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**DESIGN ISSUES OF HYBRID POWER SUPPLY
SYSTEMS**

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SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

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DESIGN ISSUES OF HYBRID POWER SUPPLY SYSTEMS

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LIST OF ACRONYMS

Bat	Battery
BMS	Battery Management System
BPOM	Battery Power Only Mode
CCM	Continuous Conduction Mode
CM	Close Mode
DC	Direct Current
DSHC	Duel Sources Hybrid Convertor
DSP	Digital Signal Processor
E-bike	Electric Bike
ESD	Energy Storage Devices
E-load	electronic load
ESS	Energy Storage System
EV	Electric Vehicle
FCCLM	Fuel Cell Current Limit Mode
FC	Fuel Cell
FCPOM	Fuel Cell Power Only Mode
FCOLLM	Fuel Cell Over Load Limit Mode
FCLLLM	Fuel Cell Light Load Limit Mode
FCLLNM	Fuel Cell Light Load No-limit Mode
KVL	Kirchhoff's Voltage Laws
KCL	Kirchhoff's Current Laws
LDM	Load Disconnected Mode
Li	Lithium
MIHC	Multiple Input Hybrid Converter
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PWM	Pulse Width Modulation
PI	Proportional Integral
PV	Photo-Voltaic
SOC	State of Charge
SOH	State of Health
SPFC	Solid Polymer Fuel Cell
SM	Standby Mode
UC	Ultracapacitor

ABSTRACT

With increasing concerns of energy crisis, renewable energies such as photovoltaic generation, wind energy and fuel cell have caused great attention to researchers and engineers. However, such energy systems -cannot satisfy users' need individually resulted from the effect of environment or dynamic response, etc. Hybrid power supply systems have been widely studied and considered as a promising solution, which have been extensively used on portable electronics, hybrid electric vehicles, photovoltaic generation substation, etc. These hybrid power supply system make the best use of their operating characteristics, and obtain higher efficiencies than those systems which consist of a single power source. But these hybrid power supply systems' topologies are in parallel and many power converters are used; this may result to the intricateness of the controller and decrease the system's stability.

In this thesis, a Multiple Input Hybrid Converter (MIHC) topology is proposed. The small signal modeling of the MIHC was built in the study. The energy management strategy for the MIHC, which has considered the actual vehicle operation cases and the most serious situation, was also developed. Based on MATLAB/SIMULINK, the proposed topology is simulated. In Chapter 4, a testing platform of PEM fuel cell/battery hybrid power supply system for the proposed MIHC topology is developed to verify the correctness of the presented theory and design. The simulation and experimental results have shown the feasibility and priority of the proposed MIHC topology. In the advanced research, a modified MIHC is developed to achieve regenerative function. To validate the practical performance of the proposed topology, a hybrid system with battery and ultra-capacitor as power sources, is developed and applied on an electric bicycle based on the modified MIHC. In order to improve the performance of the battery stack's discharge capacity and prolong its lifetime, a battery equalization system is also studied and applied in the simulation and experiment setup.

As can be seen from the fourth chapter's experiment results, the fuel cell current could be controlled at nearly constant when the load varied in a large

range. The battery provided the extra-current for the load, which firmly validated that the low dynamic response characteristic of fuel cell can be compensated and its efficiency will be improved with the MIHC. Additionally, it also proved MIHC's effectiveness to combine the characteristics of different sources together with a proper control strategy. In the advanced research, the battery charge current is controlled at a limited range ($<3\text{A}$). Most of the regenerative current is absorbed by the ultra-capacitor. In this way, the battery can be prevented from inrush charge current damage and lifetime will be prolonged. Moreover, the hybrid power supply system can recycle more energy during regenerative braking. The battery equalization system can significantly compensate the SOC and capacity difference between the cells and improve stack's charge and discharge efficiency.

CHAPTER 1 Introduction

1.1 Background

Renewable energy sources (solar, wind, tidal, fuel cells, etc.) are attracting more attention as alternative energy sources as conventional fossil-fuel energy sources are diminishing and worldwide environmental concerns about global warming and acid deposition increase. Nevertheless, standalone photovoltaic (PV) or wind energy system cannot produce usable energy for considerable portion of time all the time; fuel cell is also unable to response to the load demand timely. In this background, hybrid systems are proposed and widely applied in renewable energy generation systems, hybrid electric vehicles and so forth.

Hybrid power supply systems with battery as the energy storage device are often the most cost-effective and reliable way for solar and wind energy to attenuate fluctuation in power produced when the photovoltaic or wind are not available ([1], [2]). Battery storage also smoothen the mismatch between time of occurrence of peak load and maximum power generated. It is competitive for fuel cell hybrid systems with battery or ultra-capacitor as an auxiliary power source ([3], [4], [5], [6], [7]). This not only improves the stability and capacity of the system, but also compensates the low response characteristic of the fuel cell.

Nanyang Technological University has also developed a hybrid bus with Tsinghua University (Figure 1-1(a)), which employed a 40kW Proton Exchange Membrane (PEM) fuel cell as the main source and Lithium based batteries (Li-batteries) as an auxiliary power supply for peak load power demand. The basic structure of the power supply system is shown in Figure 1-1(b).

As represented above, hybrid systems have exhibited their priority and practicality in renewable energy application.

(a) Fuel cell and battery hybrid Bus

(b) Basic Structure of the power supply system

Figure 1-1: Fuel cell and battery hybrid bus

1.2 Motivation

A variety of hybrid power supply systems have been proposed in the last few years based on multiple DC/DC converters connected in parallel ([8], [9], [10], [11], [12]) (Figure 1-2), which has taken advantage of the merits of different power sources, resulting in a system with improved performance and potentially reduced size. But these systems still have the following problems as listed:

- 1) For the stabilization of the system, the power rating of main power source must be higher than the maximum load power. This will increase the cost of hybrid system, meanwhile, decrease its efficiency.
- 2) In directly connected topology in parallel, the energy storage device's voltage level must match with the direct current (DC) bus voltage value. This will increase the devices' size and cost.

4) The power electronic converters in the parallel hybrid system are controlled respectively; this will delay the controller's response time, which may cause instability of the fuel cell, even damage in serious situation.

5) In parallel topologies, the communication between the DC/DC converters and the controller will result in the complexity of the hybrid system; it may even cause instability problems.

In this thesis, a multi-input hybrid power supply system topology was proposed (Figure 1-3), in which communication between converters are not necessary. Therefore, the proposed topology decreases the cost consumption and time delay of the system's response speed. It will also reduce the inrush impact on the main source when the load varies greatly with a reasonable control strategy, especially for power sources with low dynamic response characteristic.

Figure 1-2: Conventional Multiple DCDC based hybrid power system

Figure 1-3: Proposed multi-input hybrid system topology

1.3 Major contributions of the research

As a result of the research work, the following major contributions were included:

a) In this thesis, a multi sources hybrid converter (MIHC) was proposed. The working principle of MIHC was also developed to combine the advantages of fuel cell and battery. A general case of the MIHC was derived to prove the universality of the proposed MIHC. Moreover, the small signal of the dual sources hybrid convertor (DSHC) was built based on the space average method. The dual loop proportion-integral (PI) control was adopted. The control parameter of the PI was optimized based on the small signal of the DSHC. A rule-base energy management method was developed to improve the dynamic characteristic of PEM fuel cell and increase the efficiency of the fuel cell.

2) The regenerative braking was studied in the research. A braking energy recovery method was proposed based on the proposed MIHC. Ultra-capacitor and battery combined energy storage system (ESS) was adopted in the MIHC. The inrush charging current of the battery can be limited by adjusting the current distribution of the battery and ultra-capacitor. The energy recovery efficiency was improved compare with a pure battery ESS. The system was designed in

different operation modes. A Matlab simulink was built to verify the control method of the regenerative braking.

3) The battery management system was researched in this thesis. Two types of unbalancing of the battery were investigated. The effect of the unbalance of battery was studied. A compensate method was developed for the imbalance of the battery, and it was adopted in the Li-battery pack. The performance of the battery was improved.

4) A testing platform was built to test the proposed MIHC and the energy management strategy. In the last part of the research, an E-bike based testing platform was built. The MIHC with regenerative braking function was tested in the platform.

1.4 Outline of the thesis

This report is organized into six chapters.

Chapter 1 is the introduction of this research. The motivation and objectives are represented in this chapter.

Chapter 2 presents the hybrid power supply system, which contains three power sources, PEM fuel cells, batteries and ultra-capacitors. The general knowledge about fuel cell systems and the basic theory of PEM fuel cell are explained. The knowledge of the energy storage system is introduced as well. The literature reviews of hybrid power supply systems, hybrid system control methods and energy management methods are given in this chapter.

In Chapter 3, a Multiple Input Hybrid Converter (MIHC) for a general hybrid power supply system is proposed. The topology and operation principle are discussed. Based on the proposed hybrid power supply system, a dual source hybrid converter (DSHC) is developed. The dynamic modeling of DSHC and its control system design are studied in this chapter.

In Chapter 4, the control structure of the MIHC is developed. A close-loop controller for DSHC is designed based on the modeling of the DSHC. An energy management strategy for DSHC is proposed in this chapter. Finally, a dual source

hybrid converter is made and tested to verify the MIHC. The testing results are given in this chapter.

Chapter 5 presents the basic regenerative braking theory first. A modified MIHC is proposed. The new design of the hybrid system with the regenerative braking function is discussed. The modified MIHC topology and the operation strategies are developed in this chapter. To improve the efficiency of the MIHC, a battery management system (BMS) is proposed in the second part of the chapter. The proposed BMS and an improved MIHC are tested. The results of the experiment are shown in this chapter.

The main conclusions of the research and recommendations for the future works are given in Chapter 6.

CHAPTER 2 Review of Hybrid Systems

2.1 Basic principles of sources for hybrid systems

A well designed hybrid system with high performance should take advantage of the merits of the power sources' respectively, and avoid the each source's shortcomings at the same time. Therefore, study of characteristics of the power sources is great value for developing a robust and outstanding hybrid system. The hybrid power supply system considered in the thesis contains three power sources, PEM fuel cells, batteries and ultra-capacitors. The following parts will introduce these three power sources used in the proposed hybrid system.

