Design and implementation of modular DC micro-grid for integration of battery energy storage and solar PV

Zhao, Zhenyu

2016

Zhao, Z. (2016). Design and implementation of modular DC micro-grid for integration of battery energy storage and solar PV. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/68974>

<https://doi.org/10.32657/10356/68974>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**Design and Implementation of Modular DC Micro-
Grid for Integration of Battery Energy Storage and
Solar PV**

ZHAO ZHENYU

**SCHOOL OF ELECTRICAL AND ELECTRONIC
ENGINEERING**

2016

Table of Contents

	<u>Page</u>
Abstract	i
Acknowledgment	iii
Acronyms	iv
List of Figures	v
List of Tables	viii
Chapter 1 Introduction	1
1.1 Background	
1.2 Motivation	
1.3 Objectives and Specifications	
1.4 Major Contribution of the Dissertation	
1.5 Organization of the Dissertation	
Chapter 2 Literature Review	11
2.1 DC/DC Converter	
2.2 Solar Photovoltaics	
2.3 Operation Modes of Modular DC Micro-grid	
2.4 Closed-loop Control Algorithms	
Chapter 3 Modular DC Micro-Grid Hardware Setup	31
3.1 Power Supply	
3.2 DSP Board	
3.3 Drive Cards	
3.4 Bidirectional DC/DC Converters	
Chapter 4 Control Algorithms	41
4.1 MB Control Algorithm	
4.2 MPPT Control Algorithms	
4.3 Modular DC Micro-grid Control Algorithm	
Chapter 5 Conclusion and Recommendations	62
5.1 Conclusion	
5.2 Recommendations for Future Research	
References	64

Abstract

With more and more electronic devices using DC power supply, DC micro-grid is playing an important role. Compared to conventional centralized AC system, DC micro-grid not only has higher conversion efficiency but also uses renewable energy sources (RESs). So, they are clean and sustainable compared with traditional fossil fuels. Usually, power generation of RESs is intermittent, it also has many LC components in a DC micro-grid. In order to maintain system's reliability and reduce size and cost of LC components, a modular DC micro-grid was proposed. The modular DC micro-grid is such a grid which integrates multiple DC/DC converters, RESs and energy storage system (ESS) together. When the generation of RESs is larger than loads consumption, surplus energy is charged into ESS. When the generation of RESs is smaller than loads consumption, lack of energy is discharged by ESS. Thus, bus voltage can be constant with collaborative operations of RESs and ESS. Except it, multiple DC/DC converters share a set of LC components in a modular DC micro-grid, which increases utilization of LC components and reduce cost and size of them.

In RESs, solar PVs and wind turbines are most common. Wind turbines are usually used in rural areas. However, this project is conducted in Singapore, which is a big city located in the equator. The sunlight of this area is very sufficient. Therefore, solar PVs were chosen as RESs. What is more, battery energy system (BES) was chosen as ESS.

In this project, the modular DC micro-grid has three channels. The battery is used in channel one, solar PVs are used in channel two and channel three. One of the objects in this project is maintaining DC bus voltage stable. In order to achieve this goal, a monitoring bus (MB) algorithm was proposed. In addition, the output power of solar PVs is influenced by many factors, such as irradiance, temperature. It just has one maximum power point (MPP) in each condition. So, another object of this project is making solar PVs operate in MPP. In order to complete this object, improved maximum power point tracking (MPPT) algorithm was chosen. In MB algorithm, we chose double closed-loop PI control method whose inner loop is inductor current feedback loop and the external loop is DC bus voltage feedback loop. In MPPT algorithm, we took perturbation and observe (P&O) method. Considering control of

current is better than control of power, another inductor current PI controller was added into the system to improve system's control effect. Then, each channel was checked with these algorithms to ensure them can operate well.

Finally, a modular DC micro-grid control method was proposed. From the results, this modular DC micro-grid could maintain DC bus voltage stable when solar PVs operate in MPPT mode, which increased system's stability and reliability. In addition, it reduced the size and cost of the whole system.

Key Words: Modular DC Micro-grid, MPPT Algorithm, P&D Method, MB Algorithm, PI controller

Acknowledgment

Firstly, I sincerely thank my team members Chen Shuxin and Lin Jieyu. In the process of the whole project, we cooperated and encouraged each other. I believe that I am hard to finish this project if I have not their help and encouragement.

Secondly, I very thank Professor Tang gave me this chance, from which I have learned much about modular DC micro-grid. I believe that this knowledge will play an important role in my later work.

Thirdly, if there is no help and guidance from Dr. Xiao Jianfang, Guyang and Nguyen Xuan Bac in the process of the project, it will be hard to finish this project. Therefore, I thank them very much.

Finally, I sincerely wish every people have a nice work in the future.

ZHAO ZHENYU

April 2016

Acronyms

D	Duty cycle
I_{in}	Average input current
I_L	Average inductor current
I_{max}	MPP current of solar PV
I_{out}	Average output current
P_{PV}	Output power of solar PV
P_{max}	Maximum power of solar PV
V_C	Capacitor voltage
V_{in}	Average input voltage
V_{max}	MPP voltage of solar PV
V_{PV}	Average input voltage
V_{out}	Average output voltage
ΔV_{out}	Variation of output voltage

List of Figures

Figure 1-1 The modular DC micro-grid.....	1
Figure 1-2 Boost converter	2
Figure 1-3 Buck converter	3
Figure 1-4 Bidirectional converter.....	3
Figure 1-5 Roof-top solar PVs.....	4
Figure 1-6 Building-integrated solar PVs.....	5
Figure 1-7 Utility-scale solar PVs.....	5
Figure 1- 8 Electrical energy storage systems	6
Figure 1- 9 Different applications of ESS.....	7
Figure 2-1 Bidirectional DC/DC Converter.....	11
Figure 2-2 Boost Mode	12
Figure 2-3 Boost Mode Switch Is On	13
Figure 2-4 Boost Mode Switch Is Off.....	14
Figure 2-5 Inductor Current Waveform.....	14
Figure 2-6 Current and Voltage Waveforms	16
Figure 2-7 DCM.....	17
Figure 2-8 BCM.....	17
Figure 2-9 Buck Mode	19
Figure 2-10 Buck Mode Switch Is On	19
Figure 2-11 Buck Mode Switch Is Off	20
Figure 2-12 Current and Voltage Waveforms	21
Figure 2-13 Output Current and Voltage Curves.....	23
Figure 2-14 Equivalent Circuit of Solar PV	24
Figure 2-15 I_{PV} - V_{PV} Curve And P_{PV} - V_{PV} Curve of Solar PV	25
Figure 2-16 The Equivalent Circuit of Solar PV	25
Figure 2-17 Different Temperatures At 1000 W/M^2	27
Figure 2-18 Different Irradiances At 25°C	27
Figure 3-1 The Hardware of The Modular DC Micro-Grid	31
Figure 3-2 Power Supply of Control Parts.....	32
Figure 3-3 The Real Components of Power Supply	32

Figure 3-4 DSP Board.....	33
Figure 3-5 Expansion Circuit Board of DSP	34
Figure 3-6 Test of DSP Board When Input Is Zero	35
Figure 3-7 Drive Cards Circuit	35
Figure 3-8 Real Component of Drive Cards	36
Figure 3-9 Test Of PWM Signals	37
Figure 3-10 Circuit of Bidirectional DC/DC Converters.....	38
Figure 3-11 Circuits In Both Low And High Voltage Sides	38
Figure 3-12 Series Inductor Added Between Plugs In Low Voltage Side	39
Figure 3-13 Inductor Measurement Device	39
Figure 3-14 Real Three Phases Bidirectional DC/DC Converters Board.....	40
Figure 4-1 MATLAB Simulation Model of Channel 1 Without Any Controller	42
Figure 4-2 Output Voltage Waveform Without Controller	43
Figure 4-3 Current Waveforms Without Controller	43
Figure 4-4 Simulation Model of Channel 1 With PI Controllers.....	44
Figure 4-5 PWM Waveform	45
Figure 4-6 Output Voltage Waveforms	45
Figure 4-7 Current Waveforms.....	46
Figure 4-8 The Logic Diagram of Perturb & Observe Method	48
Figure 4-9 MATLAB Simulation Model of Perturb & Observe Algorithm.....	49
Figure 4-10 MATLAB Simulation Model of Channel Two.....	50
Figure 4-11 Waveforms In Four-Series-PV Modules.....	51
Figure 4-12 Waveforms In Five-Series-PV Modules	52
Figure 4-13 Waveforms In $T = 50^{\circ}\text{C}$	53
Figure 4-14 Waveforms In $T = 25^{\circ}\text{C}$	53
Figure 4-15 Waveforms In $T = 0^{\circ}\text{C}$	54
Figure 4-16 Waveforms In $1000\text{W}/\text{M}^2$	55
Figure 4-17 Waveforms In $500\text{W}/\text{M}^2$	55
Figure 4-18 Waveforms In $100\text{W}/\text{M}^2$	56
Figure 4-19 Control Algorithms of Modular DC Micro-Grid	58
Figure 4-20 Total MATLAB Simulation Model	59
Figure 4-21 Bus Voltage Waveform	
Figure 4-22 Solar Pvs Waveform.....	60

Figure 4-23 Inductor Current

Figure 4-24 MPP In Different Irradiance 60

List of Tables

Table 1-1 Project Schedule	9
Table 2-1 Operation Modes of The Modular DC Micro-Grid.....	28
Table 4-1 Some Parameters of Battery	42
Table 4-2 Load's Influence to DC Bus	46
Table 4-3 The Judge Principle of Perturb & Observe Method	49
Table 4-4 Some PV Array's Electrical Parameters.....	50
Table 4-5 Load Influences to System	57
Table 4-6 Operation Modes of Ress and BES in Modular Operation Condition	58

Chapter 1 Introduction

1.1 Background

As shown in figure 1-1, a modular DC micro-grid is made up of multiple DC/DC converters, renewable energy sources (RESs) and energy storage system (ESS), which is often located in distribution power system.

