Coordination control of hybrid AC/DC building microgrid

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**COORDINATION CONTROL OF HYBRID AC/DC BUILDING
MICROGRID**

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COORDINATION CONTROL OF HYBRID AC/DC BUILDING MICROGRID

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

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Statement of Originality

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

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Abstract

Advantages such as environmental friendliness and flexibility have made microgrid an attractive option for in modern power systems. Microgrid is a localized grouping of distributed generators, storages and loads. Microgrid integrates with sustainable energy sources could reduce carbon emission. A microgrid can serve specific purposes, such as to enhance reliability, diversification of energy sources, and cost reduction. Therefore, microgrid has been introduced into building distributed networks as it makes both power generation and consumption more efficient. In order to obtain better power conversion and utilization efficiency, the configuration, control strategy, and energy management of building microgrid need to be further studied. This thesis introduces the overall configuration of building microgrid and the specific subsystem controllers in a building microgrid.

Microgrid configuration, operation and control have been investigated for many years. Various microgrid configurations for building distributed networks have been proposed with each claiming some aspects of improvements. To achieve better energy efficiency, a novel hybrid building microgrid is introduced in this thesis. A building photovoltaic system (BPVS), a building motor drive system (BMDS) and a hybrid building energy storage system (HBES) are introduced respectively based on the common features among PV systems, motor driving circuits and various energy storages. The objective of the building hybrid microgrid (BHMG) is to improve building's energy efficiency through reducing multiple reverse conversion loss in conventional building distributed networks (CBDN), to achieve more efficient connection of subsystems, and to reduce building energy consumption and peak power demand through power generation from BPVS and power regeneration in BMDS.

In building microgrid, motor drives are essential devices and widely used in lifts, air-conditioning and water pumping systems. In a high rise commercial building, lift motors not only consume energy but also regenerate energy. A building's lift

system is proposed to classify and integrate all lifts together to improve the efficiency in the building's energy utilization. A novel distributed lift control approach based on fuzzy logic and DTC is proposed in this chapter to integrate lift operating system optimization and motor control. The objective of the novel control system is to choose the lift which makes the waiting & riding time shorter and consumes less power, and it can even regenerate power and channel back into energy storage. The motor controller with self-tuning has a smaller ripple and shorter response and recovery time. By using this controller, the power efficiency in high rise multi story building can be improved.

Another essential component in building microgrid is energy storage. Different types of energy storages with high power density and high energy density have to operate under different modes like voltage regulation and power exchange. An adaptive area droop control approach has been proposed to demonstrate an autonomous mode change and a stable operating performance for energy storage converters. The coordination control is introduced to reduce the battery charging/discharging times of miner cycle and discharge depth.

Plug-in hybrid electric vehicle (PHEV) is gaining popularity in today's automotive market and more charge stations for PHEV are installed in commercial buildings. The conventional charge circuit can only produce an output DC voltage that is higher than the peak AC input voltage. An efficient single-phase PFC converter that features sinusoidal input current, three-level output characteristic and flexible output DC voltage is introduced to cater for variable voltage levels of the battery pack (50V-600V). The charging efficiency is improved since it is partially contributed by the reduced switching voltage in the PFC stage, and also partially by the reduced power conversion in the DC/DC buck stage.

All design configurations and control algorithms have been thoroughly verified in MATLAB/Simulink and PLECS. Suitable experimental prototypes have been built in the laboratory for validating the practicalities of all theoretical findings.

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Abbreviations

CBDN	Conventional Building Distributed Network
BHMG	Building Hybrid Microgrid
CDCB	Common DC Bus
LDCB	Low Voltage DC Bus
BDAC	Bi-directional DC/AC Converter
BPVS	Building Photovoltaic System
HESS	Hybrid Energy Storage System
HBES	Hybrid Building Energy Storage System
BMDS	Building Motor Drive System
DTC	Direct Torque Control
PFC	Power Factor Correction
V2G	Vehicle to Grid
MPC	Model Predictive Control

Chapter 1

Introduction

Buildings are considered to be among the largest energy consumption unites in modern cities. With the increase of building energy consumption, the drawbacks of conventional building power distributed network topology arise progressively. The theme of this thesis is to design a novel building hybrid microgrid and its coordination control. Each subsystem in this novel building hybrid microgrid is designed to improve the whole system efficiency and meet specific requirements. The objectives and structure of this thesis are introduced in this chapter.

1.1 Background

For over hundreds of years, power grid has been expanded into today's giant network which can cover an entire country as big as China or Canada with several hundreds of large conventional fossil generators. In such large scaled power grid, buildings are always considered as large energy consumption units. Based on the building energy data book from U.S Departure of Energy [1], transportation, industrial plants and buildings are three large energy consuming sectors. 41% of primary energy is consumed by the buildings sector, compared to 30% by the industrial sector and 29% by the transportation sector. Twenty quads of delivered energy, which does not include energy loss during production and transmission, is consumed in a year. With the growth in population, households and commercial floor space, the energy consumption in the building sector keeps growing.

With the building energy consumption growth, the drawbacks of conventional topology of building power distributed network in large scale power grids arise progressively. Conventional energy depletion in buildings and the associated environmental problems are becoming public concerns. Based on the statistics from The Energy Information Administration (EIA), 75% of the energy sources used by the building sector come from fossil fuels, 16% from nuclear generation and 9% from renewables. The other downside is that, long distance transmission and large network not only cause instability and security problems of grid operation but also could not meet the diverse requirements of power supply.

To overcome those energy shortcomings and meet specific requirements, the concept of microgrid was proposed and introduced into building power networks. Microgrid is the localized grouping of distributed generators, storages and loads. Building distributed networks were used to be established as microgrid with conventional power generation. Accompanying the penetration of renewable energy sources, microgrids with integrated sustainable energy sources have been developed into the worldwide. It could meet localized requirements and make both

power generation and consumption more efficient. Conventional building distributed network is AC microgrid integrated with renewable energy sources such as PV or fuel cell. In order to obtain better power conversion and utilization efficiency, building distributed network needs to be further studied in the areas of configuration, control strategy, and energy management.

In building energy consumption, the top four end usages are space heating, space cooling, water heating and lighting, which account for 68% of total energy consumption in the building. The new issue about how to reduce the peak load demand arises. A promising method is to use regenerative energy from motor drives since it is widely used in space temperature control and lift system. The controller for motor drive has to be improved to meet requirements such as to generate (or regenerate) more energy, to maintain constant speed and achieve faster response.

Energy storage is recognized as the key to improving the reliability and dynamic stability of building distributed networks due to the penetration of large amount of intermittent and stochastic power [2]. For large stationary energy storages in the power grid, the advantages include peak power shaving, load levelling and standby reserves [3]. In building distributed networks, the energy storage has capacity and sizing limitations. At the same time, energy storage has to meet the high frequency power exchange requirement by the motor drive operation system. The question about which kind of energy storage and proper controller is truly more stable is therefore left unanswered.

With these challenges to explore and the growing importance of building distributed networks, the theme of this thesis is firmly set on the design of building hybrid microgrid configuration and its coordination control. For further study, each subsystem in building distributed networks has to be designed to improve efficiency. Issues such as lift operation optimization, power transfer loss reduction, converter controller simplification and feedback variables self-tuning are promptly discussed. The relevant topics are now elaborated as follows.

1.2 Objectives

A number of objectives, which are supposed to be achieved throughout the course of this research, are explained as follows:

1.2.1 Building system energy efficiency improvement

A novel smart building hybrid microgrid (BHMg) is proposed to improve buildings' energy efficiency through reducing multiple reverse conversion loss in conventional building distributed networks (CBDN), to achieve highly efficient connection of subsystems. Multi-level voltage DC bus is proposed in the BHMg for easier and more efficient integration of various DC links which exist in the motor driving circuits, energy storages, loads and PV systems of the CBDN. A common DC bus (CDCB) and a low voltage DC bus (LDCB) are introduced to reduce energy loss from multiple reverse conversions such as DC/AC/DC and AC/DC/AC in CBDN, also to realize direct power exchange between generation (or regeneration) and consumption, as well as to eliminate some parts of redundant hardware such as rectifier in many loads.

1.2.2 Maximum building load demand reduction

In conventional building distributed networks, motor drives are considered as large energy consumers. The regenerative energy is wasted as heat generated by resist friction and or dumped back into the utility grid. In BHMg, the regenerative power from motor drives is reused or restored back in the energy storage. Among the motor drives, the regenerative energy can be used for powering the other motors even loads. The maximum load demand is reduced by designing the motor controller which is to maximize the regenerative power during regenerative braking and to share the power between different operating mode motors.

1.2.3 Optimal lift operation

For further improvement, a novel distributed lift control approach based on fuzzy logic and DTC is proposed to integrate lift operating optimization and motor control. Lift operating optimization method is based on the fuzzy logic. The inputs of the fuzzy logic-based optimization are real time call level, original level and destination level, which are the 3 key areas of a real-life lifts operation system. The motor controller is designed based on the DTC. A fuzzy self-tuning method is introduced in motor controller. The proportional and integral gains in controller can be self-tuning according to the lift operation. The novel approach is set for each motor in a building's lift system. By using this method, the lift operation is optimized and the peak power demand can be reduced.

1.2.4 Simplify the hybrid energy storage controller

Based on the building microgrid configuration, hybrid building energy storage system (HBES) has different operating modes. Energy storage converters are able to work in either voltage regulation mode or power exchange mode. The proposed adaptive area droop control is introduced to HBES which could automatically alter the energy storage operating mode by changing the droop coefficient. The energy storage converter does not need multiple controllers to achieve different objectives. This also means that the energy storage converter is simplified.

1.2.5 Extend the DC output voltage range

A highly efficient single-phase PFC converter features sinusoidal input current, three-level output characteristic and flexible output DC voltage. Its attractiveness is that the embedded bidirectional DC/DC buck converter only needs to process partial input power rather than full scale of input power, and therefore energy conversion efficiency can be largely improved compared with the conventional two stage solution. Also, the PFC stage exhibits three-levels of output voltage, and the

dV/dt across the switches are reduced, so as the switching losses. An added advantage of this converter is that, the fluctuating 100Hz or 120Hz harmonic power in the single-phase system can be almost diverted into the DC link capacitor through proper control design, and the terminal voltage and/or the charging current of battery pack will be fairly constant, which may extend its working lifetime.

1.3 Thesis Overview

This thesis addresses eight chapters organized as follow:

Chapter 1 provides the rationale for the research and outlines the goals and scope as well as summarizes all original contributions documented in the thesis.

Chapter 2 reviews the literature concerning conventional building distributed networks and its control strategy. It discusses the essential relationships among the various types of microgrid and their control strategy. The relative devices controller such as motor controller and energy storage controller are reviewed as well. Recent related developments are also discussed with their benefits and limitations identified. The knowledge gained helps in the understanding of new control schemes and generalized design procedures proposed from chapter 3 onwards.

Chapter 3 introduces the concept of smart building hybrid microgrid and its coordination control. The novel configuration is proposed for improving the building energy efficiency and reducing the building energy consumption and maximum load requirement. In the building hybrid microgrid, a building photovoltaic system (BPVS), a building motor drive system (BMDS) and a hybrid building energy storage system (HBES) are introduced respectively. The following chapters will discuss the improvement on them.

Chapter 4 elaborates on the improvement on building motor drive system (BMDS), especially the lifts in building microgrid. The distributed lift operation control is

proposed in this chapter. The novel controller integrates optimized operation controller and motor DTC controller with self-tuning PID. The fuzzy logic is introduced into the lift control system to optimize operation and self – tuning in motor DTC control. The presented controller is compared with existing alternatives to clearly identify their steady – state and dynamic performance.

Chapter 5 elaborates on the improvement of hybrid energy storage system. An adaptive area droop controller is designed to switch HBES from voltage regulation mode to power control mode automatically by changing the droop coefficient. The mathematical analysis is presented in this chapter to verify the validation.

Chapter 6 presents a high efficiency single-phase PFC converter that features sinusoidal input current, three-level output characteristic and flexible output DC voltage. Its attractiveness is that the embedded bidirectional DC/DC buck converter only needs to process partial input power rather than full scale of input power, and therefore its conversion efficiency can be much improved compared with the conventional two stage solution. Also, the PFC stage exhibits three-level output voltage, and the dV/dt across the switches are reduced, so as the switching losses. An added benefit of this converter is that, the fluctuating 100Hz or 120Hz harmonic power in the single-phase system can be diverted into the dc-link capacitor through proper control design, and the terminal voltage and/or the charging current of battery pack will be fairly constant, which may expand its working lifetime. Its operation principle and control strategies are discussed in detail in this paper, and both simulations and experimental results are provided for validation.

Chapter 7 concludes the research findings presented in this thesis and suggests some prospective research topics for future investigation.

1.4 Originality

This research led to several novel outcomes by:

1. Design of a novel smart building hybrid microgrid configuration and its coordination control
2. Design of a novel lift distributed control which correlates lift optimize operation and motor DTC control. By using the novel controller, the response time is reduced and makes a better performance
3. Improve an adaptive droop area control for hybrid energy storage system which can automatically change the operation modes by tuning the droop coefficient
4. Design of a PFC converter with flexible output voltage to improve the energy efficiency which is used as EV charger
5. Improve a motor controller with MPC which is able to achieve multiple objectives

Chapter 2

Existing Topology and Control Techniques for Building Microgrids

In this chapter, some fundamental studies which include building distributed network configuration, attributes classification and their controllers are reviewed. Conventional building distributed network is based on AC microgrid, which is introduced in this chapter. The essential components such as motor drives and energy storages are necessary to achieve the smart building requirement. DTC and fuzzy logic controller are introduced into motor drive control. The hybrid energy storage system is the promising method to improve the efficiency. The details are introduced in the following sections.

2.1 Introduction

With the rapid growth of population, the cities become more crowded. To achieve more efficient land usage, more high-rise and multi-story buildings appear in mega cities. According to the recent data and forecasts from U.S. Department of Energy (DOE), buildings, especially commercial buildings, are the largest energy consuming units in the modern world [4]. A promising way to control this continuously rising global energy consumption is to improve building energy utilization efficiency. To realize this, building distributed network (CBDN) has to meet the requirements which are explicitly described in following certain commanded references. Designing a proper building distributed network configuration and controller for each subsystem in CBDN configuration is therefore crucial and has in fact been a relevant topic for many microgrid applications.

Various microgrid configurations for building distributed networks have been proposed with each claiming some aspects of improvement. This chapter briefly reviews fundamental microgrid concepts and introduces the basic coordination control that is popular and relevant to the research contributions of this thesis. There are many power devices in the microgrid such as PV panels, motor drives and different types of energy storages. For each device controller, many references have proposed some improving techniques. Materials presented in the following sections in this chapter are therefore not exhaustive, but would definitely help with understanding of concepts proposed in the subsequent chapters.

2.2 Building Distributed Network

In this chapter, some basic concepts about smart building and microgrid are introduced before reviewing the existing control schemes for building distributed network. Understanding of these basic concepts helps greatly with control design targeted in building microgrid.

2.2.1 Conventional Building Distributed Network Configuration

In early times, buildings are considered as large loads which are connected to the utility grid. Accompanying the penetration of renewable energy sources, many renewable energy sources are connected into the building power system. The building distributed network becomes a microgrid which is a cluster of loads and micro sources operating as a single controllable system that provides both power and heat to its local area. The first generation building distributed network is based on the main AC bus which is connected to the utility grid. Hence, the first generation conventional building distributed network is an AC microgrid [5]. Fig. 2.1 shows the basic configuration of AC microgrid.

Figure 2.1 AC microgrid configuration.

Under AC topology, DC inherent renewable energy sources such as PV conversion systems are integrated to conventional AC systems through DC/DC/AC inverters. Moreover, continuously increasing DC loads requires AC/DC rectifiers for connection to AC grids. AC microgrids can control the active power through the demand reactive power, as well as supply the reliable power when the system is disconnected from the utility grid if utility grid faults occur [6] [7] [8] [9] [10] [11].

CBDN as shown in Fig. 2.2 is designed for easy connection of loads on AC sides. However, AC/DC rectifiers are required in CBDN for fundamental loads on DC sides. Motor-driving loads such as air conditioning and lift systems are connected to CBDN through AC/DC/AC converters. There are many hidden DC links as shown in Fig. 2.2. Among all loads, building's lift and air conditioning systems are critical and special loads because of their contribution to building's maximum power demand and energy consumption [12]. In CBDN, motors in lifts and some of air conditioning systems are connected to AC bus in parallel through AC/DC/AC converters and operate separately as shown in Fig. 2.2.

Figure 2.2 Conventional building distributed network.

With the development of renewable energy sources and electric vehicles (EVs) in recent years, building distribution network has become more complicated. In CBDN, power from rooftop PV systems is dumped to grid through DC/AC grid-tied inverters. Therefore, the same power from PV can only be used to supply local DC loads through another AC/DC converter. Battery energy storages are inherent DC loads. An AC/DC rectifier is required for EV connection to CBDN. In order to reduce the effect of intermittence and uncertainty of renewable power sources, energy storage systems are connected to CBDN through Bi-directional DC/AC Converters (BDAC).

Obviously, there are inherent multiple DC/AC and AC/DC reverse conversions in

CBDN, which result in additional power loss and cost from unnecessary converters. The recessive individual DC links in various converters make system control more complex. Many AC/DC converters and AC/DC inverters in CBDN can be eliminated. Therefore, a smart building microgrid is proposed in next section to reduce multiple reversion conversion, simplify network configuration and improve energy utilization efficiency.

Conversions between DC and AC devices in AC microgrid reduce system efficiency based on the nonlinear stability analysis in [13] [14]. DC microgrids are becoming more popular due to their higher efficiency and easier to be controlled than AC microgrids [15] [16]. DC microgrids predominately generate, distribute and use electrical energy in native DC form at low voltage. Moreover, DC microgrids are able to be connected to and operate in conjunction with AC power grids to form smart grids [17]. Based on this, DC microgrid is introduced into building distributed network. The DC microgrid configuration is represented in Fig. 2.3.

Figure 2.3 DC microgrid configuration.