2.1.1 PEM fuel cell

Fuel cell is an electrochemical energy device that converts the chemical energy of fuel directly into DC electricity and heat, with water as a byproduct of the reaction. The proton exchange membrane (PEM) fuel cell, also is called the solid polymer fuel cell (SPFC), was first developed by General Electric in the United States in the 1960s for use by National Aeronautics and Space Administration (NASA) on their first manned space vehicles [13].

The main components are the anode, cathode, electrolyte, and catalyst. The anode conducts the electrons that are freed from the hydrogen fuel so that they can be used in an external circuit. It has channels etched into it that disperse the hydrogen gas evenly over the surface of the catalyst. The electrolyte is a proton exchange membrane, which blocks electrons and only conducts positively charged ions. The cathode has channels etched into it that distribute the oxygen evenly over the surface of the catalyst. The results of the reaction are water and heat. Figure 2-1 represents a schematic of a PEM fuel cell.

Figure 2-1: Schematic of a PEM fuel cell

Hydrogen atoms are stripped of their electrons at the anode.

The protons diffuse through one side of the porous membrane and migrate towards the cathode. The electrons pass from the anode to the cathode through an external circuit and provide electric power along the way. At the cathode, the electrons, hydrogen protons and oxygen from the air combine to form water. [13], [14]

The overall reaction is:

Volt-ampere characteristics

Figure 2-2 shows the polarization curves of the PEM fuel cell. Three parts, namely activation polarization, ohmic polarization, and concentration polarization, mainly contribute to irreversible losses in practical fuel cell [13], [15].

Figure 2-2: Polarization curves of PEM fuel cell

a) *Activation polarization*: this is caused by the slowness of the reactions taking place on the surface of the electrodes. A proportion of the voltage generated is lost in driving the chemical reaction that transfers the electrons to or from the electrode. It is presented by ΔV_a in Figure 2-2 [13].

b) *Ohmic polarization*: this voltage drop is the straightforward resistance to the flow of electrons through the material of the electrodes and the various interconnections, as well as the resistance to the flow of ions through the electrolyte. This voltage drop is essentially proportional to current density, linear, and it is also called ohmic losses. It is presented by ΔV_Ω in Figure 2-2. This resistance is mainly caused by the electrolyte and the cell interconnects or bipolar plates.

c) *Concentration polarization*: this occurs over the entire range of current density, but become prevailing at high current density where the insufficient reactant flows are provided to the cell reaction. It is presented by ΔV_c in Figure 2-2. This part is the main part to decrease the dynamic response of the PEM fuel cell.

In Figure 2-2, V_r is the ideal voltage of the PEM fuel cell. The ΔV_0 is called the rest voltage drop. The reason of ΔV_0 is the existence of a significant kinetic hindrance to the electrode process.

From Figure 2-2, it can be found that the voltage and efficiency of the stack will change as the output current changes. So how to select the working point [16], [17] to maintain fuel cell stack working at its highest efficiency is a significant research to improve the performance of the system.

2.1.2 Batteries

A battery is a device that converts the chemical energy contained in its active materials directly into electric energy by means of an electrochemical oxidation-reduction reaction [18], [19], [20].

One of most important parameter for battery is the State of Charge (SOC). SOC is defined as the ratio of remaining capacity to the fully charged capacity. With this definition, the SOC for a fully charged battery is 100%, and a fully discharged battery is 0%. As the different capacities at different discharge rates, the change of *SOC* in a time interval, *dt*, with discharging or charging current *i* can be expressed as:

$$\Delta_{soc} = \frac{idt}{Q(i)} \quad (2-4)$$

where, $Q(i)$ is the ampere-hour capacity of the battery at current rate *i*. *i* is positive when discharging and negative when charging. So the *SOC* can be expressed as [21]:

$$SOC = SOC_0 - \int \frac{idt}{Q(i)} \quad (2-5)$$

SOC_0 is the initial value of the *SOC*.

Many types of battery have been used in the hybrid system such as Lead–Acid Batteries, Nickel-Based Batteries, and Lithium-Based Batteries.

There are some issues when we use a battery in a hybrid system [19], [22].

1) Batteries have the maximum safe charge rate and hence usually can't fully

capture the regenerative braking energy, which negatively affects the overall fuel economy.

2) Safety is also a problem that exists in larger power batteries designed for electric vehicle. Over charging and discharging must be considered in the system design.

3) A battery management device is needed to manage the balancing of cell during charging (or discharging) and maintain the safety of battery.

2.1.3 Ultra-capacitors

The ultra-capacitor [20], [23] is also called double-layer capacitor. It is an electrochemical capacitor with relatively high power density, typically in the order of thousands of times greater than a normal electrolytic capacitor.

In a conventional capacitor, energy is stored by the removal of charge carriers, typically electrons, from one metal plate and depositing them on another. This charge separation creates a potential between the two plates, which can be harnessed in an external circuit. Ultra-capacitor does not have a conventional dielectric. Rather than two separate plates separated by an intervening substance, these capacitors use "plates" that are in fact two layers of the same substrate, and their electrical properties, the so-called "electric double layer", result in the effective separation of charge despite the vanishingly thin (in the order of nanometers) physical separation of the layers.

The basic principle of a double-layer capacitor is illustrated in Figure 2-3 [18]. When two carbon rods are immersed into a thin sulfuric acid solution, separated from each other and applied with increasing voltage from zero to 1.5V, almost nothing happens up to 1V; then at a little over 1.2V; a small bubble appears on the surface of both electrodes. Bubbles at a voltage above 1V indicate the electrical decomposition of water. Below the decomposition voltage, while the current does not flow, an "electric double layer" occurs at the boundary of electrode and electrolyte. The electrons are charged across the double layer and for a capacitor [21], [22], [24], [25].

Figure 2-3: Basic principles of a typical electric double-layer capacitor.

Energy, E , is stored in the electric field according to the equation

$$E = \frac{1}{2} CV^2 \quad (2-6)$$

where C is the capacitance in farads and V is the cell voltage in volts. Since the capacitance is proportional to the area of the plates, ultra-capacitors are made to have much larger surface areas than traditional capacitors, which lead to their comparatively high-power density.

The terminal voltage of the ultra-capacitor during discharge can be expressed as:

$$V_{ocap} = V_c - iR_s \quad (2-7)$$

Where V_{ocap} is the terminal voltage of the ultra-capacitor; V_o is the capacitance itself voltage; R_s is the series resistance; i is the discharge current.

At different discharge current rates, the voltage linearly decreases with discharge time. At a large discharge current, the voltage decreases much faster than at a small current rate.

The SOC of the ultra-capacitor can be expressed as [25]:

$$SOC = \frac{V_c^2}{V_{crate}^2 - V_{cstop}^2} \quad (2-8)$$

Where V_c is the terminal voltage of ultra-capacitor, V_{crate} is the rate voltage of ultra-capacitor, V_{cstop} is the bottom voltage. Generally, an ultra-capacitor usually has a voltage which the ultra-capacitor will stop delivering energy under this voltage. This voltage is called bottom voltage.

Compared with battery, some advantages of ultra-capacitor [22], [26] are listed as follows.

- (1) Longer life expectancy than batteries in terms of charge/discharge cycles.
- (2) Higher specific power than batteries, specifically in the ability to accept higher power during charging.
- (3) Higher efficiency than batteries due to lower internal resistance.
- (4) The ultra-capacitor SOC can be determined from the voltage.

It can be found that two types of energy storage devices (ESD) were used in the hybrid system, batteries and ultra-capacitors [7], [22], [23]. It is important to hybridize the renewable energy source system using energy storage system for the following reasons:

- (1) ESD can recover of regenerative braking energy (when the system was used in a vehicle), thus increasing the overall efficiency of the system. The ESD stores this captured energy to be used during the next acceleration, or whenever else needed.
- (2) ESD can provide fast and additional power during peak demand periods such as acceleration. It has been found that the some kind of energy sources has a time-delayed response, and is limited in power output.
- (3) The cost of renewable energy sources is expensive. A lower rated power energy source can be significantly lighter and cheaper than a higher rated power source. Thus, adding ESD is also a cost-reduction method, since energy storage

components are generally cheaper than renewable energy source.

Figure 2-4 shows the power density and energy density for some commercial batteries, and ultra-capacitors. The energy and power densities for the commercial fuel cells are also shown for comparison purposes.

Figure 2-4: Comparison energy and power density as for different energy sources

From Figure 2-4 [27], it can be found that the batteries and the ultra-capacitors are far superior to fuel cells in terms of power density. Ultra-capacitors have energy densities perhaps one tenth that of a rechargeable battery, but power densities typically 10 to 100 times greater. The conventional capacitor was used as milliseconds power device. Ultra-capacitor is designed for the second power device, since it is suitable to absorb the surge power during the starting and braking of the vehicle. Batteries are used as power device in minute or hour scale. The power density is lower than the ultra-capacitors, especially in charging. In this thesis, a combination of ultra-capacitor and Li-battery ESS was developed. The advantages of high power density of ultra-capacitor and high energy density of batteries were combined. The combined energy storage system (ESS) can increase the recovery energy during the braking and reduce the surge power of the batteries and fuel cell. The combined battery and

ultra-capacitor ESS has the potential of being smaller and lighter than an ultra-capacitor-only ESS or a battery-only ESS.

Figure 2-5: Illustration waveform for an energy storage system

The ideal operation principle of ESS is illustrated in Figure 2-5. The blue line represents the energy source (e.g. fuel cell) available power, and the sharp power (the green area) gap has been bridged through the ESS (e.g. an ultra-capacitor and battery combined energy storage system). In the steady state the power was provided by the main power source (blue line e.g. fuel cell). The ESS supplied transient power and peak load demands. The output power variation of the main power source was reduced. The review of topologies and controller method will be discussed in the following section.

2.2 Topology of hybrid systems

Previous researches have done some work in the hybrid system [8-12], [28-36].