Figure 1-1 The modular DC micro-grid

Compared to conventional centralized AC system, DC micro-grids have many advantages. Firstly, the efficiency of DC micro-grid is very high, which is 10% ~ 20% improvement over than conventional AC system [1]. In some cases, the efficiency even can reach 95% [2]. Secondly, the demand for DC power source is gradually increasing with more and more electric devices using DC power supply. DC micro-grid can supply DC power to these loads directly unlike AC power grid, which needs to convert AC power into DC power firstly. Thus, DC micro-grid avoids using rectifier and makes system more efficient [3]. Thirdly, distribution grid even can operate in isolation condition when the transmission line or transformer is outage with the addition of DC micro-grid into distribution system. It charges surplus electricity to

energy storage system (ESS) when the RESs exceeds the loads consumption. So, DC micro-grid improves the stability and reliability of the distribution system [4-6].

However, RESs generation in DC micro-grid is usually intermittent, and there are also many LC components in DC micro-grid. In order to increase system's reliability, a modular DC micro-grid integrating RESs and ESS together is proposed. In this modular DC micro-grid, ESS is added into system in order to maintain power supply stable [7]. When power generation of RESs is larger than load consumption, surplus energy is charged into ESS. When power generation of RESs is smaller than load consumption, lack of energy is discharged by ESS. Thus, bus voltage can be constant with collaborative operations of RESs and ESS. Except it, multiple DC/DC converters share a set of LC components in a modular DC micro-grid, which increases utilization of LC components and reduce cost and size of them.

1.1.1 Power Converters

Power electronic components are firstly used in electricity conversion in 1970s, it has obtained deep development in recent years. Until now, there are plenty kinds of power converters, such as boost, buck and bidirectional converters, which are shown in figure 1-2, 1-3, 1-4 respectively.

Figure 1-2 Boost converter

Figure 1-3 Buck converter

Figure 1-4 Bidirectional converter

Different kinds of converters have different function. For example, boost converter is mainly used in voltage step-up occasion and buck converter is mainly used in voltage step-down occasion, both of them are unidirectional transformer. However, bidirectional converter not only can be used in step-up occasion, but also can be used

in step-down occasion. Except them, there are many other kinds of converters, like Cuk [8], flyback [9], forward [10] and bridge converters [11].

1.1.2 Solar Photovoltaic

With the development of micro-grid, RESs are becoming more and more popular. One hand, RESs are clean energy, they have less environmental pollution than conventional fossil fuels. On the other hand, RESs are sustainable energies, compared to limited fossil fuels, they are inexhaustible. So far, solar PVs and wind turbines are most common methods to harvest these renewable energies [12]. Considering this project is conducted in Singapore, which is a big city lies in equator. The sunlight of this area is sufficient all over the year. Adding wind turbine's generation is mainly conducted in area which is far away from city, it is not available to use wind turbines in big cities like Singapore. So, in this project, solar PVs are chosen as RESs.

Solar PVs are usually divided into roof-top PVs [13], building-integrated PVs [14] and utility-scale PVs [15]. As shown in the figure 1-5, roof-top solar PVs are mainly used to provide power electricity to a single home or even an isolated device, sometimes, it is also used with a connected main grid.

Figure 1-5 Roof-top solar PVs [16]

As shown in figure 1-6, the building-integrated solar PVs are usually installed on the wall, roof and windows of the building. Compared to roof-top solar PVs, the difference between them is that energy produced by building-integrated PVs can be sold back to the electricity companies in some sort of net metering agreements.

Figure 1-6 Building-integrated solar PVs [17]

Utility-scale solar PVs are mainly used to provide energy to large numbers of customers. They are usually considered as central generation plants, unlike roof-top and building-integrated solar PVs, they generate electricity fed into the transmission lines.

Figure 1-7 Utility-scale solar PVs [18]

The principle of solar PV is photovoltaic effect, which PVs absorb and directly change solar energy (sunlight) into electricity. Because the irradiation is inconstant all over the day, so, there must be a maximum power point. If PVs can operate in this point, they will provide maximum power output to system. In order to find the maximum power point of solar PVs, some maximum power point tracking (MPPT) [19] algorithms are proposed, which will be introduced in Chapter 2.

1.1.3 Energy Storage System

With the increasing popularity of RESs, some problems taken by RESs are began to attract people's attention. For example, the intermittence and unreliability of RESs will take some serious concerns to system's stability. In order to improve system's stability, a possible method is adding energy storage system (ESS) [20] into power grid to cope with the intermittence of RESs.

The definition of energy storage system is that it must be able to store energy from another source easily and quickly, and subsequently return it back to an appropriate energy form, usually electricity. The principle of ESS improving power system's stability is that when power generation of RESs is larger than loads consumption, surplus energy is stored in ESS, and when power generation of RESs is smaller than loads consumption, ESS provide the rest of power to loads so as to maintain all loads' normal work.

ESS has many species, according to the difference of their storage principle, they can be classified as shown in figure 1-8.

Figure 1- 8 Electrical energy storage systems [21]

Different ESS have different power density, energy density and economic characteristics. Hence, they have different applications. Some available applications of ESS are shown as figure 1-9.

Figure 1- 9 Different applications of ESS [22]

We can know from figure 1-9 that high-power flywheels [23], high-power super capacitors [24] and superconducting magnetic coil (SMES) [25] are mainly used in transient storage, which the discharging time is just a few seconds, which is too short to be used in the modular DC micro-grid. Moreover, the pumped hydro [26] and compressed air (CAES) [27] are major used in bulk power management, so, they are too large to suit this modular DC micro-grid, which the voltage of the connected DC bus is only 400V. However, different kinds of batteries are suitable to be used in the modular DC micro-grid. They have many advantages. For example, their discharging time is continuous from a few minutes to hours, so, most of them can be used as uninterrupted power supplies to improve the power quality of the power system. What is more, they also act as a role of load shifting through supplying power to loads and cutting down power provided by main grid. Considering these advantages of battery, battery energy storage (BES) devices are used as ESS in this project.

1.2 Motivation

A modular DC micro-grid with integrating RESs and BES have many advantages.

- 1) DC/DC converters can directly change one DC voltage into another DC voltage, which have higher conversion efficiency than DC-AC-DC devices. DC-AC-DC devices have more conversion loss and transmission loss.
- 2) Compared to traditional fossil fuels, RESs are clean and sustainable energy, which can reduce pollution and improve environment.
- 3) The use of BES can reduce effects of RESs' fluctuation to system and maintain output voltage stable. Moreover, it can be used as backup power supply when RESs are outage. So, it increases system's stability.
- 4) DC micro-grid can operate in isolation state when main grid is outage, which enhance reliability of the system.
- 5) The use of modular DC micro-grid can reduce the size and cost of LC components, which increases the economy of the system.

1.3 Objectives and Specifications

The objectives of this project are mainly divided into two parts. One is simulation analysis for the modular DC micro-grid. Another is design and implementation of modular DC micro-grid in hardware. Considering this project is conducted by three people, my work is simulation analysis and hardware setup. Shuxin's work is implementation of MB control algorithm with Battery in hardware. Jieyu's work is implementation of MPPT control algorithm with Solar PVs in hardware. Therefore, my works are shown as follows:

- 1) Hardware setup and check in order for the other two group members can use it to conduct hardware developing.
- 2) Using MATLAB to simulate and implement BES function in channel one, which is maintaining output voltage stable through double PI closed-loop control method.
- 3) Using MATLAB to simulate and implement RESs function in channel two and channel three, which is maintaining MPP output of solar PVs all the time through improved MPPT algorithm.
- 4) Integrating RESs and BES together, using MATLAB to simulate and implement the whole modular DC micro-grid, which is maintaining DC bus

voltage constant all the time. If RESs generation is larger than loads consumption, DC bus voltage will increase. Surplus energy is charged into BES, then voltage will remain stable value. Oppositely, if RESs generation is smaller than loads consumption, DC bus voltage will decrease. The lack of energy is discharged by BES, then voltage will remain stable again.

In order to complete this project well, a schedule has been made as shown in table 1-1.

Table 1-1 Project schedule

Start time---September 2015	
Semester One	
Week 4-6	Read about DC/DC converter, RESs, BES from papers.
Week 7-8	Read about MB algorithm and MPPT algorithm from papers.
Week 9-12	Soldering and checking DC/DC converters, DSP board, DSP expansion board and other relative boards.
Week 13	Prepare final examination.
Semester Two	
Week 1-2	Simulation and implementation of channel one with BES by MB algorithm.
Week 3-4	Simulation and implementation of channel two and channel three with solar PVs through MPPT algorithm.
Week 5-7	Simulation and implementation of the whole modular DC micro-grid with RESs and BES.
Week 8-10	Write dissertation and submit the draft to Professor Tang.

Week 11-12	Modify dissertation and submit the formal version to Professor Tang.
Week 13	Prepare final examination
Due time---May 2016	

1.4 Major Contribution of the Dissertation

In the dissertation, a modular DC micro-grid integrating RESs and ESS together was proposed. ESS is added into the modular DC micro-grid in order to maintain power supply stable. When power generation of RESs is larger than load consumption, surplus energy is charged into ESS. When power generation of RESs is smaller than load consumption, lack of energy is discharged by ESS. Thus, bus voltage can be constant with collaborative operations of RESs and ESS. Except it, multiple DC/DC converters share a set of LC components in a modular DC micro-grid, which increases the utilization of LC components and reduce cost and size of them.

1.5 Organization of the Dissertation

This report is mainly divided into five chapters. Chapter one is focus on introduction of modular DC micro-grid and motivations of conducting the project. Also making main objectives and a project schedule. Chapter two is about literature review, it shows principles of DC/DC converter, solar PVs, multiple operation modes and relative control methods. Chapter three introduces hardware setup and test, which is mainly about power supply, DSP board, drive cards and DC/DC mainboard. Chapter four is simulation and implementation of DC/DC converters with MB and MPPT algorithms. In chapter four, it first introduces MB algorithm in channel one with BES. Then, it introduces MPPT algorithm in channel two and channel three with solar PVs. Finally, it integrates the whole modular DC micro-grid together with RESs and BES and introduces multiple level control algorithms. Chapter five concludes the project and makes some recommendations for future work.

