

ES1, which is of the highest ramp rate, operates in VRM with reference voltage of the nominal value V_n so that the high frequency component of system net power can be compensated autonomously. The rest ESs are scheduled to operate in PCM to absorb the low frequency component. When the SoC exceeds predefined limitations, ES1 over-charge/discharge damage, which deteriorates the lifetime, will be induced [48]. Therefore, ES1 SoC should be checked first to ensure enough stored energy for next iteration cycle.

In case of ES1 SoC range violation, reassignment of slack terminal for bus voltage regulation is activated. ES2 with the second highest ramp rate is changed to operate in VRM to regulate system bus voltage. ES1 is changed to operate in PCM to retrieve the nominal state of charge [118]. During the transition, no slack terminal exists and thus system bus voltage is not regulated actively. Therefore, bus voltage variations will be induced due to system power imbalance. ES1 VRM operation will be activated when the SoC has reached the nominal value.

ESs Power Dispatch

Conventionally, LPF/HPF in the central controller is implemented for system net power decomposition. The low frequency component is set as the reference power for LRESs. In case of system net power change, the change rate of ESs output power decreases gradually after the transition. Therefore, ESs ramp rates and power capacities cannot be fully utilized. An iteration process based on the real-

time system operation status is proposed in this thesis for ESs power dispatch to maximize the utilizations of ESs ramp rates and power capacities.

System operation status is updated every iteration cycle. ESi output power, RESs generation and load consumption in K^{th} iteration are obtained with SCADA system as $P_{ESi}(t_K)$, $P_{RESs}(t_K)$ and $P_{Loads}(t_K)$, respectively. System net power for iteration $K+1$ is obtained based on the measurements in K^{th} iteration:

$$P_{net}(t_{K+1}) = P_{Loads}(t_K) - P_{RESs}(t_K) \quad (5-17)$$

$P_{net}(t_{K+1})$ is set as the power reference for HESS in iteration $K+1$. The power dispatch starts from ESn which has the lowest ramp rate. ESn output power in iteration $K+1$ is limited by its ramp rate. The maximum and minimum power of ESn in iteration $K+1$ ($P_{ESn}^{max}(t_{K+1})$ and $P_{ESn}^{min}(t_{K+1})$) are:

$$P_{ESn}^{max}(t_{K+1}) = P_{ESn}(t_K) + r_{ESn}^{max}T \quad (5-18)$$

$$P_{ESn}^{min}(t_{K+1}) = P_{ESn}(t_K) + r_{ESn}^{min}T \quad (5-19)$$

where T is the iteration duration; r_{ESn}^{max} and r_{ESn}^{min} are the maximum ramp up and ramp down rates of ESn, respectively. The power reference of ESn $P_{ESn}^*(t_{K+1})$ can thus be obtained as:

$$P_{ESn}^*(t_{K+1}) = \begin{cases} P_{net}(t_{K+1}) & (P_{ESn}^{min}(t_{K+1}) \leq P_{net}(t_{K+1}) \leq P_{ESn}^{max}(t_{K+1})) \\ P_{ESn}^{max}(t_{K+1}) & (P_{ESn}^{max}(t_{K+1}) < P_{net}(t_{K+1})) \\ P_{ESn}^{min}(t_{K+1}) & (P_{net}(t_{K+1}) < P_{ESn}^{min}(t_{K+1})) \end{cases} \quad (5-20)$$

When $P_{net}(t_{K+1})$ is within the range of ESn output power limitation, $P_{net}(t_{K+1})$ is set as the power reference for ESn. Otherwise, either $P_{ESn}^{max}(t_{K+1})$ or $P_{ESn}^{min}(t_{K+1})$ is selected. The output power of ESn is also limited by its power capacity. The maximum charge/discharge power ($P_{ESn}^{min}/P_{ESn}^{max}$) will be set as the power reference when $P_{ESn}^*(t_{K+1})$ exceeds the power capacity.

The power deficiency is updated by taking the difference between $P_{net}(t_{K+1})$ and $P_{ESn}^*(t_{K+1})$ as:

$$P_{net}^n(t_{K+1}) = P_{net}(t_{K+1}) - P_{ESn}^*(t_{K+1}) \quad (5-21)$$

where $P_{net}^n(t_{K+1})$ is the updated net power with exclusion of ES_n output power in iteration $K+1$. Power references for other ESs are generated by repeating (5-18) - (5-21). The generalized method for obtainment of ES_i power reference is:

$$P_{net}^{i+1}(t_{K+1}) = P_{net}(t_{K+1}) - \sum_{j=1}^n P_{ESj}^*(t_{K+1}) \quad (5-22)$$

$$P_{ESi}^*(t_{K+1}) = \begin{cases} P_{net}^{i+1}(t_{K+1}) & (P_{ESi}^{\min}(t_{K+1}) \leq P_{net}^{i+1}(t_{K+1}) \leq P_{ESi}^{\max}(t_{K+1})) \\ P_{ESi}^{\max}(t_{K+1}) & (P_{ESi}^{\max}(t_{K+1}) < P_{net}^{i+1}(t_{K+1})) \\ P_{ESi}^{\min}(t_{K+1}) & (P_{net}^{i+1}(t_{K+1}) < P_{ESi}^{\min}(t_{K+1})) \end{cases} \quad (5-23)$$

where $P_{net}^{i+1}(t_{K+1})$ is the net power with exclusion of combined power of ES_j ($i+1 \leq j \leq n$); $P_{ESi}^{\max}(t_{K+1})$ and $P_{ESi}^{\min}(t_{K+1})$ are the maximum and minimum output power of ES_i for iteration $K+1$, respectively. Same as ES_n, the power reference of ES_i is limited by its power capacity. ESs power dispatch ends until the obtainment of power reference for ES₂. The power difference between the real-time system net power and the combined ESs (ES₂ to ES_n) output power is compensated by ES₁.

When net power variation diminishes, ES_i output power can be expressed as:

$$P_{net}^{i+1} = P_{net} - \sum_{j=1}^n P_{ESj} \quad (5-24)$$

$$P_{ESi} = \begin{cases} P_{net}^{i+1} & (P_{ESi}^{\min} \leq P_{net}^{i+1} \leq P_{ESi}^{\max}) \\ P_{ESi}^{\max} & (P_{ESi}^{\max} < P_{net}^{i+1}) \\ P_{ESi}^{\min} & (P_{net}^{i+1} < P_{ESi}^{\min}) \end{cases} \quad (5-25)$$

The output power of ES₁ is zero if system net power is within the combined power capacity of the rest ESs. Bus voltage restoration as described in Section 4.1 is implemented to eliminate bus voltage deviation in steady state so that to enhance system power quality [117].

Autonomous SoC Recovery

Based on ESs power dispatch described in (5-24) - (5-25), ES1 output power is determined by system net power and the combined power capacities of the rest ESs. Autonomous SoC recovery by tuning system net power is proposed to reduce the possibility of ES1 stored energy range violation. ES1 real-time SoC is compared with SoC_{nom} . The difference is amplified with coefficient K_{lc} to tune the system net power as:

$$P'_{net}(t_{K+1}) = P_{net}(t_{K+1}) + K_{lc}(SoC_{nom} - SoC(t_K)) \quad (5-26)$$

where $P'_{net}(t_{K+1})$ is the modified system net power at iteration $K+1$; $SoC(t_K)$ is ES1 state of charge in iteration K . The compensated ES1 output power ΔP_{ES1} in steady state is:

$$\Delta P_{ES1} = K_{lc}(SoC(t_K) - SoC_{nom}) \quad (5-27)$$

Coefficient K_{lc} is limited by the ranges of ES1 output power and SoC.

$$K_{lc} = \frac{P_{ES1}^{\max} - P_{ES1}^{\min}}{SoC_{\max} - SoC_{\min}} \quad (5-28)$$

When SoC is lower than the nominal value, the compensated power is negative, and vice versa. ΔP_{ES1} turns to zero when ES1 SoC is equivalent to its nominal value. With proposed autonomous SoC recovery, ES1 SoC can be retrieved to the nominal value in steady state.

HESS centralized control has been refined with implementations of online iteration, bus voltage regulation and autonomous SoC recovery in this report. Compared with the conventional LPF/HPF, online iteration helps maximizing the utilizations of ESs ramp rates and power capacities. Bus voltage restoration minimizes bus voltage deviation and thus system power quality is enhanced. Proposed autonomous SoC recovery helps reducing the possibility of ES1 SoC range violation.

System operates with centralized control in normal state. In case of communication failure, distributed control of HESS will be activated to retain system operation. Therefore, system reliability is ensured. System net power decomposition and ESs dispatch can be realized effectively with localized LPF imposed. Autonomous SoC recovery has also been proposed for HESS distributed control to limit the variation of ES1 stored energy.