[8-12] represents parallel connected DC/DC topologies. Separate DC/DC conversion stages are employed for individual power source. These converters are linked to the DC bus and controlled independently. The converters are interleaved buck converter, boost converter, push-pull converter, bridge converter, etc. In a practical system, a communication bus will be included to exchange information and manage power flow between the power sources. The drawback of such system lies in the fact that it is inherently complex and has a high cost due to the multiple conversion stages and communication devices between individual converters [8]. Figure 2-6 [9], [10], [33] illustrates a typical connection for a Fuel Cell, battery and ultra-capacitor system. A single direction

boost (buck) type converter connects the fuel cell to the bus. This topology connects the ultra-capacitor and battery through the bi-direction DC/DC converter (2-quadrant DC/DC). The ultra-capacitor and battery are controlled by the DC/DC converters. When the up-switch is working, the DC bus will transfer the energy from DC bus to the ultra-capacitor and battery, the charging current will be controlled by adjusting the duty ratio. The ultra-capacitor or battery will transfer the energy to the load by a boost converter, when the low-switch is working. So the energy flow will be fully controlled in two directions.

Figure 2-6: Parallel connect hybrid converter

In [30-32], [37], the approach of driving hybrid converters is based on the principle of flux additivity. In this method, all the power sources are interconnected through a multiple winding transformer. It is easier to connect multiple power sources having quite different voltage levels. All the power sources are galvanically isolated, which could be a compulsory for the safety reason in some special applications. In this type of systems, energy sources are combined in the magnetic form by adding up their produced magnetic flux together in the magnetic core of the coupled transformer instead of combining them in the electric form. Figure 2-7 shows a topology which the full-bridge and half-bridge modules are coupled by means of a four-winding transformer. The

power flow between sources and sinks can be controlled by shifting the switching patterns with respect to the master module. The main advantage of this circuit is that it is easy to couple with the power source with a widely voltage range. On the other hand, this circuit requires more switches and a high-frequency transformer. A complex control method must be used to maintain the whole system working properly.

Figure 2-7: Magnetic coupled hybrid converter

In both methods, bidirectional converters are used. Bidirectional power flow enables the energy capture of regenerative brake and energy release during startup and hill climbing [8], [30], [32]. The regenerative brake energy is always desirable no matter how high the losses are, as this energy would otherwise be dissipated and lost as heat in the friction brakes. The energy recovered during regenerative braking, which transformed from the inertia of the vehicle, is originally imparted to the vehicle by the driving system, so efficient energy management power conversion and storage for regenerative braking is of course desirable and leads to improve the system efficiency for transient drive cycles.

[38] integrates an ultra-capacitor bank with the fuel cell system using two power diodes and two semiconductor power switches. The hybrid power system corresponds to direct integration of the fuel cell and ultra-capacitor in parallel, as illustrated in Figure 2-8(a). The ultra-capacitor can be charged by the fuel cell or regenerative braking energy when the charging switch is closed. The ultra-capacitor will provide the power to the load when the discharging switch is closed. The topology is simpler than other topologies. But the output power of the fuel cell cannot be controlled. The output voltage is unregulated. The charging current of the ultra-capacitor cannot be controlled.

[39] represents the topology as shown in Figure 2-8(b). The fuel cell is connected to the ultra-capacitor by a unidirectional DC/DC converter. The ultra-capacitor was designed as an output buffer for the DC bus. The DC/DC converter is adopted to control the output power of the fuel cell. The charging current of the ultra-capacitor can be controlled by the DC/DC converter. The output voltage is unregulated

Figure 2-8(a)

Figure 2-8(b)

Figure 2-8: The topology of connecting the ESS directly

2.3 Energy management strategy

[40] presents a hybrid power supply system that consists of three individual sources with different power-density characteristics - fuel cell, battery, and supercapacitor - which are connected to the same voltage bus through appropriate dc-dc power converters and controller. Three energy sources are used to meet the load power demands in hours, minutes and seconds respectively. The fuel cell is operated under nearly steady state conditions. The devices are assigned three different aims. The fuel cell is controlled to maintain

the battery to a given state of charge. The battery is controlled to realize a classic DC link voltage regulation. The supercapacitor power is controlled to maintain a given state of charge or supply intensive power when the battery current exceeds the limits. Inner current regulation loop is used to achieve the fast dynamic response.

[41] adopts a model-predictive control scheme to solve the oxygen starvation of the fuel cell. A bank of ultra-capacitors supplements the PEM fuel cell during fast current transients. The model-predictive controller is used to control the compressor motor voltage and fuel cell output current. The load requirement current was the set point of the model-predictive controller. [43] presents a system integration and control strategy for managing power transients on a fuel cell with the assistance of an ultra-capacitor. The two degrees of freedom provided by the use of two DC/DC converters enable the independent low-level control of DC bus voltage and the current split between the fuel cell and ultra-capacitor. The supervisory-level control objectives are to respond to rapid variations in load while minimizing damaging fluctuations in fuel cell current and maintaining the ultra-capacitor charge (or voltage) within allowable bounds. The use of a model-predictive controller balances the distribution of power between the fuel cell and ultra-capacitor.

[42] designs a control strategy for a voltage-regulated dc hybrid power source. The fuel cell is the main energy source and ultra-capacitors are the auxiliary power source for a distributed generation system. The control strategy is based on a standard DC link voltage regulation. The main target is to maintain the voltage of the DC link. The ultra-capacitor is the primary power source of the system. The ultra-capacitor is used to satisfy the energy requirement from the DC bus. A voltage-to-energy transformation function is adopted to get the power-reference of the ultra-capacitor. The output current of the ultra-capacitor is determined by the power reference and voltage of the ultra-capacitor. An ultra-capacitor voltage-regulation-loop is used to maintain the SOC of the ultra-capacitor. The output of the ultra-capacitor voltage-regulation-loop is the current reference of the fuel cell. This method reduces the dynamic changing of the fuel cell.

[8] designs and tests a purely ultra-capacitor ESS for the power conditioning of automotive system having a PEM fuel cell as main source. The control strategy is that the fuel cell is simply operating in almost steady-state conditions in order to lessen the mechanical stresses of fuel cell and to insure a good synchronization between fuel flow and fuel cell current. Ultra-capacitors will function during absence of energy from fuel cell, transient energy delivery or transient energy recovery. Further work, [44] investigates a fuel cell/battery hybrid power source for EV applications. The fuel cell is connected to a DC bus by a classical boost converter, and the battery bank is directly connected to the DC bus. The control strategy is used to control power from the fuel cell, power to the motor, and state-of-charge (SOC) of the battery.

[9] introduces an energy management strategy based on fuzzy logic supervisory for electric vehicle, combining a fuel cell power source and two energy storage devices. The control strategy achieves the high-efficiency operation region of the individual power source and regulated current and voltage at peak and average power demand. The control system manages the power flows between the power sources and the load. The fuzzy logic supervisory for energy management of a specific power electronic converter control algorithm is proposed. [45] presents an energy management method in an electric hybrid power source for electric vehicular applications. The method is based on the flatness control and fuzzy logic control. The fuel cell system is the main source and two energy storage sources (ultra-capacitors and batteries) are the auxiliary source. The flatness control has been used to manage the energy between the main and the auxiliary sources, and the fuzzy logic control has been employed to share the power flow between the ultra-capacitors and the batteries. The power sharing depends on the load power and the state of charge of the ultra-capacitors and the batteries.

2.4 Summary

This chapter introduced the hybrid power supply system which contains three power sources, PEM fuel cells, batteries and ultra-capacitors. The batteries and ultra-capacitors can be considered as both power supplies and energy storage devices. The operating principles of PEM fuel cell, batteries and

ultra-capacitors were introduced. The advantages and drawbacks of the battery and ultra-capacitor were compared. The characteristic of the PEM fuel cell was discussed. The function of the ESS was also represented in the chapter. The operation requirement of the ESS was represented. Three type topologies of the PEM fuel cell hybrid system were reviewed. The characteristics of these three topologies were discussed respectively. In the last part of this chapter, the energy management methods of the fuel cell hybrid system were reviewed.

CHAPTER 3 Design and Modeling of Multiple Input Hybrid Converter

As mentioned in Chapters 1 and 2, the topologies of renewable sources used in practical areas are limited to the structures. All converters are parallel connected to the bus terminal to drive external loads. A common structure of this hybrid power supply system is shown Figure 3-1. Each converter can handle a single kind of energy source. In order to exert all sources' maximum advantages, an individual converter is needed for every energy source when two or three or even more energy sources are employed in a hybrid system. This kind of structure, which needs a large number of components, will increase the development cost, enhance the difficulty in installation and controller design, and reduce system stability and reliability. In this type of system a master controller is needed, which will be used to control the energy balance among each energy source [9], [31], [32], [33], [46], [47]. The dynamic response of the whole system will rely on the converters' response speed and the speed of communication. These may cause a control delay when the load is changing. The control delay will make the energy source work under overload state for a while. The energy source may be damaged by the overshoot. Therefore, development a Multiple Input Hybrid Converter (MIHC), which has fast dynamic response, higher efficiency, and lower cost, is very important for a hybrid power system.

Figure 3-1: Conventional structure of a hybrid system

3.1 The proposed MIHC topology

An ideal and practical multiple input power supply device should be compatible for various sources, which have different voltages and current characteristics and utilize their advantages automatically and appropriately while they are able to be interchangeable with high reliability. In practical application, load connected to power supply will inevitably change rapidly under different conditions and circumstances. In this thesis, PEM fuel cell was adopted in the hybrid system. Because of its electrical output characteristic, the change of supply power from the PEM fuel cell could not catch up with that of the demanded load in time. Therefore, it is usually expected to keep the fuel cell operating on a stable situation whenever and however the load changes to ensure the maximum operation duration of the PEM fuel cell and the best load response performance for hybrid power supply (Similar optimizations exist with other renewable energy source combinations).