Chapter 2 Literature Review

2.1 DC/DC Converter

DC/DC converter is a kind of voltage conversion device which serves to change one DC voltage into another DC voltage in different level. DC/DC converter have plenty of applications. For example, they are often used to produce suitable voltage for portable electronic devices and improve conversion efficiency as switch mode power supply (SMPS) [28]. What is more, they are increasing used in distribution energy storage and renewable energy generation [29]. Usually, RESs produce unstable DC voltage. In order to get stable voltage from these fluctuation RESs, DC/DC converters start to work.

DC/DC converters can be divided into isolated converters and non-isolated converters by judging electrical connection between input voltage source and output voltage. Common isolated converters are forward converter, fly-back converter and bridge converter and common non-isolated converters are buck, boost and bidirectional converters [30]. Considering this project using bidirectional DC/DC converter, a bidirectional DC/DC converter was chosen as an example of analysis. The topology of bidirectional DC/DC converter is shown in figure 2-1.

Figure 2-1 Bidirectional DC/DC converter

A bidirectional DC/DC converter has two operation modes, one is called boost or step-up mode, another is named buck or step-down mode. Both of the two operation modes will be discussed respectively.

2.1.1 Boost Mode

Figure 2-2 shows the topology circuit of boost mode. At the time, V_{low} is input voltage V_{in} and V_{high} is output voltage V_{out} . Input current $I_{in} = I_L$, output current $I_{out} = I_R$. D is duty cycle of down switch and T is period. So, the switching-on time is DT and switching-off time is $(1 - D)T$. In fact, the up switch operates as a diode in boost mode.

Figure 2-2 Boost mode

2.1.1.1 Voltage Relation

Assuming the capacity of inductor and capacitor are sufficient, inductor current and capacitor voltage can be thought constant in whole cycle, thus

$$I_L = i_{L_{on}} = i_{L_{off}} \quad (1)$$

$$V_C = v_{C_{on}} = v_{C_{off}} \quad (2)$$

Because inductor and capacitor are reactive components, average voltage of inductor and average current of capacitor are zero.

$$V_L = Dv_{L_in} + (1 - D)v_{L_off} = 0 \quad (3)$$

$$I_C = Di_{C_on} + (1 - D)i_{C_off} = 0 \quad (4)$$

Figure 2-3 shows operation topology circuit when (down) switch is on. During switch is on, V_{in} charges to inductor L , inductor current increases and the left side of inductor L is positive polarity, it has

$$L \frac{di_L}{dt} = v_{L_on} = V_{in} \quad (5)$$

$$i_{in_on} = i_{L_on} = I_L \quad (6)$$

Another way, the diode (up switch) is inversely biased, capacitor C discharges to load R , thus

$$v_{C_on} = V_c = v_{out_on} \quad (7)$$

$$i_{c_on} = i_{out_on} \quad (8)$$

Figure 2-3 Boost mode switch is on

Figure 2-4 shows topology circuit when switch is off. During switch is off, input voltage source V_{in} series inductor L then discharges to capacitor and load. Inductor current will decrease in order for inductor current at the start of a cycle is same as current at end of the cycle. For inductor current decreasing during switch-off, the diode must be positive biased. So, it has

$$V_{in} + v_{L_off} = V_{out} \quad (9)$$

$$\frac{di_L}{dt} = \frac{V_{in} - V_{out}}{L} \quad (10)$$

Figure 2-4 Boost mode switch is off

The relationship between inductor current and time is shown in figure 2-5.

Figure 2-5 Inductor current waveform

From figure 2-5, increasing of inductor current during switch-on equals to decreasing of inductor current during switch-off. So, it has

$$I_{max} - I_{min} = \frac{V_{in}}{L} DT \quad (11)$$

$$I_{min} - I_{max} = \frac{V_{in} - V_{out}}{L} (1 - D)T \quad (12)$$

From equation (11) and (12), the relationship between input voltage and output voltage is

$$V_{out} = \frac{1}{1-D} V_{in} \quad (13)$$

2.1.1.2 Circuit Current

Currents across switch, diode and inductor in a cycle are shown in figure 2-6. In order to find their current curves, I_{max} and I_{min} must be determined. Considering active power loss in DC/DC converter can be neglected, input average power equals output average power.

Input power:

$$P_{in} = \frac{I_{max} + I_{min}}{2} V_{in} \quad (14)$$

Output power:

$$P_{out} = \frac{V_{out}^2}{R} \quad (15)$$

Substituting equation (13) and (15) into (14), it has

$$I_{max} + I_{min} = 2I_L = 2 \frac{V_{in}}{R(1-D)^2} \quad (16)$$

$$I_L = \frac{V_{in}}{R(1-D)^2}, \Delta I_L = \frac{DTV_{in}}{L}$$

Therefore,

$$I_{max} = I_L + \Delta I_L = \frac{V_{in}}{R(1-D)^2} + \frac{DTV_{in}}{L} \text{ and } I_{min} = I_L - \Delta I_L = \frac{V_{in}}{R(1-D)^2} - \frac{DTV_{in}}{L} \quad (17)$$

Figure 2-6 Current and voltage waveforms

The definition of current variation ratio is $\xi = \frac{\Delta I_L/2}{I_L}$. According to equation (16), the

current variation ratio is $\xi = \frac{\Delta I_L/2}{I_L} = \frac{DTV_{in}}{2L} / \frac{V_{in}}{R(1-D)^2} = \frac{D(1-D)^2 TR}{2L}$.

2.1.1.3 Operation Modes

The common operation modes of DC/DC converter are continuous conduction mode (CCM), discontinuous conduction mode (DCM) and boundary conduction mode (BCM). A DC/DC converter operates in CCM if current through the inductor never falls to zero during a cycle. Oppositely, if current through the inductor falling into zero before the end of a cycle, this kind of operation mode is DCM, which is shown in figure 2-7.

Figure 2-7 DCM

When current through the inductor just falls to zero at the end of a cycle, thus $I_{L_min} = 0$. It was called BCM, which is shown in figure 2-8.

Figure 2-8 BCM

Different conduction modes will cause different relationships between currents and voltages. The preceding relationship deviation are all dependent on CCM. In this project, DC/DC converters also operate in CCM. So, it is very important to ensure these converters operating in CCM. For a given DC/DC converter, the boundary point is when $I_{L_min} = 0$ at the end of a cycle. Taking $I_{L_min} = 0$ into equation (17), it has

$$L_{min} = \frac{D(1-D)^2}{2} TR \quad (18)$$

Therefore, when $L_{min} > \frac{D(1-D)^2}{2}TR$, converter operates in CCM. When $L_{min} < \frac{D(1-D)^2}{2}TR$, it operates in DCM. When $L_{min} = \frac{D(1-D)^2}{2}TR$, it operates in BCM.

2.1.1.4 Output Voltage Ripple

When the capacity of shunt capacitor C is infinite, capacitor voltage can be thought as constant. But, the value of shunt capacitor can never be infinite. Therefore, capacitor voltage will fluctuate periodically. It is meaningful to determine output voltage ripple. When switch is on, capacitor C discharges to load, total charge during switch-on is

$$\Delta Q = DT I_C = DT I_{out} = DT \frac{V_{out}}{R} \quad (19)$$

$$\Delta Q = C * \Delta V_C = C * \Delta V_{out} = \frac{DT V_{out}}{R}$$

Therefore, output voltage variation is

$$\Delta V_{out} = \Delta V_C = \frac{DT V_{out}}{RC} \quad (20)$$

From equation (20), the output voltage ripple can be determined.

$$\xi = \frac{\Delta V_{out}/2}{V_{out}} = \frac{DT}{2RC} \quad (21)$$

2.1.2 Buck Mode

As shown in figure 2-9, a bidirectional DC/DC converter operates in buck mode where output voltage is lower than input voltage. In buck mode, up switch acts as a switch and down switch acts as a diode.

Figure 2-9 Buck mode

2.1.2.1 Voltage Relation

Before voltage relation of buck mode is analyzed, a same assumption is conducted like boost mode. Therefore, equation (1), (2), (3), (4) are still suitable for buck mode. Figure 2-10 shows equivalent circuit when switch is on.

Figure 2-10 Buck mode switch is on

During switch-on, diode is inverse biased. Inductor L is charging by input voltage source V_{in} , so the right side of inductor L is positive polarity, inductor current increase.

Figure 2-11 Buck mode switch is off

When switch-off, diode is positive biased, the equivalent circuit is shown in figure 2-11. Inductor L is discharging, the left side of inductor L is positive polarity, inductor current decrease.

During switch is on, it has

$$V_{in} = V_L + V_C \quad (22)$$

$$V_C = V_{out}, V_L = L \frac{di_L}{dt} \quad (23)$$

Substituting equation (23) into (22), it has

$$\frac{di_L}{dt} = \frac{(V_{in} - V_{out})}{L} \quad (24)$$

From equation (24), inductor current increases linearly as a speed of $\frac{di_L}{dt} = \frac{(V_{in} - V_{out})}{L}$ during switch-on (DT). At start of a cycle, inductor current is minimum and at DT of a cycle, inductor current is maximum, which is shown in figure 2-12.

During switch-off, assuming this converter operates in CCM. it has

$$V_L + V_C = 0 \quad (25)$$

$$V_C = V_{out}, V_L = L \frac{di_L}{dt} \quad (26)$$

Substituting equation (26) into (25), it has

$$\frac{di_L}{dt} = -\frac{V_{out}}{L} \quad (27)$$

From equation (27), inductor current decreases linearly as a speed of $\frac{di_L}{dt} = -\frac{V_{out}}{L}$ during switch-off. At DT of a cycle, inductor current is maximum, and at end of a cycle, inductor current is minimum, which is shown in figure 2-12.