Many research studied DC microgrid. In [18], a detailed description and analysis for a DC microgrid by using small signal model is introduced. However, multiple

reverse conversions for AC loads and sources still exist in DC microgrids. Two-DC bus topology was proposed for high efficient V2G applications [19]. In recent years, many rooftop PV systems have been installed in buildings around the world to harness energy. Different topologies of rooftop PV inverters are investigated in [20]. Power imbalanced operation is a common problem for CBDN. A detailed description about a comprehensive voltage imbalance sensitivity analysis and stochastic evaluation has been presented [21].

To overcome drawbacks of AC or DC building distribution network, the concept of hybrid microgrid is proposed. Typical hybrid microgrid is designed to operate in both grid-tied mode and autonomous mode [22] [23] [24] [25] [26] [27].

Figure 2.4 Hybrid microgrid configuration.

Hybrid microgrids combine the advantages in AC and DC microgrids and overcome the conversion inefficiency problem. In the future, hybrid microgrids will have wider applications. The proposed smart building hybrid microgrid configuration is designed based on the structure and operation of DC microgrid and hybrid microgrid.

2.2.2 Smart Building Definition and Building Attributes Classification

Smart building is a newly proposed concept. Building owners, designers, contractors and facility managers are all trying to build or renovate buildings identified as “smart” buildings. In general, smart buildings are innovative, with advanced technology and materials, contributing to reduced energy usage and the sustainability of the building, and providing more efficient and effective operation [28].

Although buildings are too complex and the features of a smart building are numerous, some attributes have to be considered in the building distributed network configuration to serve its purpose. In this thesis, various types of electrical devices are considered as the attributes in smart building. Table 2.1 shows the building attributes classification [29].

Table 2.1 Building attributes classification

Attributes	Description
Communication/Data Infrastructure	<i>Plug Load</i>
Network and Security	<i>Fundamental Load</i>
Digital Lighting Control System	<i>Fundamental Load</i>
Plumbing and Water	<i>Motor Load</i>
Access Control System (ACS)	<i>Plug Load</i>
Video Surveillance System	<i>Fundamental Load</i>
Fire Alarm	<i>Fundamental Load</i>
Audio/Visual	<i>Plug Load</i>
Metering	<i>Plug Load</i>
Occupant Satisfaction	<i>Plug Load</i>
Integrated Building Management System	<i>Fundamental Load</i>
Lifts	<i>Motor Load</i>
Air-Conditions	<i>Motor Load</i>

Building loads consist of three parts. One is the fundamental load such as lighting system or water pump, which consumes energy all the time during a day. The fundamental loads make building operate properly. Another one is the plug load, which is the electricity used for electrical appliances. This kind of loads satisfy the building's occupants everyday needs. Plug loads make up 20 - 30% of energy loads in commercial buildings [30]. The last one is the motor-driving loads. Motor drives are widely used in lifts, air-conditions and water pumps. In conventional building distributed network, motor drives are considered as large energy consumption units since the regenerated power from motors is usually burned by a resistance or sent back to the grid in CBDN. In the proposed smart building configuration which is introduced in the next chapter, the motor drive is considered as a partial-consuming load because of the re-usage or restoring of regenerative power.

2.3 Control Strategy of Building Distributed Network

Many techniques about microgrid and its components controller have been studied. The following sections concentrate on the basic and related control strategies of the same topic.

2.3.1 Control Strategy of Hybrid Microgrid

Microgrid controls require to integrate different technologies and control strategies of power electronics, telecommunications, distributed generators and distributed storages system together [31]. Many publications have discussed the control strategy in microgrids in both grid-tied mode and isolated mode.

In [32], a decentralized parallel inverter control is proposed for microgrid operation. The droop control is introduced into generators. The frequency is set by output active power. The magnitude of voltage is set by the reactive power. Therefore, distribution system is able to operate without PLLs. Moreover, load active and reactive powers can be shared according to the converter ratings. However, this

paper just assumes the distributed loads are dominantly inductive. The harmonic current of nonlinear load sharing strategy is discussed in [33]. Decentralized parallel inverter control is focus on the grid-tied mode.

In [34], the hierarchical control is proposed for microgrids, and can operate in both grid-tied mode and isolated mode. The hierarchical control consists of three levels. The primary control deals with the inner control of the DG units by adding virtual inertias and controlling their output impedances. This level is implemented by sensing the local variable. The control objectives are to share the total load, guarantee stability on DC or AC subgrid and actively damp oscillations between the output filters. The secondary control is conceived to restore the frequency and amplitude deviations produced by the virtual inertias and output virtual impedances. They are different measures and correspond with each other by the telecommunication in the whole grid. The tertiary control regulates the power flows between the grid and the microgrid at the point of common coupling (PCC). This level does the power balance in the whole grid and transfers the power automatically based on the load condition. Much research has been done focusing on the specific elements in microgrid, which is in the first and second level as described above. However, the coordination control of the whole grid is less complete in previous research. The coordination control of microgrids stabilizes the PCC voltages, determines the direction of power flow and manages the whole grid energy [35] [36] [37] [38] [39] [40].

Moreover, the solutions for energy efficiency improvement in hybrid microgrid are proposed in recent publications. In [41], a hierarchical power scheduling approach to manage the system power, which consists of user utility, transmission cost, grid load variance and to minimize the power generation and transmission cost. In [42], a load shifting demand side management technique is investigated to shift building loads in response to time of day tariff which is in turn, able to reduce peak energy in the existing distribution system. However, these existing publications do not consider the realistic device efforts like regenerative energy from motor drives in

building microgrid.

2.3.2 Control Strategy of Motor Drive

The motor control method is relatively mature. There are many types of motors used in building distributed networks. Most common type is induction motor. Reference [43] investigates motor with energy storage topology. The motor controller is designed based on the dual-loop control. Reference [44] investigates the field oriented control (FOC) and direct torque control (DTC) methods in detail. Comparing with the FOC control strategy, DTC has some advantages such as no current control loop, no need for coordinate transformation. These features make the controller respond fast. Since a lift moves up and down frequently, fast response is a basic requirement. The DTC method was implemented in [45]. Since the lift operating mode changes frequently, the proportional and integral gains of the controller have to be changed correspondingly for better performance. Fig. 2.5 represents the control block diagram for DTC.

In DTC controller, the stator flux controller imposes the time duration of the active voltage vectors, which move the stator flux along the reference trajectory, and the torque controller determines the time duration of the zero voltage vectors, which keep the motor torque in the defined- by-hysteresis tolerance band. At every sampling time the voltage vector selection block chooses the inverter switching state (S_a , S_b , S_c), which reduces the instantaneous flux and torque errors.

The energy regenerated from motors was proposed to reduce energy consumption [46]. Some techniques are introduced for energy regeneration. The authors in [47] propose a novel feedback topology for a single lift system. The regenerated power is fed back to utility grid with near-unity power factor and low harmonic distortion. Nevertheless, the AC/DC/AC reverse conversion in the proposed technique causes additional power loss. The second solution is to use energy storage in each lift motor system [48]. The existing techniques mainly focus on elimination of power

peak and sizing of super capacitors to compensate rated power for a single lift [49]. However, when lift motors are operating in different modes, the direct power exchange among the two or more lifts are not considered. Different motor operation modes affect the building distributed network operation.

Figure 2.5 Control block diagram of DTC.

In the regenerative braking control strategy, the most important variable is braking torque. [50] proposed an optimal torque determination. A mathematical model of rotor is represented as:

$$T_e = J\dot{\omega}_r + D\omega_r \quad (2.1)$$

In which T_e is torque; J is inertia of rotor; D is damping coefficient; ω_r is rotor angular speed. T_e is determined by the motor operation condition. T_e is positive for motor acceleration. T_e is negative because of power regeneration.

Since the iron loss is too small, the induction motor interior power loss is the sum of rotor and stator copper loss. The interior power loss is described as:

$$P_{loss} = \frac{R_s}{L_m^2} \varphi_r^2 + \left(\frac{R_s L_r^2}{L_m^2} + R_r \right) \frac{T_e^2}{p^2 \varphi_r^2} \quad (2.2)$$

where R_s and R_r represent the stator and rotor resistance respectively; L_m is the mutual inductance; L_r is rotor inductance; φ_r is rotor flux; p is pole number. From the control strategy described in chapter 5.2, φ_r is constant by the control. Hence, P_{loss} is a function with one variable T_e .

The output power of induction motor as generator is represented as:

$$P_{out} = -\omega_r T_e \quad (2.3)$$

The regeneration power is derived as:

$$P_{regen} = P_{out} - P_{loss} \quad (2.4)$$

The P_{regen} is derived as:

$$P_{regen} = -\left(\frac{R_s L_r^2}{L_m^2} + R_r \right) \frac{J^2 \dot{\omega}_r^2}{p^2 \varphi_r^2} - \left[1 + \left(\frac{R_s L_r^2}{L_m^2} + R_r \right) \frac{2D}{p^2 \varphi_r^2} \right] J \dot{\omega}_r \omega_r - \left[1 + \left(\frac{R_s L_r^2}{L_m^2} + R_r \right) \frac{D}{p^2 \varphi_r^2} \right] D \omega_r^2 - \frac{R_s}{L_m^2} \varphi_r^2 \quad (2.5)$$

Assuming that the motor operates on the generator condition in the time interval $[t_0 \ t_1]$, the integrated regeneration work in the time interval is derived from P_{regen} as:

$$W_{regen} = \int_{t_0}^{t_1} P_{regen} dt \quad (2.6)$$

If W_{regen} has extremum value, it means that regeneration power is at appropriate point. Since W_{regen} depends on ω_r and $\dot{\omega}_r$, the behaviour of ω_r is derived by using

calculus of variations. The optimal torque can be obtained from the behaviour of ω_r and T_e . Equation of P_{regen} is differentiated partially with respect to ω_r and $\dot{\omega}_r$, the equations change to follow equations:

$$\begin{cases} \frac{\partial P_{regen}}{\partial \dot{\omega}_r} = -2 \left(\frac{R_s L_r^2}{L_m^2} + R_r \right) \frac{J^2 \dot{\omega}_r^2}{p^2 \varphi_r^2} - \left[1 + \left(\frac{R_s L_r^2}{L_m^2} + R_r \right) \frac{2D}{p^2 \varphi_r^2} \right] J \omega_r \\ \frac{\partial P_{regen}}{\partial \omega_r} = - \left[1 + \left(\frac{R_s L_r^2}{L_m^2} + R_r \right) \frac{2D}{p^2 \varphi_r^2} \right] D \omega_r - 2 \left[1 + \left(\frac{R_s L_r^2}{L_m^2} + R_r \right) \frac{D}{p^2 \varphi_r^2} \right] D \omega_r \end{cases} \quad (2.7)$$

The Euler's equation:

$$\frac{d}{dt} \left(\frac{\partial P_{regen}}{\partial \dot{\omega}_r} \right) = \frac{\partial P_{regen}}{\partial \omega_r} \quad (2.8)$$

The complete form of equation is:

$$- \left(\frac{R_s L_r^2}{L_m^2} + R_r \right) \frac{J^2}{p^2 \varphi_r^2} \ddot{\omega}_r + \left[1 + \left(\frac{R_s L_r^2}{L_m^2} + R_r \right) \frac{D}{p^2 \varphi_r^2} \right] D \omega_r = 0 \quad (2.9)$$

If W_{regen} has extremum value, ω_r is represented as:

$$\omega_r = \alpha \exp \left(- \sqrt{\frac{D}{J^2} \left(D + \frac{p^2 \varphi_r^2 L_m^2}{R_s L_r^2 + R_r L_m^2} \right)} t \right) + \beta \exp \left(\sqrt{\frac{D}{J^2} \left(D + \frac{p^2 \varphi_r^2 L_m^2}{R_s L_r^2 + R_r L_m^2} \right)} t \right) \quad (2.10)$$

The optimal torque T_e is derived from ω_r .

$$\begin{aligned} T_e = & \left(-J \sqrt{\frac{D}{J^2} \left(D + \frac{p^2 \varphi_r^2 L_m^2}{R_s L_r^2 + R_r L_m^2} \right)} + D \right) \alpha \exp \left(- \sqrt{\frac{D}{J^2} \left(D + \frac{p^2 \varphi_r^2 L_m^2}{R_s L_r^2 + R_r L_m^2} \right)} t \right) + \\ & \left(J \sqrt{\frac{D}{J^2} \left(D + \frac{p^2 \varphi_r^2 L_m^2}{R_s L_r^2 + R_r L_m^2} \right)} + D \right) \beta \exp \left(\sqrt{\frac{D}{J^2} \left(D + \frac{p^2 \varphi_r^2 L_m^2}{R_s L_r^2 + R_r L_m^2} \right)} t \right) \end{aligned} \quad (2.11)$$

where α and β are coefficients from following equations.

$$\begin{cases} \omega_0 = \alpha \exp \left(- \sqrt{\frac{D}{J^2} \left(D + \frac{p^2 \varphi_r^2 L_m^2}{R_s L_r^2 + R_r L_m^2} \right)} t_0 \right) + \beta \exp \left(\sqrt{\frac{D}{J^2} \left(D + \frac{p^2 \varphi_r^2 L_m^2}{R_s L_r^2 + R_r L_m^2} \right)} t_0 \right) \\ \omega_1 = \alpha \exp \left(- \sqrt{\frac{D}{J^2} \left(D + \frac{p^2 \varphi_r^2 L_m^2}{R_s L_r^2 + R_r L_m^2} \right)} t_1 \right) + \beta \exp \left(\sqrt{\frac{D}{J^2} \left(D + \frac{p^2 \varphi_r^2 L_m^2}{R_s L_r^2 + R_r L_m^2} \right)} t_1 \right) \end{cases} \quad (2.12)$$

where ω_0 is rotor speed at t_0 ; ω_1 is rotor speed at t_1 ; $[t_0 \ t_1]$ is time interval when the motor is working on the generator mode.

From the above analysis, the optimal torque T_e or optimal rotor speed ω_r for the regeneration is obtained from ω_0 , ω_1 , t_0 and t_1 . The optimal torque is used in the lift motor controller.

Fuzzy controller is used to optimize lift operation and improve the lift motor performance. Fuzzy logic is an approach of computation based on ‘degrees of truth’ rather than the usual ‘true or false’ (1 or 0) Boolean logic on which the modern computer is based. The fuzzy logic is based on the implementation of human understanding and human thinking in control algorithms, which is able to improve the response speed even if the system is complex. In recent publications, fuzzy controller is introduced into optimal operation of lift system. A general method for minimizing passenger waiting time within a reasonable limit has been proposed [51]. The fuzzy logic algorithm has been implemented in the optimization. A fuzzy BP neural network for multiple elevator operation is introduced to further improve the performance of lift system [52]. However, the input data such as the average waiting time, power consumption, and floor traffic, etc. are not online data which cannot be sensed and used directly. The lift operating optimization is usually controlled by a central controller.

2.3.3 Control Strategy of Energy Storage

Hybrid energy storage system is constituted of super capacitors and batteries as the core and the auxiliary storage system respectively since supercapacitors are of high power density, with long servicing life and small size, light weight energy storage units [53] [54] [55].

The existing studies about hybrid energy storages mainly focus on the specific use and its controller. Hybrid energy system is widely used in Wind-PV system. Study [56] gives detailed description of controller which can avoid the possibility of overcharging and discharging of battery. The current control is used for supercapacitor in this energy storage system. However, the controller in this

publication has not done the power sharing between the energy storages. Study [57] introduces an adaptive droop control which has a fast transient response for close-loop system and ensures the optimal operation of voltage source inverter. The other application of a hybrid energy storage system for grid connected and standalone wind energy application is given in [58] and [59].

These literatures particularly focus on the performance of the hybrid energy storage system rather than considering the system level investigations. Moreover, the application of hybrid energy storage system in building microgrid has received little research attention. The other aspect which attracts researchers is how to prolong the battery life in hybrid energy storage system. The common method is to sort out high and low frequency variations and reduce the battery operating time. Authors in [60] explained the method which could sort out the high and low frequency variations. The common method is to use wavelet analyses. However, a central controller is requested for frequency separation. Another method mentioned in [61] is using high and low pass filter to do the net power decomposition. This method could separate frequencies in distributed controller, but cannot enhance the damping of microgrids nor guarantee the stable operation. In this paper, coordination control of hybrid energy storage system is proposed to determine an activate sequence of battery and supercapacitor based on the system variations and it is able to prolong the battery life as well.

2.3.4 Control Strategy of Power Factor Correction

AC/DC converter is one of the most common power conversion systems and can be found in many industrial as well as residential applications, for example, variable speed drive, electric vehicle chargers, and power supplies for consumer electronics. In order to meet the ever more stringent grid codes like the IEC61000-3-2 harmonic limits, high-power factor and sinusoidal current regulation are required for basically all such applications as long as their power ratings exceed 75 W [62].

Presently, single-phase power factor correction (PFC) converter is a very popular solution to ensure the compliance of such regulations because of its simplicity, cost effectiveness, and good current shaping capability. However, most of the existing single-phase PFC converters are of boost type and can only provide an output voltage that is higher than the peak voltage of the ac input [63] [64] [65] [66] [67]. Wide range of output voltage is indeed desired in some applications like plug-in hybrid electric vehicle (PHEV) charging systems where the terminal voltage of battery packs may vary between 100 V and 600 V [68], depending on their configuration and state-of-charge. In this case, a second stage DC/DC buck converter has to be implemented to further step down the PFC output voltage, which undoubtedly decreases the overall system efficiency.

In order to provide flexible DC output voltages, PFC converters with buck–boost capabilities have been studied in past literatures and they are usually based on buck–boost, fly back, Cuk, and single-ended primary inductance converter (SEPIC) topologies, and can be derived in both non-isolated and isolated versions [69] [70] [71] [72] [73]. A common problem for these topologies is that there is no direct energy transfer path during power conversion and all input power must be processed by active switches and stored by intermediate passive components (either inductors or capacitors) before being supplied to the end loads [74].

This indicates that the components will be working under increased voltage/current stresses, which may consequently lead to decreased power density and conversion efficiency. In order to improve the performance of Cuk and SEPIC-based PFC topologies, their bridgeless variants have recently been proposed in [75] [76] [77] [78] with most of them being operated in discontinuous conduction mode (DCM). In this case, the PFC converter can be constructed with less semiconductor switches and the on-state conduction losses can be reduced. The switching losses are reduced as well due to their DCM operation. However, the main power switches in these bridgeless topologies are still under high-voltage stress and the DCM operation also

implies that they are only suitable for relatively low-power applications because of the high peak current in the boost inductor.