Compared with the conventional HESS, the proposed hierarchical HESS has advantages including: 1) higher reliability as system changes to distributed control in case of communication failure; 2) limited SoC variation with implementation of SoC recovery in both distributed and centralized control; 3) maximized the utilization of ES ramp rates.

5.4. Multi-level EMS for HESS operation in DC Microgrids

Hierarchical HESS control described in Section 5.3 ensures both control accuracy and system reliability. However, there are two main disadvantages:

- Slack terminal reassignment in case of ES1 SoC range violation. System bus voltage is not regulated actively during the transition which will induce significant bus voltage variations.
- Operating mode changes of ESs during the transition from centralized to distributed control in case of communication failure.

5.4.1. HESS distributed control

HESS distributed control with implementation of the multiple-slack-terminal is described in Chapter III. All ESs are scheduled as slack terminals to regulate system bus voltage. Droop relationships are imposed for power sharing among ESs in distributed manner. With droop coefficient obtained based on the power capacity and bus voltage range, the power sharing among ESs is proportional to their power capacities. Same as Eqn. (5-5), the steady state bus voltage varies with the real-time system net power.

ESs are categorized as LRES and HRES based on their ramp rates. For HRESs, the control schematic diagram remains the same as in Figure 5-3(a). The reference voltage is generated based on droop control. The conventional double-loop PI controller is used to track the reference voltage and generate the duty ratio for power electronic switches. While for LRES, localized LPFi is applied to the feedback voltage so that it only response to low frequency bus voltage variations as shown in Figure 5-6.

Figure 5-6. Control schematic diagram of LRES.

The difference between the reference voltage and low frequency component of the actual bus voltage is proposed with a PI controller to generate the reference inductor current. Assume that the inner current loop is fast enough to track the reference inductor current, the relationship between ESi inductor current and system bus voltage is:

$$I_{Li}(t) = K_{Pi}(V_n - m_i P_i(t) - \frac{e^{-t/T_i}}{T_i} V(t)) + K_{Li} \int (V_n - m_i P_i(t) - \frac{e^{-t/T_i}}{T_i} V(t)) \quad (5-29)$$

where K_{Pi} and K_{Li} are the proportional and integral coefficients of ESi in outer voltage loop, respectively; Therefore, ESi output power is:

$$I_{Li}(t) = V_{teri} K_{Pi}(V_n - m_i P_i(t) - \frac{e^{-t/T_i}}{T_i} V(t)) + V_{teri} K_{Li} \int (V_n - m_i P_i(t) - \frac{e^{-t/T_i}}{T_i} V(t)) \quad (5-30)$$

where V_{teri} is ESi terminal voltage. Take the differentiation of (5-30) and simplify the equation with constant A:

$$A = K_{Pi} + K_{Li} V_n - K_{Li} m_i P_i(t) \quad (5-31)$$

$$\frac{dP_i(t)}{dt} = \frac{(A - K_{li} \frac{e^{-t/T_i}}{T_i} V(t))(-\frac{e^{-t/T_i}}{T_i} \frac{dV(t)}{dt} + \frac{e^{-t/T_i}}{T_i^2} V(t))}{\frac{1}{V_{teri}} + m_i(A - K_{li} \frac{e^{-t/T_i}}{T_i} V(t))} \quad (5-32)$$

Replace the differentiation of bus voltage with net power variation as in (5-1), the relationship between system net power change ΔP_{net} and ESi output power change is:

$$\frac{dP_i(t)}{dt} = \frac{(A - e^{-t/T_i} K_{li} f_i V(t))(\frac{-f_i \Delta P_{net}}{V(t)C} + e^{-t/T_i} f_i^2 V(t))}{\frac{1}{V_{teri}} + m_i(A - e^{-t/T_i} K_{li} f_i V(t))} \quad (5-33)$$

where f_i is the cut-off frequency of LPFi. This explains how LRES responses to low frequency net power change. ESi output power change is limited by its maximum ramp rate $r_{ESi}^{\max}$. The maximum output power variation occurs at $t=0$.

$$\frac{(A - K_{li} f_i V(t))(\frac{-f_i \Delta P}{V(t)C} + f_i^2 V(t))}{\frac{1}{V_{teri}} + m_i(A - K_{li} f_i V(t))} \leq r_{ESi}^{\max} \quad (5-34)$$

Take the real-time bus voltage to be the nominal value V_n .

$$\frac{-K_{li} V_n^2 f_i^3 + (A V_n + \frac{K_{li} \Delta P_{net}}{C}) f_i^2 - \frac{A \Delta P_{net}}{V_n C} f_i}{\frac{1}{V_{teri}} + m_i A - m_i K_{li} V_n f_i} \leq r_i^{\max} \quad (5-35)$$

Solve the equation (5-35) by taking the net power variation ΔP_{net} with the maximum load change $dP_{net}^{\max}$, the maximum cut-off frequency $f_{ESi}^{\max}$ can be obtained. To maximize the utilization of LRESi ramp rate, $f_{ESi}^{\max}$ is set as the cut-off frequency for the LPF of LRESi.

5.4.2. Multi-level EMS for HESS control

With the proposed HESS distributed control with implementation of multiple-slack-terminal DC microgrid, system net power decomposition and ESs power dispatch can be realized autonomously. However, system bus voltage deviation, power tracking errors exist due to transmission line impedance and droop relationships imposed [70]. Besides, HRES shared power in steady state is determined by system net power and their power capacities. It might lead to HRESs SoC range violation, as a result of which, HESS overall ramp rate will be degraded.

Figure 5-7. Control schematic diagram of multi-level EMS for HESS control.

Multi-level EMS is proposed to enhance control accuracy while retaining system reliability. HESS distributed control with multiple-slack-terminal DC microgrid control is scheduled as the primary control as shown in Figure 5-7. HESS distributed control with localized LPF for system net power decomposition and ESs power sharing is scheduled as the primary control. Bus voltage regulation and power sharing compensation described in Section 4.1 are implemented in secondary control to enhance system control accuracy. HRES SoC recovery is

applied in tertiary control to retrieve HRES SoC to the nominal value in steady state.

The difference between the nominal bus voltage and actual system bus voltage, which is indicated with the average value of bus voltages measured at sensitive loads, is processed with a PI controller to generate voltage compensator for bus voltage restoration ΔV_V . Power sharing compensation is realized by processing the difference between the reference and actual output power with PI controller to generate the voltage compensator for power sharing compensation of respective slack terminal ΔV_{Pi} . The voltage compensators generated in secondary control is used to tune the threshold voltage of slack terminals.

$$V'_{oi} = V_n + \Delta V_V + \Delta V_{Pi} \quad (5-36)$$

The updated threshold voltage generated in the central controller is sent to converter local controllers and generate respective reference voltage in droop control block.

Tertiary Control

HRES like ultra-capacitor is usually of low energy capacity. The SoC variation is much more significant compared with ESs with high energy capacities in actual implementation. When HRES SoC exceeds upper/lower limitation, operating mode change from VRM to PCM is needed to prevent over- charged/discharged damage. HESS overall ramp rate will thus be degraded severely. To prevent HRES SoC range violation, autonomous SoC recovery is proposed in tertiary control as shown in Figure 5-7.

The SoC of HRES_j, which is obtained with Coulomb-counting method, is compared with the nominal value SoC_n . The difference is amplified with coefficient K_j to generate power reference P_j^* .

$$P_j^* = K_j (SoC_j - SoC_{nom}) \quad (5-37)$$

When the SoC_j is lower than the nominal value, a negative power reference is generated to charge HRES_j, and vice versa. The coefficient for autonomous SoC recovery is obtained as:

$$K_j = \frac{P_j^{\max}}{\Delta SoC_j^{\max}} \quad (5-38)$$

The generated reference voltages are sent used to generate the voltage compensator for power sharing compensation in secondary control.

Compared with the hierarchical control of HESS discussed in Section 5.3, the advantages of the proposed multi-level EMS based control for HESS include:

- Eliminated the need for slack terminal reassignment in case of ES1 outage due to stored energy range violation or converter failure.
- Smooth transition between centralized and distributed control as no operating mode change is needed.

5.5. Experimental Verifications

5.5.1. Hierarchical HESS control

Table 5.2. Experimental Setups for Hierarchical HESS Control

<i>Parameter</i>	<i>Unit</i>	<i>Value</i>
Nominal bus voltage	V	380
RES power capacity	kW	2.7
ES1 power capacity	kW	2
ES2 power capacity	kW	1
ES1 energy capacity	kWh	0.5
ES2 energy capacity	kWh	10
Maximum resistive load power	kW	5
Maximum programmable load power	kW	5
ES1 nominal SoC	-	50%
Bus voltage range in distributed control	V	380±20

Lab-scale DC microgrid as shown in Figure 4-11 is used for experimental verification. The central controller acquires system operation status with iteration period of 1s. Li-ion battery with higher ramp rate and power capacity is assigned as

ES1 to compensate the high frequency net power variations. Lead acid battery (ES2) compensates the low frequency component of system net power. As the physical characteristics of ES1 and ES2 are close, the ramp rate of lead acid battery is set to be 1 kW/min to showcase the effectiveness of both HESS hierarchical and multi-level EMS control more intuitively. Detailed experimental setups for HESS hierarchical control are as shown in Table 5.2.