Figure 2-12 Current and voltage waveforms

From the figure 2-12, increasing of inductor current during switch-on equals to the decreasing of inductor current during switch-off. So, it has

$$\text{switch-on} \quad I_{max} - I_{min} = \frac{V_{in} - V_{out}}{L} DT \quad (28)$$

$$\text{switch-off} \quad I_{min} - I_{max} = -\frac{V_{out}}{L} (1 - D)T \quad (29)$$

Substituting equation (29) into (28), the relationship between input voltage and output voltage is

$$V_{out} = DV_{in} \quad (30)$$

2.1.2.2 Circuit Current

Currents through switch, diode and inductor in a cycle are shown in figure 2-12. In order to find their current curves, I_{max} and I_{min} must be determined. From equation (28) and (29), the value of I_{max} and I_{min} can be calculated.

$$I_{max} = DV_{in} \left(\frac{1}{R} + \frac{1-D}{2L} T \right) \quad (31)$$

$$I_{min} = DV_{in} \left(\frac{1}{R} - \frac{1-D}{2L} T \right) \quad (32)$$

From equation (31) and (32), the change of inductor current is

$$\Delta I_L = I_{max} - I_{min} = DV_{in} \frac{1-D}{2L} T \quad (33)$$

The average value of inductor current is

$$I_L = \frac{V_{out}}{R} = D \frac{V_{in}}{R} \quad (34)$$

Definition of current variation ratio is $\xi = \frac{\Delta I_L / 2}{I_L}$. According to equation (33) and (34),

$$\text{current variation ratio is } \xi = \frac{\Delta I_L / 2}{I_L} = \frac{D(1-D)TV_{in}}{2L} / \frac{DV_{in}}{R} = \frac{(1-D)TR}{2L}.$$

2.1.2.3 Operation Modes

Operation modes of buck converter are also CCM, DCM and BCM. It will not repeat relative statements. The BCM condition of buck converter is $I_{min} = 0$. Therefore, it has $L_{min} = \frac{1-D}{2} TR$ from equation (32). When $L_{min} > \frac{1-D}{2} TR$, converter operates in

CCM. When $L_{min} < \frac{1-D}{2}TR$, converter operates in DCM and when $L_{min} = \frac{1-D}{2}TR$, converter operates in BCM.

2.1.2.4 Output Voltage Ripple

Relationship between capacitor voltage and capacitor current is shown in figure 2-13. Considering capacitor is shunt with load, the output voltage ripple equals capacitor voltage ripple.

Figure 2-13 Output current and voltage curves

From figure 2-13, change of inductor current ΔI_L equals change of capacitor current ΔI_C . So, $\Delta I_L = \Delta I_C = I_{max} - I_{min}$. The peak value of capacitor current is $\frac{I_{max} - I_{min}}{2}$. When $I_C > 0$, it indicates capacitor C is charging by input voltage source V_{in} . Therefore, charge of capacitor in a cycle is the area of the triangle which $I_C > 0$. The charging time of capacitor in a cycle is $\frac{T}{2}$. It has

$$\Delta Q = \frac{1}{2} \frac{I_{max} - I_{min}}{2} \frac{T}{2} = \frac{I_{max} - I_{min}}{8} T \quad (35)$$

The change of capacitor voltage in a cycle is

$$\Delta V_{out} = \Delta V_C = \Delta Q / C \quad (36)$$

Substituting equation (33), (35) into (36), the output voltage ripple is

$$\Delta V_{out} = \frac{I_{max} - I_{min}}{8C} T = \frac{D(1-D)V_{IN}}{8CL} T^2 \quad (37)$$

2.2 Solar Photovoltaics

Solar PV is one of most common RESs which is very suitable in Singapore. As the complicated inner structure of solar PV, there are many kinds of equivalent circuits for it. Figure 2-14 shows one of the equivalent circuits used in this project [31].

Figure 2-14 Equivalent circuit of solar PV

As shown in figure 2-14, the equivalent circuit of solar PV is consist of a current source I_{ph} , a diode D , a shunt resistor R_{SH} and a series resistor R_S . The current through diode D is I_D , which can be expressed as

$$I_D = I_0 e^{q\left(\frac{V_{PV} + I_{PV}R_S}{KT}\right) - 1} \quad (38)$$

Which I_0 is saturation current of diode D , q is the electron charge (1.6×10^{-19}), V_{PV} and I_{PV} are out put voltage and output current of PV respectively, K is Boltzman constant ($1.38 \times 10^{-23} J/K$) and T is temperature of PV.

Therefore, the output current of solar PV is

$$I_{PV} = I_{ph} - I_D - I_{SH} \quad (39)$$

In addition,

$$I_{SH} = \frac{V + I_{PV}R_S}{R_{SH}} \quad (40)$$

Substituting equation (38) and (40) into (39), it has

$$I_{PV} = I_{ph} - I_0 e^{q\left(\frac{V_{PV} + I_{PV}R_S}{KT}\right) - 1} - \frac{V + I_{PV}R_S}{R_{SH}} \quad (41)$$

2.2.1 Maximum Power Point of Solar PV

For a solar PV (model type is SPR-415E-WHT-D), its $I_{PV} - V_{PV}$ curve and $P_{PV} - V_{PV}$ curve at 25°C and 1000W/m² are shown in figure 2-15.

Figure 2-15 $I_{PV} - P_{pv}$ curve and $P_{PV} - V_{PV}$ curve of solar PV

From figure 2-15, solar PV always exists a maximum power point under a specific temperature and irradiation. If solar PV can operate in its maximum power point (MPP) all the time, the utilization efficiency of solar PV is maximum. This operation condition is called maximum power point tracking (MPPT) of solar PV.

MPPT algorithm is aimed to find the MPP of solar PV and maintain this point operation. The principle of this method is making equivalent external resistance R_{eq} match inner equivalent resistance R_{in} of solar PV through controlling down switch of bidirectional DC/DC converter (boost mode). Thus, PV will produce maximum output power. As shown in figure 2-16.

Figure 2-16 The equivalent circuit of solar PV

From figure 2-16, output power of solar PV (P_{PV}) is maximum when $R_{in} = R_{eq}$. When solar PV series a DC/DC converter which operates in boost mode, equivalent external resistance equals to load resistance on input side. It has

$$V_{in} = (1 - D)V_{out} \quad (42)$$

$$I_{in} = \frac{1}{1-D} I_{out} \quad (43)$$

$$R_{eq} = \frac{V_{in}}{I_{in}} \quad (44)$$

$$R_{load} = \frac{V_{out}}{I_{out}} \quad (45)$$

Substituting equation (42), (43) into (44) and (45) It has

$$R_{eq} = (1 - D)^2 R_{load} \quad (46)$$

From equation (46), when load changes with other conditions are constant, MPP operation of solar PVs can be maintained by controlling duty cycle D of switch.

In fact, the maximum power output of solar PV is influenced by many factors. For a given solar PV, the most important factors are temperature and irradiance. Figure 2-17 and 2-18 show influences of temperature and irradiance respectively. The type of solar PV is SunPower SPR – 415E – WHT – D which comes from PV models in MATLAB. Figure 2-17 shows $I_{PV} - V_{PV}$ curve and $P_{PV} - V_{PV}$ curve at 0°C, 25°C and 50°C when irradiance is $1000W/m^2$. With the decrease of temperature, the MPP of solar PV will increase and its corresponding voltage will increase too, but the corresponding current is almost no change.

Figure 2-17 Different temperatures at 1000 W/m^2

Figure 2-18 shows $I_{PV} - V_{PV}$ curve and $P_{PV} - V_{PV}$ curve when irradiance is 1000 W/m^2 , 500 W/m^2 and 100 W/m^2 at 25°C . With increase of irradiance, the MPP of solar PV and corresponding current will increase significantly. However, the increase of corresponding voltage is not obvious.

Figure 2-18 Different irradiances at 25°C

2.3 Operation Modes of Modular DC Micro-grid

The RESs and BES of this modular DC micro-grid are two solar PVs and one battery respectively. This micro-grid has three DC/DC channels, the rated power of each channel is about 2kW. Channel one is used for regulate output voltage with BES, channel two and three are used for power supply with solar PVs. When solar PVs generation is larger than loads consumption, surplus energy is charged into battery. At this time, solar PVs operate in MPPT mode, battery operates in MB mode.

But, battery is fully charged and can not regulate voltage more with further increase of generation. Then, solar PVs change MPPT mode into MB mode to maintain bus voltage in a limited range. At this time, solar PVs and battery both operate in MB modes.

When solar PVs generation is smaller than loads consumption, the lack of energy is provided by battery's discharge. So, channel one with battery operates in MB mode, channel two and channel three with solar PVs operate in MPPT mode. Further, when the lack of energy becomes larger which exceeds capacity of battery, battery can not regulate bus voltage anymore. It should add non-renewable energy source (NRS) to provide lack of energy to loads. At this time, solar PVs operate in MPPT mode, battery operate in MB mode and NRS operates in MB mode.

Considering bus energy matches bus voltage, bus voltage will increase when there is surplus energy in DC bus. If the surplus energy becomes larger, bus voltage will become higher too. Similarly, bus voltage will decrease when there is lack energy in DC bus. If the lack of energy decrease more, bus voltage will become lower. So, the operation modes of solar PVs and BES can be determined according to bus voltage, which is shown in table 2-1.

Table 2-1 Operation modes of the modular DC micro-grid

Bus voltage	Battery	Solar PVs	NRS
V_{h2}	MB	MB	-
V_{h1}	MB	MPPT	-

V_{low1}	MB	MPPT	-
V_{low2}	MB	MPPT	MB

In table 2-1, $V_{h2} > V_{h1} > V_{rated} > V_{low1} > V_{low2}$.

2.4 Closed-loop Control Algorithms

In this project, the modular DC micro-grid connects to a 400V DC bus. It is expected that the high voltage side of the DC micro-grid remains 400V when this modular DC micro-grid is operating. Considering the intermittence of RESs generation, the output voltage (DC bus voltage) will fluctuate if there is no nay control algorithm. Therefore, some control algorithms must be used in order to maintain bus voltage stable. Open-loop control methods are significantly not suitable for this project because the input voltage is unstable. So, closed-loop control methods are taken. Common closed-loop control methods are proportional control (P), proportional-integral (PI) control, proportional-derivative (PD) control and proportional-integral-derivative (PID) control [32].

2.4.1 P Controller

P controller is one of common closed-loop controllers. The main function of P controller is decreasing steady state error. With the increasing of proportional value K, the transient response of system will increase and the rise time will decrease. However, P controller can not eliminate the steady state error. Meantime, with the increasing of proportional value K, system's noise will be amplified and it will produce overshoot. Therefore, P controller can just be used in this kind of system that can tolerate a steady state error.