Figure 3-2 represents the basic concept of Multiple Input Hybrid Converter (MIHC) in a general condition. Previously researchers had done some study on magnetic-coupling multi source converter [30], [31], [32], [37], [48], [49], [50]. However, in these approaches, one of the disadvantages is that it prevents the simultaneous operation of more than one source at a given time. The output power of each source cannot be added. Furthermore, most of previously researches force on the output characteristic study. To compensate the disadvantage above mentioned, this research proposed a topology which, each power source will be paralleled with a high capacity capacitor, and is connected to a common inductor with a high speed power switch (MOSFET was recommended). The power split between the sources is controlled by the turn-on time of its switches. The function of the parallel capacitor is used to store the energy when the switch is turned off, especially when PEM fuel cell is used as the power source (Because the PEM fuel cell may not provide the required power during the turn on time of switches). Each power source will operate during the whole switching period instead of working at its turn on period. The energy of each source which is accumulating in the whole switching period, and it will be released when that source switch is turn on. The total output power of the

MIHC has been increased and the output power capacities of all sources are added together. Figure 3-3(a) shows the power waveform and the inductor current on an ideal condition. i_L represents the current of the inductor. Figure 3-3(b) shows the diagrammatic wave form of each power source. The first line represents the total output current of each source i_{sn} ($n = 1, 2, 3 \dots$). The second line represents the output current of each source i_{osn_s} ($n = 1, 2, 3 \dots$). The third line represents the output current of the parallel capacitor of each source i_{osn_c} ($n = 1, 2, 3 \dots$). It can be found that $i_{sn} = i_{osn_s} + i_{osn_c}$. The forth line represents the voltage of the parallel capacitor of each source v_{nc} ($n = 1, 2, 3 \dots$). In the Figure 3-3(b) wave form, S_1 is turned on from 0 to t_1 . The $source_1$ and its parallel capacitor provide the power to the load together. S_1 is turned off and S_1 is turned on at t_1 . The $source_2$ and its parallel capacitor provide the power to the load together. At the same time, $source_1$ charges its parallel capacitor until next period turn on time (The output current of i_{os1_c} is below 0). The energy of $source_1$ is stored in its parallel capacitor for the next switching period. This operation is repeated until the last source. As above mentioned, each source provides the power to the load with its capacitor when it is turned on. And it will charge its parallel capacitor during turn off time. This is different from previous researches that each power source is discharged during the switching on period only. The energy is stored in the parallel capacitor during the switch off time. The utilization of each source and total output power of the system are increased.

The average output power of each source is equal to the dynamic power of each source. Therefore the total output power is equal to each average power added together. Finally, each energy source is hybridized by this structure. These are expressed as:

$$P_{snavg} \cdot T = \int_{t_{1n}}^{t_{2n}} P_{dynamic} dt$$

$$P_{out} = P_{s1avg} + P_{s2avg} + \dots + P_{snavg}$$

where n is the number of source, t_{1n} is the time of switch n turn on, t_{2n} is the time of switch n turn off. The turn on time of switch n was represented by T_n' , which

was expressed as $t_{1n}-t_{2n}$. T is the period of switching. P_{snavg} is the average output power of source n . $P_{dynamic}$ is the dynamic power of source n from t_{1n} to t_{2n} . P_{out} is the total output power of the converter.

The output power of each source can be controlled based on its duty cycle by applying a high switching frequency. On the other hand, as the switching frequency is very high, the dynamic response of each source can be controlled in a few switching periods. This will improve transient behavior of the hybrid system.

Figure 3-2: Basic concept of Multiple Input Hybrid Converter (MIHC)

Figure 3-3(a): Power waveform and inductor current in ideal condition

Figure 3-3(b): Source and capacitor waveform in ideal condition

3.2 Operation principle in general condition (k sources)

The power source and parallel capacitor in Figure 3-2 can be replaced by an ideal DC source. Figure 3-4 (a) shows the simplification schematic in general case. The switching sequence and time are shown in Figure 3-4 (b). The number of power source is k in the MIHC. The thesis assumes the MIHC working at Continuous Conduction Mode (CCM).

Figure 3-4: MIHC schematic and switching patterns in general case.

The corresponding switching patterns of the DSHC used in the report are described in Figure 3-5.

In one switch period, the switch of source 1 (S_1) is conducted firstly. S_1 and its input capacitor provide the power to the load together. When the turn on duration of S_1 is reach to D_1T (at t_1), S_1 is off, S_1 stops providing the power to the load and the input capacitor of S_1 was charged by S_1 . At the same time, the switch of source 2 (S_2) is turned on and provide the power to the load (In the real system, a dead band will be added between S_1 turning off and S_2 turning on to prevent the short circuit). Same as S_1 , when the turn on duration of S_2 is reach to D_2T (at t_2), S_2 is off, S_2 stops providing the power to the load and the input capacitor of S_2 was charged by S_2 . In this analogy, S_k is turned on at t_{k-1} and turned off at t_k . When the last source is turned off, the freewheel-diode is conducted. In a completely switching period, each source provides the power to the load respectively in different time.

$0 \sim t_1$ is the time length when S_1 is on duty, $t_1 \sim t_2$ is the time length when S_2 is on duty, $t_{(k-1)} \sim t_{(k)}$ is the time length when S_k is on duty. t_c is the time length when all $S_{(x)}$ are off. T is the period of all the switches' frequency. D_k is the duty cycle of each switch. D_c is the duty cycle of freewheel diode D .

Figure 3-5: Switching patterns of the proposed DSHC

The relationship between D_k and D_c can be expressed as

$$D_c + \sum_{j=1}^k D_j = 1 \quad (3-1)$$

For source₁, v_{s1} is on, all others are off. Only v_{s1} supplies load through S_1 and L , which can be referred to a classical one-input buck converter. Meanwhile, others sources charge their parallel capacitors, to store the energy during the period where switch is turned off. v_L is the subtraction between v_{s1} and v_o . The inductor current ripple in source k can be derived by the following equation:

$$\Delta i_{L1} = \int_0^{t_1} \frac{v_{s1} - v_o}{L} dt = \frac{v_{s1} - v_o}{L} D_1 T \quad (3-2)$$

Similar to source₁; the inductor current variation during each switching time can be expressed as

$$\left. \begin{aligned} \Delta i_{L1} &= \frac{v_{s1} - v_o}{L} D_1 T \\ \Delta i_{L2} &= \frac{v_{s2} - v_o}{L} D_2 T \\ \Delta i_{L3} &= \frac{v_{s3} - v_o}{L} D_3 T \\ &\vdots \\ \Delta i_{Lk} &= \frac{v_{sk} - v_o}{L} D_k T \end{aligned} \right\} \quad (3-3)$$

According to the theory of energy conservation, if the system is in stable operation, it can be considered that the variation of inductor current in one operation cycle is zero. This can be expressed as

$$\sum_{j=1}^k \Delta i_{Lj} + \Delta i_c = 0 \quad (3-4)$$

In the last period of the switch cycle all the switches are off. The load is powered by the energy storing in L and C. D is on, making a closed-loop circuit of current for load. v_L equals $-v_o$. The variation of inductor when the freewheel diode D is conducted can be expressed as

$$\Delta i_c = \frac{-v_o}{L} D_c T \quad (3-5)$$

Using Eq. (3-1) and (3-5) replace Δi_{Lk} and Δi_c in Eq. (3-4). Eq. (3-4) can be modified as

$$-\frac{-v_o}{L} D_c T + \sum_{j=1}^k \frac{v_{sj} - v_o}{L} D_j T = 0 \quad (3-6)$$

In order to find the relationship between $D_{(x)}$ and v_o , put Eq. (3-1) into Eq. (3-6). Solving the equation in (3-6) for the output voltage v_o gives:

$$v_o = \sum_{j=1}^k v_{sj} D_j \quad (3-7)$$

The output voltage v_o can be controlled by adjusting the $D_{(x)}$.

The average current of each source can be expressed as Eq. (3-8), where I_k is the average current of each source. T'_k is the turn on time of each source. ($T'_k = T D_k$)

The integration limitation 0 of Eq. (3-8) is the initial time of each switch is turned on. All the time of each switch turn on was set as 0 to simplify the derivation.

$$\left. \begin{aligned} I_{s1} &= \frac{1}{T} \int_0^{T'_1} i_{L1} dt \\ I_{s2} &= \frac{1}{T} \int_0^{T'_2} i_{L2} dt \\ I_{s3} &= \frac{1}{T} \int_0^{T'_3} i_{L3} dt \\ &\vdots \\ I_{sk} &= \frac{1}{T} \int_0^{T'_k} i_{Lk} dt \end{aligned} \right\} \quad (3-8)$$

The instantaneous current i_{Lk} of the inductor in each power source turn on can be express as Eq. (3-9), where I_{min} is the initial value in the begin of each switching cycle.

$$\left. \begin{aligned} i_{L1} &= \frac{v_{s1} - v_o}{L} t + I_{min} \\ i_{L2} &= \frac{v_{s2} - v_o}{L} t + \frac{v_{s1} - v_o}{L} T'_1 I_{min} \\ i_{L3} &= \frac{v_{s3} - v_o}{L} t + \frac{v_{s1} - v_o}{L} T'_1 + \frac{v_{s2} - v_o}{L} T'_2 + I_{min} \\ &\vdots \\ i_{Lk} &= \frac{v_{sk} - v_o}{L} t + \sum_{j=1}^{k-1} \frac{v_{sj} - v_o}{L} T'_j + I_{min} \end{aligned} \right\} \quad (3-9)$$

Substituting Eq. (3-9) into Eq. (3-8) gives that the average current of each power source I_{sk}

$$\left. \begin{aligned} I_{s1} &= \frac{v_{s1} - v_o}{2Lf} D_1^2 + I_{min} D_1 \\ I_{s2} &= \frac{v_{s2} - v_o}{2Lf} D_2^2 + \frac{v_{s1} - v_o}{Lf} D_1 D_2 + I_{min} D_2 \\ I_{s3} &= \frac{v_{s3} - v_o}{2Lf} D_3^2 + \frac{v_{s1} - v_o}{Lf} D_1 D_3 + \frac{v_{s2} - v_o}{L} D_2 D_3 + I_{min} D_3 \\ &\vdots \\ I_{sk} &= \frac{v_{sk} - v_o}{2Lf} D_k^2 + \sum_{j=1}^{k-1} \frac{v_{sj} - v_o}{Lf} D_j D_k + I_{min} D_k \end{aligned} \right\} \quad (3-10)$$

In Eq. (3-10) the output voltage (v_o), each source voltage (v_{sk}), period of the switching time (T), the initial current of the inductor (I_{min}) and the value of inductor (L) are constants for a given system. The average current of each source I_{sk} is determined by the switching duty cycle D_k . The average power of each source can be controlled by D_k . It can be found that the output voltage v_o and the average current (or power) of each source I_{sk} is controllable by applying an appropriate controller.