Case 1:

Online iteration and centralized LPF for system net power decomposition and ESs power dispatch are compared in case 1. ES1 was scheduled to operate in VRM to compensate the high frequency component of system net power. ES2 operated in PCM to compensate the low frequency component. Experimental results including bus voltage, ESs output powers and system net power in both cases are as shown in Figure 5-8.

Figure 5-8. Experimental result for comparison between online iteration and LPF.

For online iteration, ES2 reference power was generated iteratively according to (5-17)-(5-25) as described in Section 5.3. In the beginning, system net power P_{net} was constant to be -0.5 kW. System bus voltage V was regulated by ES1 at 397.8 V

with deviation of 0.2 V. ES2 compensated the low frequency net power and the output power P_{ES2} was maintained at -0.5 kW. In contrast, ES1 output power was zero. When system net power was increased to 0.5 kW at 4 min by switching on the programmable load which was configured in constant power mode, ES1 changed to discharging stage instantly to maintain system power balance. Upon the increase in system net power, ES2 power reference increased accordingly. Due to the limitation of ramp rate, ES2 output power has increased gradually till stabilized at 0.5 kW. The duration of transition was 1.2 mins and system bus voltage was stabilized at 379.6 V. ES2 incremental output power in every iteration cycle in the experimental result has coincided with the theoretical value. ES1 compensated the power deficiency between system net power and ES2 output power. Therefore, ES1 output power has decreased gradually and stabilized at zero.

In comparison, the experimental case was repeated by implementation of LPF in the central controller for system net power decomposition and ESs power dispatch. Newly obtained bus voltage V' and ESs shared powers (P'_{ES1} and P'_{ES2}) in steady state remained the same as the online iteration. However, ES2 incremental output power in each iteration cycle decreased gradually during the transition. As a result, ES2 ramp rate cannot be fully utilized and the duration of the transition, which is 2.2 mins, was much longer than that of online iteration.

System net power decomposition and ESs power dispatch can be realized with both online iteration and central LPF effectively as in the experimental result. Compared with the central LPF, online iteration has maximized the utilization of ES ramp rate and power capacity in every iteration cycle. Therefore, the transition duration of the proposed online iteration in case of net power change was much shorter. However, steady state system bus voltage deviation existed in both methods. Lack of ES1 SoC feedback control might also result in SoC range violation.

Case 2:

The proposed HESS centralized control was verified in case 2. System net power decomposition and ESs power dispatch have followed the online iteration as in

case 1. Secondary voltage regulation was carried out to minimize bus voltage deviation. Autonomous SoC recovery based on (5-26)-(5-28) was implemented to generate power references for ES2 so that the SoC of ES1 can be retrieved to the nominal value in steady state. The coefficient K_{Ic} was obtained to be 5 kW. The initial SoC was 58%. The experimental result is as shown in Figure 5-9.

Figure 5-9. Experimental results for HESS centralized control.

Rooftop solar PV was integrated in this case and the PV converters operated in MPPT mode through the case study. The output power range of solar PV was 0.5-1.33 kW as shown in the figure. The variations of PV generation P_{PV} according to the real-time solar irradiation were of low frequency. In the beginning, the load consumption was 1 kW and system bus voltage was regulated by ES1. System bus voltage deviation was eliminated with bus voltage restoration in secondary control. The relationship between ES1 output power and the real-time SoC is as shown in Figure 5-10. With initial SoC of 58% in the beginning, the theoretical ES1 output power generated based on (5-26) was 0.4 kW. The actual ES1 output power has coincided with the theoretical value closely. ES1 operated in discharging stage and the real-time SoC has decreased gradually. ES1 output power which is determined

by the SoC was decreased accordingly. At 12.8 min, ES1 power compensator changed to zero and the SoC was stabilized at the nominal value.

When system load power was increased to 2 kW at 13.5 min, ES1 changed to discharging stage immediately to rebalance system power. Upon detection of system net power change, ES2 output power was scheduled accordingly to track the low frequency component of net power. Due to the limitation of ES2 output power change rate in every iteration cycle, ES2 output power was increase gradually. The duration of transition was 1.3 min. Bus voltage sag with magnitude of 1.5 V has been induced during the transition due to instant system power deficiency. The voltage deviation was eliminated with secondary voltage regulation at 13.9 min. ES1 SoC was decreased to 48% at 14.4 min due to cumulated energy output during the transition. The power compensator, generated with (5-26), changed to -0.1 kW. System was stabilized at 15 min with ES1 and ES2 output power of -0.1 and 0.9 kW, respectively.

Figure 5-10. Experimental result for relationship between ES1 SoC and output power in centralized control.

PV generation has dropped slowly from 15 min due to the solar irradiation reduction. As the PV output variation is of low frequency, ES2 discharging power has followed system net power change closely. When ES2 output power reached its power capacity at 17 min, the maximum discharging power of 1 kW was set as the reference power to prevent over-current discharge. ES1 compensated the remaining power deficiency and changed to discharging stage. Therefore, ES1 SoC was further reduced even though it was lower than SoC_{nom} .

System load consumption reduction of 1 kW was activated at 23.6 min. ES1 output power of has decreased instantly to maintain system power balance. Upon the detection of system net power change, ES2 reference power was reduced gradually. The step change of ES2 output power was limited by its ramp rate in the central controller. The real-time ES1 SoC was 44% and the power compensator was -0.3 kW. System was stabilized at 24.3 min with ES1 and ES2 output power of -0.3 kW and 0.56 kW, respectively. ES1 output power has followed the theoretical value precisely and the SoC was retrieved to the nominal value at 34.2 min.

Case 2 has demonstrated the effectiveness of the proposed centralized control. System net power decomposition and ESs power dispatch based on ramp rates were realized successfully with online iteration. System bus voltage deviations were eliminated with secondary voltage regulation to ensure system power quality. Autonomous SoC recovery has helped retrieving ES1 SoC to the nominal value in steady state.

Case 3:

The proposed HESS distributed control was activated in case of communication failure to ensure system reliability. ES1 was configured to operate in VRM and the reference bus voltage was obtained as (5-16). ES2 operated in PCM and the reference power was generated based on reverse droop control as (5-3). The allowable voltage range was 380 ± 20 V in this case. Droop coefficients of ES1 and ES2 determined based on the power capacities and bus voltage range were 10 V/kW and 20 V/kW, respectively [53]. LPF with cut-off frequency of 3.7 Hz,

obtained according to (5-10), was applied for system net power decomposition. Autonomous SoC recovery coefficient K_{Id} was 50 V based on (5-15). The experimental results are as shown in Figure 5-11.

In the beginning, only PV1 was turned on and operated in MPPT mode with power generation of 0.76 kW. The load consumption was 0.26 kW. System was stabilized with ES1 and ES2 output power of -0.75 kW and 0.25 kW, respectively. The bus voltage was regulated by ES1 at 375 V with steady state bus voltage deviation of 5 V. At 5 min, PV2 was turned on and the output power has increased by 0.7 kW. ES1 output power was reduced instantly to rebalance system power. System bus voltage was inversely related to ES1 output power based on the droop control. Therefore, system bus voltage increase was induced. ES2 output power, scheduled according to reverse droop control, was reduced. The output power change of ES2 was limited by the localized LPF. Therefore, it only responded to low frequency bus voltage variations.

Figure 5-11. Experimental Result for case 3.

High frequency PV generation variations have been observed due to solar irradiation change in 5-10 min. Both ES1 output power and system bus voltage

have followed the solar PV generation closely. In contrast, ES2 responded to low frequency variation of system bus voltage and thus the output power change was insignificant.

At 10 min, the programmable load with constant power consumption of 0.5 kW was turned on. ES1 changed to discharging stage instantly to rebalance system power and the bus voltage has decreased accordingly. Bus voltage sag with magnitude of 1.1 V and duration of 0.15 min was observed during the transition. Upon detection of local bus voltage variation, ES2 output power has increased by 0.2 kW gradually. System bus voltage was regulated at 376.4 V with deviation of 3.6 V in steady state.

When load power increment of 1 kW was activated at 15 min, system bus voltage drop was induced due to instant increase of ES1 output power. The output power of ES2, whose feedback voltage was filtered with LPF, increased gradually. Bus voltage sag with magnitude of 3.5 V and duration of 0.6 min has appeared. System bus voltage was stabilized at 16 min with deviation of 13 V.

Figure 5-12. Experimental result for relationship between ES1 SoC and output power in centralized control.