In view of this, AC/DC converters with direct buck capability are highly desirable in high-power PHEV battery charger applications and a buck-type PFC topology, named as Swiss Rectifier which has already been proposed in [79] and [80] for three phase AC/DC systems. For single-phase AC/DC rectifiers, a lot of researches have been recently carried out to study the performance and operation of a buck-topology-based PFC converter [81] [82] [83] [84] [85] [86], which can produce a lower output DC voltage and meanwhile maintain high efficiency under universal line voltage. The bridgeless derivative of the buck PFC was also proposed in [87] to further improve its conversion efficiency.

Unfortunately, such buck PFC converters may be inherently subject to a so-called “dead angle” limitation when the input voltage is lower than the output voltage. The AC side input current cannot be regulated to be purely sinusoidal and unity power factor is not achievable. An improved buck PFC converter with high-power factor is proposed in [88], where an auxiliary switch and two diodes are added in the circuit to provide current regulation during the “dead angle” period. Although the power factor can be improved, the input current waveform is still not sinusoidal and therefore, they may only be suited for low-power applications (less than 1 kW), such as laptop adapter and TV sets power supplies. Another buck PFC converter with power decoupling capability has recently been proposed in [89], and it features high-quality input current as well as ripple free output voltage.

However, the limitation of this topology is that, its output voltage must be lower than half of the peak AC input voltage, and this may largely constrain the output voltage range during low-line operation. Some integrated bidirectional AC/DC and DC/DC converter topologies were proposed in [90], [91], which combines all necessary operation modes that are required for the power converter of PHEVs, namely plug-in charging from power grid, vehicle-to-grid discharge, pumping

power to drive electric motor, and regenerative braking. Despite its powerful functionalities, these converters involve a number of semiconductor devices, and therefore, it may not be an efficiency optimized and cost-effective solution.

2.4 Summary

This chapter reviews some of the existing building distributed networks and their controller. Conventional building distributed network is based on AC microgrid. Environmental incentives, local customer demand and economic are changing the system of electricity generation and transmission from the AC power grids to microgrids. Buildings have to meet the smart building requirements. Although buildings are too complex and the features of a smart building are too numerous, some attributes have to be considered in the building distributed network configuration to achieve these objectives. The essential components in smart building such as motor drives and energy storages and their controller are reviewed as well. DTC and fuzzy logic controller are introduced into motor drive controller. Hybrid energy storage is the promising method to increase the efficiency. To a great extent, a smart building hybrid microgrid configuration and its coordination control is investigated in chapter 3 based on the fundamental studies review in this chapter.

Chapter 3

A Smart Building Hybrid Microgrid for Energy Efficiency Improvement

A novel building AC/DC hybrid microgrid (BHMg) is proposed in this chapter. A building photovoltaic system (BPVS), a building motor drive system (BMDS) and a hybrid building energy storage system (HBES) are introduced respectively based on the common features of PV systems, motor driving circuits and various energy storages. The objective of the BHMg is to improve building energy efficiency through reducing multiple reverse conversion loss in conventional building distributed networks (CBDN), to achieve efficient connection of subsystems, and to reduce building energy consumption and peak power demand through power generation from BPVS and power regeneration in BMDS. A common DC bus (CDCB) and a low voltage DC bus (LDCB) are proposed to reduce inefficiency from multiple reverse conversions and to realize direct power exchange between power regeneration and consumption in CBDN. A HBES, which adopts the advantages of different energy storages, is proposed to mitigate system operating problems. Smart distributed control is implemented for coordinating the operation of BMDS, BPVS and HBES. The proposed BHMg structure is verified through simulations.

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3.1 Introduction

According to the recent data and forecasts from U.S. Department of Energy (DOE), buildings, especially commercial buildings, are the largest energy consuming units in the modern world. A promising way to control continuously rising global energy consumption is to increase building energy utilization efficiency. Microgrid is an appropriate infrastructure for improving building energy efficiency [92]. The common features of loads and distributed generations in CBDN have been investigated in chapter 2. The obvious disadvantages of the conventional building power grid are large maximum load demand and high multiple reverse conversion loss.

In this chapter, the improved building hybrid microgrid configuration and its distributed control are introduced. The contribution of the current study contains two aspects. A novel hybrid AC/DC building microgrid (BHMg) configuration is proposed for improving the building energy efficiency and reducing the building energy consumption and maximum load demand. The BHMg is a three-bus three-subsystem configuration which integrates a building photovoltaic system (BPVS), a hybrid building energy storage system (HBES) and a building motor drive system (BMDS) together. A common DC bus (CDCB) and a low voltage DC bus (LDCB) are proposed to reduce efficiency loss from multiple reverse conversions such as DC/AC/DC and AC/DC/AC in CBDN, to realize direct power exchange between generation (or regeneration) and consumption, and to eliminate parts of hardware such as rectifier in many loads. The voltage of CDCB is a good indication of system power balance between AC and DC subgrids. High and Low frequency components are used for triggering the operation of supercapacitor and battery. The HBES is proposed to eliminate the disadvantages of different energy storages to mitigate different system problems. The other aspect is the smart distributed control for the BHMg. Smart distributed control is implemented for coordination control to maintain the reliable and stable operation of BHMg under variable sources and loads conditions.

3.2 Smart Building Hybrid Microgrid Architecture

The proposed smart building hybrid microgrid architecture is shown in Fig. 3. 1.

Figure 3.1 Smart building hybrid microgrid architecture.

A two-level DC network is proposed for easy and efficient integration of various DC links which exist in the motor driving circuits, energy storages, loads and PV systems of the CBDN. CDCB is proposed for the connection of all motors through DC/AC converters, which eliminates the AC/DC rectifiers of motor driving circuits in CBDN. Energy storage systems can also be connected to the CDCB through DC/DC converters to replace the more complicated AC/DC/DC converters in CBDN. The voltage level for the CDCB is selected based on the voltage of the hidden DC links in lift and air conditioning systems. In a CBDN, PV systems and DC energy storages and electric vehicles are connected to AC network through various DC/AC inverters. In such connection, PV panels or battery cells are connected in series or through DC/DC booster in order to achieve the required minimum DC voltage for efficient connection to AC network. LDCB is proposed for BPVS and low voltage DC loads, which can further reduce multiple DC/DC/DC conversion due to direct power exchange between PV systems and DC loads. The voltage level for the LDCB is selected based on easy connection of DC loads and

PV systems. A common BDAC is proposed for power exchange between DC and AC bus to eliminate AC/DC rectifiers for individual loads in CBDN. A common bidirectional DC/DC converter (BDCC) is proposed between CDCB and LDCB to reduce the boost ratio of individual DC/DC converters. Three sub-systems are proposed for the high efficient connection of motors, energy storages and PV panels.

In CBDN, each motor is controlled individually no matter it is in motor driving mode (MDM) or regenerative braking mode (RBM). The regenerated power is usually burned by a resistance or sent back to the grid in CBDN. In BHMg, the BMDS connected CDCB is proposed in this chapter. The CDCB integrates all the DC links in the BMDS for direct power exchange among motors operating in different modes. Hence, the energy consumption of the BMDS and maximum demand are reduced.

BPVS is connected to LDCB to directly supply some of DC loads to further reduce DC/DC conversions. To avoid the complexity of power management and enforce coincident control strategy to distributed storages, the HBES connected to the CDCB is proposed to operate as a common energy buffer. The HBES with different power and energy density can be controlled coordinately to compensate low and high frequency voltage variations. Supercapacitors are used to provide high power density to reduce the short time maximum demand when motors in BMDS change the operation mode. Supercapacitor capacity is determined by motor drive system and derived by $W_{regen} = \sum P_{regem}$, where motor regenerative power is derived as

$$P_{regen} = -\left(\frac{R_s L_r^2}{L_m^2} + R_r\right) \frac{J^2 \dot{\omega}_r^2}{p^2 \phi_r^2} - \left[1 + \left(\frac{R_s L_r^2}{L_m^2} + R_r\right) \frac{2D}{p^2 \phi_r^2}\right] J \dot{\omega}_r \omega_r - \left[1 + \left(\frac{R_s L_r^2}{L_m^2} + R_r\right) \frac{D}{p^2 \phi_r^2}\right] D \omega_r^2 - \frac{R_s}{L_m} \phi_r^2 \quad (3.1)$$

R_s and R_r represents the stator and rotor resistance respectively; L_m is the mutual inductance; L_r is rotor inductance; ϕ_r is rotor flux; p is pole number; J is inertia of rotor; D is damping coefficient; ω_r is rotor angular speed.

Batteries are used to store regenerative energy from BMDS and energy surplus from BPVS during peak solar duration and low load demand. The HBES direct connection to the CDCB makes it easy for power exchange among BPVS, BMDS and HBES. The total hybrid energy storage system size is determined according to the value for 5 days of autonomy days building energy consumption data. The total capacity of HBES is bounded by

$$0 \leq E_{HBES} \leq \frac{5 * E_{day}}{DOD * \eta_b} \quad (3.2)$$

where E_{HBES} is capacity of HBES, E_{day} is maximum energy consumption of single day, η_b is the conversion efficiency and we assume the efficiency is 95% [93].

There are four advantages from this new configuration. First, instantaneous power generated from lifts and air condition motors in RBM can be instantly observed by other motors operating in MDM. Therefore, the size of energy storage rating is reduced. The second advantage is that CDCB eliminates AC/DC conversion stage for all motor-driven converters. Only DC/AC converters are required for the motors in lifts and air conditioners. The size of the equipment will be reduced. The control and operation of motors becomes easy. The third advantage is that two-level DC network is more efficient because of the boost ratio of DC/DC converter is reduced for PV connections and low voltage DC loads can consume partial energy locally. The novel architecture also provides the opportunity of V2G application of EVs as building energy storage. Finally, the system maximum demand is reduced. There are two approaches to reduce the maximum demand. One is to reduce the types of loads. In CBDN, the maximum load demand consists of fundamental loads, plug loads and motor drives in the building. Motor drives for lifts and air conditioners are used to have as large electrical demands. In BHMG, the BMDS integrated all motor drives and the regenerative energy of motors are reused and stored in HBES. Hence, the BMDS is able to operate individually by using the regenerative energy. In BHMG, the maximum demand only consists of fundamental loads and plug loads. The other one is the design of the HBES and the CDCB which is able to directly

exchange power among BPVS, BMDS and HBES. The frequency of power exchange between BHMg and utility grid is reduced.

3.3 Operation and Control of each subsystem in BHMg

Building hybrid microgrid contains BPVD, BMDS, and HBES. Each subsystem has individual operation and control strategy.

3.3.1 Operation and Control of Building Motor Drive System (BMDS)

The operation and control of the multiple motors can be classified into three operating modes as shown in Fig. 3.2, where two parallel motors are used as an example.

Figure 3.2 Building motor drive system operating modes.

When two motors are operating in MDM, power is supplied from utility grid, HBES or BPVS. When two motors are operating in RBM, the regenerated energy can be consumed by local loads, stored in HBES or sent back to the grid. When two motors are operating in different modes, the regenerated power from one motor can be directly used by others through the CDCB. The control objectives are to maximize the regenerative power during regenerative braking and to share the power among different operating mode motors. Since lift and air-condition motors change

operating mode frequently, the motor control should meet the requirement of fast response [94]. The direct torque control (DTC) is applied to motors [95]. Compared with other induction motor control, DTC provides a fast torque response without the field oriental block or inner current loop. Because motor is directly connected to DC bus, the impact on DC bus voltage should be considered during mode switching.

3.3.2 Operation and Control of Hybrid Building Energy Storage System (HBES)

The HBES consists of battery storages and super capacitors (SUPCAP). The SUPCAP is controlled to mitigate high frequency DC bus voltage variation due to fast renewable source variation and motor mode switching as shown in Fig. 3.3.

Figure 3.3 Control block diagram of the HBES.

A SOC detection block is used for checking the battery or supercapacitor's SOC range. In the block, the horizontal axis is SOC and vertical axis is the output value. The bounds of SOC are set between 20% and 80% by considering the limited life cycle of the storage system and degradation costs. Low frequency variation of bus voltage due to inadequate power supply and power surplus is compensated through

the charging and discharging of battery storage system. High and low frequency components of DC bus voltage variation are decoupled by the wavelet analysis [96].

Wavelet analysis is used for decomposing HF and LF DC link voltage ripple. The DC link voltage ripple can be expressed as:

$$V_{ripple} = \frac{V_0 - V_{iSUP}}{R_{L_{SUP}} C f} + \frac{V_0 - V_{iBS}}{R_{L_{BS}} C f} \quad (3.3)$$

where C is the DC link capacitor; f is the ripple frequency; V_0 is the DC link voltage; V_{iSUP} is the supercapacitor terminal voltage; V_{iBS} is the battery terminal voltage.

The ripple is the input of wavelet analysis block. The output of wavelet analysis block can be expressed as:

$$V_{L \& H} = \frac{1}{\sqrt{b}} \int_0^\infty \int_0^\infty \left(\frac{V_0 - V_{iSUP}}{R_{L_{SUP}} C f} + \frac{V_0 - V_{iBS}}{R_{L_{BS}} C f} \right) \varphi \left(\frac{t-a}{b} \right) dt \quad (3.4)$$

where a is positive and defines the scale and b is any real number and defines the shift. HF and LF ripples are decomposed by defining the a and b.

3.3.3 Operation and Control of Building Photovoltaic System (BPVS)

The objective of BPVS is to harness the maximum power from sun. The control strategy of BPVS converter is to track the maximum power point through regulating the PV output voltage. The improved P&O algorithm with variable step has been implemented in [97] for the maximum power point tracking (MPPT).

3.4 Coordination Control of BHMg

The main objectives of the BHMg operation and control are to maintain stable AC/DC bus voltage, reduce building maximum demand and to achieve efficient power utilization through minimizing DC/AC/DC and AC/DC/AC reverse conversions. The coordination of different inverters and converters and the bidirectional AC/DC converter plays an important role for stabilizing system

operation. Distributed control of individual converters is adopted to achieve the defined control objectives. The BPVS is controlled to always operate in the MPPT mode to harness the maximum energy from renewable sources. Motors in the BMDS can operate either in the motor driving mode or in the regenerative braking mode. The HBES is the core subsystem to be managed for reducing maximum load demand and improving the system energy efficiency.

Figure 3.4 The schematic diagram of the compact BHMg.

When all subsystems are connected together, energy flow among them must autonomously be managed to retain their overall high efficiency and reliability. The bi-directional AC/DC converter is critical to manage power transfer between AC and DC networks, which can be controlled to operate in any of the three modes: Mode 0 with zero power transfer between AC and DC; Mode 1 with power transfer from AC to DC; Mode 2 with power transfer from DC to AC. The amount of power

transferred between DC and AC sides are based on the SOC of the BHES and the net power mismatch P_m between power generation and demand in DC side as

$$P_m = P_{BPVS} + P_{BMDS} - P_{LDC} \quad (3.5)$$

where P_{BPVS} is the BPVS output power, P_{BMDS} is the BMDS output power, and P_{LDC} is the total power of DC loads. If $P_m = 0$, bi-directional AC/DC converter operates on mode 0; $P_m < 0$, bi-directional AC/DC converter operates on mode 1; $P_m > 0$, bi-directional AC/DC converter operates on mode 2.

A compact BHMg, which consists of a BPVS, BHES and a two-motor BMDS as shown in Fig. 3.4, is used to illustrate the mode switching and control of converters in a BHMg. The droop control is introduced to achieve the BHMg coordination control.

3.4.1 Mode 0

When there is sufficient power from the BPVS and the HBES to supply DC demand, the bidirectional AC/DC converter is not activated. The DC and AC networks operate independently. In this case, the utility grid maintains AC bus voltage and supplies AC loads.

Figure 3.5 DC side droop characteristic: (a) common DC bus droop characteristic; (b) low voltage DC bus droop characteristic; (c) nominal droop characteristic.

The HBES converter operates in the voltage control mode to maintain voltage V_{DH} of the common DC bus. The bidirectional DC/DC converter is controlled to maintain the voltage V_{DL} of the low voltage DC bus through controlling the power flow between two DC buses. The power flow direction and amount through bidirectional DC/DC converter can be determined by common DC bus and low voltage DC bus droop characteristic. Fig. 3.5 shows the droop characteristic in DC side.

Fig. 3.5. (a) represents common DC bus droop characteristic and it is derived as:

$$V_{DH} = V_{DH_n} + d_{DH} \cdot P_{DH} \quad (3.6)$$

where V_{DH_n} is reference common DC bus voltage; d_{DH} is droop coefficient; P_{DH} is required power at common DC bus.

Fig. 3.5. (b) represents low voltage DC bus droop characteristic and it is derived as:

$$V_{DL} = V_{DL_n} + d_{DL} \cdot P_{DL} \quad (3.7)$$

where V_{DL_n} is reference common DC bus voltage; d_{DL} is droop coefficient; P_{DL} is required power at low voltage DC bus.

Figure 3.6 Control block diagram of bidirectional DC/DC converter for mode 0.

In order to obtain the combine droop expression of common DC bus and low voltage DC bus, a normalization method is used to merge the two variables V_{DH} and V_{DL} in (3.6) and (3.7) into a same dimension.

$$\begin{cases} (V_{DH})' = 1 + \frac{d_{DH}}{0.5(V_{DH_max} - V_{DH_min})} \cdot P_{DH} \\ (V_{DL})' = 1 + \frac{d_{DL}}{0.5(V_{DL_max} - V_{DL_min})} \cdot P_{DL} \end{cases} \quad (3.8)$$

By equation (4), the normalized value can be placed in the same frame of reference with common vertical and horizontal axis as shown in Fig. 3.5. (c). Realization of power flow between common DC bus and low voltage DC bus can then be inferred by equalizing and through a PI controller.

$$P_{DH-DL} = [(V_{DH})' - (V_{DL})'] (k_p + \frac{k_i}{s}) \quad (3.9)$$

where P_{DH-DL} is power flows on bidirectional DC/DC converter. The control block diagram is shown in Fig. 3.6.

3.4.2 Mode 1

The BHMG operates in the power transfer modes when there is power surplus or inadequate power supply under different load and resource conditions. The BMDS at different modes require different active power and reactive power that affect the power transfer direction between AC and DC sides. Since utility grid is connected to AC bus, the AC side can be considered as an ideal source. The power flow direction and amount are determined by DC side droop characteristic. DC side droop characteristic integrates common DC bus droop characteristic and low voltage DC bus droop characteristic. Fig. 3.7 shows the DC side characteristic.