2.4.2 PI Controller

Compared to P controller, PI controller can eliminate steady state error result from P. However, because of the existence of I, the transient response speed of system will decrease, thus increase the rise time of system. In addition, PI controller can not predict future errors and eliminate oscillations of system. So, PI controller is mostly used in areas where speed of the system is not an issue.

2.4.3 PD Controller

Compared to PI controller, PD controller can increase the stability of system by predicting the future error. So, it can eliminate the oscillation of system. But, due to the PD controller has not the integral part, it has not some advantages of PI controller, like eliminating steady state errors.

2.4.4 PID Controller

Considering their own shortages of PI and PD controller, PID controller have both advantages of PI and PD controllers, such as fast transient response, no oscillations and overshoot, higher stability. But, the total structure of PID controller is more complicated than PI and PD controllers. So, PID controller is mainly used in areas where the requirements of system are very high.

In this project, the main objects are remaining bus voltage stable and zero steady state error. In addition, speed of the DC micro-grid system is not an issue. Therefore, PI controller is chosen as closed-loop control method in this project. The transfer function of PI controller in S-domain is

$$G_{pi}(S) = p + \frac{p_i}{s} \quad (47)$$

Where, p is proportional part in S domain and $\frac{p_i}{s}$ is the integral part in S domain.

Chapter 3 Modular DC Micro-Grid Hardware Setup

The processes of hardware setup are often divided into four steps. The first step is determining the list of components according to this modular DC micro-grid. The second step is purchasing these components from Element 14. The third step is soldering all necessary boards and the last step is checking all boards. The hardware of this modular DC micro-grid is shown in figure 3-1.

Figure 3-1 The hardware of the modular DC micro-grid

From figure 3-1, the hardware of this modular DC micro-grid is made of a main DC/DC converters board, a DSP board, a DSP expansion board, a power supply board and some relative accessory components like fans and cables.

3.1 Power Supply

The power supply of control parts is shown in figure 3-2. There are two input voltage sources: one is +5V DC source, another is $\pm 15V$ voltage source. +5V DC source is mainly used to provide power to digital components like DSP, and $\pm 15V$ voltage source is mainly used to provide power to analog components like LAH 50P (a kind

of current transducer used in this project). CHOKE CM ACM7060-301-2PL is a kind of common mode filter, its main function is eliminating disturbances and noises in circuits.

Figure 3-2 Power supply of control parts

The real components of power supply are shown in figure 3-3. The checking result of power supply will be presented with the result of DSP board.

Figure 3-3 The real components of power supply

3.2 DSP Board

DSP board is very important to control algorithm's implementation. It is the control center of a system. The type of DSP used is TMS320F28335, which is shown in figure 3-4. It must be careful when we are soldering DSP board, the temperature of soldering can not be too high, usually 350°C. Because DSP board is very sensitive and fragile, it will break when soldering temperature is too high.

Figure 3-4 DSP board

Figure 3-5 shows expansion DSP board. The reason why need to add another DSP expansion board is that DSP board in figure 3-4 can just complete some basic functions, which is not sufficient to this project. In DSP expansion board, it has some extra function circuits, such as button circuit, LED circuit, temperature sensor circuit and some filters. The corresponding function circuits can be selected according to projects needs.

Figure 3-5 Expansion circuit board of DSP

After having soldered DSP and DSP expansion boards, the operation performance of them were checked. Figure 3-6 shows results of ADC output when input is zero. For this type of DSP, the total output of ADC is $2^{12} = 4096$. When the input is minimum ($-K_{max}$), the ADC output a 'zero'. When the input is maximum (K_{max}), the ADC output a '4096'. In addition, the absolute values of minimum and maximum values are same. So, ADC output will be $\frac{1}{2} 2^{12} = 2048$ in ideal condition when input is zero. As shown in figure 3-6, ADC output values are between 2054 and 2063. Considering some disturbances and noises existence, the output value is around 2048, which meets this condition. Therefore, the power supply board, DSP and DSP expansion boards were checked to be good.

Expression	Type	Value
(*)= adc_a0	long	2054
(*)= adc_a1	long	2063
(*)= adc_a2	long	2060
(*)= adc_a3	long	2061
(*)= adc_a4	long	2055
(*)= adc_a5	long	2066
(*)= adc_b6	long	2062
(*)= adc_b7	long	2060
+ Add new expression		

Figure 3-6 Test of DSP board when input is zero

3.3 Drive Cards

Drive Card plays an important role in DC/DC converter. An amplified PWM signal can be sent to the gate of IGBT according to Drive Card. In this project, the modular DC micro-grid has three DC/DC channels, each channel has two IGBTs. So, each channel need two Drive Cards. Circuit of one Drive Card is shown in figure 3-7.

Figure 3-7 Drive cards circuit

As having said in chapter 3.1, digital power supply in control parts is only +5V, which is insufficient for activating IGBT. When gate voltage of IGBT is very low, IGBT will operate in linear region and overheat quickly. The rated gate-emitter voltage of IGBT

is about +20V. So, a voltage conversion circuit should be used to convert digital voltage source into +20V. The MGJ2d052005SC in figure 3-5 plays this role, it is a kind of DC/DC converter. LC components in this circuit are mainly used as filters and voltage regulators.

The main function of another circuit in figure 3-7 is providing gate driver signals to IGBT. In this circuit, ACPL333J is a 2.5 Amp output current IGBT Gate Driver Optocoupler. This component has many advantages, such as fault protection, voltage detection, under voltage lockout (UVLO), “soft” IGBT turn off, isolated open collector fault feedback and auto-fault reset. The IXDN609SI is a kind of gate driver. To other components in this circuit, C_1 and C_2 are mainly used to adjust transient response time τ . Equation (48) shows the relation between transient response time τ and C_1 and C_2 .

$$\tau = \sqrt{RC} \quad (48)$$

Except C_1 and C_2 , other LC components in this circuit are mainly used as filters and voltage regulators.

The real components of Drive Cards are shown in figure 3-8. Because each channel need two IGBTs, it has three channels in this modular DC/DC converters. So, the total number of Drive Cards are six.

Figure 3-8 Real component of Drive Cards

After having soldered these drive cards, combining DSP and DSP expansion boards together, the three channels with six IGBTs were checked. Corresponding PWM signals are shown in Figure 3-9. The precision of voltage is $20V/div$ in figure 3-9. So, the output of PWM signals is 20V, which meets the requirement of IGBT gate excitation voltage. From figure 3-9, PMW waveform is not very smooth, the reason is that it is influenced by other no-linear components in the circuits.

Figure 3-9 Test of PWM signals

3.4 Bidirectional DC/DC Converters

The circuit of bidirectional DC/DC converters are shown in figure 3-10. Taking channel one as example, high voltage side is $V_{DC} +$, which is 400V. Low voltage side is 'INDUCTOR1' port. Q_1 and Q_4 are upper switch and down switch respectively. The shunt RC components between GS (Gate and Source) aims to improve performance of input PWM signals. These bidirectional diodes like D_{13} , D_{19} are mainly used to limit voltage between DG (Drain and Gate), and other bidirectional diodes like D_{22} , D_{25} are used to limit voltage between GS (Gate and Source). Principle of bidirectional diode is that the diode will break down when applied voltage between diode arrives its breakdown voltage. After bidirectional diode have broken down, it will maintain the breakdown voltage constant. Diode like D_{16} series a resistor which is used to avoid switch like Q_1 being broken down. The main function of other capacitors is used as filters.

Figure 3-10 Circuit of bidirectional DC/DC converters

From the left circuits of figure 3-11, low voltage side series an inductor and connects a LAH 50P, which is a current transducer. From right circuits of figure 3-11, high voltage side shunt a capacitor of $470\mu F$ and low side shunt a capacitor of $10\mu F$. Other capacitors is mainly used as filters and voltage regulators.

Figure 3-11 Circuits in both low and high voltage sides

Figure 3-12 shows three series inductors added into low voltage side. You must be careful when you are making it, because any incorrect winding method will cause undesirable inductor value. According to use special inductor measurement device, we measured its value is $700\mu H$, which is shown in Figure 3-13.

Figure 3-12 Series inductor added between plugs in low voltage side

Figure 3-13 Inductor measurement device

The real bidirectional DC/DC converters board is shown in figure 3-14. When we are soldering, it will be better from small components to large components. Because it will take significant influences to small components' soldering if large components are soldered firstly. On the contrary, it will cause less effect to large components if small components are soldered firstly. What is more, the costs of large components are usually higher, it must be ensured that all small components are soldered well firstly, then large components can be soldered.

Figure 3-14 Real three phases bidirectional DC/DC converters board

Except these important devices, there are other necessary components need to be soldered. Such as different kinds of cables and power switches. Their soldering also need to be careful.

In total, soldering work is a dangerous work. Therefore, we must be careful when we are soldering, which is not only to ensure the safety of devices, but also in order to ensure the safety of people.

Chapter 4 Control Algorithms

After having completed hardware setup, next step is studying control algorithms. In this modular DC micro-grid, there are three channels in DC/DC converters. Channel one connects battery, channel two and channel three connect solar PVs. From table 2-1 we know channel one operates in MB mode, channel two and three operate in MPPT mode and MB mode. In order to let the two operation modes can be checked, we let channel one with battery operate in MB mode, channel two and channel three with solar PVs operate in MPPT mode. After having checked each channel's control algorithm, modular control algorithms with battery and solar PVs together were studied. Finally, characteristics of the modular control algorithm were obtained.

4.1 MB Control Algorithm

In the modular DC micro-grid, when solar PVs generation is larger than loads consumption, surplus energy will be charged into battery from DC bus. Oppositely, when solar PVs generation is smaller than loads consumption, lack of energy will be discharged by battery. So, channel one with battery acts as the role of maintaining bus voltage stable. In order to maintain bus voltage stable, there are many control algorithms, such as PI control, PID control etc. An excellent control algorithm can take good results to the whole system. In the contrary, the performance of a system may be bad if the system operates without any control algorithm.

4.1.1 Channel One's Operation without Any Controller

Figure 4-1 shows the MATLAB simulation model of channel one without any controller. Sampling time is $5 \times 10^{-7} s$. From chapter three, it has $C_{high} = 470 \mu F$, $C_{low} = 10 \mu F$, $L = 700 \mu H$, switching frequency is $100 KHz$. The equivalent series resistance (ESR) of both capacitors is chosen as 0.1Ω .