When the programmable load was turned off at 19 min, ES1 has changed to charging stage instantly. ES1 reference bus voltage, which was determined based on droop control, has increased accordingly. ES2 output power reduced from 0.71 kW to 0.19 kW. The magnitude and duration of bus voltage surge were 7 V and 0.65 min, respectively. The bus voltage was stabilized at 376.2 V with deviation of 3.8 V.

The theoretical bus voltage V^* was compared with the actual value as in the Figure 5-11. The bus voltage has followed the theoretical value, which was determined by the real-time system net power and ES1 SoC, closely. The difference between the theoretical and actual bus voltage during the transition was due to the limited ramp rate of ES2.

ES1 output power was compared with the theoretical value P_{ES1}^* obtained with (5-12) as in Figure 5-12. The actual output power curve has coincided with the theoretical value with negligible deviation. The deviations of ES1 shared power and system bus voltage in steady state were mainly due to the transmission line impedance.

Case 3 has exhibited the effectiveness of the proposed HESS distributed control. System reliability was enhanced as ESs operation was independent of the communication link. System bus voltage has been regulated within the predefined range precisely. System net power decomposition and ESs power dispatch based on their ramp rates were realized effectively. Autonomous SoC recovery implemented has helped limiting the variation of ES1 SoC. Compared with HESS centralized control, system bus voltage variations were much more significant, which has degraded system power quality. Besides, ES1 SoC variation in steady state existed and the possibility of SoC range violation was much higher.

5.5.2. Multi-level EMS for HESS control

Two experimental cases have been carried out to verify the effectiveness of the multi-level EMS for HESS control. Lab-scale DC microgrid, same as in Section 5.5.1, was implemented for experimental verification. Detailed experimental setups are as shown in Table 5.3.

Table 5.3. Experimental setups for multi-level EMS based HESS control.

<i>Parameters</i>	<i>Unit</i>	<i>Setting</i>
Nominal bus voltage	V	380
Allowable bus voltage variation	V	± 10
PV1 power capacity	kW	1.3
PV2 power capacity	kW	1.4
HRES power capacity	kW	2
LRES power capacity	kW	1
LRES ramp rate	kW/min	1
HRES droop coefficient	V/kW	5
LRES droop coefficient	V/kW	10
Maximum load power change	kW	1
System equivalent capacitance	μF	3140

Case 1:

HESS distributed control for system net power decomposition and ESs power scheduling was carried out in case 1. Both ES converters were configured to operate in voltage regulation mode. ESs converters reference bus voltages were generated with droop control based on local information to avoid uncontrollable circulating current. The nominal bus voltage was 380 V and the maximum allowable bus voltage variation ΔV_{max} was ± 10 V. Droop coefficients of ES1 and ES2 can thus be obtained to be 5 and 10 V/kW, respectively. With maximum load power change rate of 1 kW/min, the cut-off frequency of ES2 LPF was determined with (5-35) to be 1 Hz. Experimental results including system bus voltage, PV generation, load consumption and ESs output powers are as shown in Figure 5-13.

PV converters operated in MPPT mode throughout the case study with insignificant output power variation. With load consumption of 1.5 kW and PV generation of 0.99 kW, system net power was 0.51 kW in the beginning. The theoretical system bus voltage and ES1 shared power were 378.3 V and 0.34 kW, respectively. However, due to the transmission line impedance, ES1 shared power was 0.38 kW. System bus voltage, which was indicated with the average value of the measurements at both resistive and programmable loads, was stabilized at 378.2 V. The bus voltage deviation from the nominal value was 1.8 V.

Figure 5-13. Experimental results for HESS distributed control.

When load power reduction of 1 kW was activated at 5 min, system net power was reduced to -0.52 kW. ES1 changed to charging stage immediately to retain system power balance. Instant bus voltage increment of 7.1 V was observed due to the droop control and HESS response delay. ES2 output power was reduced gradually as it only response to low frequency bus voltage variations. System was stabilized at 5.4 min with ES2 output power of -0.25 kW and system bus voltage of 383 V. The bus voltage deviation and power tracking error in steady state were 3 V and 0.08 kW, respectively.

To showcase the transition intuitively, LeCroy oscilloscope is used to capture the outputs of battery banks as shown in Figure 5-14. Li-ion battery bank output current I_{Li-ion} reduction of 5 A was activated at 5 min and increased slowly till stabilized at -1.4 A. In contrast, lead acid battery bank output current I_{Lead} has reduced gradually from 1.3 A to -2.5 A. The maximum output current reduction rate of I_{Lead} appeared at the moment of load reduction and the reduction rate decreased gradually.

Figure 5-14. ESs response in case of load reduction.

When load power increment of 1 kW was activated at 10 min, ES1 output power was increased by 1 kW immediately to rebalance system power as shown in Figure 5-13. System bus voltage sag with magnitude of 6.6 V was observed. The output power of ES2, which has responded to low frequency bus voltage variation, has increased gradually from -0.24 kW to 0.1 kW. The duration of transition was 0.4 min. The bus voltage was stabilized at 378.2 V with deviation of 1.8 V and ES1 power tracking error was 0.06 kW.

Case 2:

In comparison, multi-level EMS was implemented for HESS centralized control in case 2. HESS distributed control implemented in case 1 was scheduled as the primary control. Bus voltage restoration and power sharing compensation were applied in secondary control. The generated voltage compensators were used to tune the threshold voltage of respective ES local controller accordingly. To demonstrate the effectiveness of the autonomous SoC recovery in tertiary control, ES1 energy capacity was set to be 0.5 kWh and the nominal SoC was 50%. ES1 power reference in steady state was determined with (5-37) based on the real-time SoC. To avoid significant system oscillation due to the change of ESs threshold voltages, the magnitude of step change in voltage restoration and power sharing

compensation were limited to be 0.1 V. The experimental results are as shown in Figure 5-15.

The solar irradiation variation was much more significant compared with the case 1. PV converters operated in MPPT mode with output power range of 0.84-1.28 kW. In the beginning, the load consumption was 0.5 kW and ES1 SoC was 58%. System bus voltage was regulated at the nominal value with bus voltage restoration in secondary control. ES1 output power has followed the reference value, which was 320 W according to (5-37), with tertiary control. The experimental result for HRES real-time SoC, reference power P_{ES1}^* and the actual output power P_{ES1} are as shown in Figure 5-16. With autonomous SoC recovery, ES1 SoC has approached to the nominal value during 0-5 min. HRES actual output power has followed the reference value closely with power sharing compensation. ES1 output power oscillation with insignificant magnitude was mainly due to the solar irradiation variations.

Figure 5-15. Experimental results for HESS control based on multi-level EMS.

When load consumption increment of 1 kW was activated at 5 min, ES1 output power has increased instantly to rebalance system power. The magnitude of system bus voltage sag was 6 V, which was nearly equivalent to that of distributed control.

ES2 has responded to the low frequency bus voltage variations and the output power was increased gradually. Upon detection of bus voltage deviation, the voltage compensator ΔV_V generated at the central controller was added to ESs threshold voltages. System bus voltage was restored to the nominal value at 5.6 min. The duration of bus voltage oscillation was much longer than that of HESS distributed control. Negative voltage compensator was generated in ES1 power sharing compensation block and was used to tune its threshold voltage. Thus ES1 output power was reduced gradually. ES1 output power was stabilized at 8 min with SoC of 50% and reference power of 0 kW.

When load power reduction to 0.5 kW was activated at 10 min, ES1 has changed to discharging stage instantly to rebalance system power. In contrast, ES2 output power has reduced slowly from 0.35 kW to -0.8 kW. System bus voltage was regulated at 380 V in steady state. Due to the cumulated energy during the transition, ES1 SoC was increased to 52% at 11.5 min. ES1 output power was stabilized at 0.08 kW with zero power tracking error at 12.8 min. The magnitude and duration of bus voltage surge were 6.6 V and 0.66 min, respectively, during the transition.

Figure 5-16. Autonomous SoC recovery in case 2.

Experimental case 1 has demonstrated the effectiveness of HESS distributed control for system net power decomposition and ESs power scheduling. In case of system net power change, ES1 has compensated the high frequency net power variations and ES2 has responded to low frequency variations autonomously. System bus voltage was regulated within the predefined range effectively. However, bus voltage deviation and power sharing errors exist in steady state. Multi-level EMS implemented in case 2 has enhanced system control accuracy. System dynamic response in case of net power variation remained the same as the distributed control. Bus voltage restoration and power sharing compensation have helped elimination of voltage deviation and ESs power tracking errors, respectively. Autonomous SoC recovery in tertiary control has limited ES1 stored energy range variation effectively. Multi-level EMS for HESS control has exhibited higher control accuracy compared with the distributed control, but the durations of bus voltage oscillation and ESs power tracking were much longer.