The droop equation is developed as:

$$V_{DH} = V_{DH_n} + D \cdot P_{DC_AC} \quad (3.10)$$

$$D = 1 / \left(\frac{1}{d_{DH}} + \frac{1}{d_{DL}} \right) \quad (3.11)$$

Figure 3.7 DC side droop characteristic when there is power transfer between AC and DC sides.

When there is inadequate power supply from DC sources and the BHES is at the minimum SOC, the bidirectional AC/DC converter operates in the rectifier mode to partially or fully supply the DC loads and to maintain common DC bus voltage. The active power is transferred from AC to DC. The operating point in Fig. 3.7 is in the first phase (left). The low voltage DC bus is controlled by bidirectional DC/DC converter and the common DC bus voltage is controlled by bidirectional AC/DC converter. The control block diagram is shown in Fig. 3.8.

Figure 3.8 Control block diagram of bidirectional DC/DC converter for mode 1 & 2.

The bidirectional AC/DC converter control provides a smooth power exchange. Power control is implemented by droop calculation and a PI controller for bidirectional AC/DC converter to determine real power from AC to DC. Active power change in common DC bus causes short time voltage fluctuation. The HBES is operating to maintain common DC bus voltage.

3.4.3 Mode 2

When there is power surplus from DC side and the BHES is fully charged, the bidirectional AC/DC converter is controlled to transfer power from DC to AC side. In this case, the bi-directional AC/DC is activated to maintain the voltage of the AC bus. The bi-directional DC/DC converter is used to maintain the voltage V_{DL} of the low voltage DC bus. The HBES converter is controlled to maintain a stable voltage V_{DH} of the common DC bus. The operating point in Fig. 3.7 is in the second phase (right). The control block diagram is as same as Fig. 3.8. The common DC bus voltage is controlled by charging and discharging of HBES.

3.5 Transit Analysis during Different Operation Modes

3.5.1 Mode 0

The time average equivalent circuit model of the converters in DC network is shown in Fig. 3.9 and the control block diagram is shown in Fig. 3.10.

Figure 3.9 Time average model of the converters for the idle mode.

The BDCC controls the power flow between the CDCB and LDCB. If the power from the BPVS is larger than the total load in the LDCB, the BDCC operates in the booster mode to transfer power from LDCB to CDCB. Otherwise, the BDCC operates in the buck mode to transfer power in opposite direction.

Figure 3.10 Control block diagram of the converter and BDCC in the idle mode.

LDCB voltage is controlled by the BDCC. The CDCB voltage V_E is regulated by the HBES converter. The differential equations for control and operation of BPVS are as

$$\begin{cases} V_s = (1 - d_1)V_{DC} + L_1 \frac{di_1}{dt} + R_1 i_1 \\ i_s = i_1 + C_1 \frac{dV_s}{dt} \\ (1 - d_1)i_1 = C_2 \frac{dV_{DC}}{dt} + \frac{V_{DC}}{Z_{DC}} + i_2 \end{cases} \quad (3.12)$$

where d_1 is the duty ratio of the PV converter, Z_{DC} is impedance of DC loads, V_s is PV output voltage, V_{DC} is LDCB voltage, i_1 is the input current of the BPVS converter, i_2 is the input current of the BDCC, R_1 and L_1 are the resistance and inductance of the BPVS converter respectively, and C_2 is the equivalent capacitance of LDCB.

The differential equations for control and operation of BDCC are as

$$\begin{cases} V_{DC} = (1-d_2)V_E + L_2 \frac{di_2}{dt} + R_2 i_2 \\ i_2 = (1-d_1)i_1 - C_2 \frac{dV_{DC}}{dt} + \frac{V_{DC}}{Z_{DC}} \\ (1-d_2)i_2 = C_3 \frac{dV_E}{dt} + \frac{V_E}{Z_E} + i_{ES} \end{cases} \quad (3.13)$$

where d_2 is the duty ratio of BDCC, V_E is the voltage of the CDCB, Z_E is the equivalent impedance of BMDS, i_{ES} is HBES current, L_2 is the inductance of the BDCC, R_2 is resistance of the BDCC, and C_3 is the capacitance of the CDCB.

3.5.2 Mode 1

When there is inadequate power supply from DC sources and the HBES is at the minimum SOC, the BDAC operates in the rectifier mode to partially or fully supply the DC loads and to maintain CDCB voltage. The active power is transferred from AC to DC. The time average equivalent circuit model is shown in Fig. 3.11.

Figure 3.11 Time average model of the converters for the mode 1.

The LDCB is controlled by BDCC and the CDCB voltage is controlled by BDAC. The differential equations of BPVS and BDCC are the same as (3.12) and (3.13).

The differential equations for control and operation of the bidirectional AC/DC converter in the d-q coordinates are as

$$\begin{cases} d_{3d}V_E = V_d + L_3 \frac{di_d}{dt} + R_3 i_d - \omega L_3 i_q \\ d_{3q}V_E = V_q + L_3 \frac{di_q}{dt} + R_3 i_q + \omega L_3 i_d \end{cases} \quad (3.14)$$

where d_{3d} and d_{3q} are the duty ratio of the BDAC in d-q coordinates respectively, V_d and V_q are the AC bus voltage in d-q coordinates respectively; i_d and i_q are current in d-q coordinates respectively.

The control block diagram of the BDCC and BDAC based on the time average equivalent circuit model is shown in Fig. 3.12.

Figure 3.12 Control block diagram of the converter and BDCC in mode 1.

These two converters provide a smooth power exchange. The power flow direction is determined by ε . Power control is implemented by two PI controllers for the BDAC to determine real power from AC to DC. Active power change in CDCB causes voltage fluctuation. The active power transferred from AC to DC if the ε is positive. In the BDAC power controller, the magnitude of i_d^* changes following the changing of ε . In the inner current loop, i_d is tuned by regulating i_d^* .

3.5.3 Mode 2

When there is power surplus from DC side and the HBES is fully charged, the BDAC is controlled to transfer power from DC to AC side. In this case, the BDAC transfers power from DC to AC and to maintain the voltage of the AC bus. BDCC maintains LDCB voltage. The time average equivalent circuit is shown in Fig. 3.13.

Figure 3.13 Time average model of the converters for the mode 2.

The HBES converter is controlled to maintain a stable CDCB voltage. The LDCB voltage is controlled by BDCC. The differential equations for control and operation of HBES are as

$$\begin{cases} d_4 V_E = V_{ES} + L_4 \frac{di_{ES}}{dt} + R_4 i_{ES} \\ d_4 i_{ES} = (1 - d_2) i_2 - C_3 \frac{dV_E}{dt} - \frac{V_E}{Z_E} - i_{AC} \end{cases} \quad (3.15)$$

where d_4 is the duty ratio of HBES converter and V_{ES} is the output voltage of the HBES.

The AC bus voltage is regulated by the BDAC. The AC bus voltages in the d-q coordinates are expressed as

$$\begin{cases} V_d = d_{3d} V_E - L_3 \frac{di_d}{dt} - R_3 i_d + \omega L_3 i_q \\ V_q = d_{3q} V_E - L_3 \frac{di_q}{dt} - R_3 i_q - \omega L_3 i_d \end{cases} \quad (3.16)$$

The AC side currents in the d-q coordinates i_{AC_d} and i_{AC_q} are expressed as

$$\begin{cases} i_{AC_d} = i_d + C_4 \frac{dV_d}{dt} + \omega V_q \\ i_{AC_q} = i_q + C_4 \frac{dV_q}{dt} + \omega V_d \end{cases} \quad (3.15)$$

The control block diagram of BHMg is shown in Fig. 3.14. Two dual loop PI controllers are used in the BDAC to maintain stable AC bus voltage and control the

active and reactive power. The BDCC maintains LDCB voltage and control the power flow between LDCB and CDCB.

The CDCB voltage is controlled by charging and discharging of HBES. A dual PI loop for the HBES converter is to switch between charging and discharging modes automatically. Mode switching is activated by the power mismatch P_m in DC side.

Figure 3.14 Control block diagram of the converter and BDCC in mode 2.

3.6 System Studies Results

The operation and control of the proposed BHMg as shown in Fig. 3.4 are verified in this section. Table 3.1 shows the system parameters. The devices parameters are set according to the datasheet. The maximum demand reduction and the system efficiency improvement are discussed in the case studies. The simulation results have been obtained by MATLAB/Simulink.

To illustrate the maximum demand reduction of the BHMg under various load and resource conditions, and operating modes of the sub-systems, four cases were designed to simulate the BHMg a day operation. Fig. 3.15 shows the power output of subsystems and bus voltages and current. Power from BPVS is assumed at three

solar radiation levels. The BPVS output power rating is 15kW at high radiation level, 10kW at medium radiation level and 1.5kW at low radiation level. The occupier behavior determines the plug load demand. According to the building operation profile [98], the load consuming power is assumed to be at three levels in a day. Loads consume 15kW at high level, 10kW at medium level, and 2kW at low level. Lift operation during a day has peak period and off-peak period. At peak period, the lift usually travels round trip. Lift motors alternate between MDM and RBM. Hence, BMDS consumes no power or regenerates power at peak period. Motors under MDM usually occur at off-peak period.

Table 3.1 The parameters of the compact system

Symbol	Quantity	Value
P_M	Motor Power Rating	4 kW
V_n	Motor Voltage Rating	460 V
f	frequency	60 Hz
L_s	Stator Inductance	$0.3027 \times 10^{-3} H$
L_r	Rotor Inductance	$0.3027 \times 10^{-3} H$
L_m	Mutual Inductance	$10.46 \times 10^{-3} H$
R_s	Stator Resistance	$14.85 \times 10^{-3} \Omega$
R_r	Rotor Resistance	$9.295 \times 10^{-3} \Omega$
C_1	BPVS Converter Capacitance	$470 \times 10^{-6} F$
L_1	BPVS Converter Inductance	$3 \times 10^{-3} H$
R_1	BPVS Converter Resistance	$1 \times 10^{-3} \Omega$
C_2	BDCC Capacitance	$2200 \times 10^{-6} F$
L_2	BDCC Inductance	$10 \times 10^{-3} H$
R_2	BDCC Resistance	$1 \times 10^{-3} \Omega$
C_3	BDAC Capacitance	$470 \times 10^{-6} F$
L_3	BDAC Inductance	$3 \times 10^{-3} H$
R_3	BDAC Resistance	$1 \times 10^{-3} \Omega$
L_4	HBES Converter Inductance	$10 \times 10^{-3} H$
R_4	HBES Converter Resistance	$1 \times 10^{-3} \Omega$
V_{DC}^*	LDCB Bus Reference Voltage	380 V
V_E^*	CDCB Reference Voltage	640 V
V_{AC}^*	AC Bus Voltage	220 V (rms)
L_{L_AC}	AC Side line Inductance	$0.1 \times 10^{-3} H$
R_{L_AC}	AC Side line Resistance	$10 \times 10^{-3} \Omega$
R_{L_DC}	DC Side line Resistance	0.5 Ω

Case 1: This case indicates the BHMG operation between 6 am to 10 am. The simulation time is within 2.5s. The BPVS works at medium level to generate power at 9932W. This is the peak period for lift operation system since it transfers the building occupier frequently. The lift motor rating is set as 4kW and the motor factor of maximum utilization is 0.75. In BMDS, one motor operates at MDM and the other one operates at RBM. The BMDS just consumes 76W since the lack of power conversion loss compensation. HBES discharge 295W to balance the system power. The load of building consumes power at 9561W which consists of fundamental loads 5kW at DC subgrid and plug loads at AC subgrid. The BDAC operates at power transfer mode 2 to transfer 4786W from DC to AC subgrid.

Case 2: This case illustrates the BHMG operation between 10 am to 4 pm. The simulation time is between 2.5s and 3.5s. The BPVS supply power of 14847W since the solar radiation becomes stronger. The BMDS consumes 5946W at off-peak period since two motors are at MDM. HBES discharges more power to supply the whole system. More plug loads connect to the BHMG which make the load demand increase to 14254W. The BDAC operates at power transfer mode 2 as well to transfer 3863W from DC to AC subgrid.

Case 3: This case illustrates the BHMG operation between 4 pm to 8 pm. The simulation time is between 3.5s and 4.5s. The BPVS operates at medium level to generate 7762W. The BMDS regenerates 5374W at peak period since two motors are at RBM. Plug loads decrease and load power consumption is reduced to 11328W. The HBES charges at 2051W in this case. The BDAC transfers more power to supply the loads on AC side.

Case 4: This case illustrates the BHMG operation between 8 pm to 6 am. The simulation time is beyond 4.5s. The BPVS works at low level to generate 1314kW because of the PV energy storage. Loads of building only consume 1759W to maintain the basic operation, which is set at DC subgrid. The BMDS consumes power at 2035W since only one motor is operating. The HBES discharge power at

Figure 3.15 Operating performance of BHMg: (a) Power from the BPVS; (b) Power consumed by loads; (c) Power of the BMDS; (d) Power from the HBES; (e) Power of the BDAC; (f) LDCB voltage; (g) CDCB voltage; (h) AC bus voltage and current; (i) AC bus transition voltage and current at 2.5s; (j) AC bus transition voltage and current at 3.5s.

2906W to compensate the system power gap. The BDAC operates in idle mode. Fig. 3.15 (f) and (g) represent the LDCB and CDCB voltage stabilizing under variable source and loads conditions. Fig. 3.15 (h), (i) and (j) show the AC bus voltage and current.

Fig. 3.16 represents the CBDN operation performance under the same condition as Fig. 3.15. CBDN is represented in chapter 2. There is no energy storage in CBDN to balance the system power. Only PV energy storage is used for PV panels. The regenerative power from motors in RBM is not able to be reused or restored. The BMDS consumes 2987W at case 1 and 154W at case 3. The detail of CBDN is represented in Table 3.3. The BDAC changes its operating mode from power transfer mode 2 to power transfer mode 1 in case 4. Fig. 3.16 (d) shows the current direction changes at 4.5s.

Figure 3.16 Operating performance of CBDN: (a) Power of the BMDS; (b) Power of the BDAC; (c) AC bus voltage and current; (d) AC bus transition voltage and current at 4.5s.

From Table 3.2 and Table 3.3, the maximum demand of HBMG is significant decreased. The power of each subsystem in each case is assumed at a mean value. The building energy consumption during a day can be calculated. The proposed BHMG consumes from 2.33 kWh from utility grid, which is significantly less than the energy consumption of CBDN at 72.6 kWh.

Table 3.2 The details of BHMG operation

Condition	Case 1	Case 2	Case 3	Case 4
<i>Loads in DC side</i>	5000 W	5000 W	5000 W	1759 W
<i>Loads in AC side</i>	4561 W	9254 W	6328 W	0 W
<i>BMDS</i>	76 W	5946 W	-5376 W	2035 W
<i>BPVS</i>	9932 W	14847 W	7762 W	1314 W
<i>BDAC</i>	4856 W	3901 W	6328 W	0 W
<i>HBES</i>	-295 W	-4964 W	2051 W	-2706 W
<i>Maximum demand</i>	0 W	389 W	0 W	0 W
<i>Energy consumption</i>		2.33 kWh		

Table 3.3 The details of CBDN operation

Condition	Case 1	Case 2	Case 3	Case 4
<i>Loads in DC side</i>	5000 W	5000 W	5000 W	1759 W
<i>Loads in AC side</i>	4561 W	9254 W	6328 W	0 W
<i>BMDS</i>	2987 W	5946 W	154 W	2535 W
<i>BPVS</i>	9932 W	14847 W	7762 W	1314 W
<i>BDAC</i>	1945 W	3901 W	2608 W	-1512 W
<i>Maximum demand</i>	2616 W	5353 W	3720 W	1512 W
<i>Energy consumption</i>	10.5 kWh	32.1 kWh	14.9 kWh	15.1 kWh

3.7 Summary

A novel building hybrid microgrid is proposed in this chapter to reduce building power demand and energy consumption, to improve building energy utilization efficiency and to simplify building distribution network. Under various load and resource conditions, the BHMGM can maintain reliable operation. The simulation results show that the BMDS, BPVS and HBES can smoothly change operating mode. AC/DC bus voltages are stable under different operating conditions and during modes switching. The power can transfer smoothly between AC and DC and between LDCB and CDCB. The duration of the grid-tied operation and power input from utility grid has been reduced. The building maximum demand and energy consumption have been significantly reduced using the energy storage and direct power exchange through CDCB. Therefore, it can be concluded that the CDCB and LDCB network architecture is more efficient topology for power exchange among motors in driving and regenerating modes and therefore can significantly reduce multiple reverse conversions in CBDN. A hybrid building energy storage system (HBES) can provide cost-efficient solutions for different operation problems. The succeeded work will still focus on how to further improve the building microgrid efficiency. The controller for each subsystem can be improved. For the BDMS, a novel approach integrating elevator operating optimization and motor control will be proposed for further use the regenerative energy among the motor drives. In the HBES, adaptive area droop control will be proposed for automatically switch the energy storage operating mode by changing the droop coefficient and to achieve the coordination control between battery and supercapacitor. Moreover, the centralized control will be introduced in building microgrid to further reduced maximum demand. These improvements for each subsystem will be introduced in the following chapters.

Chapter 4

Distributed Lift Operating Control in Smart Building Hybrid Microgrid

In this chapter, a novel control approach which integrates optimal operation and direct torque control (DTC) for motors in building hybrid microgrid is introduced. The optimal control and operation of lifts is based on fuzzy logic which uses the real time data inputs such as original level, destination level, call level, etc. DTC is used in motor controllers. The fuzzy PID controller in DTC is designed to achieve a smaller overshoot and faster response compared with the conventional PID controller. The proposed control approach is verified through simulations.

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4.1 Introduction

With growing population, cities become more crowded. To achieve efficient land use, more high-rise and multi-story buildings appear in mega cities. To reduce building energy consumption is important in improving building energy utilization efficiency. In a high rise commercial building, lift motors not only consume energy but also can regenerate energy. A building lift system is proposed to classify and integrate all lifts together to improve building energy utilization efficiency.