In channel one, DC bus is output side, which can be equal to a load resistor. Considering rated power of each channel is about $2 kW$, load resistance is taken as $\frac{400^2}{2 kW} = 80 \Omega$. The operation mode of channel one is boost mode when battery discharges to loads. So, the upper switch acts as a diode and the down switch acts as a switch. Duty cycle of down switch is duty cycle of channel one. Table 4-1 shows some

parameters of battery model used in this project. The nominal voltage of battery is 200V, DC bus voltage is 400V. Duty cycle is chosen as $D = 1 - \frac{V_{in}}{V_{out}} = 1 - \frac{200}{400} = 0.5$.

Table 4-1 Parameters of battery

Type	Nominal voltage (V)	Fully charged voltage (V)	Rated capacity (Ah)	Initial state-of-charge (%)
Nickel-Metal-Hydrde	200	235.5932	6.5	100

Figure 4-1 MATLAB simulation model of channel one without any controller

The steady state response and transient state response simulation results of output voltage is shown in figure 4-2a and figure 4-2b respectively.

Figure 4-2a Steady state response

Figure 4-2b Transient state response

Figure 4-2 output voltage waveform without controller

From the figure 4-2a, the maximum voltage value in steady state is 513.5V, and the minimum steady state value is 512.1V. The average voltage is 512.8V, which is far away from ideal bus voltage 400V. The reason why cause significant steady state error are no closed-loop control algorithms. In transient state, overshoot is very high. What is more, figure 4-3a and figure 4-3b shows input current waveform and output current waveform respectively.

Figure 4-3a Input current waveforms

Figure 4-3b Output current waveforms

Figure 4-3 Current waveforms without controller

From figure 4-3a and figure 4-3b, average values of input current and output current are 14.30A and 6.41A respectively. The ideal average value of output current is 10A. Therefore, in order to eliminate steady state error and overshoot of the system, PI controllers should be added into channel one.

4.1.2 Channel One's Operation with PI Controller

Figure 4-4 shows the simulation model of channel one with PI controllers. In order to eliminate transient overvoltage when start the channel, LC components in channel one are pre-charged. Thus, initial condition values of LC components are not zero.

Figure 4-4 Simulation model of channel one with PI controllers.

As shown in figure 4-4, two PI controllers are used as double closed-loop feedback control. The inner loop control is inductor current control and the external loop control is output voltage control. Feedback value of external loop is used as reference current value of inner loop. The reason why adds another PI controller to control inductor current is that it can help improve performance of output voltage. For example, when output voltage is low, inductor current can be increased to step up output voltage. When output voltage is high, inductor current can be decreased to step down output voltage. After having conducted multiple attempts, the best PI values of inner controller were $P_{ii} = 1$, $I_{ii} = 50$ and PI values of external controller were $P_{ev} = 0.1$, $I_{ev} = 5$. It must be careful when values of PI controller are chosen. Because too large or too small PI values will cause abnormal conditions, which it has talked about in

Chapter 2. Usually, PI values of external loop are smaller than PI values of inner loop, because response speed of inner loop is required to be faster than external loop.

The PWM waveform and voltage feedback loop output value of channel one are shown in figure 4-5a and figure 4-5b respectively. After adding PI controllers, it can be seen from figure 4-5 that the duty cycle is 0.422 and average value of voltage loop output value is 8.605A, which is the average value of inductor current.

Figure 4-5a PWM waveform

Figure 4-5b Voltage loop output value

Figure 4-5 PWM waveform

Figure 4-6 shows output voltage waveforms. Steady state waveform is shown in figure 4-6a and the transient state waveform is shown in figure 4-6b.

Figure 4-6a Steady state waveform

Figure 4-6b Transient state waveform

Figure 4-6 Output voltage waveforms

From figure 4-6a, average value of output voltage is 400V, the maximum value is 400.4V and the minimum value is 399.5V, which is very closed to ideal output value. From figure 4-6b, there is no overshoot in transient response. In addition, figure 4-7a and figure 4-7b also show output current and input current waveforms.

Figure 4-7a Output current waveform

Figure 4-7b Input current waveform

Figure 4-7 Current waveforms

From figure 4-7, the average value of output current is 5A and the average value of inductor current is 8.607A. The steady state errors and fluctuations of output and input current are very smaller than no PI controllers.

4.1.3 Load's Influences to DC Bus

In order to study load's influences to DC bus, load resistance is divided into 80 Ω , 200 Ω and 500 Ω respectively. The simulation results are shown in table 4-2.

Table 4-2 Load's influence to DC bus

R_{load}/Ω	V_{out}/V	I_{out}/A	I_{in}/A	D
80	400	5	8.607	0.422
200	400	2	3.424	0.415
500	400	0.8	1.375	0.410

From table 4-2, output voltage remain 400V with increase of load resistance. Therefore, load variation will not effect output voltage value. However, output current and input current decrease with the increase of load resistance. Duty cycle is almost the same.

On the whole, the double closed loop control algorithm will improve channel one's performance well when channel one operates in MB mode with two PI controllers.

4.2 MPPT Control Algorithms

Compared to other RESs, the equivalent circuit of solar PVs is special. It can be equivalent to a constant current source shunt a diode and resistor then series another resistor, which is shown in figure 2-14. The $I_{PV} - V_{PV}$ curve and $P_{PV} - V_{PV}$ curve of solar PV are shown in figure 2-15. From figure 2-15, it must exist a MPP for a given solar PV. If a solar PV can always operate in its MPP as power supply, then this operation mode is called MPPT mode. The corresponding voltage value and current value are called V_{max} and I_{max} respectively.

The most challenging work of MPPT implementation is that there is no constant reference value when environment is various. After having seen some relative papers, a method named Perturb & Observe was found to solve this problem. The logic diagram of Perturb & Observe method is shown in figure 4-8.

Figure 4-8 The logic diagram of Perturb & Observe method

The first step is measuring output current and output voltage of solar PVs at time $K=1$, then calculating corresponding output power of solar PVs through $P_{PV}(k) = V_{PV}(k) * I_{PV}(k)$. The following step is using memory components to memory values of $P_{PV}(k-1)$ and $V_{PV}(k-1)$ in the last sampling time so that voltage and power changes during a cycle can be got, which are $\Delta V = V(k) - V(k-1)$ and $\Delta P =$

$P(k) - P(k - 1)$. The next step is judging the value of ΔP , if $\Delta P > 0$, output '1', others, output '0'. Then, system update value of $D(k)$ by judging the value of ΔP and ΔV through the judge principle which is shown in table 4-3.

Table 4-3 Judge principle of Perturb & Observe method

$\Delta P(k)$	$\Delta V(k)$	$D(k)$	Next perturbation direction
$\Delta P(k) > 0$	$\Delta V(k) > 0$	$D(k-1) + \Delta D(k)$	Positive
$\Delta P(k) > 0$	$\Delta V(k) < 0$	$D(k-1) - \Delta D(k)$	Negative
$\Delta P(k) < 0$	$\Delta V(k) > 0$	$D(k-1) - \Delta D(k)$	Negative
$\Delta P(k) < 0$	$\Delta V(k) < 0$	$D(k-1) + \Delta D(k)$	Positive

From table 4-3, when $\Delta P(k) > 0 \& \Delta V(k) > 0$ or $\Delta P(k) < 0 \& \Delta V(k) < 0$, $D(k) = D(k - 1) + \Delta D(k)$. The next perturbation direction will be positive. However, when $\Delta P(k) > 0 \& \Delta V(k) < 0$, or $\Delta P(k) < 0 \& \Delta V(k) > 0$, $D(k) = D(k - 1) - \Delta D(k)$. The next perturbation direction will be negative. After updated $D(k)$, let $k=k+1$ and feedback new k to start side. A new cycle will continue until $\Delta P(k)=0$, then P_{max} is found. Figure 4-9 shows MATLAB simulation model of Perturb & Observe algorithm.

Figure 4-9 MATLAB simulation model of Perturb & Observe algorithm

In order to get good control performances, another PI inductor current controller was added into control system. Output value of MPPT controller is used as reference current value of inductor current. The reason why PI inductor current controller can improve performances of system is that control of inductor current is better than control of solar PVs output power. Figure 4-10 shows the whole MATLAB simulation model of channel two.

Figure 4-10 MATLAB simulation model of channel two

From chapter two, MPP of solar PVs are influenced by many factors. The most common factors are types and quantities of PV, temperature and irradiance. We first studied influences of types and quantities, then studied effects of temperature and finally studied effects of irradiance.

4.2.1 Influences of Types and Quantities

Different types of PV modular have different electrical characteristics. Table 4-4 shows some PV's electrical parameters per module in MATLAB. In the analysis of following chapters, Sun Power SPR-415-WHT-D model is chosen as project's solar PVs model.

Table 4-4 Some PV array's electrical parameters

Types	Cells /module	P_{max} /W	V_{max} /V	I_{max} /A	I_0/A	R_{SH}/Ω	R_S/Ω
SunPower SPR-415- WHT-D	128	414.801	72.9	5.69	7.1712×10^{-13}	419.7813	0.5371
Sun Energy Engineering SE14-50	14	52.0372	8.62	7.79	4.3144×10^{-10}	422.3191	0.1172
Suniva OPT255-60-4- 700	60	254.888	30.2	8.44	9.0522×10^{-10}	160.0882	0.3158

In order to study influences of solar PV's quantity to output power, four-series-PV modules and five-series-PV modules was conducted respectively. Remain other conditions constant: irradiance $1000W/m^2$, temperature $25^\circ C$.

Case 1 four-series-PV modules

Reference Values: $P_{max} = 1650W$, $V_{max} = 291.6V$, $I_{max} = 5.69A$

Simulation Results: $P_{max} = 1651W$, $V_{max} = 291.7V$, $I_{max} = 5.66A$

Figure 4-11a Reference Values

Figure 4-11b Simulation results

Figure 4-11 Waveforms in four-series-PV modules

Case 2 five-series-PV modules

Reference Values: $P_{max} = 2073W$, $V_{max} = 364.5V$, $I_{max} = 5.69A$

Simulation Results: $P_{max} = 2071W$, $V_{max} = 364.6V$, $I_{max} = 5.68A$

Figure 4-12a Reference Values

Figure 4-12b Simulation results

Figure 4-12 Waveforms in five-series-PV modules

From case 1 and case 2, the quantities of PV module is proportional with MPP of solar PVs. So, if we want to increase MPP of solar PVs, one of most efficient ways is adding more PV modules into system.