5.6. Conclusion

Hierarchical control of HESS, which is comprised of both centralized and distributed control, is proposed to ensure both system control accuracy and reliability. System operates in centralized control in normal state. HESS centralized control is refined with implementations of online iteration, secondary voltage regulation and autonomous SoC recovery. Online iteration based ESs power dispatch maximizes the utilizations of ESs ramp rates and power capacities in every iteration cycle. Secondary voltage regulation has helped minimizing the steady state bus voltage deviations and enhancing system power quality. The possibility of ES1 SoC range violation has been reduced significantly with implementation of autonomous SoC recovery. HESS distributed control will be activated in case of communication failure. System net power decomposition and ESs power dispatch can be realized with localized LPF applied to ESs with low ramp rates effectively. Autonomous SoC recovery by tuning the reference voltage of slack terminal has managed to limit the SoC variation. Compared with the

centralized control, HESS distributed control has higher reliability and faster speed of response, but lower system control accuracy.

Slack terminal reassignment in case of ES1 outage and ESs operating mode change in case of communication failure are the main drawback of HESS hierarchical control. HESS distributed control, in which all ESs are scheduled to operate in voltage regulation mode, is proposed to eliminate the slack terminal reassignment. System net power decomposition and ESs power sharing are realized with implementation of localized LPF autonomously. The relationship between the cut-off frequencies and ES ramp rate has been elaborated in detail. Multi-level EMS is implemented to enhance system control accuracy. In case of communication failure, system operation can still be retained with HESS distributed control without ESs operating mode change. The effectiveness of the hierarchical and multi-level EMS based HESS control has been verified with a lab-scale DC microgrid in experiment Section.

Chapter VI. DC Microgrid Transitions

between Grid-tied and Islanded States

Microgrids are designed to be capable of operation in both grid-tied and islanded states to enhance system reliability. For DC microgrid with bidirectional interlinking converter (BIC) for power exchange between the utility grid and DC grid, both the utility grid and localized ESs can be regarded as the energy buffer to mitigate system power mismatch between generation and consumption [9, 18, 148, 149]. In case of utility grid fault, DC microgrid changes to operate in islanded state to isolate the disturbance. Only BESs can be used to mitigate system power imbalance [11, 32].

Conventionally, BIC is scheduled to operate in VRM to regulate system bus voltage in grid tied state [26, 41, 69]. Localized ESs operate in PCM and the power references are generated based on system control objectives, like ESs SoC equalization, operation cost minimization, bus voltage variation minimization, *etc.* [18, 39, 46]. In islanded state, BIC changes to operate in idle mode to isolate the utility grid disturbance. One of the BESs, normally the one with the highest power capacity and ramp rate, is changed to VRM operation [27, 48, 88]. Operating modes of BIC and BESs in both grid-tied and islanded states have been explained in many research works [32, 75, 150]. However, the detailed procedure during the transition has seldom been discussed in detail.

6. 1. Transitions between Grid-tied and Islanded States

The schematic diagram of a generic grid-tied DC microgrid with integration of various RESs, BESs and loads is as shown in Figure 6-1. A bidirectional DC/AC converter is installed as the BIC to interlink the utility grid with the DC bus [151, 152]. A contactor is installed between the BIC and DC microgrid for autonomous islanding and reconnection. The functionality and control method of the contactor is similar to that of solid state transfer switch (SSTS) in the conventional AC microgrid [153, 154]. Bidirectional DC/DC converters are used to control the

output of the battery banks. RESs including solar PV and wind turbine generator are integrated through DC/DC and AC/DC converters, respectively. Converters of RESs including solar PV and wind turbine are normally controlled to operate in Maximum Power Point Tracking (MPPT) mode to harvest the maximum renewable sources.

Figure 6-1. Schematic diagram of a grid-tied DC microgrid.

System operates in grid-tied state with BIC regulating DC bus voltage in normal state [155]. The power switches of BIC are idled to isolate the utility disturbance upon detecting the utility grid fault in converter local controller to enhance system speed of response [32]. DC microgrid is then changed to operate in islanded state. At the same time, BES VRM operation will be activated to regulate system bus voltage. BES operating mode change with centralized control is proposed in [69]. Time needed for data acquisition and operation reference assignment results in system response delay. There is a short duration when none slack terminal exists for system bus voltage regulation during the transition. Therefore, bus voltage variation might be induced due to system power imbalance.

Activation of BES operating mode change by comparing the local bus voltage with predefined threshold voltage in distributed control is proposed in [26, 27, 53]. When BES local bus voltage reaches the threshold value, BES changes from PCM

to VRM operation autonomously. System speed of response is thus enhanced significantly compared with the centralized coordination as no centralized coordination is needed. However, the threshold voltage for BES operation mode change is always set with certain deviation from the nominal bus voltage V_n to reduce the possibility of maloperation [48, 57]. As a result, significant bus voltage variation will also be induced during the transition.

When utility grid fault is cleared, DC microgrid reconnection to the utility grid will be activated. BIC changes from idle mode to VRM operation and BES changes from VRM to PCM [32]. BIC AC side voltage regulation and synchronization with the utility grid has been proposed in [26, 156]. BIC is controlled to regulate AC output voltage when reconnection is activated. The reconnection procedure is similar to that of the conventional AC microgrid [157, 158]. Utility grid voltage, frequency and phase angle are detected with phase lock loop (PLL) to generate the voltage reference for BIC AC output [153]. The SSTS will be closed when BIC AC output voltage has matched with the utility grid voltage to finish the reconnection. While, BIC and BES operating mode change after the reconnection is needed. Besides, matching of three quantities, including bus voltage magnitude, frequency and phase angle, is required [159, 160]. Therefore, BIC DC side voltage matching, which only requires the control over bus voltage, appears to be a simpler and more reliable alternative [161].

The sequence of operating mode change during reconnection is crucial. If BES operating mode is changed first, system bus voltage is not regulated actively during the transition, which might result in bus voltage variations due to system power imbalance. On the other hand, if BIC changes to VRM mode first, coexistence of multiple slack terminals might result in uncontrollable circulating current due to the difference in terminal voltages [75].

In conclusion, the disadvantages of conventional method for transitions between grid-tied and islanded states include:

- Bus voltage fluctuation due to BIC and ESs operating mode change.

- No active bus voltage regulation during the islanding.
- Uncontrollable circulating current in case of multiple slack terminals connected in parallel.
- Response lags due to centralized control.

6.2. Multiple-slack-terminal DC Microgrid for Operating States Transitions

Multiple-slack-terminal DC microgrid with droop control discussed in Chapter III enables the slack terminals with plug-and-play capability. In case of any slack terminal failure, system bus voltage regulation can still be retained and the power deficiency will be shared by the rest slack terminals autonomously [75]. Circulating current can also be limited with the droop control for connection of additional slack terminals, which make it suitable for DC microgrid reconnection. Implementation of multiple-slack-terminal DC microgrid, in which both BIC and ESs are scheduled to operate in DC voltage regulation, is proposed in this report to minimize the effect of transitions between grid-tied and islanded states. Detailed experimental setups for BIC and ESs including schematic diagram, control diagram, droop coefficient, *etc.* can be found in Chapter III. Detailed transition procedures for both islanding and utility grid reconnection, including activation signal for transition and system units' response sequence, are presented.

Islanding

System changes from grid-tied to islanded state when utility grid disturbance appears. BIC operating mode change is activated based on local controller in this case to enhance system speed of response. Upon detecting the violations of AC side power quality, BIC changes to idle mode operation instantly by disabling all power electronic switches. The contactor as shown in Figure 6-1 is opened to isolate the DC microgrid from the utility grid physically.

In the proposed multiple-slack-terminal DC microgrid, ESs operate in VRM in both grid-tied and islanded states. Therefore, no operation mode change of ESs is needed and system bus voltage is regulated actively throughout the transition. It helps minimizing the bus voltage fluctuation due to ESs operating mode change and ESs response delay. System bus voltage is regulated by ESs in islanded state. The steady state bus voltage is:

$$V_{bus} = V_n - P_{net} \left/ \sum \frac{1}{m_{ESi}} \right. \quad (6-1)$$

System power deficiency due to utility grid outage is compensated by ESs autonomously.

$$P_{ESi} = \frac{P_{ESi}^{\max}}{P_{ESs}^{\max}} P_{net} \quad (6-2)$$

Reconnection

Reconnection is activated when utility grid disturbance has been cleared. Instead of matching the conventional AC side bus voltage for synchronization, a rather simpler and more reliable alternative by matching BIC DC side output voltage with DC microgrid is proposed. The flowchart for the proposed reconnection procedure is as shown in Figure 6-2. The utility grid power quality is checked first at BIC local controller to ensure the disturbance has been cleared. When the utility grid power quality has met the criteria, the signal for disturbance clearance is sent to the central controller through the supervisory control and data acquisition (SCADA) system. Otherwise, utility grid power quality is checked again until the power quality is satisfactory.