A novel distributed lift control approach based on fuzzy logic and DTC is proposed in this chapter to integrate lift operating optimization and motor control. Lift operating optimization method is based on the fuzzy logic. The inputs of the fuzzy logic-based optimization are real time call level, original level and destination level, which are more related with the real lifts operation. The motor controller is designed based on DTC. A fuzzy self-tuning method is introduced in motor controller. The proportional and integral gains in controller can be self-tuning according to the lift operation. The novel approach is set for each motor in building lift system. By using this method, the peak power demand can be reduced.

4.2 Lift Control System

The distributed lift operating controller consists of three parts: operating optimization, selector and motor controller. Fig. 4.1 shows the overall control block.

The objective of operating optimization is to choose the lift which gives a better quality of occupants' journey experience and consume less or regenerate more power. The core part of optimization is advanced fuzzy controller. Compared with conventional fuzzy controller, advanced fuzzy controller has one more layer to process the input signal. The selector is a comparator to determine whether the lift is operating.

Figure 4.1 Overall block diagram of lift control system.

The motor controller is based on DTC control. Comparing with other induction motor control, DTC provides a fast torque response without field oriented block or inner current loop. This is suitable for lift operating system. Moreover, because of the difference in lift operating distance, the optimize control parameters are not the same. To regulate the optimization control parameter, fuzzy PID control is introduced to DTC controller to eliminate the overshoot in transient and decrease the response time.

4.3 Operating Operation Controller

The lift motor operating optimization controller is represented in Fig. 4.2.

Figure 4.2 Lift motor operating optimization controller.

Operating optimization controller has five layers as shown in Fig. 4.3. The input layer collects the input signals. Layer two is the data processing layer, the lift reference parameters are generated in this layer, and are sent to motor controller.

Fuzzy logic output comes from layer five. The output from the output layer is a value between zero and one. In a building lift system with two lift motors, the fuzzy logic has two outputs for the selector to determine which lift to deliver the passengers.

Figure 4.3 Detailed description of fuzzy logic layers.

4.3.1 Layer I

This layer is the input layer. Conventional inputs are waiting time, riding time, etc. However, in reality, the input signals are only at call level, original level and destination level. The call level is where the passenger waits. The original level is at which the lift parks before the passenger press the button. Destination level is the level the passenger wants to go. In layer II, these three signals are used to calculate the waiting time, riding time, etc.

4.3.2 Layer II

This layer is the data processing layer. Define I_1 as the call level; I_2 as the original level; I_3 as the destination level. Use these three parameters to calculate $O_1^l, O_2^l, O_3^l, O_4^l$, where O_1^l is waiting time; O_2^l is riding time; O_3^l is crowded degree; O_4^l is power consumption.

Equation (4.1) shows the waiting time calculation.

$$\begin{cases} O_1^l = \frac{S_w}{V_n} + \frac{V_n}{a} \\ S_w = |I_1 - I_2| \times H \end{cases} \quad (4.1)$$

where S_w is the operating distance from the original level to call level, H is the height of each level, V_n is operating speed of an accelerator.

In lift operating system, operating speed and accelerator are essential parameters. If the speed is too high, passengers in lift car feel uncomfortable. If the speed is too low, time will be wasted in the lift. Moreover, different speeds have relative accelerators. Through a look-up table, different speeds are chosen by different distances. The look-up table is provided by lift manufactory. Hitachi VFH-II model is chosen in this chapter.

As it is in the waiting time calculation, equation (4.2) shows the riding time calculation.

$$\begin{cases} O_2^l = \frac{S_R}{V_n} + \frac{V_n}{a} \\ S_R = |I_3 - I_1| \times H \end{cases} \quad (4.2)$$

where S_R is the operating distance from the call level to destination level.

In lift operating optimization, waiting time and riding time are most important. However, constraints are not only confined by these two parameters. Suppose the lift is full, the lift will not stop at call level. The priority of an empty lift is higher

than a full lift. Hence, under this assumption, crowded degree is another essential parameter.

Equation (4.3) shows the crowded degree calculation.

$$O_3^1 = \frac{m}{M_{\max}} \quad (4.3)$$

where m is the weight of the car. $M_{\max}$ is the maximum weight of the car.

The other parameter is power consumption. Equation (4.4) shows the power consumption calculation.

$$\begin{cases} O_4^1 = W_M - W_G \\ W_M = \int P_M dt = \int (\omega_{rm} T_{em} + P_{loss}) \cdot dt \\ W_G = \int P_G dt = \int (-\omega_{rm} T_{er} - P_{loss}) \cdot dt \\ P_{loss} = \frac{R_s}{M^2} \phi_r^2 + (\frac{R_s L_r^2}{M^2} + R_r) \frac{T_e^2}{P^2 \phi_r^2} \end{cases} \quad (4.4)$$

where W_M is the energy consumed by motor, and W_G is the energy generated by lift in regenerative mode, P_{loss} is the power loss in motor, T_{em} is the electromagnetic torque when motor is at motor mode, T_{er} is the electromagnetic torque when motor is at regenerative mode, R_s is stator resistance, M is the mutual inductance, L_r is the rotor inductance; P is pole number. O_1^1 , O_2^1 , O_3^1 , O_4^1 are regarded as input signals to next layer.

4.3.3 Layer III

This is the fuzzification layer. Each input signal from layer two is fuzzified by membership functions. Each input consists of three parts: negative large (NL), zero (ZE) and positive large (PL). For each input, three membership functions are chosen for different parts. Membership functions are based on sigmoid function and triangle function.

Equation (4.5) shows the sigmoid function.

$$y = sig(x; a, b) = \frac{1}{1 + e^{-a(x-b)}} \quad (4.5)$$

where parameter a is weight value. It determines the curve slope. Parameter a is larger; the curve slope is steeper. Parameter b is threshold value; it determines the center point of the curve. Sigmoid function is appropriate for representing concepts such as “NL” or “PL”.

Equation (4.6) shows the triangle function.

$$y = triangle(x; \alpha, \beta, \chi) = \begin{cases} 0, & x \leq \alpha \\ \frac{x-\alpha}{\beta-\alpha}, & \alpha < x \leq \beta \\ \frac{\chi-x}{\chi-\beta}, & \beta < x \leq \chi \\ 0, & \chi < x \end{cases} \quad (4.6)$$

Fuzzification process by membership functions are described by equation (4.7).

$$\begin{cases} \mu^{NL}(O_1^1) = sig(O_1^1; \frac{-T_{W,max}}{8 \times 10}, \frac{3}{8}T_{W,max}) \\ \mu^{ZE}(O_1^1) = triangle(O_1^1; \frac{1}{4}T_{W,max}, \frac{1}{2}T_{W,max}, \frac{3}{4}T_{W,max}) \\ \mu^{PL}(O_1^1) = sig(O_1^1; \frac{T_{W,max}}{8 \times 10}, \frac{5}{8}T_{W,max}) \\ \mu^{NL}(O_2^1) = sig(O_2^1; \frac{-T_{r,max}}{8 \times 10}, \frac{3}{8}T_{r,max}) \\ \mu^{ZE}(O_2^1) = triangle(O_2^1; \frac{1}{4}T_{r,max}, \frac{1}{2}T_{r,max}, \frac{3}{4}T_{r,max}) \\ \mu^{PL}(O_2^1) = sig(O_2^1; \frac{T_{r,max}}{8 \times 10}, \frac{5}{8}T_{r,max}) \\ \mu^{NL}(O_3^1) = sig(O_3^1; -0.01, 0.4) \\ \mu^{ZE}(O_3^1) = triangle(O_3^1; 0.3, 0.5, 0.7) \\ \mu^{PL}(O_3^1) = sig(O_3^1; 0.01, 0.6) \\ \mu^{NL}(O_4^1) = sig(O_4^1; \frac{-W}{24 \times 10}, \frac{5}{12}W) \\ \mu^{ZE}(O_4^1) = triangle(O_4^1; \frac{1}{3}W, \frac{1}{2}W, \frac{2}{3}W) \\ \mu^{PL}(O_4^1) = sig(O_4^1; \frac{W}{24 \times 10}, \frac{7}{12}W) \\ W = (W_{min} + W_{max}) \end{cases} \quad (4.7)$$

where $T_{w.\max}$ is the maximum waiting time passengers can endure, $T_{r.\max}$ is the maximum riding time passengers can endure, $W_{\min}$ is the motor maximum regenerative power, since it is negative, it can be regarded as minimum power consumption of motor, $W_{\max}$ is the maximum power consumption of motor. The calculation results are sent to the next layer to do the rule process.

4.3.4 Layer IV

This is the fuzzy rule process layer. The data from layer III will be sent to the fuzzy rule base. Each data is converted to a value through base rule base. Sum all the value and send the results to the next layer.

4.3.5 Layer V

This is the output layer. The fuzzy logic output is sent to the motor controller. The output is a value between 0 and 1. The value represents priority. The motor with higher priority is operating. When a motor in building lift system is operating and a new request is sent to the controller, the controller in each motor will calculate again based on the real time condition.

4.4 Motor Controller

The direct torque control (DTC) is introduced into lift motor since lift changes the operating mode frequently. The motor with DTC can meet the requirement of fast response. Compared with other induction motor control, DTC provides a fast torque response without field oriental block or inner current loop. Fig. 4.4 shows the control block diagram of motor controller.

Flux and Torque Estimation block could be described by equation (4.8).

$$\begin{cases} \varphi_{\alpha s} = \int (V_{\alpha s} - R_s i_{\alpha s}) dt \\ \varphi_{\beta s} = \int (V_{\beta s} - R_s i_{\beta s}) dt \\ T_e = \frac{3}{2} P (\varphi_{\alpha s} i_{\beta s} - \varphi_{\beta s} i_{\alpha s}) \end{cases} \quad (4.8)$$

where $V_{\alpha s}$ and $V_{\beta s}$ are the stator voltages, $i_{\alpha s}$ and $i_{\beta s}$ are the stator currents, $\varphi_{\alpha s}$ and $\varphi_{\beta s}$ are the stator fluxes, R_s is the stator winding resistance, T_e is the electromagnetic torque.

Figure 4.4 Control block diagram of motor controller.

Change the conventional PID controller, fuzzy-PID controller is used in outer speed loop. Fig. 4.5 shows the speed loop fuzzy-PID controller.

The following equation (4.9) is a mathematic description.

$$\begin{cases} T_e^* = K_p^* e + K_i^* \int e dt + K_d^* \frac{de}{dt} \\ K_p^* = K_p \alpha + K_{pf} \\ K_i^* = K_i \alpha + K_{if} \\ K_d^* = K_d \alpha + K_{df} \end{cases} \quad (4.9)$$

where α is weight, K_{pf} , K_{if} and K_{df} are tuning parameters from fuzzy logic. In these equations, four parameters are working independently. These parameters cannot affect each other. They increase the tuning accuracy.

Figure 4.5 Speed loop Fuzzy-PID controller.

4.5 System Studies

The simulation model of building lift system is based on compact model in Fig. 4.6. Using MATLAB/SIMULINK to simulate passenger lift system operation.

Assume a building has 100 floors, the call level is the first floor, and destination level is 30 floor. Motor one stays at 10 floor, motor two stays at 20 floor. When the passenger pushes the button at the first floor, the operating optimization controller starts to calculate, and sends the results to motor controller. Fig. 4.7 shows the priorities from two operating optimization controller.

Figure 4.6 Compact Model of Passenger Lift System.

Figure 4.7 Optimal scheduling results of building lift system.

From the Fig. 4.7, the priority of motor 1 is higher than motor 2. It means motor 1 starts operating and motor 2 remain stationary. Fig. 4.8 shows the two motors operating performance.

Figure 4.8 Operating performance of two motors: (a) Motor speed; (b) Motor flux; (c) Torque; (d) DC link voltage.

It is obvious to find that motor 1 is operating and motor 2 is not moving. Fig. 4.9 shows the motor operating voltage and current around 2s.

Figure 4.9 Motor 1 voltage and current.

In order to test the self-tuning DTC control, the compare test between conventional DTC and self-tuning DTC is conducted. From 0s to 1.5s, two motors are operating at no-load condition. From 1.5s to 3s, two motors are operating at positive 100N.M.

From 3s to 4s, two motors are operating at negative 100N.M. Fig. 4.10 shows the operating performances between two control strategies.

Figure 4.10 The results from the conventional DTC and the self-tuning DTC.

It is obvious to compare two control strategies from three sections, I, II and III. When the conditions change, motor with self-tuning controller has a smaller ripple than motor with conventional controller. The response time is shorter as well. In section III, for safety consideration, the author sets a lower limit in conventional DTC controller, and controller takes longer time to recover to a new stable condition. In self-tuning DTC controller, the ripple cannot reach the limit before it recovers to the reference value. The response time and recovery time is shorter than

conventional method. Therefore, the motor with self-tuning controller is more stable than the conventional controller.

4.6 Summary

A novel lift control approach is proposed in this chapter. Evaluation of novel control method is investigated. The detailed control algorithm is introduced. Model established by MATLAB/Simulink is designed to test the validation of novel control. The results show the novel lift control can choose a more proper lift to operate. This lift control system ensures shorter waiting time and riding time. It consumes less power, it can even regenerate power and dump it back into SUPCAP. The motor controller with self-tuning has a smaller ripple and shorter response and recovery time. By this method, the power efficiency in high rise multi story building can be improved. The other subsystem in building hybrid microgrid, hybrid energy storage system, is modified in the next chapter.

Chapter 5

Adaptive Area Droop Control for Hybrid Energy Storage System in Building Hybrid Microgrid

To reduce the complexity of power management and enforce coincident control strategy of distributed energy storages for individual PV systems and lift systems in a smart building microgrid, a centralized hybrid building energy storage system (HBES) is proposed to serve multiple functions such as energy buffer and power balancer. The objective is to reduce the building maximum power demand under the minimum system marginal cost. HBES consists of a battery bank with high energy density as auxiliary storage and a super capacitor bank with high power density as priority storage. An adaptive area droop controller is designed to switch HBES automatically from voltage regulation mode to power control mode by changing the droop coefficient. A coordination control is proposed for battery and supercapacitor in HBES. The proposed adaptive area droop controller is verified through simulations and experiments.

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5.1 Introduction

Compared to the utility grid, converter-based microgrids have low rotational inertia which makes the microgrids unstable under particular operating conditions. Energy storages introduce equivalent inertia into microgrids and enhance dynamic stability against loads or changing of renewable power sources [99]. In building microgrid, Energy storages for renewable power sources such as photovoltaic (PV) power source require high energy density. Nevertheless, loads with high-pulse power requirement such as portable electric devices and electric vehicles require energy storages with high power density. Therefore, hybrid energy storage system (HESS) which consists of both high energy density storages like battery and high power density storage like supercapacitor is proposed to meet the aforementioned requirements in building microgrid [100].

In this chapter, study system configuration is introduced first. Based on this configuration, hybrid building energy storage system (HBES) has different operating modes. The proposed adaptive area droop control is introduced to HBES which could automatically change the energy storage operating mode by changing the droop coefficient. Then, the coordination control of hybrid energy storage system is investigated which gives the activation criterion of battery and supercapacitor.

5.2 Building System Configuration

5.2.1 System Configuration

The system configuration is shown in Fig. 5. 1. The system is a two-level four-subsystem configuration, which is proposed for easy and efficient integration of various DC links in the motor driving circuits, DC energy storages, DC loads and PV systems.

A common DC bus is proposed to integrate all motors through DC/AC converters, which eliminates the AC/DC rectifiers of motor driving circuits connecting to the AC bus [101]. To simplify the complex connection of distributed energy storages in different buses, hybrid energy storage system is proposed to be connected to common DC bus. Hybrid energy storage system works as a central energy buffer not only to balance the power gap caused by motor drives, but also to balance the entire system power gap caused by PV and load change. Building PV system is a renewable energy source and connected to low voltage DC bus. Loads are placed at common DC bus or low voltage DC bus according to their voltage requirements.

Figure 5.1 Building system configuration.

5.2.2 Hybrid Energy Storage System Operating Modes

Batteries are widely used as energy buffers to compensate the building power gap caused by PV and load change. PV output power is related to solar radiation curve and the variation frequency is low. Some kinds of loads in buildings such as lighting system also have low frequency variation characteristic. Batteries with high energy density balance the entire system's power under low frequency variation.

Motor drives are essential devices in buildings and they are used in lifts and air-cons. When lift starts to operate, the lift motor has to reach the required speed in a very short time period. In this time period, the peak magnitude of power is large. After the starting process, the lift has to operate at a constant speed and then the lift motor starts to brake. In order to make the lift's operation smoother, the energy storage used for motors has to meet the requirements of fast response and high power density. Compared to batteries, supercapacitors are more suitable for lift motors since supercapacitors have the advantage of high power density, long service life, small size and light weight.

Hybrid energy storage system is the integration of super capacitors with high power density and batteries with high energy density. Both supercapacitors and batteries have to work in two operating modes, voltage regulation mode and power exchange mode. By using supercapacitor as the parallel controller, battery charging and discharging times of minor cycle are reduced and the discharge depth is decreased. Hence, battery service life can be prolonged. In this paper, the activation of supercapacitor and battery is based on the definition of adaptive area instead of using filter to separate high and low frequency variations or large and small variation ramp rate.

5.3 Adaptive Area Droop Control

5.3.1 Definition of droop characteristic

Fig. 5. 2 shows the droop characteristic of energy storage converter. In this figure, the horizontal axis represents the power charged or discharged by energy storage and the vertical axis represents voltage error e_v .

Voltage error e_v is given by

$$e_v = V_{\max} - V_{dc,mean} \quad (5.1)$$

where V_{max} is the maximum allowable CDCB voltage which is a constant value usually set as ten percent plus the reference bus voltage; $V_{dc,mean}$ is the mean value of real-time DC bus voltage. $V_{dc,mean}$ is calculated by maximum and minimum values. In [102], the mean value calculator implementation in controller is introduced. The double frequency ripple in output voltage is eliminated by using the mean value calculator. Moreover, the controller has a high bandwidth compared to conventional controller using real time sensed voltage.

Figure 5.2 Droop characteristic definition.

The red line represents the droop curve which is given by

$$P_s = k_i P_{max} - k_{droop} e_{v-s} \quad (5.2)$$

where P_{max} is determined by the energy storage manufacturer which is the power tolerance while operating; for safety consideration, k_i is a parameter to scale the maximum power; k_{droop} is the droop coefficient.