4.2.2 Effects of Temperature

From chapter two, solar PVs have different $P_{PV} - V_{PV}$ curve and $I_{PV} - V_{PV}$ curve in different temperatures. In order to study influences of temperature to PVs, we conducted MPPT simulation in different temperatures. Remaining five-series-PV modules in $1000W/m^2$ irradiance.

Case 1 $T = 50^\circ C$

Reference Values: $P_{max} = 1932 W$, $V_{max} = 338.7V$, $I_{max} = 5,70A$

Simulation Results: $P_{max} = 1928W$, $V_{max} = 338.5V$, $I_{max} = 5.70A$

Figure 4-13a Reference Values

Figure 4-13b Simulation results

Figure 4-13 Waveforms in $T = 50^{\circ}\text{C}$

Case 1 $T = 25^{\circ}\text{C}$

Reference Values: $P_{max} = 2073\text{W}$, $V_{max} = 364.5\text{V}$, $I_{max} = 5.69\text{A}$

Simulation Results: $P_{max} = 2071\text{W}$, $V_{max} = 364.6\text{V}$, $I_{max} = 5.68\text{A}$

Figure 4-14a Reference Values

Figure 4-14b Simulation results

Figure 4-14 Waveforms in $T = 25^{\circ}\text{C}$

Case 1 $T = 0^{\circ}\text{C}$

Reference Values: $P_{max} = 2213\text{W}$, $V_{max} = 390.7\text{V}$, $I_{max} = 5.66\text{A}$

Simulation Results: $P_{max} = 2211\text{ W}$, $V_{max} = 390.7\text{V}$, $I_{max} = 5.66\text{A}$

Figure 4-15a Reference Values

Figure 4-15b Simulation results

Figure 4-15 Waveforms in $T = 0^{\circ}\text{C}$

$P_{PV} - V_{PV}$ curve and $I_{PV} - V_{PV}$ curve were measured when $T = 50^{\circ}\text{C}$, 25°C , 0°C respectively. From these results, MPP of solar PVs will increase with the decrease of temperature when other conditions are constant. Except it, the MATLAB simulation results matched ideal curves of solar PVs well.

4.2.3 Effects of Irradiance

Except quantities of solar PV and temperature, irradiance also can effect solar PVs. In order to study effects of irradiance to solar PVs, solar PVs research was conducted when irradiance are $1000\text{W}/\text{m}^2$, $500\text{W}/\text{m}^2$, $100\text{W}/\text{m}^2$, $0\text{W}/\text{m}^2$ respectively. Remaining five-series-PV modules in 25°C .

Case 1 $1000\text{W}/\text{m}^2$

Reference Values: $P_{max} = 2073\text{W}$, $V_{max} = 364.5\text{V}$, $I_{max} = 5.69\text{A}$

Simulation Results: $P_{max} = 2071\text{W}$, $V_{max} = 364.6\text{V}$, $I_{max} = 5.68\text{A}$

Figure 4-16a Reference Values

Figure 4-16b Simulation results

Figure 4-16 Waveforms in 1000W/m²

Case 2 500W/m²

Reference Values: $P_{max} = 1031W$, $V_{max} = 361.7V$, $I_{max} = 2.85A$

Simulation Results: $P_{max} = 1030W$, $V_{max} = 362.5V$, $I_{max} = 2.84A$

Figure 4-17a Reference Values

Figure 4-17b Simulation results

Figure 4-17 Waveforms in 500W/m²

Case 3 $100W/m^2$

Reference Values: $P_{max} = 197.0\text{ W}$, $V_{max} = 345.6V$, $I_{max} = 0.57A$

Simulation Results: $P_{max} = 182.5W$, $V_{max} = 310.9V$, $I_{max} = 0.59A$

Figure 4-18a Reference Values

Figure 4-18b Simulation results

Figure 4-18 Waveforms in $100W/m^2$

After having conducted these experiments, MPP of solar PVs will decrease with the decrease of irradiance, corresponding V_{max} and I_{max} also will decrease. However, the MATLAB simulation results may not match reference values when irradiance decrease too much. Because solar PVs are not ideal constant current source, their inner structures are very complicated, some disturbances can not be ignored when irradiance is too small. What is more, when irradiance is zero, solar PVs have zero output power, which is different from the condition when temperature is zero.

4.2.4 Load Influences to System

Usually, the value of load resistance has no influence to MPP of solar PVs. It just effects system's output in DC bus. The rated power of each channel is about 2kW, rated voltage is 400V. So, rated load resistance is 80Ω . Load resistances was changed from 80Ω , 200Ω to 500Ω respectively, solar PV's output and system's output are shown in table 4-5.

Table 4-5 Load influences to system

R/Ω	P_{PV}/W	V_{PV}/V	I_{PV}/A	Duty	V_{out}/V	I_{out}/A
80	2061	366.3	5.63	0.1	404.7	5.06
200	2068	364.8	5.67	0.43	629.5	3.20
500	2071	364.6	5.68	0.53	952.9	2.02

From table 4-5, considering some disturbances and accuracy of measurement, the variation of solar PV's MPP can be neglected with increase of load resistance. However, corresponding duty cycle D and system output voltage V_{out} will increase and system output current I_{out} will decrease with the increase of load resistance R .

In total, solar PV's MPP is influenced by many factors. Types and quantities of solar PV, temperature and irradiance are common factors. Although load resistance can not influence MPP of solar PVs, it can effect system's duty cycle then effect output voltage and output current of system. What is more, it can not ensure bus voltage remain 400V all the time when channel two and channel three operate in MPPT mode. But, DC bus voltage is expected to remain stable all the time. In order to make bus voltage remain 400V when solar PVs operate in MPPT in this project, a modular DC micro-grid control algorithm was proposed in chapter 4.3.

4.3 Modular DC Micro-Grid Control Algorithm

Chapter 4.1 and 4.2 have told about MB control algorithm and MPPT control algorithm respectively. Bus voltage can be maintained by channel one with the battery. Channel two and channel three supply power to DC bus by MPPT of solar PVs. This chapter will talk about the modular operation of DC micro-grid with RESs and BES together. Usually, RESs are used as the first use power supply in a modular DC micro-grid. Because the generation cost of RESs is zero if we do not consider maintenance cost and initial cost. What is more, RESs are clean and environmental friendly compared to traditional fossil fuels, which are often used as NRSs. BES is used as backup energy and voltage regulator next. NRS can be used last when the total

generation of RESs and BES is smaller than load consumption in order to maintain power balance and bus voltage. Table 2-1 shows the operation modes of RESs, BES, and NRSs. From table 2-1, solar PVs operation mode changed MB mode from MPPT mode when bus voltage increased to V_{high2} , and NRS operation mode changed MB when bus voltage decreased to V_{low2} . In this project, the rated voltage of DC bus is 400V, boundary voltage V_{high1} is chosen as 420V and V_{low2} is 300V. In fact, the generation power supplies of this project are only RESs and BES. So, it is not been considered when bus voltage decreases below $V_{low2} = 300V$. The operation modes of RESs and BES in modular operation condition are shown in table 4-4.

Table 4-6 Operation modes of RESs and BES in modular operation condition

Bus voltage	Battery	Solar PVs
$V_{h2} > 420V$	MB	MB
$V_{h1} = 420V$	MB	MPPT
$V_{low1} = 300V$	MB	MPPT

The corresponding control algorithms of modular DC micro-grid is shown in figure 4-19.

Figure 4-19 Control algorithms of modular DC micro-grid

From figure 4-19, channel one operates in MB1 mode with battery charging by DC bus, at this time, MB4 mode are out of service because bus voltage V_{out} is larger than 400V. However, channel one operates in MB4 mode with battery discharging to DC bus, at this time, MB1 mode are out of service because bus voltage V_{out} is smaller than

400V. Channel two and channel three operate in MPPT mode when bus voltage V_{out} is smaller than 420V. Their operation mode changes MB mode from MPPT mode when bus voltage V_{out} is larger than 420V, reference voltage of solar PVs operating in MB mode is set as 420V. The total MATLAB simulation model is shown in figure 4-20.

Figure 4-20 Total MATLAB simulation model

In figure 4-20, in order to check the modular DC micro-grid can operate well during some external factors variation, irradiance is set as $1000W/m^2$ at start, $500W/m^2$ at 0.35s and $100W/m^2$ at 0.7s. Temperature is $25^\circ C$. Considering rated power of each channel is about 2kW and total rated power is 6kW, load resistor is set as $R_{load} = \frac{400^2}{6000} \approx 30\Omega$. Other conditions remain constant. Figure 4-21 shows bus voltage curve under MATLAB simulation. Figure 4-22 and 4-23 show some solar PVs waveforms and battery waveforms. Figure 4-24 shows MPP waveforms of solar PVs in different irradiances.

Figure 4-21 Bus voltage waveform

Figure 4-22 Solar PVs waveform

Figure 4-23 Inductor current of channel 1 Figure 4-24 MPP in different irradiance

From figure 4-21, 4-22 and 4-23, bus voltage remains 400V when irradiance is $1000\text{W}/\text{m}^2$ during 0~0.35s. At that time, $P_{pv_max} = 2059\text{W}$, $V_{max} = 364.4\text{V}$, $I_{max} = 5.63\text{A}$. From figure 4-24, solar PVs can be proved to operate in MPPT mode and battery operates in MB modes. When irradiance decreases to $500\text{W}/\text{m}^2$ at 0.35s, power generation of solar PVs start to decrease, which will be smaller than loads

consumption. At that time, the battery discharges to DC bus in order to maintain power balance and prevent bus voltage decrease. So, bus voltage back to 400V again. When irradiance is $500W/m^2$, $P_{pv_max} = 1025W$, $V_{max} = 363.3V$, $I_{max} = 2.823A$. Solar PVs operate in MPPT mode. Inductor current of channel one is larger than zero, which means battery discharging to DC bus during the time. When irradiance further falls to $100W/m^2$, power generation of solar PVs will further decrease, which will be smaller than loads consumption again. At the time, battery discharges to DC bus so as to maintain power balance and bus voltage stable. Therefore, bus voltage increases to 400 again. When irradiance is $100W/m^2$, $P_{pv_max} = 179.3W$, $V_{max} = 343.2V$, $I_{max} = 0.528A$. Solar PVs operate in MPPT mode. Inductor current of channel one increase from 0.7s, which means battery discharging more energy to DC bus during the time.