Once the utility disturbance has been cleared, BIC VRM operation is activated to regulate DC side output voltage. The reference bus voltage is generated based on droop control with V_n as the threshold voltage. As the contactor is still open, BIC output power is zero. BIC DC output capacitor voltage is thus maintained at the nominal value.

Due to the limited magnitude of transmission line impedance, voltage difference across the contactor will result in significant inrush current when the contactor is closed. It might result in maloperation of circuit breakers and activating the protection schemes of converters unintentionally [162]. Therefore, the difference between system bus voltage and BIC DC output voltage should be minimized before the contactor is closed to reduce the inrush current.

Figure 6-2. Flowchart for grid reconnection procedure.

System bus voltage V_{bus} measured at the point where the contactor is connected is compared with BIC output capacitor voltage V_{BIC} . When the magnitude of the voltage difference is smaller than the threshold value δV , BIC output voltage is considered matching with system bus voltage. Otherwise, BIC threshold voltage should be tuned accordingly to reduce the voltage difference. The voltage tuning direction is determined by the sign of the voltage difference. The magnitude of voltage tuning in every step is also limited to prevent significant voltage variation.

A counter is used to ensure that the voltages at both sides of the contactor have been regulated stably. When the absolute value of the bus voltage difference is smaller than δV , the counter is increased by 1. Otherwise, it indicates that either DC microgrid bus voltage or BIC output voltage is unstable. The counter is reset to zero and the process for DC voltage checking should be restarted. BIC output voltage is considered to be matched with DC microgrid bus voltage stably only if the voltage difference has been within the allowable range for N times continuously. The contactor is then closed to interlink the DC microgrid bus with the BIC. DC microgrid changes to operate in grid-tied state.

With the multiple-slack-terminal DC microgrid, BESs operating mode change is eliminated during islanding and system bus voltage is regulated actively throughout the transition. The contactor implemented helps decoupling BIC operating mode change and grid connection. Therefore, BIC operating mode change does not affect the stable operation of DC microgrid. The counter used has managed to ensure that voltages at both sides of contactor have been matched stably so that the inrush current can be minimized.

6.3. Multi-level Energy Management System

System bus voltage deviation and power tracking error are the main drawbacks of the multiple-slack-terminal DC microgrid in distributed control. Multi-level EMS [65, 163] discussed in Chapter IV is thus implemented to enhance system control accuracy. Bus voltage deviation and power tracking errors can be eliminated with secondary voltage regulation [91]. All slack terminals are usually assigned with the same utilization priority and the reference powers are generated in proportion to their power capacities [47, 70]. However, the coordination between utility grid and localized BESs, whose utilization priorities are different, has not been covered. In the proposed work, BIC and BESs power references are generated based on their utilization priority, battery SoC and real-time system net power.

Bus voltage restoration implemented in secondary control follows that as in Section 5.1.1. The average value of the bus voltage measurements at the sensitive

loads is used for the indication of system bus voltage. To eliminate the voltage deviation, bus voltage restoration is implemented in the central controller. The average bus voltage measurement $\bar{V}$ is compared with the nominal value. The difference is processed with a PI controller to generate the voltage compensator ΔV_V [70, 91]. The threshold voltages of ESs and BIC are tuned with the voltage compensator in real time to minimize the voltage deviation.

In DC microgrid, system net power varies due to the intermittence of RESs generation and uncertainty of load consumption [39]. Both localized ESs and the utility grid can be used to mitigate system power imbalance. ESs and BIC power sharing in proportion to their installed power capacities is normally implemented for multiple-slack-terminal DC microgrid [47, 70]. However, the electricity from the utility grid is generated from the central power plant which is located far away. Therefore, localized ESs are assigned with higher utilization priority [69, 164]. It helps reducing the power loss due to long distance transmission which takes significant portion of the overall energy consumed. ESs are scheduled to compensate for system net power until reaching their power capacities. The reference powers of the BESs P_{ESs}^* and BIC P_{BIC}^* are:

$$P_{ESs}^* = \begin{cases} P_{ESs}^{\min} & (P_{net} \leq P_{ESs}^{\min}) \\ P_{net} & (P_{ESs}^{\min} < P_{net} \leq P_{ESs}^{\max}) \\ P_{ESs}^{\max} & (P_{ESs}^{\max} < P_{net}) \end{cases} \quad (6-3)$$

$$P_{BIC}^* = \begin{cases} P_{net} - P_{ESs}^{\min} & (P_{net} \leq P_{ESs}^{\min}) \\ 0 & (P_{ESs}^{\min} < P_{net} \leq P_{ESs}^{\max}) \\ P_{net} - P_{ESs}^{\max} & (P_{ESs}^{\max} < P_{net}) \end{cases} \quad (6-4)$$

where $P_{ESs}^{\min}$ and $P_{ESs}^{\max}$ are the minimum and maximum output power of the combined localized ESs, respectively.

To ensure enough ESs energy capacity for system islanded state operation, SoC is another constraint for ESs power dispatch [9, 39, 89]. Threshold values, SoC_{max} and SoC_{min} , are set to limit the variation of battery stored energy. SoC_{max} is set as 100% to indicate the limitation of stored energy. When battery SoC reaches the upper

limitation SoC_{max} , ESs charging power capacity is reduced to zero. The reference powers of ESs and BIC are:

$$P_{ESs}^* = \begin{cases} 0 & (P_{net} \leq 0) \\ P_{net} & (0 < P_{net} \leq P_{ESs}^{max}) \\ P_{ESs}^{max} & (P_{ESs}^{max} < P_{net}) \end{cases} \quad (6-5)$$

$$P_{BIC}^* = \begin{cases} P_{net} & (P_{net} \leq 0) \\ 0 & (0 < P_{net} \leq P_{ESs}^{max}) \\ P_{net} - P_{ESs}^{max} & (P_{ESs}^{max} < P_{net}) \end{cases} \quad (6-6)$$

Similarly, when SoC is lower than SoC_{min} , ESs discharging power capacity is zero.

$$P_{ESs}^* = \begin{cases} P_{ESs}^{min} & (P_{net} \leq P_{ESs}^{min}) \\ P_{net} & (P_{ESs}^{min} < P_{net} \leq 0) \\ 0 & (0 < P_{net}) \end{cases} \quad (6-7)$$

$$P_{BIC}^* = \begin{cases} P_{net} - P_{ESs}^{min} & (P_{net} \leq P_{ESs}^{min}) \\ 0 & (P_{ESs}^{min} < P_{net} \leq 0) \\ P_{net} & (0 < P_{net}) \end{cases} \quad (6-8)$$

To eliminate the errors between the reference and actual output powers of slack terminal, power sharing compensation is implemented in tertiary control. The reference power is compared with the actual output power and the difference is processed with a PI controller to generate the power sharing voltage compensator. The threshold voltage is tuned accordingly in respective local controllers.

6. 4. Experimental Verifications

The control schematic diagram of the lab scale DC microgrid is as shown in Figure 6-3. System bus and the SCADA system remained the same as those in Chapter IV but only the lead-acid battery bank is used as the localized ES. Besides, the DC bus is connected to the utility grid through a BIC as in the figure. The contactor, which is used to activate the transitions between grid-tied and islanded states, is installed inside the circuit panel. Details of experimental setups are as shown in Table 6.1.

The nominal bus voltage is set to be 380 V, which has followed the standard of data center application proposed by Rebus Alliance [3]. BES and BIC droop coefficients are determined with allowable bus voltage variation of ± 10 V. Both resistive load and programmable load are used to emulate different load types and loading profiles.

Figure 6-3. Schematic layout of the lab-scale DC microgrid.

Table 6.1. Experimental Setups

<i>Parameters</i>	<i>Unit</i>	<i>Setting</i>
Nominal bus voltage	V	380
PV1 power capacity	kW	1.3
PV2 power capacity	kW	1.4
BI power capacity	kW	2
BES power capacity	kW	2
BI droop coefficient	V/kW	5
BES droop coefficient	V/kW	5
System bus capacitance (grid-tied)	μF	5340

Case 1:

In case 1, comparison for islanding processes with the proposed multiple-slack-terminal DC microgrid and the conventional method was conducted. The experimental results, including bus voltage, BES and BIC output current, for the

conventional method obtained with oscilloscope are as shown in Figure 6-4. BIC operated in VRM with reference voltage of 380 V. BES operated in PCM and the reference power was set as 0 kW in the beginning. System load consumption of 1 kW was compensated by BIC as shown in the figure. The bus voltage measured at BES output capacitor was 378.3 V.

When utility grid disturbance was detected in BIC local controller, BIC idle mode operation was activated by disabling all power electronic switches. BIC output current was reduced to 0 instantly and system bus voltage dropped due to system power deficiency was induced. BES operating mode change was activated by comparing with the threshold voltage, which was set to be 365 V, in the local controller. BES operated in VMR and compensated for the load consumption. Due to the response delay of BES, the magnitude of the voltage dip was 36 V. The bus voltage measured at BES output was stabilized at 380 V after transition.