From Eq. (3-10), D_1 to D_k are fixed if each source's current are controlled. In order to control the voltage v_o , as can be seen from Eq. (3-7), there is at least one $D_{(x)}$ that is changeable. So only $(k - 1)$ source currents are selected to be controlled, with one left to adjust the voltage v_o . Many application situations can be found to prove that the characteristics of the proposed MIHC are significant for hybrid systems. For example, NTU bus which has been mentioned in Chapter 1 (the basic structure of the power supply system is shown in Figure 1-1(b)), which the fuel cell current must be controlled because of its slow dynamic response speed, meanwhile, batteries are used to maintain the DC-bus voltage to meet the system dynamic response requirement.

3.3 The analysis and dynamic modeling of the DSHC

To prove this concept, a Dual Source Hybrid Converter (DSHC) topology is made and tested in this thesis, as showing Figure 3-6, for fulfilling the expectations of the control target. Two separated power sources S_1 (PEM fuel cell) and S_2 (Battery) with a pair of source-to-source MOSFETs (M_1 -to- M_2 , M_3 -to- M_4) linked behind are parallel connected as converter inputs. As explained

previously, the two sources share a common inductor L . The structure design of source-to-source MOSFETs, which is also known as the four-quadrant switch structure [58], can pave way for the future bidirectional converter study and development. Because of a parasitic diode inside MOSFET, M_2 (or M_4) can be regarded as a diode to prevent from opposite current flowing back into the PEM fuel cell branch when unidirectional buck converter is in practice. The alternative is that diode can be used to replace MOSFET in this proposed circuit. It is assumed that S_{M12} is put on M_1 and M_2 simultaneously as well as S_{M34} on M_3 and M_4 . Each source is in parallel connected with a big voltage-regulation electrolytic capacitance (C_1 for S_1 , C_2 for S_2) for being charged by the source when MOSFET is controlled to switch off and supplying power in company with source when MOSFET is on. Therefore, no interrupted current status in operation will come out and control of source output current (or power) can be implemented. C_{buf1} , R_{buf1} and D_{buf1} in S_1 branch (C_{buf2} , R_{buf2} and D_{buf2} in S_2 branch) jointly compose a shutoff buffer circuit for dispersing power loss during switch-off period of $M_1 \sim M_4$. D and C are used to keep output current and voltage of the DSHC uninterrupted and constant. The reference positive directions of voltage or current of each component are assumed and marked in Figure 3-6 as well.

Figure 3-6: Proposed dual source hybrid converter topology

The output voltage of the above topology can be derived according to Eq. (3-7)

$$v_o = v_{s1}D_1 + v_{s2}D_2 \quad (3-11)$$

Based on energy conservation theory, the average current of S_1 or S_2 in one operation cycle, according to Eq. (3-10), can be expressed as

$$\left. \begin{aligned} I_{s1} &= \frac{v_{s1} - v_o}{2Lf} D_1^2 + I_{min} D_1 \\ I_{s2} &= \frac{v_{s2} - v_o}{2Lf} D_2^2 + \frac{v_{s1} + v_{s2} - 2v_o}{Lf} D_1 D_2 + I_{min} D_2 \end{aligned} \right\} \quad (3-12)$$

D_1 and D_2 in Eq. (3-8) are replaced with i_{s1} , i_{s2} and i_o in Eq. (3-9), the following conclusion can be reached:

$$v_o = v_{s1}D_1 + v_{s2}D_2 \quad (3-13)$$

From Eq. (3-13), it can be seen that the average output power of DSHC equals to algebra addition of the two power sources, which makes the realization of hybrid supply power system available using the DSHC. The relation between v_o and that of the two sources is indicated in Eq. (3-11), while the relation between i_o and output currents of two sources is represented in Eq. (3-12). Both duty cycles of S_1 and S_2 together determine the value of v_o . It can be easily verified that D_1 and D_2 can have infinite combination solutions, supposing v_o keeps constant. i_{s1} (or i_{s2}) is related to i_o and its duty cycle D_1 (or D_2) only, being independent to i_{s2} and D_2 (or i_{s1} and D_1). As a result, it provides a possibility to make the two parameters of the DSHC v_o and i_{s1} (or i_{s2}) be under control simultaneously. v_o can be controlled by finding a certain combination of D_1 and D_2 with a proper control method, while D_1 (or D_2) from the same combination determining the output current of Source₁ (or Source₂) as well.

Dynamic modeling of the DSHC

The approaches of the dynamic modeling for DSHC are 3 steps, which are represented by Figure 3-7. In the Step 1, the state space modeling [51], [52], [53] of the DSHC is built. In the Step 1, the relationships between inductor current,

capacitor voltage and D_1 , D_2 are built. This is represented by Figure 3-7(a).

In the Step 2, the relationships between sources current $i_{(x)}$, v_o and D_1 , D_2 (represented by Figure 3-7(b)) are derived based on the results of Step 1.

In the last step of the modeling the small-signal model (represented by Figure 3-7(c)) of the DSHC is built. The perturbation of system is considered. The small-signal model is built and will be used to design the control parameters in Chapter 4.

Figure 3-7: The approaches of the modeling of DSHC

The detailed derivation of these three steps is given in the following.

Step 1

The DSHC circuit can be expressed by Figure 3-8. The R_L and R_c are parasitic resistances (ESR, equivalent series resistance) of the inductor and capacitor. Two power supplies are represented by two ideal voltage sources. In all of these, the MOSFET and diode operate as an ideal single-pole switch.

Figure 3-8: Equivalent circuit of DSHC

Three states are defined during the operation period.

State 1: S_1 is turned on, S_2 is turned off and D is reverse biased;

State 2: S_1 is turned off, S_2 is turned on and D is reverse biased;

State 3: S_1 is turned off, S_2 is turned off and D is conducted;

For the State 1, the equivalent circuit can be expressed by Figure 3-9

Figure 3-9: Equivalent circuit of DSHC in state 1

According to Kirchhoff's current laws (KCL)

The capacitor current (i_c) can be expressed as Eq. (3-14)

$$i_c = i_L - i_o = i_L - \frac{v_o}{R_o} \quad (3-14)$$

i_c also can be expressed as Eq. (3-15)

$$i_c = C \frac{dv_c}{dt} \quad (3-15)$$

Eq. (3-16) can be derived when Eq. (3-14) is substituted for Eq. (3-15)

$$C \frac{dv_c}{dt} = i_L - \frac{v_o}{R_o} \quad (3-16)$$

According to Kirchhoff's voltage laws (KVL), the following Eq. (3-17) can be obtained.

$$-v_1 + v_{R_L} + v_L + v_o = 0 \quad (3-17)$$

Where, $v_{R_L} = i_L R_L$, $v_L = L \frac{di_L}{dt}$

In Eq. (3-17), the output voltage v_o can be derived by circuit superposition theorem. The response of a single voltage source excitation v_c can be expressed

as $v_c \frac{R_o}{R_o + R_c}$. The response of a single current source excitation i_L can be expressed as $i_L \frac{R_o R_c}{R_o + R_c}$. According to circuit superposition theorem v_o can be expressed as

$$v_o = v_c \frac{R_o}{R_o + R_c} + i_L \frac{R_o R_c}{R_o + R_c} \quad (3-18)$$

Substituting Eq. (3-18) into Eq. (3-17) gives the following equation:

$$-v_1 + i_L R_L + L \frac{di_L}{dt} + v_c \frac{R_o}{R_o + R_c} + i_L \frac{R_o R_c}{R_o + R_c} = 0 \quad (3-19)$$

Combining Eq. (3-16) with Eq. (3-19), the DSHC state function in time-domain can be expressed as

$$\left. \begin{aligned} L \frac{di_L}{dt} &= v_1 - i_L R_L - v_c \frac{R_o}{R_o + R_c} - i_L \frac{R_o R_c}{R_o + R_c} \\ C \frac{dv_c}{dt} &= i_L \frac{R_o}{R_o + R_c} - \frac{v_c}{R_o + R_c} \end{aligned} \right\} \quad (3-20)$$

For the state 2, the equivalent circuit can be expressed by Figure 3-10

Figure 3-10: Equivalent circuit of DSHC in state 2

The circuit state function of state 2 in time-domain can be derived by the same method of state 1. It can be expressed as

$$\left. \begin{aligned} L \frac{di_L}{dt} &= v_2 - i_L R_L - v_c \frac{R_o}{R_o + R_c} - i_L \frac{R_o R_c}{R_o + R_c} \\ C \frac{dv_c}{dt} &= i_L \frac{R_o}{R_o + R_c} - \frac{v_c}{R_o + R_c} \end{aligned} \right\} \quad (3-21)$$

For state 3, the equivalent circuit is depicted in Figure 3-10.

Figure 3-11: Equivalent circuit of DSHC in state 3

According to KCL and KVL, the circuit equation can be expressed as

$$\left. \begin{aligned} -i_L R_L + L \frac{di_L}{dt} - v_o &= 0 \\ v_o &= v_c \frac{R_o}{R_o + R_c} + i_L \frac{R_o R_c}{R_o + R_c} \\ C \frac{dv_c}{dt} &= i_L \frac{R_o}{R_o + R_c} - \frac{v_c}{R_o + R_c} \end{aligned} \right\} \quad (3-22)$$

Eq. (3-22) can be simplified and expressed as

$$\left. \begin{aligned} L \frac{di_L}{dt} &= -i_L R_L - v_c \frac{R_o}{R_o + R_c} - i_L \frac{R_o R_c}{R_o + R_c} \\ C \frac{dv_c}{dt} &= i_L \frac{R_o}{R_o + R_c} - \frac{v_c}{R_o + R_c} \end{aligned} \right\} \quad (3-23)$$

Based on the state-space average method which has been presented in [51], [53], the state-space average model of DSHC can be expressed as

$$D_1 \times \text{Eq. (3-20)} + D_2 \times \text{Eq. (3-21)} + (1 - D_1 - D_2) \times \text{Eq. (3-23)}$$

After the simplification, the state-space average model of DSHC was expressed as

$$\left. \begin{aligned} L \frac{di_L}{dt} &= D_1 v_1 + D_2 v_2 - i_L R_L - v_c \frac{R_o}{R_o + R_c} - i_L \frac{R_o R_c}{R_o + R_c} \\ C \frac{dv_c}{dt} &= i_L \frac{R_o}{R_o + R_c} - \frac{v_c}{R_o + R_c} \end{aligned} \right\} \quad (3-24)$$

The state-space function of the DSHC was shown as Eq. (3-25)

$$\begin{aligned} \begin{bmatrix} \dot{i}_L(t) \\ \dot{v}_c(t) \end{bmatrix} &= \begin{bmatrix} -\left[\frac{R_L}{L} + \frac{R_o R_c}{L(R_o + R_c)} \right] & -\frac{R_o}{L(R_o + R_c)} \\ \frac{R_o}{C(R_o + R_c)} & -\frac{1}{C(R_o + R_c)} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_c(t) \end{bmatrix} \\ &+ \begin{bmatrix} 1 \\ 0 \end{bmatrix} \frac{1}{L} [D_1 v_1 + D_2 v_2] \end{aligned} \quad (3-25)$$

Step 2

Now the relationship between D_1, D_2 and v_c, i_L has been represented in Eq. (3-25). As mentioned before (In Figure 3-7), the control variable of the DSHC are v_o and i_1 (or i_2), it is important to find the relationship between D_1, D_2 and v_o, i_1 (or i_2).