The blue line represents the load curve which is given by

$$P_s = I_{dc} (V_{max} - e_{v-s}) \quad (5.3)$$

where P_s is the power charged or discharged from energy storage to balance the system power; I_{dc} is the value of CDCB current injected into or out of the energy storage converter; e_{v-s} is the bus voltage error at operating point. According to the

figure, the load curve is changing in two phases. In the right phase, the CDCB current injects into converter and energy storage operates in charging mode. I_{dc} is positive. In the left phase, the CDCB current is dumped out from converter and energy storage operates in discharging mode. I_{dc} is negative. The blue line with arrow in the figure represents the current decrease direction.

The operating point (O.P) of energy storage is the intersection between load and droop curve. The meaning of operating point is that, if the CDCB voltage has a voltage variation e_{v_s} , the energy storage should charge or discharge power P_s to maintain the voltage and make the system operating properly. In the figure, the operating point is in the right phase, the energy storages is charged the surplus power when the CDCB voltage error is e_{v_s} , which means PV and loads power do not balance.

5.3.2 Voltage regulation

The basic requirement for building microgrid proper operation is to ensure each bus voltage is stable in the system. Energy storages in the HESS are working as an energy buffer which can regulate bus voltage. Fig. 5.3 illustrates the adaptive droop control for voltage regulation.

The nominal CDCB voltage V^* is derived as subtracting nominal CDCB voltage error e_{v_0} by V_{max} . In order to achieve a stable bus voltage, the nominal CDCB voltage error e_{v_0} which is determined by operating point has to be a constant value. In the other word, e_{v_0} moves alone a vertical line. In Fig. 5. 3, e_{v_0} moving curve is a dotted horizontal line. In order to place the intersection point alone the e_{v_0} moving curve, the droop coefficient has to be modified adaptively. By equating (5.2) and (5.3), the droop coefficient is derived as

$$k_{droop} = \frac{k_i P_{max} - I_{dc} V_{max}}{e_v} - I_{dc} \quad (5.4)$$

Equation (5.4) represents k_{droop} is a function of CDCB voltage and CDCB current injected to energy storage converter. This controller is able to regulate the bus voltage. However, for hybrid energy storage system controller, voltage regulation is not the only control objective. Power exchange control is needed for the power transfer between energy storages and microgrid.

Figure 5.3 Voltage regulation droop control.

5.3.3 Power exchange

When large variation of energy storage output power occurs, power exchange control of energy storage will be activated to fast compensate the power gap. Moreover, for some extreme conditions like sudden change in load demand or reconnection of power generation to the grid, the energy storage need to respond quickly to balance the grid energy which requires energy storage to charge or discharge fast. Fig. 5.4 illustrates the adaptive droop control for power control.

Figure 5.4 Power exchange droop control.

The reference charging or discharging power P_s is introduced into droop control to achieve the fast power balance requirement and it is determined by the energy storage power rating. In Fig. 5.4, P_s moving curve is a vertical dotted line. The operating point has to move along the P_s moving curve. By equating (5.2) and (5.3), the droop coefficient is derived as

$$k_{droop} = \frac{k_i P_{\max} - P_s}{V_{\max} - \frac{P_s}{I_{dc}}} \quad (5.5)$$

The equation also represents the droop coefficient as a function of $V_{\max}$ and I_{dc} .

In the figure, two conditions are presented for energy storage charge and discharge. If building PV system's output power is larger than loads requirement, the surplus power has to be absorbed. P_s^{charge} is set for the energy storage fast charging. Operating point 1 has to move along the P_s^{charge} moving curve. If building PV system is not able to supply the loads, $P_s^{discharge}$ is set for the energy storage fast discharging. Operating point 2 has to be placed on the $P_s^{discharge}$ moving curve.

This controller is advantageous for power balance in the system which is able to fast charging and discharging. However, this control approach cannot control the bus voltage. If the voltage error related with intersection point is far from the nominal voltage error, the bus voltage is unstable which makes the system to breakdown. Therefore, there should be a trade-off between voltage regulation and power exchange control.

5.3.4 Adaptive droop area control

Adaptive area droop control integrates voltage regulation and power exchange. Fig. 5.5 represents the definition of adaptive area.

A bus voltage error tolerance is set when the energy storage converter controller is operating and this error tolerance does not affect the microgrid operating stability. The error tolerance is defined as the e_v range around the nominal CDCB voltage error e_{v_0} . The lower limitation is e_{v_min} and the upper limitation is e_{v_max} . In this research, the range from e_{v_min} and e_{v_max} is 10V. These two parameters determine the voltage error edges of adaptive area.

Figure 5.5 Definition of adaptive area.

A charging and discharging power tolerance is set according to the energy storage power rating, which means the charging or discharging power also has the upper limitation P_{s_max} and lower limitation P_{s_min} . The chosen of P_{s_max} and P_{s_min} for supercapacitor converters is based on the motor characteristic since the supercapacitors are used for the high frequency power variation caused by motors.

The $P_{s_min}^{SUP}$ and $P_{s_max}^{SUP}$ of supercapacitor converters are set as

$$\begin{cases} P_{s_min}^{SUP} = (P_m^* - P_{regen}) \\ P_{s_max}^{SUP} = N \cdot (P_m^* + P_{regen}) \\ P_{regen} = -\left(\frac{R_s L_r^2}{L_m^2} + R_r\right) \frac{J^2 \omega_r^2}{p^2 \phi_r^2} \\ \quad - \left[1 + \left(\frac{R_s L_r^2}{L_m^2} + R_r\right) \frac{2D}{p^2 \phi_r^2}\right] J \omega_r^* \omega_r \\ \quad - \left[1 + \left(\frac{R_s L_r^2}{L_m^2} + R_r\right) \frac{2D}{p^2 \phi_r^2}\right] D \omega_r - \frac{R_s \phi_r^2}{L_m^2} \end{cases} \quad (5.6)$$

where N is the number of motors in building system; P_m^* is the motor rating power; P_{regen} is the motor regenerative power.

The P_{s_max} and P_{s_min} for battery converters are determined by PV and loads operation since the batteries are used to compensate the whole system power gap.

The $P_{s_min}^{BAT}$ and $P_{s_max}^{BAT}$ of battery converters are set as

$$\begin{cases} P_{s_min}^{BAT} = |P_{pv_max} - P_{load_min}| \\ P_{s_max}^{BAT} = |P_{pv_min} - P_{load_max}| \end{cases} \quad (5.7)$$

where P_{pv_min} and P_{pv_max} are the PV maximum and minimum output power respectively; P_{load_min} and P_{load_max} are the maximum and minimum load power respectively.

These two power limitation parameters determine the power exchange edges of adaptive area.

Two cases are designed when the energy storage converter with adaptive area droop control is operating. One is that, after sudden change, the operating point is still in the adaptive area. The other is when the operating point is out of the adaptive area after sudden change. In order to clearly show the case study, only the adaptive area in right phase is represented. The theory of adaptive area droop control in the left phase is the same as that in the right phase.

Case 1: The operating point is still in the adaptive area after sudden change. This case usually happens when the load is slightly change or partial motors change the operating modes. The regenerated energy from motors can be consumed by other motors or local loads. The CDCB voltage varies slightly. In building microgrid, the motor drive used for lifts changes the operating mode frequently. The supercapacitor is used for compensating the high frequency power variation and the battery does not need to respond to the variation. Fig. 5.6 illustrates this condition and the red dotted line investigates the battery converter operating point moving direction.

Figure 5.6 Battery converter operating point changing in the adaptive area (I_{dc} decrease condition).

In this case, the battery converter is charging the same power as before the operating point. If I_{dc} decreases, the battery converter operating point is moving forward to the e_{v_min} edge along the vertical line. Once the operating point reach the edge, the battery converter has to get ready for the operating mode change. If I_{dc} decreases further, the droop coefficient determine the operating point moves along the e_{v_min} edge and the battery converter starts to respond to the power variation and changes the operating mode from power exchange mode to voltage regulation mode.

Fig. 5.7 shows the condition in which I_{dc} increases. The battery converter operating point moves forward to the e_{v_max} edge along a vertical line by tuning the droop coefficient. If I_{dc} increases further after operating point placed on the edge, the battery converter starts to respond to the power variation and changes the operating mode from power exchange mode to voltage regulation mode.

Figure 5.7 Battery converter operating point changing in the adaptive area (I_{dc} increase condition).

When the supercapacitor converter operating point is in the adaptive area, the supercapacitor is always working in power exchange mode as shown in Fig. 5.4 to respond to the power change quickly. Once the operating point places on the

voltage error edges, and further changes in the voltage error disallow the system to work properly, the supercapacitor converter starts to work for the voltage regulation. Case 2: The operating point is out of the adaptive area after sudden change. This case usually happens in three conditions. First is when the energy storage converter starts working. The initial operating point is outside the adaptive area. In order to avoid this condition, the droop coefficient has to be tuned before the controller starts working. Second condition is when motors are under starting procedure or large loads change suddenly. The motor's starting current is four times higher than the rating current and it will cause large bus voltage variation. Under this condition, the battery and supercapacitor converters operating points are out of the voltage error edges. Last condition is when most motors change operating modes, the supercapacitors take fast response after motors mode change and the supercapacitor converter's operating point is out the power exchange edges.

Figure 5.8 Operating point out of the adaptive area (O.P place on e_v edge).

Both battery and supercapacitor controllers are tuning the droop coefficient first which let the operating point move along the load curve and place on the edge of the adaptive area. If the operating point is placed on the voltage error edge, the battery converter starts working on voltage regulation mode and makes the operating point move along the voltage error edge. The supercapacitor converter

gets ready to work in power exchange mode. If the operating point is changing in the adaptive area, battery is charging the same power as the operating point placed on the voltage error edge. The supercapacitor is always working in power exchange mode as case 1 to fast response the power change. Fig. 5.8 represents this condition and the red dotted line investigates the battery converter operating point moving direction.

Fig. 5.9 shows the condition when the operating point places on the power exchange edge after moving along the load curve. The supercapacitor converter is working on power exchange mode. The battery controller is still tuning the droop coefficient to the point related reference voltage error. Then the battery is working in voltage regulation mode.

Figure 5.9 Operating point out of the adaptive area (O.P place on P_s edge).

Adaptive area droop controller with these two designed cases offers instant action during transient by increasing the response speed of the controller. Moreover, it is able to improve the stability of energy storage converter.

5.3.5 Steady-State and Dynamic Analysis of the Proposed Controller

Adaptive area droop controller has to be demonstrated with stable performance before it can be used for hybrid energy storage system. For steady-state analysis, the O.P is located in the adaptive area, and the bus voltage has to be stable. The steady-state CDCB voltage V_{dc_s} derived from equations (5.1), (5.2) and (5.3) as

$$V_{dc_s} = \frac{k_{droop} V_{\max} - k_i P_{\max}}{k_{droop} - I_{dc}} \quad (5.8)$$

It is obvious to find that the steady state DC bus voltage depends on droop coefficient, DC bus current and system parameters. The criterion of droop coefficient depends on the existence of O.P. Therefore, two conditions are considered. Either of them is able to guarantee the O.P excising.

$$\text{Condition 1: } \begin{cases} k_i P_{\max} > I_{dc} V_{\max} \\ V_{\max} > \frac{k_i P_{\max}}{k_{droop}} \end{cases}$$

$$\text{Condition 2: } \begin{cases} k_i P_{\max} < I_{dc} V_{\max} \\ V_{\max} < \frac{k_i P_{\max}}{k_{droop}} \end{cases}$$

Condition 1 is used to design the droop coefficient since the DC bus current can be zero. The droop coefficient has to make sure all the operating conditions are taken into consideration. Then, the system is stable at steady-state if the droop coefficient reaches the requirement in equation (5.9)

$$\begin{cases} k_i P_{\max} > I_{dc} V_{\max} \\ V_{\max} > \frac{k_i P_{\max}}{k_{droop}} \end{cases} \quad (5.9)$$

For dynamic analysis, the dynamic equation of CDCB voltage is derived. The transient performance of DC bus voltage is estimated according to the fast state

variables which should be able to reach the steady-state variables. Considering the time period as $2\omega t$, the CDCB voltage is able to be written as

$$\frac{dV_{dc}}{dt} = \left[\frac{1}{C_{dc}} (i_{conv} - i_{dc}) \right]_{2\omega t} \quad (5.10)$$

where C_{dc} is DC bus capacitance; i_{conv} is the output current of converter. Insert the equations (5.2) and (5.3), the dynamic equation (5.8) is written as

$$\frac{dV_{dc}}{dt} = \frac{k_i P_{\max} - k_{droop} V_{\max} - k_{droop} V_{dc} - I_{dc}}{C_{dc}} \quad (5.11)$$

The eigenvalue of dynamic equation (5.11) is calculated as

$$\lambda = -\frac{k_{droop}}{C_{dc}} \quad (5.12)$$

The value of C_{dc} is positive. If the system is stable, the droop coefficient has to be positive. Based on the steady-state and dynamic analysis, the system is operating properly by choosing the proper droop coefficient.

5.4 Coordination Control of HESS

Coordination control based on the adaptive area droop control is used to maintain the HESS and stable operation of building hybrid microgrid. The coordination control logic diagram is shown in Fig. 5. 10.

At the HESS level, operation modes of the individual converter are determined by operating point positions in droop characteristic. Operating point detection is based on the adaptive area definition which is introduced in Fig. 5.5. At local level, the individual converter operating mode are based on commends from HESS level, the individual energy storage constraints and the charging/discharging rate of energy storages in HESS. The energy storage constraints of battery or supercapacitor are determined according to the state of charge (SOC) which is described as

$SOC_{min} \leq SOC \leq SOC_{max}$. The battery and supercapacitor have to work in power exchange mode when the SOC is below the lower limit. Moreover, the battery has to charge or discharge a constant amount of power when the operating point is in the adaptive area but not on the voltage error edges. The battery is not activated when the power change is in the adaptive area. For the other cases, battery has to work in the voltage regulation mode to maintain the CDCB voltage. Supercapacitor has to operate in voltage regulation mode to assist battery to maintain the voltage when the operating point is moving along the voltage error edges or in the adaptive area. In these cases, supercapacitors are ready for power exchange mode to fast respond to the power variation.

Figure 5.10 Control mode diagram of energy storage converters.

Based on Fig. 5.10, the control scheme diagram is represented in Fig. 5.11. Multi-loop droop controller is used for both battery and supercapacitor converters. This control scheme is applied for HESS in building microgrid to provide a stable CDCB voltage in building microgrid and fast power exchange between HESS and microgrid. During operating scenario change, the control objective can be changed automatically by tuning the droop coefficient.

Figure 5.11 Control mode diagram of energy storage converters.

5.5 System Studies

The simulation results are presented in this section for adaptive area droop controller in this paper. The simulation results have been obtained by MATLAB/Simulink. TABLE 5.1 shows the parameters used for the simulations. The devices parameters are set according to the datasheet.

Table 5.1 The parameters of the simulation implementation

Symbol	Quantity	Value
V_{max}	Maximum CDCB Voltage	520 V
V_n	Nominal CDCB Voltage	500 V
e_{v_o}	Nominal CDCB Voltage Error	20 V
$e_{v_{max}}$	Maximum CDCB Voltage Error	25 V
$e_{v_{min}}$	Minimum CDCB Voltage Error	15 V
$P_{s_{max}}^{BAT}$	Maximum Battery Converter Power Tolerance	2500 W
$P_{s_{min}}^{BAT}$	Minimum Battery Converter Power Tolerance	100 W
$P_{s_{max}}^{SUP}$	Maximum Supercapacitor Converter Power Tolerance	6000 W
$P_{s_{min}}^{SUP}$	Minimum Supercapacitor Converter Power Tolerance	100 W
L	HESS Converter Inductance	$1.8 \times 10^{-3} H$
R	HESS Converter Equivalent Resistance	$1 \times 10^{-3} \Omega$
C	HESS Capacitance	$20 \times 10^{-6} F$
C_{dc}	CDCB Capacitance	$470 \times 10^{-6} F$

Fig. 5.12 represents the condition when the operating point is still in the adaptive area after a sudden change. At the initial state, the operating point is at the nominal voltage. The battery supplies 1000W to compensate the power gap between PV and loads. At 1.2s, the load suddenly changes, which makes the CDCB voltage drop to 496V. The operating point is still in the adaptive area. The battery holds its operating mode and supplies the same amount of power as at the initial state. The supercapacitor is working at voltage regulation mode to balance the power change. The supercapacitor responds quickly to the load change and follows the load recovery. At around 1.8s, the load is recovered and the supercapacitor is at reverse charging mode. After 1.9s, the voltage is back to the nominal value of 500V.

Fig. 5.13 shows the condition in which the operating point is out of the adaptive area after a sudden change. In the initial state, the operating point is at the nominal voltage and battery supplies 1000W. At 1.2s, the CDCB voltage drops to 490V

since the load suddenly changes. The operating point is out of the adaptive area. The supercapacitor responds to the change quickly and the battery starts to discharge more power. The operating point is moving along the load curve. In the results, the CDCB voltage is recovering. At about 1.5s, the CDCB voltage reaches 495V which means the operating point is placed on the voltage error edge. The supercapacitor and battery are working in voltage regulation mode. The CDCB voltage is maintained at 495V.

Figure 5.12 Simulation results of the operating point still in the adaptive area after a sudden change.

Figure 5.13 Simulation results of the operating point out of the adaptive area after a sudden change and placed on voltage error edge.

Fig. 5.14 illustrates the operating point placed on the power exchange edge after a sudden change. In the initial state, the operating point is at the nominal voltage and battery supplies 1500W. At 1.2s, the CDCB voltage drops to 486V since the sudden large load change. The supercapacitor fast response but it reaches the maximum power limitation 6000W and the supercapacitor supplies 5914W in a short time period. With the load slowly recovers and battery discharges, the supercapacitor discharge power decreases. Between 1.36s to 1.49s, the battery discharge power reaches the maximum and supplies 2448W. In this period, the supercapacitor ends discharge and starts to reverse charge. The ramp rate of voltage recovery is reduced. At 1.66s, the voltage is back to the nominal value of 500V and the battery supplies the power gap as the initial state.

Figure 5.14 Simulation results of the operating point out of the adaptive area after a sudden load change and placed on power exchange edge.