Figure 6-4. System response during islanding with the conventional method.

In contrast, DC microgrid islanding with the proposed multiple-slack-terminal DC microgrid was implemented. Both BES and BIC operated in VRM with droop control in the beginning. It helps elimination of BES operating mode change during islanding. To compare the result more intuitively, the threshold voltage of BIC was increased gradually until BES output power was stabilized at 0. Therefore BIC

compensated system load as in the conventional method. The experimental results are as shown in Figure 6-5.

When BIC operating mode change was activated, the output power was reduced to zero. BES operating mode remained the same as in grid-tied state and the output power has increased instantly to compensate for system power deficiency. Bus voltage dip during the transition was mainly due to the droop relationship imposed and instant system power deficiency. The magnitude of voltage dip was 19 V during the transition, which was much smaller than that in the conventional method. System bus voltage reduction of 5 V in steady state was observed due to the increase in output power. Compared with the conventional method, the magnitude of bus voltage variation during the transition was reduced significantly.

Figure 6-5. System response during islanding with the proposed method.

DC microgrid bus voltage can be regulated effectively in grid-tied and islanded states with both the conventional and proposed method. However, the magnitude of bus voltage variation during the islanding was reduced significantly with the proposed multiple-slack-terminal DC microgrid.

Case 2:

DC microgrid islanding with multi-level EMS was carried out in case 2. Distributed control of DC microgrid as described in case 1 was scheduled as the

primary control. Multi-level EMS was implemented to enhance system control accuracy. Due to the limited number of measurement channels of the Lecroy Oscilloscope, DC meter data acquired through the SCADA system with data updating frequency of 1 Hz is used to showcase system operation statuses. The experimental results are as shown in Figure 6-6. The average value of the bus voltages measured at the loads was used as system bus voltage.

Figure 6-6. Experimental results for islanding with multi-level EMS.

PV converters operated in MPPT mode throughout the case study. Significant PV generation variation has occurred due to the real-time solar irradiation change during 0.5-7.3 min. The load consumption remained constant to be 1.5 kW as shown in the figure. In the beginning, system bus voltage was feedback to the central control to generate the voltage compensator. Threshold voltages of BES and BIC were tuned accordingly to maintain the bus voltage at nominal value. BES initial SoC was at the minimum value SoC_{min} , thus BES discharging power capacity was zero. With system net power of 0.14 kW, the power references of BES and BIC were 0 and 0.14 kW, respectively. Power tracking errors were eliminated with power sharing compensation implemented in tertiary control.

Due to the high frequency variation of PV generation from 0.5 min onwards, significant output power change of BES and BIC have been observed. The instant output power changes are inversely proportional to the droop coefficient assigned. System bus voltage variations due to the droop relationships imposed have occurred accordingly. With multi-level EMS, system bus voltage was retrieved to the nominal value to minimize the voltage deviation. BES output power has followed the reference value of 0 kW effectively with power sharing compensation in steady state.

When utility grid disturbance was detected at 5 min, BIC idle mode operation is activated by disabling all power electronic switches. BIC output power changed to zero immediately and the DC microgrid has changed to operate in islanded state. BES became the only slack terminal for mitigation of system power mismatch between power generation and consumption. BES output power has increased instantly to regulate system bus voltage. System has been stabilized after the islanding. BES output power variation is mainly due to solar irradiation change.

It has happened that the PV generation reduction of 0.65 kW has occurred simultaneously during the transition, which has enlarged system power deficiency. As a result, bus voltage reduction with magnitude of 5.1 V was observed. Upon detection of bus voltage deviation, BES threshold voltage was tuned with the bus voltage restoration. The bus voltage was increased gradually and stabilized at the nominal value. BES output power has followed the variation of PV generation closely afterwards. System was stabilized at 7.6 min and the bus voltage was maintained at the nominal value.

With secondary voltage regulation, system bus voltage deviations were eliminated in steady state regardless of system net power change. System power quality was thus enhanced. Power sharing compensation implemented helped active power dispatch of BESs and BIC based on the utilization priority settings, battery SoC and the real-time system net power. Therefore, system control accuracy was enhanced with multi-level EMS both in grid-tied and islanded states.

Case 3:

In case 3, DC microgrid transitions from islanded to grid-tied state with both the conventional and proposed methods were compared. The experimental result for reconnection with conventional method is as shown in Figure 6-7. In the beginning, system operated in islanded state with BES regulating system bus voltage at 380 V. When utility grid disturbance was cleared, BIC changed to operate in VRM with V_n as the reference voltage. The contactor remained open and thus BIC output power was 0 kW. BIC DC side voltage was tuned gradually as the flowchart in Figure 6-2 to minimize the voltage difference at two sides of the contactor. The threshold voltage δV was set to be 1 V in this case.

Figure 6-7. System response during reconnection with the conventional method.

The contactor was closed when bus voltages at both sides were stabilized to 100 continuous iteration cycles. Theoretically, uncontrollable circulating current will be induced with multiple slack terminals in parallel. In actual implementation, the output power change of BES was limited by the transmission line impedance. However, due to the limited magnitude of line impedance, significant output current change has been induced. BES output current reduction of 1.4 A was stabilized at 0.25s after the transition. Bus voltage surge with insignificant magnitude and duration was observed during the transition.

In comparison, reconnection was repeated with the proposed multiple-slack-terminal DC microgrid. The experimental results are as shown in Figure 6-8. Both BES and BIC operated in VRM with droop control before the contactor is closed. When the voltage difference was controlled to be lower than the threshold value stably, the contactor was closed. The output current change of BES was limited by both transmission line impedance and the droop relationships imposed. BES output current was reduced by 0.2 A, which was much smaller comparing with the results obtained with the conventional method. The duration of transition was also reduced significantly. System bus voltage has remained unchanged throughout the transition.

Figure 6-8. System response during reconnection with the proposed method.

With the procedure proposed as in Figure 6-2, smooth transition was ensured during the reconnection. Bus voltage variation during the transition for both methods was insignificant. However, sudden change in BES output current has been induced when the contactor was closed due to the coexistence of multiple slack terminals in the conventional method. BES output power change with the proposed multiple-slack-terminal DC microgrid was reduced significantly due to the droop relationships imposed.

Case 4:

In case 4, DC microgrid reconnection with the proposed multi-level EMS was verified as shown in Figure 6-9. In the beginning, BES was the only slack terminal for system bus voltage regulation. The net power was compensated by BES to ensure system power balance. Bus voltage restoration in secondary control helped maintaining system bus voltage at the nominal value in steady state. When significant solar generation occurred during 2-4 min, BES output power has followed the net power change closely. Bus voltage variation has been induced due to BES output power change. System bus voltage was retrieved to the nominal value in steady state with bus voltage restoration.

Figure 6-9. Experimental results for reconnection with multi-level EMS.

When BIC has detected the clearance of utility grid disturbance, DC microgrid reconnection was activated. System has followed the procedure for transition from islanded to grid-tied state as in Section 6.2. When the bus voltages at two sides of the contactor have been matched stably at 5 min, the contactor was closed. DC microgrid changed to operate in grid-tied state. System bus voltage change during the transition was insignificant. BES instant power increment of 0.08 kW was induced due to the actual bus voltage difference between V_{BIC} and V_{bus} . It has matched with the result obtained in case 3. As system net power was positive, BES

is set with lower utilization priority. Power sharing compensation was implemented to track the BES reference power of 0 kW in steady state.

6. 5. Conclusion

Implementation of multiple-slack-terminal DC microgrid has helped reducing bus voltage fluctuation and inrush current during islanding and reconnection. Detailed procedures proposed have managed to ensure smooth transitions between grid-tied and islanded states. Multi-level EMS applied has eliminated the bus voltage deviation and power tracking errors in both grid-tied and islanded states. BESs and BIC power dispatch based on utilization priority setting, battery SoC and real-time system net power has been realized successfully. The effectiveness of the proposed control methods has been verified with a lab-scale DC microgrid. Cases 1 and 3 have demonstrated the significance of the proposed multiple-slack-terminal DC microgrid and transition procedures in comparison with the conventional system. Cases 2 and 4 have shown the effectiveness of the multi-level EMS for enhancement of system control accuracy.

Chapter VII. Conclusion and Future Works

7.1. Conclusion

With increasing penetration of DC-compatible energy sources, storages and loads, DC microgrids with minimized DC/AC/DC power conversions are becoming more popularized. Proper control algorithm for coordination of various system units is necessary to ensure system reliability and stability while considering operation cost, energy storage lifetime, bus voltage variation, *etc.* Conventionally, centralized energy management system is proposed to ensure systematic optimization. Slow response and low system reliability due to the necessity of the communication link between the central controller and system units are the main drawbacks.