By Laplace transformation, the solution of Eq. (3-24) can be written as

$$\left. \begin{aligned} L s i_L &= D_1 v_1 + D_2 v_2 - v_c \frac{R_o}{R_o + R_c} - i_L \frac{R_o R_c}{R_o + R_c} - i_L R_L \\ C s v_c &= i_L \frac{R_o}{R_o + R_c} - \frac{v_c}{R_o + R_c} \end{aligned} \right\} \quad (3-26)$$

The solution of Eq. (3-26) is given by Eq. (3-27)

$$\left. \begin{aligned} v_c &= \frac{R_o(D_1v_1 + D_2v_2)}{\left[Cs + \frac{1}{(R_o + R_c)}\right][Ls + R_L + R_o]} \\ i_L &= \frac{[(R_o + R_c)Cs + 1] \frac{R_o(D_1v_1 + D_2v_2)}{\left[Cs + \frac{1}{(R_o + R_c)}\right][Ls + R_L + R_o]}}{R_o} \end{aligned} \right\} \quad (3-27)$$

Substituting both v_c and i_L into Eq. (3-18) gives that v_o can be expressed as

$$v_o = \frac{R_o(D_1v_1 + D_2v_2)[R_o + R_c[(R_o + R_c)Cs + 1]]}{[Cs(R_o + R_c) + 1][Ls + R_L + R_o]} \quad (3-29)$$

Based on the same method, the input current of source₁ (i_1) can be expressed as

$$i_1 = D_1i_{1_D1} + D_2i_{1_D2} + (1 - D_1 - D_2)i_{1_c} \quad (3-30)$$

Where i_{1_D1} is the source₁ current when S_1 is conducting, i_{1_D2} is the source₁ current when S_2 is conducting and i_{1_c} is the source₁ current when the diode is conducting. It can be found that $i_{1_D1} = i_L$, i_{1_D2} and i_{1_c} are equal to zero. i_1 is shown in Eq. (3-31) as

$$i_1 = D_1i_L \quad (3-31)$$

Substituting i_L (in Eq. (3-27)) into Eq. (3-31), it follows that i_1 can be expressed as

$$i_1 = \frac{D_1R_o[(R_o + R_c)Cs + 1](D_1v_1 + D_2v_2)}{\left[Cs + \frac{1}{(R_o + R_c)}\right][Ls + R_L + R_o]} \quad (3-32a)$$

Use the power balance equation between input and output of the converter $(\frac{v_o}{R_o}v_o = i_1v_1 + i_2v_2)$. i_2 can be expressed as Eq.(3-32b)

$$i_2 = \frac{\frac{v_o^2}{R_o} - \frac{D_1 R_o [(R_o + R_c)Cs + 1](D_1 v_1 + D_2 v_2)}{\left[Cs + \frac{1}{(R_o + R_c)}\right] [Ls + R_L + R_o]}}{v_2} \quad (3-32b)$$

Combining Eq. (3-29), Eq.(3-32a) and Eq.(3-32b), the relationship of i_1 , i_2 , v_o and D_1, D_2 is shown in Eq.(3-33)

$$\left. \begin{aligned} v_o &= \frac{R_o(D_1 v_1 + D_2 v_2)[R_o + R_c[(R_o + R_c)Cs + 1]]}{[Cs(R_o + R_c) + 1][Ls + R_L + R_o]} \\ i_1 &= \frac{D_1 R_o [(R_o + R_c)Cs + 1](D_1 v_1 + D_2 v_2)}{\left[Cs + \frac{1}{(R_o + R_c)}\right] [Ls + R_L + R_o]} \\ i_2 &= \frac{\frac{v_o^2}{R_o} - \frac{D_1 R_o [(R_o + R_c)Cs + 1](D_1 v_1 + D_2 v_2)}{\left[Cs + \frac{1}{(R_o + R_c)}\right] [Ls + R_L + R_o]}}{v_2} \end{aligned} \right\} \quad (3-33)$$

The relationship between v_o and i_1 with D_1 and D_2 has been represented by Eq.(3-33). In the next part of derivation the disturbance of the source voltage and duty ratio will be considered. The small-signal model of the DSHC will be built.

Step 3

The ac small-signal solution is found by the substitution $v_1 = \widehat{v}_1 + v_1, v_2 = \widehat{v}_2 + v_2, D_1 = \widehat{d}_1 + D_1$ and $D_2 = \widehat{d}_2 + D_2$ into Eq.(3-33), where $\widehat{v}_1 + v_1$ represents the input voltage 1 variations, $\widehat{v}_2 + v_2$ represents the input voltage 2 variations, $\widehat{d}_1 + D_1$ represents the duty ratio 1 variations, and $\widehat{d}_2 + D_2$ represents the duty ratio 2 variations.

To simplify the equation, $\frac{R_o[R_o + R_c[(R_o + R_c)Cs + 1]]}{[Cs(R_o + R_c) + 1][Ls + R_L + R_o]}$ in v_o is replaced by Q.

$\widehat{v}_o + v_o$ is expressed as Eq.(3-34).

$$\widehat{v}_o + v_o = [D_1 v_1 + D_2 v_2 + \widehat{d}_1 v_1 + D_1 \widehat{v}_1 + \widehat{d}_2 v_2 + D_2 \widehat{v}_2 + \widehat{d}_1 \widehat{v}_1 + \widehat{d}_2 \widehat{v}_2]Q \quad (3-34)$$

As above represented, $\widehat{v}_o + v_o$ is nonlinear owing to the presence of the product of the two time dependent quantities $\widehat{v}_x$ and $\widehat{d}_x$.

$$\frac{\widehat{v}_x}{v_x} \ll 1, \frac{\widehat{d}_x}{D_x} \ll 1$$

Neglect all nonlinear terms such as the second-order terms in Eq.(3-34) and obtain once again a linear system.

$$\widehat{v}_o = [\widehat{d}_1 v_1 + D_1 \widehat{v}_1 + \widehat{d}_2 v_2 + D_2 \widehat{v}_2]Q \quad (3-35)$$

To simplify the equation, $\frac{R_o[(R_o+R_c)Cs+1]}{[Cs+\frac{1}{(R_o+R_c)}][Ls+R_L+R_o]}$ in i_1 is replaced by P.

$\widehat{i}_o + i_o$ is expressed as Eq.(3-36).

$$\begin{aligned} \widehat{i}_1 + i_1 = P \Big[& D_1(D_1 v_1 + D_2 v_2) + D_1 \widehat{d}_1 v_1 + D_1^2 \widehat{v}_1 + D_1 \widehat{d}_2 v_2 + D_1 D_2 \widehat{v}_2 \\ & + D_1 \widehat{d}_1 \widehat{v}_1 + D_1 \widehat{d}_2 \widehat{v}_2 + \widehat{d}_1(D_1 v_1 + D_2 v_2) + \widehat{d}_1^2 v_1 \\ & + D_1 \widehat{d}_1 \widehat{v}_1 + \widehat{d}_1 \widehat{d}_2 v_2 + D_2 \widehat{d}_1 \widehat{v}_2 + \widehat{d}_1^2 \widehat{v}_1 + \widehat{d}_1 \widehat{d}_2 \widehat{v}_2 \Big] \end{aligned} \quad (3-36)$$

The same as above, $D_1 \widehat{d}_1 \widehat{v}_1$, $D_1 \widehat{d}_2 \widehat{v}_2$, $(\widehat{d}_1^2 v_1 + D_1 \widehat{d}_1 \widehat{v}_1 + \widehat{d}_1 \widehat{d}_2 v_2 + D_2 \widehat{d}_1 \widehat{v}_2 + \widehat{d}_1^2 \widehat{v}_1 + \widehat{d}_1 \widehat{d}_2 \widehat{v}_2)$ can be neglected. $\widehat{i}_1$ can be expressed as Eq.(3-37).

$$\widehat{i}_1 = P[D_1 \widehat{d}_1 v_1 + D_1^2 \widehat{v}_1 + D_1 \widehat{d}_2 v_2 + D_1 D_2 \widehat{v}_2 + \widehat{d}_1(D_1 v_1 + D_2 v_2)] \quad (3-37)$$

The small-signal model of the DSHC can be expressed as Eq.(3-38).

$$Y(s) = \begin{bmatrix} \widehat{v}_o(s) \\ \widehat{i}_1(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix} \cdot \begin{bmatrix} \widehat{d}_1(s) \\ \widehat{d}_2(s) \end{bmatrix} \quad (3-38)$$

Where

$$G_{11}(s) = \left. \frac{\widehat{v_o}(s)}{\widehat{d_1}(s)} \right|_{\widehat{d_2}(s)=0}$$

$$G_{12}(s) = \left. \frac{\widehat{v_o}(s)}{\widehat{d_2}(s)} \right|_{\widehat{d_1}(s)=0}$$

$$G_{21}(s) = \left. \frac{\widehat{i_1}(s)}{\widehat{d_1}(s)} \right|_{\widehat{d_2}(s)=0}$$

$$G_{22}(s) = \left. \frac{\widehat{i_1}(s)}{\widehat{d_2}(s)} \right|_{\widehat{d_1}(s)=0}$$

$$G_{11}(s) = \frac{v_1 R_o [R_o + R_c [(R_o + R_c)Cs + 1]]}{[Cs(R_o + R_c) + 1][Ls + R_L + R_o]}$$

$$G_{12}(s) = \frac{v_2 R_o [R_o + R_c [(R_o + R_c)Cs + 1]]}{[Cs(R_o + R_c) + 1][Ls + R_L + R_o]}$$

$$G_{21}(s) = \frac{R_o [(R_o + R_c)Cs + 1][D_1 v_1 + (D_1 v_1 + D_2 v_2)]}{\left[Cs + \frac{1}{(R_o + R_c)}\right][Ls + R_L + R_o]}$$

$$G_{22}(s) = \frac{R_o [(R_o + R_c)Cs + 1]D_1 v_2}{\left[Cs + \frac{1}{(R_o + R_c)}\right][Ls + R_L + R_o]}$$