5.6 Summary

An adaptive area droop control approach has been proposed in this chapter, which demonstrates an automatic mode change and stable operating performance for energy storage converters in HESS. The proposed control method is based on droop control and integrates voltage regulation and power exchange control. The voltage

regulation is able to regulate a bus voltage to a constant value by tuning the droop coefficient. This is well-suited for energy storage converter where a constant bus voltage is required. The power exchange control can enable fast power exchange between energy storage and building microgrid. Moreover, adaptive area droop control is designed for battery and supercapacitor in HESS. The coordination control is introduced in HESS which reduces the battery charging and discharging times of miner cycle and discharge depth. Hence, the battery service time is also prolonged.

Chapter 6

A PFC Converter with Flexible Output Voltage and Improved Efficiency for Building Hybrid Microgrid

A three-level quasi-two-stage single-phase power factor correction (PFC) converter is proposed in this chapter, which is used for EV connection in building hybrid microgrid. The proposed PFC converter features sinusoidal input current, three-level output characteristic, and a wide range of output DC voltages, and it will be very suitable for high-power applications where the output voltage can be either lower or higher than the peak AC input voltage, e.g., plug-in hybrid electric vehicle charging system. Moreover, the involved DC/DC buck conversion stage may only need to process partial input power rather than full scale of the input power, and therefore the overall system efficiency can be much improved. Through proper control of the buck converter, it is also possible to mitigate the double-line frequency ripple power that is inherent in a single-phase AC/DC system, and the resulting load end voltage will be fairly constant. The dynamic response of this regulation loop is also very fast and the system is therefore insensitive to external disturbances. Both simulation and experimental results are presented to show the effectiveness of this converter as well as its efficiency improvement against a conventional two-stage solution.

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6.1 Introduction

Plug-in hybrid electric vehicle (PHEV) is gaining popularity in today's automotive market due to increasing concerns on environment and sustainable development. Because of its hybrid propulsion nature, a battery storage system must be equipped inside, which can be recharged from the utility electrical grid through an AC/DC converter with power factor correction (PFC) function [103].

Battery chargers supplied by single-phase AC mains are usually rated below 5kW and the most commonly used topologies for front-end AC/DC conversion are the simple boost type PFC converter and the full bridge rectifier. Nevertheless, these two topologies are both of boost type and can only produce a DC voltage that is higher than the peak AC input voltage (greater than 325V for 230V grid). In order to cater for variable voltage levels of the battery pack (50V-600V) [104], a second stage DC/DC buck converter has to be implemented to step down the PFC output voltage, which undoubtedly decreases system overall efficiency.

To provide a simple but effective solution, this chapter presents a high efficiency single-phase PFC converter that features sinusoidal input current, three-level output characteristic and flexible output DC voltage. Its attractiveness is that the embedded bidirectional DC/DC buck converter may only need to process partial input power rather than full scale of input power, and therefore its conversion efficiency can be much improved compared with the conventional two stage solution. Also, the PFC stage exhibits three-level output voltage, and the dV/dt across the switches are reduced, so as the switching losses. An added benefit of this converter is that, the fluctuating 100Hz or 120Hz harmonic power in the single-phase system can be almost diverted into the DC-link capacitor through proper control design, and the terminal voltage and/or the charging current of battery pack will be fairly constant, which may expand its working lifetime. Its operation principle and control strategies are discussed in details in this paper, and both simulation and experimental results are provided for validation.

6.2 Converter Description and the Operation Principle

The circuit diagram of the proposed single-phase AC/DC converter is shown in Fig. 6.1, which consists of a standard diode bridge, a three-level PFC, and a bidirectional DC/DC converter. In the case that V2G support is needed, the diode bridge can be replaced by an unfolding bridge and the diodes of the PFC stage should be replaced by MOSFETs or IGBTs with anti-parallel diode so that active power can be reversely converted from the battery pack to the utility grid. As shown in Fig. 6.1, the rechargeable battery pack is directly connected to the output of the three-level PFC, and it is also interconnected with the high voltage DC bus through the bidirectional DC/DC converter. This high voltage DC bus may also serve as the DC-link of a three-phase inverter that is usually used to drive a rear-end traction motor.

Figure 6.1 Circuit diagram of proposed three-level PFC converter for single-phase PHEV chargers.

As mentioned previously, the proposed three-level PFC has a wide range of output voltages and it can function as either a buck or a boost converter. During the boost operation, there are two operation modes for Q_1 and Q_2 . When the low DC bus voltage or simply the load voltage V_L is higher than the instantaneous input voltage $V_{in} |\sin \omega t|$, where V_{in} is the peak value of input voltage and ω is the fundamental angular frequency, Q_2 will be always on. Q_1 and D_1 then form up a standard boost

PFC that directly converts input power for DC load consumption, and the converter pole voltage V_{AB} will be changed between 0 and V_L . In order to realize the PFC function, the duty cycle of Q_1 should comply with

$$d_1 = 1 - \frac{V_{in} |\sin \omega t|}{V_L} \quad (6.1)$$

which is the basic equation for a boost PFC. It should be noted that, in this operation period, the buck converter does not need to process any input power as they are all directly supplied into the battery through this PFC converter.

In second operation interval when V_L is less than $V_{in}|\sin \omega t|$, Q_1 remains off. Q_2 and D_2 will modulate and form up another boost PFC. V_{AB} is now changing between V_L and the high DC bus voltage V_H . Again, to ensure sinusoidal input current and unity power factor, the duty cycle of Q_2 must comply with

$$d_2 = 1 - \frac{V_{in} |\sin \omega t| - V_L}{V_H - V_L} \quad (6.2)$$

Intuitively, when D_2 is conducting, excessive input power will be flowing into the DC-link capacitor C_H and this high bus voltage will be subsequently stepped down by the bidirectional DC/DC converter so as to charge the battery, and this is the root reason that why the DC/DC converter only process partial input power and higher conversion efficiency can be obtained.

In order to ensure smooth transition between low and high voltage level commutations, an offset is injected into the carrier of pulse-width modulation (PWM) for Q_2 as shown in Fig. 6.2. As a result, a unified reference signal V_m can be derived to simultaneously modulate Q_1 and Q_2 , which is written as

$$v_m(t) = \begin{cases} 1 - \frac{V_{in} |\sin \omega t|}{V_L}, & V_{in} |\sin \omega t| \leq V_L \\ \frac{V_L - V_{in} |\sin \omega t|}{V_H - V_L}, & V_{in} |\sin \omega t| > V_L \end{cases} \quad (6.3)$$

Compared with the conventional boost PFC, the proposed converter has slightly higher conduction losses because of the series connection of Q_2 and D_1 . However, its switching losses can be greatly reduced due to its three-level characteristic that splits the high DC bus voltage into two portions. Moreover, efficiency gain from the DC/DC converter is also significant because it only converts the input power that flow through D_2 .

Figure 6.2 Idealized operating waveforms for proposed three-level PFC converter.

To estimate the percentage of input power λ that is converted by this buck stage, it is assumed that the power converter is lossless and harmonic free. In this case, the instantaneous input power from AC side will be

$$p_{in} = V_{in} |\sin \omega t| \cdot I_{in} |\sin \omega t| = \frac{V_{in} I_{in}}{2} (1 - \cos 2\omega t) \quad (6.4)$$

where I_{in} is the peak value of boost inductor current.

If the PFC is commutating at high voltage levels, part of input power will be directly supplied into the battery when Q_2 is on, and can be found as

$$\begin{aligned}
p_{batt_H} &= I_{in} |\sin \omega t| \cdot d_2 \cdot V_L \\
&= I_{in} |\sin \omega t| \left(1 - \frac{V_{in} |\sin \omega t| - V_L}{V_H - V_L} \right) V_L \\
&= V_L I_{in} |\sin \omega t| \left(\frac{V_H - V_{in} |\sin \omega t|}{V_H - V_L} \right)
\end{aligned} \tag{6.5}$$

Plotting (6.4) and (6.5) will give rise to the time domain waveforms of power distribution shown in Fig. 3, and it is clear that the shaded area enclosed by p_{in} and p_{batt_H} indicates the power p_{dc} that needs to be processed by the buck converter.

Figure 6.3 Instantaneous power distribution in PFC converter and buck converter, given fixed grid voltage, output voltage, and dc-link voltage.

Taking the integration of p_{in} and p_{dc} over half fundamental period, it is possible to find that

$$\begin{aligned}
\lambda &= \frac{\int_{\arcsin(V_L/V_{in})}^{\pi - \arcsin(V_L/V_{in})} (p_{in} - p_{batt_H}) d\omega t}{\int_0^{\pi} p_{in} d\omega t} \\
&= \frac{\int_{\arcsin(V_L/V_{in})}^{\pi - \arcsin(V_L/V_{in})} p_{dc} d\omega t}{\int_0^{\pi} p_{in} d\omega t} \\
&= \frac{\int_{\arcsin(V_L/V_{in})}^{\pi - \arcsin(V_L/V_{in})} V_H I_{in} |\sin \omega t| (1 - d_2) d\omega t}{\int_0^{\pi} \frac{V_{in} I_{in}}{2} (1 - \cos 2\omega t) d\omega t} \\
&= \frac{\int_{\arcsin(V_L/V_{in})}^{\pi - \arcsin(V_L/V_{in})} V_H |\sin \omega t| \left(\frac{V_{in} |\sin \omega t| - V_L}{V_H - V_L} \right) d\omega t}{\int_0^{\pi} \frac{V_{in}}{2} (1 - \cos 2\omega t) d\omega t} \\
&= \frac{2V_H}{\pi V_{in}} \left[\frac{V_{in}}{V_H - V_L} \frac{1}{2} \left(\pi - 2 \arcsin \frac{V_L}{V_{in}} \right) \right. \\
&\quad \left. - \frac{V_L}{V_H - V_L} \cos(\arcsin \frac{V_L}{V_{in}}) \right] \tag{6.6}
\end{aligned}$$

Obviously, λ is a function of V_L , V_{in} and V_H , where $V_L \leq V_{in} \leq V_H$. By setting $\alpha = V_L / V_{in}$ and $\beta = V_{in} / V_H$, the above equation can be further simplified as

$$\lambda = \frac{1}{\pi} \left[\frac{1}{1 - \alpha\beta} (\pi - 2 \arcsin \alpha) - \frac{2\alpha}{1 - \alpha\beta} \cos(\arcsin \alpha) \right] \tag{6.7}$$

To visualize this relationship in a more straightforward way, a 3D plot of equation (6.7) is shown in Fig. 6.4 and it is clear that the value of λ will mainly depends on α , which indeed makes sense because α directly determines the conduction time of D_2 .

Taking a typical system parameter design where $\alpha = 250 / (230\sqrt{2}) = 0.77$ and $\beta = 230\sqrt{2} / 400 = 0.81$, according to (6.7) and also as shown in Fig. 6.3, it is easy to find that only 34% of the input power will be processed by the DC/DC converter, and this justifies the merit of this topology stated above.

Figure 6.4 3D plot of (6.7) showing the percentage of input power converted by the buck converter as a function of V_L/V_{in} (alpha) and V_{in}/V_H (beta).

6.3 Converter Controller Design

The control system of the proposed three-level AC/DC converter will be relatively more complicated than that of a conventional boost PFC, because it requires at least two voltage control loops to regulate the output voltage V_L and the DC-link voltage V_H , respectively. Also, the intermittent operation of Q_1 and Q_2 impose a disturbance to the system, and a fast control loop must be designed to reject this periodic disturbance. In order to realize these control objectives, two independent control loops are designed for controlling the PFC stage and the buck stage, respectively, and the control algorithms will be elaborated as follows.

6.3.1 PFC Converter Control

A classic cascaded control structure is employed to regulate the PFC converter. Its outer voltage control loop is tasked at balancing input and output power, and the

DC-link voltage V_H is chosen as the control variable because the charging power into the dc-link capacitor C_H is directly proportional to input power as long as V_L , V_{in} , and V_H are fixed. This voltage control loop will also maintain the average value of V_H to be constant, whereas its instantaneous value is not necessary to be constant, because the DC-link capacitor C_H has to absorb the double line frequency harmonic in this single-phase system. The control loop is therefore of slow response and its control bandwidth is set below 20Hz as per usual design, and this is realized by tuning the parameters of a proportional-integral (PI) regulator $G_v(s)$ as follow

$$G_v(s) = K_{pv} \left(1 + \frac{1}{\tau_v s} \right) \quad (6.8)$$

where K_{pv} is the proportional gain to adjust control bandwidth, and τ_v is the time constant of the integral term to achieve high DC compensation gain.

In order to prevent the DC-link ripple voltage from distorting the reference of inner current control loop, a second order notch filter tuned at 2ω is added at the output of the PI regulator

$$G_{notch}(s) = \frac{s^2 + (2\omega)^2}{s^2 + K_2 s + (2\omega)^2} \quad (6.9)$$

where K_2 is a coefficient that determines the quality factor of this notch filter. Large K_2 can give rise to more attenuation of double line frequency harmonic, but in the meantime, it may reduce the phase margin of the control loop, and thus deteriorate system dynamic response.

The inner current control loop will force the boost inductor current to be rectified sinusoidal shape that is also in phase with input voltage. Using small signal modeling discussed in [105], it is derived that the transfer function of duty cycle-to-inductor current $G_{di_ac}(s)$ can be simply regarded as a first order inertial element in high frequency analysis and it can be written as

$$G_{di_ac}(s) = \frac{I_{in}(s)}{d_{ac}(s)} = \frac{V_{dc}}{sL_{in}} \quad (6.10)$$

where V_{dc} is the output voltage that may change between V_L and $(V_H - V_L)$, depending on the operation mode of the PFC.

It is worth noting that this voltage change is undesired in the system, because it may give rise to a variable bandwidth of the current control loop and affect its regulation performance. In order to have a fixed control bandwidth for the inner current loop, a dynamic gain compensator is implemented as shown in the right bottom part of Fig. 6.5, and an upper saturation is set to limit the gain value G_{dy} in case that V_L is approaching V_H . In this case, the inner current loop can be easily controlled by another PI regulator

$$G_c(s) = K_{pc} \left(1 + \frac{1}{\tau_c s}\right) \quad (6.11)$$

where K_{pc} is its proportional gain and τ_c is the time constant. These two coefficients should be tuned such that the bandwidth of current control loop is around one tenth of the system switching frequency.

Figure 6.5 Overall control block diagram for the proposed three-level PFC converter.

In order to achieve accurate current tracking and make the control system robust against line voltage change, a duty cycle feed-forward control scheme is also implemented in the current loop. The open loop duty cycle as derived in (6.3) is added to the output of the current regulator to arrive at the final reference signal for PWMs of Q_1 and Q_2 .

6.3.2 Buck Converter Control

As mentioned earlier, the output voltage of buck converter should be as constant as possible because it is directly connected to end loads. Therefore, a single voltage control loop is designed for this power stage to expedite its dynamic response. Another reason for pursuing fast response of this voltage control loop is that it has to reject the periodic disturbance induced by its intermittent operation. Again, using small signal modeling approach, the control duty cycle-to-output voltage transfer function $G_{dv_dc}(s)$ of the bidirectional buck converter can be derived as

$$G_{dv_dc}(s) = \frac{V_L(s)}{d_{dc}(s)} = V_H \frac{1 + \frac{s}{\omega_z}}{1 + \frac{s}{Q\omega_o} + \frac{s^2}{\omega_o^2}} \quad (6.12)$$

$$\omega_o = \frac{1}{\sqrt{L_{dc}C_L}}, \omega_z = \frac{1}{R_{CL}C_L}, Q = \frac{\sqrt{\frac{L_{dc}}{C_L}}}{R_{CL} + R_{Ldc}} \quad (6.13)$$

where ω_o is the LC resonant frequency introduced by the output filter. R_{CL} is the equivalent series resistance (ESR) of output capacitor and it introduces a zero ω_z in the open loop gain. R_{Ldc} is the ESR of boost inductor and these two ESRs together determine the quality factor Q of this second order system and they can provide damping effect to the LC resonance. Using the parameters listed in Table 6.1, the Bode diagram of (6.12) can then be plotted as dotted line in Fig. 6.6. As shown, its closed-loop control system is inherently stable even a simple proportional gain is used. However, if the crossover frequency of this control loop is tuned to be less than one tenth of the switching frequency, e.g. 1kHz, the system phase margin is only 17° , which is obviously insufficient. Furthermore, this system has limited DC gain, and its steady-state tracking error may not be zero.

In order to solve these issues, a type III compensator is then designed to control this buck converter and its standard form can be written as

Table 6.1 Circuit parameters used for simulation and experiment

Symbol	Quantity	Value
V_g	Grid Voltage	$230 \sqrt{2} \text{ V}$
f_n	Line Frequency	50 Hz
L_{in}	Boost Inductance	2.0 mH
R_{Lin}	ESR of L_{in}	0.2Ω
C_L	Output Capacitance	$470 \mu\text{F}$
R_{CL}	ESR of C_L	0.1Ω
V_L	Output Voltage	250 V
R_{load}	Nominal Load	32Ω
L_{dc}	Buck Inductance	2.0 mH
R_{Ldc}	ESR of L_{dc}	0.2Ω
C_H	DC-Link Capacitance	$470 \mu\text{F}$
V_H	DC-Link Voltage	400 V
R_{CH}	ESR of C_H	0.1Ω
f_{sw}	Switching Frequency	12.5 kHz

Figure 6.6 Bode diagrams of original system (dotted line), type III compensator (dashed line), and compensated system (solid line).

$$G_{dc}(s) = \frac{K_{dc} \left(1 + \frac{s}{\omega_{z1}}\right) \left(1 + \frac{s}{\omega_{z2}}\right)}{s \left(1 + \frac{s}{\omega_{p1}}\right) \left(1 + \frac{s}{\omega_{p2}}\right)} \quad (6.14)$$

Clearly, the integral term is to produce infinite DC gain for zero steady-state tracking error, and the two zeros ω_{z1} and ω_{z2} should be placed around the LC resonance frequency ω_o so that phase boost capability can be realized as shown in Fig. 6.6. The first high frequency pole ω_{p1} is to cancel the ESR zero introduced by the output capacitor, while the other pole ω_{p2} acts as a low pass filter (LPF) which increases gain attenuation at high frequencies. A common way is to set ω_{p2} within one tenth to one fifth of the switching frequency.