In DC microgrids, which are usually of capacitive, the bus voltage varies with system power imbalance. DC bus signaling, in which bus voltage is regarded as the global indicator for system power balance, has been implemented for distributed control of DC microgrids. To realize the coordination among various system units in different loading conditions, multiple modes operation is proposed. The allowable bus voltage range, which is determined by the industrial standards, is divided into several regions. Meanwhile, system units are prioritized based on their utilization costs. Different operating modes of system units are scheduled in different bus voltage regions to ensure stable bus voltage and maximized RESs utilization. The operating modes of system units are configured based on the comparison of the local bus voltage with the predefined threshold voltages to realize distributed control. However, in case of multiple slack terminals operating in parallel, the power sharing among them is uncontrollable. Besides, discretized system bus voltage results in significant bus voltage fluctuations during voltage region transitions.

Voltage-power (V/P) droop control is an effective solution for power sharing among slack terminals. The resultant shared power is inversely proportional to the droop coefficient assigned. Therefore, multiple-slack-terminal DC microgrid with combination of multiple modes operation and droop control is proposed for the distributed control of DC microgrids. The droop coefficients are generated based on the range of bus voltage region and power capacity of respective slack terminals. It ensures continuous system bus voltage in different loading conditions so that to reduce system bus voltage fluctuation during the voltage regions transitions. At the same time, active power sharing among slack terminals can be realized effectively.

To overcome the disadvantages of distributed control, including the steady-state bus voltage deviation and power sharing error due to transmission line impedance and droop relationships imposed, multi-level energy management system is proposed to ensure both system reliability and control accuracy. Multiple-slack-terminal DC microgrid operation in distributed manner is scheduled as the primary control. Bus voltage restoration is implemented in secondary control to minimize bus voltage deviations and enhance system power quality. The power references of system units are determined based on the comparison of their marginal costs to minimize system operation cost. Power sharing compensation in tertiary control helps eliminating the power tracking errors. In case of communication failure, system operation can still be retained with distributed control to ensure system reliability. But the control accuracy is degraded as secondary and tertiary control malfunction without the communication link.

Hybridization of energy storages with different characteristics is an effective and economic solution to comply with all system specifications including power density, energy density, ramp rate, *etc.* To minimize system bus voltage due to the variation in real time operation, system net power is decomposed into high and low frequency components. HRES is scheduled to compensate for the high frequency net power variations and LRES compensates the low frequency variations. The main drawbacks of HESS centralized control, which is normally implemented, include slow response and low system reliability. Hierarchical HESS control

comprised of both centralized and distributed control is proposed to ensure system reliability and control accuracy. HESS centralized control with implementation of iteration based power dispatch, bus voltage restoration and autonomous SoC recovery is proposed. In case of communication failure, system switches to operate with distributed control. Droop and reverse droop relationships are imposed for HRES and LRES, respectively. Localized LPF is applied to LRES to realize system net decomposition and ESs power dispatch in distributed manner. Autonomous SoC recovery by tuning HRES threshold voltage according to the real-time SoC is also proposed for HESS distributed control to reduce the possibility of HRES stored energy range violation.

In case of HRES outage or communication failure, LRES operating mode change is needed for hierarchical HESS control, which might induce significant system bus voltage variation. Beside, slack terminal reassignment is needed when HRES fails. Multi-level EMS based HESS control is thus proposed. Both HRES and LRES are configured to operate in VRM and the reference voltages are generated based on droop control. Localized LPF is applied to the feedback bus voltage of LRES so that LRES only response to the low frequency net power variations. The cut-off frequency of LPF has been obtained based on the ramp rate of LRES and the maximum system net power change rate. To enhance system control accuracy, bus voltage restoration and power sharing compensation are implemented in secondary and tertiary control, respectively. In case of communication failure, system operation can still be retained with distributed control without ESs operating mode change, but the control accuracy will be degraded.

DC microgrid normally operates in grid-tied state with BIC for power exchange between the utility grid and DC bus. In case of utility grid failure, system changes to operate in islanded state to isolate the utility grid disturbance. Conventionally, BIC is configured as the only slack terminal for DC bus voltage regulation. Localized ES operating mode change from PCM to VRM will be activated when system changes to islanded state. Slack terminal reassignment and system response delay results in significant bus voltage fluctuations. Multiple-slack-terminal DC

microgrid, in which both BIC and localized ES operate in DC voltage regulation, is proposed to minimize the effect due of system state transitions. Detailed procedures for islanding and utility grid reconnection have been proposed to minimize the bus voltage fluctuation and inrush current during the transitions.

To verify the proposed control methods, a lab-scale DC microgrid with integration of rooftop solar PV, various energy storages, loads and energy sources has been developed for experimental verifications. Power electronic converters for integration of various system units have been designed and tested. Supervisory control and data acquisition (SCADA) system has been developed for centralized coordination. DC microgrid operation with distributed, centralized and multi-level EMS based controls has been verified. Both hierarchical control and multi-level EMS control of HESS have been tested with the lab-scale DC microgrid in different loading conditions. The effectiveness of the proposed islanding and reconnection procedures for system transitions between islanded and grid-tied states.

7. 2. Future Works

The PhD work has mainly focused on the feasibility study of different control algorithms for DC microgrid operation. Yet there is some research topics which should be further investigated:

- System stability analysis

System stability analysis for different control algorithms should be carried out to study the stability boundaries. It also helps providing advices for modification of the controllers so that to enlarge the safety margin.

- Optimization of system units sizing

Optimization of capacity design for various system units is crucial to ensure minimized system installation cost. Estimation of the load consumption and RESs generation to determine the power and energy capacities of energy storages is needed.

- Reliability of power electronic converters

Power electronic converters are widely implemented for integration of various RESs, ESs and loads. The converters are assumed to be 100% reliable during system operation. The reliability analysis of the power electronic converters is necessary to investigate the reliability of DC microgrid system in actual implementation.

- Operation of hybrid AC/DC microgrid

For system with both AC- and DC-compatible energy sources, loads and storages, hybrid AC/DC microgrid, in which a BIC is implemented for bidirectional power exchange between the DC and AC sub-grids, is a better alternative.

- DC microgrid protection

The mechanisms of DC and AC protections are different. Therefore, DC microgrid protection is also an important topic for actual implementation.

- Commercialization

Lacking of available product for integration of DC-compatible energy sources, storages and loads is one of the major barriers for DC microgrid development. Commercialization of DC microgrids by development of market available products helps driving up the momentum.

List of Publications

Journals Papers:

- C. Jin, P. Wang, J. Xiao, Y. Tang, and Choo, "Implementation of Hierarchical Control in DC Microgrids," *Industrial Electronics, IEEE Transactions on*, vol. 61, pp. 4032-4042, 2014.
- J. Xiao, P. Wang, Leonardy Setyawan, "Hierarchical Control of Hybrid Energy Storage System in DC Microgrid," *Industrial Electronics, IEEE Transactions on*, vol. 62, pp. 4915 - 4924, 2015.
- J. Xiao, P. Wang, L. Setyawan, "Multilevel Energy Management System for Hybrid Energy System in DC Microgrids," *Smart Grid, IEEE Transactions on*, vol. pp, no.99, pp.1-1, 2015.
- J. Xiao, P. Wang, L. Setyawan, "Implementation of Multiple-Slack-Terminal DC Microgrids to Ensure Smooth Transitions between Grid-tied and Islanded States," *Smart Grid, IEEE Transactions on*, , vol. pp, no.99, pp.1-1, 2015.
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- J. Xiao, P. Wang, Leonardy Setyawan, "Hierarchical Power Management for Real-time Operation of DC Microgrids with Multiple Slack Terminals," *Energy Conversion, IEEE Transactions on*, vol. pp, no.99, pp.1-1, 2015.
- Leonardy Setyawan, P. Wang, J. Xiao, "Optimal Depth-of-Discharge Range and Capacity Settings for Battery Energy Storage in Microgrid Operation," *Energy Conversion, IEEE Transactions on*, **submitted**.

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- P. Wang, J. Xiao, L. Setyawan, "Multi-level EMS for hybrid AC/DC microgrids," in *Industrial Electronics and Applications (ICIEA), 2015 IEEE 10th Conference on*, **Presented**.
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- Qianwen Xu, Peng Wang, Jianfang Xiao, Changyun Wen, Lee Meng Yeong, "Modeling and Stability Analysis of Hybrid Energy Storage System under Hierarchical Control," in *Power and Energy Engineering Conference (APPEEC), 2013 IEEE PES Asia-Pacific*, 2015. **Accepted**.

- Qianwen Xu, Xiaolei Hu, Peng Wang, Jianfang Xiao, Leonardy Setyawan, “Design and Stability Analysis for an Autonomous DC Microgrid with Constant Power Load,” *Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2016 ***Accepted.***

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