After simplification

$$G_{11}(s) = \frac{v_1 R_o [R_c Cs + 1]}{CLs^2 + s \left[(R_L + R_o)C + \frac{L}{R_o + R_c} \right] + \frac{R_L + R_o}{R_o + R_c}}$$

$$G_{12}(s) = \frac{v_2 R_o [R_c Cs + 1]}{CLs^2 + s \left[(R_L + R_o)C + \frac{L}{R_o + R_c} \right] + \frac{R_L + R_o}{R_o + R_c}}$$

$$G_{21}(s) = \frac{R_o[(R_o + R_c)Cs + 1][D_1v_1 + (D_1v_1 + D_2v_2)]}{CLs^2 + s[(R_L + R_o)C + \frac{L}{R_o + R_c}] + \frac{R_L + R_o}{R_o + R_c}}$$

$$G_{22}(s) = \frac{R_o[(R_o + R_c)Cs + 1]D_1v_2}{CLs^2 + s[(R_L + R_o)C + \frac{L}{R_o + R_c}] + \frac{R_L + R_o}{R_o + R_c}}$$

The small signal block diagram can be expressed as Figure 3-12 based on the above derivation.

Figure 3-12: Small-signal block diagram of the DSHC

The inputs of the block diagram are the output voltage reference and the source₁ current reference. As represented in previously, $(k-1)$ sources current (or power) and output voltage v_o can be controlled in the proposed MIHC. In the DSHC, source₁ current i_1 (or source₂) and output voltage v_o are selected as the control objects. In the Figure 3-12, the controller of the source₁ current is represented by $G_{ic}(s)$. The output voltage controller is represented by $G_{vc}(s)$. $G_{if}(s)$ and $G_{vf}(s)$ represent the sampling function of the source₁ current and output voltage respectively. The $G_{PWM}(s)$ represents the PWM generator function which is built in the microcontroller. In the next chapter $G_{ic}(s)$ and $G_{vc}(s)$ will be designed based on Figure 3-12 represented block diagram.

3.4 Conclusion

In this chapter, an MIHC was proposed. The more general MIHC with k input sources was derived. The derived results indicated that the proposed MIHC can be used for k input sources. Output voltage v_o and $(k-1)$ source current can be controlled by adjust the duty ratio $D_{(x)}$. The proposed MIHC can be adopted in many hybrid systems. In the perspective of mathematics and control theory, the developed DSHC topology has been proven to be able to realize the control target of regulating both the output voltage of the DSHC and the output current of source₁ (PEM fuel cell) simultaneously. v_o can be controlled by means of finding a certain combination of D1 and D2 with a proper control method, while D1 (or D2) from the same combination can determine the output current of S1 (or S2) as well. Finally, the small signal model of DSHC was built for the control system design in the next stage of the research.

In this chapter, although the proposed MIHC was designed for PEM fuel cell, battery and ultracapacitor, it is suitable for others type renewable energy sources such as solar PV and wind. As approved in this chapter, the MIHC can be use to control the power distribution of each source. This feature of the MIHC is very useful for the maximum point power tracking. The output power of the solar PV or the wind turbine is variable in different time. The output power of the solar PV or wind turbine can be adjusted by the MIHC. Consequently, the maximum point power can be track the by the proposed MIHC and it is a significant topology for these kinds of renewable energy.

In next chapter the design of control strategy and the selection of control parameters will be given.

CHAPTER 4 Control, Energy Management and Experimental Study of MIHC

As depicted in Chapters 2 and 3, for the proposed MHIC, according to the law of the conservation of energy, the expression between the load demand and k sources is given as

$$p_{Load} = \underbrace{v_1 i_1 + v_2 i_2 + \dots + v_{k-1} i_{k-1}}_{\text{controllable}} + \underbrace{v_k i_k}_{\text{provide dynamic power}} \quad (4-1)$$

For a well-designed hybrid system, the output of MHIC should track the load power demand timely. If a transient load change occurs, from Eq. (4-1), we can see that there is at least one current that is changeable in order to provide enough power for the load. In this thesis, the fuel cell power should be controlled at nearly unchangeable under a limited time [14], meanwhile, the battery or ultra-capacitor current should track the load current dynamically. In the next two parts the energy management strategy and its controller will be discussed.

4.1 Energy management strategy for DSHC

To achieve the target mentioned above, an energy management strategy [54], [55-57] is proposed in this research. Figure 4-1 shows the block diagram of the energy management strategy. In this section the energy management strategy will be presented. The selection of control system parameters for energy management strategy will be presented in next part.

Figure 4-1: Fuel Cell Li-battery Hybrid system energy management strategy

As showing Figure 4-1, there are 6 blocks in the energy management strategy diagram. It includes Close Mode (CM), Standby Mode (SM), Fuel Cell Current Limit Mode (FCCLM), Fuel Cell Power Only Mode (FCPOM), Battery Power Only Mode (BPOM) and Load Disconnected Mode (LDM).

FCCLM includes 2 sub-parts: Fuel Cell Over Load Limit Mode (FCOLLM) and Fuel Cell Light Load Limit Mode (FCLLLM).

FCPOM includes 2 sub-parts: Fuel Cell Light Load Limit Mode (FCLLLM) and Fuel Cell Light Load No-limit Mode (FCLLLNM).

There are 7 modes in the energy management strategy module. The functions of these 7 modes will be described in the following parts.

1. CM (Close Mode): The power of the whole system is turned off. The whole system stops working in this mode.
2. SM (Standby Mode): The system is powered up. All the sensors, detection circuits, drive circuits and communication circuit are working. The values of Fuel Cell and Li-battery currents are zero.
3. LDM (Load Disconnected Mode): This mode will be active when the system input power failure or the SOC of the Li-Battery is low (battery voltage v_b less than the threshold value V_{bmin}) or the overload state is detected by the control system. The MOSFET switches M_{12} and M_{34} will be closed. The charging circuit will be controlled based on the SOC of the Li-Battery and the state of Fuel Cell. The system will also transfer into this mode if it receives a control command from the host computer. If the LDM is active during the fuel cell failure or overload, the detection circuit will monitor the fuel cell or the load condition. If the failure state is cleared, the system will change to FCCLM or BPOM automatically.
4. Fuel Cell Over Load Limit Mode (FCOLLM): This mode will be active when the output current of fuel cell exceeds the threshold value I_{rfc} . The controller will adjust the duty cycle of the DSHC to maintain the output current of fuel cell at I_{rfc} . The rest power requirement of the load will be provided by the Li-Battery. The output voltage of the DSHC will be maintained at v_o .
5. Fuel Cell Light Load Limit Mode (FCLLLM): This mode will be active when the output current of fuel cell lower than the threshold value I_{rfc} as the load is lighter. In order to maintain the output current of fuel cell at I_{rfc} . The fuel cell will be used to charge the Li-battery. To protect the Li-battery, the charging current of the battery is limited at I_{bcmax} . The FCLLLM will be allowed to be active if the following condition is true:
 - 1) The charging current of the battery $i_{bc} < I_{bcmax}$.
 - 2) The SOC of the Li-battery is lower than the threshold value.

In the case that $i_{bc} > I_{bcmax}$ or that the SOC of the Li-battery is higher than the

threshold value, the system will switch to BPOM or FCLLM based the SOC of the Li-Battery.

FCOLLM and FCLLM are combined as FCCLM. In this mode, the output current of the fuel cell will be maintained at I_{rfc} . The I_{rfc} can be set at the maximum power point or maximum efficiency point.

6. Fuel Cell Power Only Mode (FCPOM): In this mode, the output current of the fuel cell is larger than the setting point (I_{rfc}). The output current of the fuel cell will be charged into the energy storage devices according to the load requirement. As mentioned above, the efficiency of the system and the life time of fuel cell will be decreased if the system works at this mode for a long time. This mode is undesirable for the controller.

This mode will be active only if the system works at BPOM. If the system works a long time at the BPOM, the SOC of the Li-battery will be lower than the threshold value. In order to maintain the system workable, the system will switch to FCLLM. But if the load requirement is unable to maintain the FCLLM, the system will switch to FCPOM. In this mode, the fuel cell will charge the battery. If the SOC of Li-battery could not be charged to the discharge threshold value, the control system will detect this charging failure. The LDM will be activated by the controller to protect the fuel cell and Li-battery.

7. BPOM (Battery Power Only Mode): In this mode, the battery will power the load individually. In the special conditions or the fuel cell failure, this mode will be activated. The special condition includes two cases.

Case 1: The fuel cell working at FCLLM will charge the Li-battery. The SOC of Li-battery is charged to the upper threshold value ($v_b > V_{bmax}$). As the fuel cell current cannot be limited by the Li-battery, the Li-battery will power the load individually.

Case 2: The fuel cell working at FCLLM will charge the Li-battery. The charging current of the Li-Battery increases as the load current falls until the charging current of the Li-Battery is higher than the maximum charging current of the Li-battery ($i_{bc} > I_{bcmx}$). If the SOC of Li-Battery is normal, to prevent

the fuel cell from working at low efficiency area, the system should switch to BPOM. A maximum discharging current of Li-battery (I_{bcmax}) will be set. If $i_{bc} < I_{bcmax}$, the system will keep at BPOM. If $i_{bc} > I_{bcmax}$ in the BPOM, the system will switch to FCCLLM to protect the Li-battery.

When the system is running, these 7 modes will be switched following the load and fuel cell variations. 12 switching conditions were designed in the energy management part. These 12 switching conditions were expressed in Figure 4-1. The controller will switch the working modes automatically, once the switching condition was matched. The energy management strategy can be summarized in Table 4-1.