The Bode diagrams for the designed type III compensator and the compensated system open loop gain are presented in Fig. 6.6 as dashed line and solid line, respectively, and it is demonstrated that 63.8° phase margin is successfully achieved when system crossover frequency is placed at 974Hz, and this confirms its stable operation and fast transient response.

6.3.3 Discussion on Alternative Control Strategies

Since the charging power into output capacitor CL is also proportional to PFC's input power, it is also possible to use V_L as the control variable of outer voltage loop for regulation of the PFC converter. The bidirectional DC/DC converter will then be controlled by V_H and it essentially becomes a DC/DC boost converter. As discussed, this DC-link voltage control loop should be of fast response in order to compensate system harmonics and disturbance, which means that its reference voltage is no long constant. Instead, the reference voltage must contain double line frequency harmonic, which cannot be obtained readily. Furthermore, it is well known that the boost converter has right-half plane (RHP) zero and it will be more difficult to stabilize than a buck converter. Therefore, V_L is adopted for regulation of the DC/DC converter in this chapter.

In fact, other control strategies, like feed-forward of input voltage, implementing an inner current control loop, and adding nonlinear control element, can also be employed to further enhance the performance of buck converter. However, they require even more sophisticated design efforts and are not compulsory for this application. The type III compensator discussed above will suffice for regulation of the proposed converter from both steady-state and transient points of view.

6.4 System Studies Results

Simulation study was carried out in MATLAB/Simulink environment and the circuit parameters are listed in Table 6.1. The steady-state operation waveforms are presented in Fig. 6.7. It can be seen that Q_1 and Q_2 operate alternatively and may produce the desired three-level converter pole voltage V_{AB} . The high level bus voltage is not constant because the dc-link capacitor needs to absorb the system double line frequency harmonic. This fluctuation voltage has basically no impact to the regulation of the boost inductor current, because it can be easily compensated by the fast current control loop. Thanks to the feed-forward mechanism of the open-loop duty cycle, the grid current is almost sinusoidal and in phase with the grid voltage, and its ripple component is very small because of the three-level output voltage. As mentioned previously, the buck converter theoretically does not need to switch when D_2 is blocking. However, in order to deal with the system harmonic power and ensure constant load voltage, the buck converter still has to work during this operation mode.

A 2-kW prototype circuit was built in the laboratory for experimental validation of the proposed PFC converter and the circuit parameters are basically the same as those used in simulation, despite some very slight differences due to the tolerance of passive components. The key active and passive components used for the tested prototype are summarized in Table 6.2.

Table 6.2 Key component used for experiment prototype

Component	Description
Diode Rectifier Bridge	<i>GBPC2506, 25A/600V, MULTICOMP</i>
$Q_1 \dots Q_4 / D_1 / D_2$	<i>IKW30N60T, 30A/600V, INFINEON</i>
L_{in} / L_{dc}	<i>200 turns, 2*AWG#16, Core DT400-40, DMEGC</i>
C_L / C_H	<i>EETED2W471LJ, 470 μF / 450V, PANASONIC</i>

Figure 6.7 Simulated steady-state waveforms under 230-V/2-kW operation, C1: grid voltage, C2: converter pole voltage, C3: buck converter current, and C4: grid current.

The proposed topology was first tested with standard 230-V/50-Hz high-line ac input and its corresponding steady state experimental waveforms are presented in Fig. 6.8. It is obvious that they can match well with those simulated ones presented in Fig. 6.7. It should be noted that there is very slight current distortion during the

mode transition period, and this is due to the limited compensation gain of the controller.

Figure 6.8 Experimental steady-state waveforms under 230-V/2-kW operation, C1: grid voltage, C2: converter pole voltage, C3: buck converter current, and C4: grid current.

Fig. 6.9 shows the dynamic response of the system when it subjects to 100% to 50% step-down load change. As shown, the transient process is very smooth and there is no obvious distortion in the grid current, and the high bus voltage can be well regulated with insignificant voltage overshoot.

In contrast, Fig. 6.10 shows the experimental waveforms when the system undergoes 50% to 100% step-up load change, and the probed signals are replaced by the two dc bus voltages, rectified input voltage, and load current in order to observe their dynamic responses. As can be seen, the load transient can be handled by the high-voltage bus and the output voltage remains undisturbed. In order to

examine the line frequency ripple component in the output voltage, its spectrum is plotted in Fig. 6.11 and compared with that of the high dc bus. From Fig. 6.11, it is clear that the high DC bus can absorb most of the second-order harmonics and therefore, the load voltage can be kept as ripple free during both steady state and dynamic process.

Figure 6.9 Experimental load step-down waveforms, C1: grid voltage, C2: converter pole voltage, C3: buck converter current, and C4: grid current.

In addition to the high-line operation, the prototype was also tested with 120 V/50 Hz low-line input, and in this case, it is simplified to a conventional two-level PFC. The steady-state waveforms under low-line operation with 1000-W load power is presented in Fig. 6.12. It shows that the converter pole voltage becomes two-level, and the input current is more sinusoidal than the high-line case. As discussed, the buck converter now functions as a harmonic compensator and there is theoretically no active power conversion required for it.

Figure 6.10 Experimental load step-up waveforms, C1: input voltage, C2: high dc bus voltage, C3: load voltage, and C4: load current.

Figure 6.11 Harmonic contents of the output voltage and high dc bus voltage under 230-V/2-kW operation.

Fig. 6.13 shows the spectrum of the steady-state grid currents under both high-line and low-line operations. It can be seen that the results can well comply with the IEC 61000-3-2 Class A standard, which is specified for equipment with power rating above 600 W. The total harmonic distortion (THD) of the input current is found to be 5.7% (calculated up to 50th harmonic order) under high-line operation and it is improved to 3.1% under low-line case. As mentioned previously, this is because the intermittent operation of the buck converter may impose disturbances to the system and affect the input current regulation under high-line operation.

Figure 6.12 Experimental steady-state waveforms under 120-V/1-kW operation, C1: grid voltage, C2: converter pole voltage, C3: buck converter current, and C4: grid current.

The proposed PFC converter is also compared with a conventional two-stage solution, i.e., a boost PFC cascaded with a DC/DC buck converter, and its circuitry is obtained by removing D_1 and Q_2 shown in Fig. 6.1. Therefore, the proposed three-level PFC will have higher cost than the conventional one, and it is

complicated with one fast recovery diode (D_1), one switch (Q_2), and one isolated gate driver. The remaining active and passive components in the two-stage PFC are exactly the same as those in the proposed one and therefore, a fair performance comparison can be conducted.

Figure 6.13 Grid current spectrum at 230-V/2-kW operation and 120-V/1-kW operation, shown in comparison with the IEC 61000-3-2 Class A harmonic current limits.

Figure 6.14 Efficiency curves of the proposed PFC converter under universal input voltages, shown in comparison with the conventional two-stage solution.

The efficiency tests were performed by a Fluke Norma 5000 power analyzer. Different tests under universal input voltage conditions (85 to 265 Vrms) were conducted for the two topologies. The output voltage and load power were fixed at 250 V and 2 kW, respectively, and the recorded efficiency curves are presented in Fig. 6.14. As shown, the proposed PFC features higher efficiency than the conventional one under all input conditions. During standard 230-V high-line operation, 1% efficiency improvement can be obtained over the entire load range and this confirms the superior performance of the proposed topology.

Figure 6.15 Efficiency curve of the proposed PFC converter under different output voltages, shown in comparison with the conventional two-stage solution.

In addition to the efficiency versus input voltage curves, the efficiency versus output voltage curve is also plotted in Fig. 6.15, and in this test, the converters were operated with 230-V input voltage and nominal load power. Fig. 6.15 shows that the proposed PFC can maintain much higher efficiency when the output voltage is low. However, as the output voltage increases, the efficiency improvement will be less significant because the proposed PFC essentially becomes equivalent to the conventional two-stage PFC and the characteristic of three-level switching is lost.

It should be noted that the power losses induced by the gate drivers were not included in the efficiency measurement. Since the required gate charge is low and the adopted switching frequency is also relatively slow, these power losses are insignificant to the system overall efficiency and the performance comparison presented previously is still reasonable.

6.5 Summary

In this chapter, a three-level quasi-two-stage single-phase PFC converter has been presented. It has flexible output voltage and can be used for single-phase PHEV charger applications, where the battery voltage can be either lower or higher than the peak AC input voltage. The proposed converter features high quality input current, three-level output voltage, and improved conversion efficiency. By designing a fast regulation loop for the buck converter, the inherent fluctuating power issue in single phase systems can also be resolved, and the load voltage will be fairly constant and insensitive to load changes and external disturbances. Moreover, a dynamic gain compensator is implemented in the current control loop and in this case, its control bandwidth can be kept relatively constant irrespective of the DC bus voltage change during two different operation modes. Therefore, the grid current can be well regulated with low THD and high-power factor. Experimental results obtained from a 2-kW laboratory prototype have been presented in this chapter, which are in good agreement with the theoretical analysis. The efficiency curves under universal input conditions were recorded from a commercial power analyzer, and it is found that the proposed PFC may have 1% efficiency gain under high-line operation as compared to a conventional cascaded two-stage solution. This efficiency improvement is partly contributed by the reduced switching voltage in the PFC stage, and also partly by the reduced power conversion in the DC/DC buck stage.

Chapter 7

Conclusions and Future Work

This thesis begins with reviewing of some basic conventional building distributed networks and some popular control strategies. A novel building hybrid microgrid is then proposed to overcome the drawbacks existing in conventional building distributed networks. The topology and controller of lifts system, building hybrid energy storage system and EV charger are introduced in the following chapters. The future work about improving building hybrid microgrid is also represented in this chapter.

7.1 Conclusion

This thesis starts with reviewing of some basic conventional building distributed network concepts which form the fundamental of this thesis. Moreover, popular control strategies about microgrid and its subsystems are reviewed. Conventional building distributed network is based on AC microgrid. Unfortunately, such networks have a number of multi reverse converters to integrate AC and DC devices, which lead to large amount of multi reverse conversion loss. To overcome this problem, a smart building hybrid microgrid is proposed in this thesis. The essential components are necessary to achieve the smart building requirement in smart building such as motor drives and energy storages. DTC and fuzzy logic controller are introduced into motor drive controller. Hybrid energy storage is the promising method to increase the system efficiency. These control strategies for building subsystems are reviewed as the fundamental studies.

A novel building hybrid microgrid is introduced to reduce building power demand and energy consumption, to increase building energy utilization efficiency and to simplify building distribution network. Under various load and resource conditions, the BHMGM can maintain reliable operation. The BMDS, BPVS and HBES in BHMGM can change operating mode smoothly. AC/DC bus voltages are stable under different operating conditions and during modes switching. The power can transfer smoothly between AC and DC as well as between LDCB and CDCB. The duration of the grid-tied operation and power input from utility grid have been reduced. The building maximum demand and energy consumption have been significantly reduced using the energy storage and direct power exchange through CDCB, especially using the regenerated power from motor drives. Therefore, it can be concluded that the CDCB and LDCB network configuration is more efficient topology for power exchange among motors in driving and regenerating modes and therefore can significantly reduce multiple reverse conversions in CBDN. A hybrid building energy storage system (HBES) can provide cost-efficient solutions for different operation problems.

Then a novel lift control approach is studied. The novel control method includes integrated operation optimization and motor DTC control. Fuzzy logic is introduced into both optimize operation controller and motor DTC control. The novel lift control is able to choose the optimal lift to operate. This lift will have the shorter waiting time and riding time. It consumes less power; it can even regenerate power and dump it back into SUPCAP. The motor controller with self-tuning has a smaller ripple and shorter response and recovery time. Through this method, the power efficiency in high rise multi-story building can be improved.

An adaptive area droop control approach has been investigated, which is able to demonstrate an autonomous mode change and a stable operating performance for energy storage converters in HESS. The novel control method is based on droop control and integrates voltage regulation and power exchange control. The voltage regulation is able to regulate a bus voltage to a constant value by adaptive tuning the droop coefficient. This is well-suited for energy storage converter where a constant bus voltage is required. The power exchange control is able to fast power exchange between energy storage and building microgrid. Moreover, adaptive area droop control is designed for battery and supercapacitor in HESS. The coordination control is introduced for HESS which reduce the battery charging and discharging times of miner cycle and discharge depth. Hence, the battery service time is prolonged.

Electrical vehicles are promising devices to save energy. In smart building microgrid, EV chargers are essential components for EV plug-in. A three-level quasi-two-stage single-phase PFC converter has been presented. It has flexible output voltage and can be used for single-phase PHEV charger applications, where the battery voltage can be either lower or higher than the peak AC input voltage. The proposed converter features high quality input current, three-level output voltage, and improved conversion efficiency. By designing a fast regulation loop for the buck converter, the inherent power fluctuating issue in single phase systems can also be resolved, and the load voltage will be fairly constant and insensitive to

load changes and external disturbances.

Moreover, a dynamic gain compensator is implemented in the current control loop and in this case, its control bandwidth can be kept relatively constant irrespective of the DC bus voltage change during two different operation modes. Therefore, the grid current can be well regulated with low THD and high-power factor. Experimental results obtained from a 2-kW laboratory prototype have been presented in the paper, which are in line with the theoretical analysis. The efficiency curves under universal input conditions were recorded from a commercial power analyzer and it is found that the proposed PFC may have 1% efficiency gain under high-line operation as compared to a conventional cascaded two-stage solution. This efficiency improvement is partly contributed by the reduced switching voltage in the PFC stage, and also partly by the reduced power conversion in the DC/DC buck stage.

To conclude, this thesis covers a few challenging topics on building microgrid configuration and its components controllers. All presented studies are verified by simulations or experiments.

7.2 Future Work

This thesis has discussed some materials about building microgrid configuration and related issues for subsystems in BHMG. Nevertheless, there are still some other challenges yet to be explored. These unresolved challenges are briefly discussed here to provide some insights for future investigation.

In chapter 5, a novel lift controller is proposed for integrating operating optimization and motor DTC control. To make the system more efficient, the controller can be further improved. MPC is widely used in motor drive control to achieve specific objectives by setting the weight in objective function. Moreover, the MPC is introduced in lift controller.

The first step is to establish the lift motor model. The model has to include two aspects, the motor mathematical dynamic equation and motor operating state equation. The state space of motor model is generally expressed as

$$\dot{x} = Ax + Bu \quad (7.1)$$

where x is motor state variables vector, $x = [i_s \ \varphi_s]^T$; u is stator voltage vector as an input vector. Vector A and B are

$$\begin{cases} A = \begin{bmatrix} -\lambda(R_s L_r + R_r L_s) + j\omega_r \lambda(R_r - jL_r \omega_r) & \\ & -R_s & 0 \end{bmatrix} \\ B = \begin{bmatrix} \lambda L_r \\ 1 \end{bmatrix} \end{cases}$$

where R_s is stator resistance; R_r is rotor resistance; L_s is stator inductance; L_r is rotor inductance; L_m is mutual inductance; ω_r is rotor speed; $\lambda = 1 / (L_s L_r - L_m^2)$.

After discretization, in period T_s , (7.1) can be written as:

$$\begin{cases} \overline{i_s(k+1)} = \left(1 - \frac{T_s R_s}{L_s}\right) \overline{i_s(k)} + \frac{T_s}{L_s} \overline{U_s(k+1)} - \frac{T_s}{L_s} \overline{e(k+1)} \\ \overline{\varphi_s(k+1)} = \overline{\varphi_s(k)} + \left[\overline{U_s(k+1)} - \overline{i_s(k+1)} R_s\right] T_s \end{cases} \quad (7.2)$$

where k is the k th sampling time.

Based on (7.2), the torque predictive function can be written as:

$$\overline{T_e(k+1)} = P \left(\overline{\varphi_{s\alpha}(k+1)} \overline{i_{s\beta}(k+1)} - \overline{\varphi_{s\beta}(k+1)} \overline{i_{s\alpha}(k+1)} \right) \quad (7.3)$$

where P is the pole number; $\varphi_{s\alpha}$ and $\varphi_{s\beta}$ are α and β elements of φ_s ; $i_{s\alpha}$ and $i_{s\beta}$ are α and β elements of i_s .

The objective function of motor drive is:

$$g = \begin{pmatrix} \lambda_1 \left[\frac{T_e(k+1) - T_e^*(k+1)}{T_e^*(k+1)} \right]^2 + \lambda_2 \left[\frac{|\varphi_s(k+1)| - |\varphi_s^*(k+1)|}{|\varphi_s^*(k+1)|} \right]^2 \\ + \lambda_3 \left[\frac{U_s(k+1) - U_s^*(k+1)}{U_s^*(k+1)} \right]^2 \end{pmatrix} f(P) \quad (7.4)$$

$$= g_1 f(P)$$

where λ_1 , λ_2 and λ_3 are weight parameters which can determined the objective priority. $f(P)$ is the objective function of lift operating optimization, $P = [O_1^1 \ O_2^1 \ O_3^1 \ O_4^1]^T$ as in chapter 5. The output of $f(P)$ is 0 or 1. If the motor is chosen, the output is 1. The control starts operating. g_1 represents the multi objective MPC motor controller.

In the motor model, the torque and flux are all related with stator voltage and the stator voltage is determined by eight switching states, S_1 to S_8 . According to this, at the next sampling time, there has to be eight potential states. The controller should choose the proper one to control the switch. Fig. 7. 1 shows the controller operating process.

Figure 7.1 Motor MPC operating process.

The above discription is the general idea about how to use the MPC to improve the lift motor control.

In chapter 5, an adaptive area droop control is introduced for hybrid energy storage converter. Further studies integrate motor control and adaptive area droop control into a motor - energy storage system coordination control. Fig. 7.2 represents the control block diagram.

Figure 7.2 Control block diagram for motor – energy storage system.

In chapter 6, a novel PFC converter is proposed for EV charger. The further study is about how to improve the controller according to the battery life prolonged. In EV, battery life is an essential aspect to be considered which is related with EV operation and EV life. However, there is not any accurate model established for battery life. The first step is to do a comprehensive literature view about energy storage modelling which is not only about battery but also about others as VRB or

supercapacitors. Related with EV design, the EV energy storage model is be established and identified as the essential aspects about energy storage life. According to this, the EV charger controller should be improved.

Publications

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- D. Zhu, P. Wang, “A Smart Building Hybrid Microgrid for Energy Efficiency Improvement”. *IEEE Transactions on Smart Grid*, under review.
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