In total, bus voltage can remain stable all the time with the effect of MB mode, solar PVs can supply maximum power under operating in MPPT mode. However, bus voltage's stable is a problem in a modular DC micro-grid when integrating solar PVs and BES together. Modular DC micro-grid control algorithms solved this problem well. It can maintain bus voltage stable when solar PVs operates in MPPT mode. Therefore, whole DC micro-grid reliability is improved.

Chapter 5 Conclusion and Recommendations

5.1 Conclusion

With the development of DC power electronic devices and distribution generation system, DC micro-grid is becoming more and more popular than conventional AC system. Compared to traditional AC grid, the conversion efficiency of DC micro-grid is higher. Except it, DC micro-grid uses RESs, which have many advantages. Firstly, RESs are clean and sustainable energy, it has less pollution compared to traditional fossil fuels. Secondly, RESs are often located in distribution networks, which has less transmission loss compared to conventional centralized AC system. It also can operate in isolation state when the utility grid is outage because of the existence of RESs. Thirdly, the cost of RESs generation is zero if maintenance cost and initial generation cost are not considered.

However, RESs generation is usually intermittent, there are also many LC components in DC micro-grid. In order to increase system's reliability, a modular DC micro-grid integrating RESs and ESS together is proposed. In this modular DC micro-grid, ESS is added into the system in order to maintain power supply stable. When power generation of RESs is larger than load consumption, surplus energy is charged into ESS. When power generation of RESs is smaller than load consumption, lack of energy is discharged by ESS. Thus, bus voltage can be constant with collaborative operations of RESs and ESS. Except it, multiple DC/DC converters share a set of LC components in a modular DC micro-grid, which increases the utilization of LC components and reduce cost and size of them.

In this project, solar PVs and BES are chosen as RESs and ESS respectively. It has two operation modes for a modular DC micro grid. One is MB mode. Another is MPPT mode. The modular DC micro-grid has three channels. Channel one is used for MB mode with battery. Channel two and channel three are often used for MPPT mode with solar PVs. Firstly, double closed-loop PI control method is used as MB algorithm in channel one. The inner loop is inductor current loop and the external loop is bus voltage loop. From the independent operation of channel one, this kind of control algorithm can remain DC bus voltage stable well. Secondly, improved perturbation &

observe method is used as MPPT algorithm in channel two and channel three. Considering current control effect is better than power control effect, an extra inductor current PI controller is added into the control system. After having confirmed each channel can operate well, a modular DC micro-grid control algorithm is proposed lastly. According to this control method, bus voltage can remain stable when solar PVs operate in MPPT mode, which improves reliability and stability of the whole system.

5.2 Recommendations for Future Research

Until now, we have studied design and layout of DC/DC converters, setup of DC micro-grid hardware, double closed-loop PI control method, perturbation & observe control method and modular DC micro-grid control method. For future works, I plan to conduct from the following aspects:

In hardware

- 1) Increasing the capacity of the modular DC micro-grid. Rated power of the modular DC micro-grid is just 6kW now, which is not sufficient to provide power to the large load.
- 2) Improving circuits structure in order to get better PWM signals and output voltage waveform.

In software

- 1) Using different MPPT algorithm. Perturbation & observe control algorithm can not make output voltage constant in rated voltage value. It will fluctuate around rated voltage, which can not meet the high requirement of some loads to the voltage supply.
- 2) Using different modular DC micro-grid control algorithms in order to get better bus voltage waveforms and transient response.

References

- [1] Anand, Sandeep, and B. G. Fernandes. "Optimal voltage level for DC micro-grids." IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society. IEEE, 2010.
- [2] Lai, Ching-Ming, Ching-Tsai Pan, and Ming-Chieh Cheng. "High-efficiency modular high step-up interleaved boost converter for DC micro-grid applications." Industry Applications, IEEE Transactions on 48.1 (2012): 161-171.
- [3] Duan, Qing, et al. "A novel power electronic transformer development and demonstration for distribution system." Industrial Electronics Society, IECON 2015-41st Annual Conference of the IEEE. IEEE, 2015.
- [4] Anand, Sruthy, and B. G. Fernandes. "Reduced-order model and stability analysis of low-voltage DC micro-grid." Industrial Electronics, IEEE Transactions on 60.11 (2013): 5040-5049.
- [5] Blaabjerg, Frede, and Josep M. Guerrero. "Smart grid and renewable energy systems." Electrical Machines and Systems (ICEMS), 2011 International Conference on. IEEE, 2011.
- [6] Baer, Jose T., Bill C. Davis, and Richard J. Blanyer. "Battery management system." U.S. Patent No. 5,701,068. 23 Dec. 1997.
- [7] Hartono B S, Budiyanto Y, Setiabudy R. Review of micro-grid technology[C] Quality in Research, 2013 International Conference on. IEEE, 2013: 127-132.
- [8] Darwish A, Holliday D, Ahmed S, et al. A single-stage three-phase inverter based on Cuk converters for PV applications[J]. Emerging and Selected Topics in Power Electronics, IEEE Journal of, 2014, 2(4): 797-807.
- [9] Erickson R, Madigan M, Singer S. Design of a simple high-power-factor rectifier based on the fly back converter[C]. IEEE Applied Power Electronics Conference. 1990: 792-801.
- [10] Tan F D. The forward converter: from the classic to the contemporary[C] Applied Power Electronics Conference and Exposition, 2002. APEC 2002. Seventeenth Annual IEEE. IEEE, 2002, 2: 857-863.

- [11] Wang B, Venkataramanan G, Illindala M. Operation and control of a dynamic voltage restorer using transformer coupled H-bridge converters[J]. Power Electronics, IEEE Transactions on, 2006, 21(4): 1053-1061.
- [12] Blaabjerg F, Ma K. Future on power electronics for wind turbine systems[J]. Emerging and Selected Topics in Power Electronics, IEEE Journal of, 2013, 1(3): 139-152.
- [13] Alam M J E, Muttaqi K M, Sutanto D. Distributed energy storage for mitigation of voltage-rise impact caused by rooftop solar PV[C]. Power and Energy Society General Meeting, 2012 IEEE. IEEE, 2012: 1-8.
- [14] Benemann J, Chehab O, Schaar-Gabriel E. Building-integrated PV modules[J]. Solar Energy Materials and Solar Cells, 2001, 67(1): 345-354.
- [15] Hernandez R R, Easter S B, Murphy-Mariscal M L, et al. Environmental impacts of utility-scale solar energy[J]. Renewable and Sustainable Energy Reviews, 2014, 29: 766-779.
- [16] <http://electronicsb2b.efytimes.com/bright-future-ahead-for-rooftop-solar-pv-systems-market>.
- [17] https://www.google.com.sg/search?q=the+building-integrated+solar+PVs&client=safari&rls=en&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjh-tjTysfMAhWOH44KHW5GAHUQ_AUIBygB&biw=919&bih=666.
- [18] http://www.pv-magazine.com/news/details/beitrag/india--72-gw-of-utility-scale-solar-plausible-in-fy-2016-17_100022729/
- [19] De Brito, Moacyr Aureliano Gomes, et al. "Evaluation of the main MPPT techniques for photovoltaic applications." Industrial Electronics, IEEE Transactions on 60.3 (2013): 1156-1167.
- [20] Jaesoon K I M. Energy storage system: U.S. Patent 9,160,178[P]. 2015-10-13.
- [21] https://www.google.com.sg/search?q=Electrical+energy+storage+systems&client=safari&rls=en&source=lnms&tbm=isch&sa=X&ved=0ahUKEwio1vrEy8fMAhUCUI4KHZLgBngQ_AUIBygB&biw=919&bih=666.

- [22] https://www.google.com.sg/search?q=Different+applications+of+ESS&client=safari&rls=en&source=lnms&tbn=isch&sa=X&ved=0ahUKEwjfqSLzMfMAhWNV o4KHXDwCH8Q_AUIBygB&biw=919&bih=666.
- [23] Jordan H E, Herbst J D, Caprio M T, et al. High speed induction motor and inverter drive for flywheel energy storage[J]. CEM Publications, 2015.
- [24] An K H, Kim W S, Park Y S, et al. Electrochemical properties of high-power super capacitors using single-walled carbon nanotube electrodes[J]. Advanced functional materials, 2001, 11(5): 387-392.
- [25] Wu C J, Lee Y S. Application of superconducting magnetic energy storage unit to improve the damping of synchronous generator[J]. Energy Conversion, IEEE Transactions on, 1991, 6(4): 573-578.
- [26] Yang, Chi-Jen, and Robert B. Jackson. "Opportunities and barriers to pumped-hydro energy storage in the United States." Renewable and Sustainable Energy Reviews 15.1 (2011): 839-844.
- [27] Madlener, Reinhard, and Jochen Latz. "Economics of centralized and decentralized compressed air energy storage for enhanced grid integration of wind power." Applied Energy 101 (2013): 299-309.
- [28] Fitzgerald W V. Switch mode power supply: U.S. Patent 6,504,733[P]. 2003-1-7.
- [29] Denholm P, Ela E, Kirby B, et al. The role of energy storage with renewable electricity generation[J]. 2010.
- [30] Claessens J M T L, Nijhof E B G. DC-to-DC converter: U.S. Patent 7,202,641[P]. 2007-4-10.
- [31] Liu X, Wang P, Loh P C. A hybrid AC/DC micro-grid and its coordination control[J]. Smart Grid, IEEE Transactions on, 2011, 2(2): 278-286.
- [32] Ang K H, Chong G, Li Y. PID control system analysis, design, and technology[J]. Control Systems Technology, IEEE Transactions on, 2005, 13(4): 559-576.