Table 4-1: Energy management state mode switching rules

Code	Activation mode	The conditions of switching	Description
0	Close→Standby	normal operation of battery SOC AND the voltage of FC and battery is normal	Fuel cell and Li-battery work at the normal state. The host PC sends a start command to the controller. DSHC start to run.
I	Standby→FCCLM	Load connected ($i_o > 0$) AND The state of SOC is normal.	Load is connected. The system starts to power the load. FCCLM was active as FCCLM is the first priority mode in standby mode.
II	FCCLM→BPOM		The state of Li-battery is normal. If any following condition is satisfied in the FCCLM:
		$(i_{fc} < I_{rfc} \ \& \ v_b \geq V_{bmax})$ OR	a) The battery Li-battery is fully charged in FCCLLM.
		$(i_{fc} < I_{rfc} \ \text{AND} \ i_{bc} \geq I_{bcmax})$ OR	b) The charging current of Li-Battery is higher than the protection current threshold value.

		(FC failure AND The load cannot be disconnected)	c) If the system cannot be maintained at FCCLM as fuel cell failure and the load cannot be disconnected.
		Fuel cell will be disconnected from DSHC and Li-battery will power the load separately.	
III	BPOM→FCCLM	The state of fuel cell is normal. If any following condition is satisfied in the BPOM :	
		$i_b \leq I_{bmax}$ AND $t_{BPO} > Settime$ OR	a) The load power is lower than the limitation of the battery power. The time of system working at BPOM is larger than a setting value.
		$i_b > I_{bmax}$ OR	b) The load increased to a threshold value which the Li-battery cannot power the load individually.
		$i_o > I_{FCCLM}$ AND $v_b < 75\%v_{bmax}$ OR	c) The Li-battery power the load (the state of the system satisfy the requirement of FCCLM) and the SOC of Li-battery is lower than a threshold value.
		Battery failure AND load cannot be disconnected	d) Li-battery is failure; Load cannot be disconnected;
		The system will be switched to FCCLM.	
IV	FCCLM→DLM	If any following condition is satisfied in the FCCLM:	
		FC failure AND load can be disconnected OR	a) Fuel cell is failure; The load can be disconnected (The fuel cell needs to be repaired).
		$v_b < V_{bmin}$ AND $i_{bc} < I_{bcmin}$ AND load can be disconnected	b) The overcharging of the Li-battery is detected, and the

		OR	SOC of the battery is low.
		$i_{fc} \geq I_{rfc}$ AND $v_b < V_{bmin}$ OR $i_o < I_{omax}$ OR	c) In FCOLL, as the load increasing, the SOC of Li-battery is lower than the threshold value, or the power of load reaches to the upper limit of two power source (Over load, load failure or short circuit).
		FC failure AND $v_b < V_{bmin}$ OR	d) Fuel cell is failure, and the SOC of Li-battery is lower than the threshold value (extreme state).
		System or two input power failure	e) The two power sources (fuel cell and Li-battery) failure (extreme state).
		The system will be switched to DLM.	
V	DLM→FCCLM	$v_b < (1 + 15\%)V_{bmin}$ AND $i_o > I_{FCCLM}$ AND The state of system is normal	In the DLM, the system will be switched to FCCLM if the battery is recharged to a threshold value.
VI	BPOM→DLM	If any following condition is satisfied in the BPOM:	
		Battery failure AND load can be disconnected	a) Li-battery is failure. And the load can be disconnected. (The Li-battery need to be repaired)
		System or two input powers failure	b) The DSHC control system failure or both two power sources are failure (extreme state).
		The system will be switched to DLM.	
VII	DLM→BPOM	The last state is BPOM AND normal operation of input power	The load or battery failure is cleared.
VIII	FCLLLM→FCLLM	$v_b < V_{bmin}$ AND $i_{bc} \geq I_{bcmax}$ AND load cannot be disconnected	The overcharging of the Li-battery current is detected. And the SOC (voltage) is lower than the protection

			value.
IX	FCLLMNM→FCLLLM	$v_b > 115\%v_{bmin}$	If the voltage of Li-battery is charged to $115\% v_{bmin}$, the system will be switched to FCLLLM.
X	FCOLLM→FCLLLM	$i_{fc} < I_{rfe}$	In FCOLLM, if the load is reduced, the system will be switched to FCLLLM. The remaining energy of the fuel cell will be used to charge the Li-battery to maintain the current of fuel cell ($i_{fc} = I_{rfe}$).
XI	FCLLLM→FCOLLM	$i_{fc} \geq I_{rfe}$	In FCLLLM, if the load is increased to a threshold value ($i_{fc} \geq I_{rfe}$), the system will be switched to FCOLLM. Fuel cell and Li-battery will power the load together to limit the current of fuel cell ($i_{fc} = I_{rfe}$).
XII	FCLLMNM→DLM	$i_o < (I_{rfe} - I_{bcmax})$ $v_b \leq 115\%V_{bmin}$ AND $t_{FCLLMNM} > T_{FCLLMNM}$	$t_{FCLLMNM}$ (The time of the system working at FCLLMNM) is longer than a threshold value. And the SOC of the Li-battery is low.

4.2 Controller development for DSHC

4.2.1 The structure of controller

As mentioned in the previous chapters, the target of the controller is to regulate the current of one source (fuel cell) on the premise of maintaining the output voltage of the DSHC at first [59]. The characteristic of input-output relation of the DSHC is proven to be able to make it realizable. A closed loop control method is proposed to realize the control target on the DSHC.

Base on the proposed energy management strategy, the controller works in three modes. Fuel Cell Current Limit Mode (FCCLM) is represented by Figure 4-4. Battery Power Only Mode (BPOM) is represented by Figure 4-3. FCLLMNM Fuel Cell Light Load No-limit Mode (FCLLMNM) is represented by Figure 4-2.

Figure 4-2: Control schematic of the proposed DSHC in FCLNM

Figure 4-3: Control schematic of the proposed DSHC in BPOM

The detail of these three loops will be presented in the next part of this section. The main structure of the control loop is based on Figure 4-4 (FCCLM). The small signal model of this mode is represented in Chapter 3 (Figure 3-12). Because other states are based on the FCCLM, the following explanations will focus on the first mode FCCLM which is represented by Figure 4-4.

Figure 4-4: Control schematic of the proposed DSHC in FCCLM

Two variables will be controlled in FCCLM. The first variable is the output voltage of DSHC. This will maintain the output voltage v_o at an appropriate level. The second one is the output current (or power) of source₁ i_{s1} . This will make sure that the source₁ (PEM fuel cell) is working at a constant current (or power) mode, which can protect the source₁ and improve the efficiency of the source₁. Two proportional–integral (PI) controllers are used to control these two variables. The output of PI controller 1 is D_{buck} which represents the total duty cycle of the DSHC. The output of PI controller 2 is D_{1temp} which represents the duty cycle of the source₁ relative to the D_{buck} (D_{1temp} much be normalized). The actual duty cycle of S_1 (D_1) and S_2 (D_2) are decided by the following equations.

$$\begin{aligned}
 D_{buck} &= K_{v1}(v_{oref} - v_o) + K_{v1} \int_0^t (v_{oref} - v_o) dt \\
 D_{1temp} &= K_{i2}(i_{s1ref} - i_{s1}) + K_{i2} \int_0^t (i_{s1ref} - i_{s1}) dt \\
 D_1 &= D_{buck} D_{1temp} \\
 D_2 &= D_{buck} - D_1 - D_{dead}
 \end{aligned} \tag{4-2}$$

Since v_o is related to both D_1 and D_2 as Eq. (3-10) presents, it is therefore defined that D_1 plus D_2 equals D_{buck} . On the other side, another closed loop is imported for maintaining i_{s1} or i_{s2} . It might as well be assumed S_1 is the source whose output current is needed to be controlled. If i_{s1} feedback value is getting lower, the error between i_{s1ref} and i_{s1} will become larger. After regulating through PI controller 2, the output D_{1temp} will increase in order to raise i_{s1} value. D_{1temp} should be multiplied by D_{buck} . That is because D_1 and D_2 together determine the

value of v_o . So if D_1 is changing, D_2 will be correspondingly modified for keeping v_o stable. The subtraction of D_{buck} and D_1 is served as D_2 . In addition, there exist a limited dead-time between D_1 and D_2 in order to prevent the situation that both S_1 and S_2 are on duty.

4.2.2 The analysis and parameters design of control system

There are two loops in the FCCLM. The parameters of the loops are related with both two PI controllers. The design of the PI parameters will become complex if the parameters are calculated in FCCLM. Because the current and voltage loops in the FCLLM were related with one PI controller, the current loop of the PI controller can be designed in the FCLLM. The PI controller parameter of the voltage loop can be designed in the FCLLM and BPOM. The two PI parameters will be substituted into the FCCLM to verify the stability of the system. If the system is unstable, the two PI parameters will be redesigned by following the above procedures. Figure 4-5 shows the block diagram of three working modes which have been mentioned above.

(a) FCCLM

(b) FCLLM

(c) BPOM

Figure 4-5: Block diagram of three working mode: FCCLM, FCLLM, BPOM

The system parameters are shown in Table 4-2. The transfer function of the PI controller can be expressed as:

$$G_{ic}(s) = k_{1i} + \frac{k_{2i}}{s}$$

$$G_{vc}(s) = k_{1v} + \frac{k_{2v}}{s}$$

The PI parameter is designed in MATLAB. As aforementioned, the current loop is designed at first in the FCLLM. Figure 4-6 shows the bode-plot of the current loop. The solid-line represents the compensated loop. The dotted-line represents the uncompensated loop.

Figure 4-6: The bode-plot of current loop in the FCLLM

Table 4-2: System parameters of the bode-plot

Parameters	FCCLM	FCLLM	BOPM
$v_1(FC)/V$	37	37	0
$v_2(Li-battery)/V$	40	0	40
I_{rf}/A	5	5	0
I_o/A	15	2	15
v_o/V	30	30	30
$L/\mu H$	43.2		
$C/\mu F$	231.47		
R_C/Ω	0.182		
R_L/Ω	0.086		
f_s/kHz	100		
R_o/Ω	2		
G_{yf}	0.025		
G_{if}	0.1		
G_{PWM}	0.333		

The outer loop of the system is the voltage loop. The inner loop of the system is the current loop. The cutoff frequency of the voltage loop (outer loop) should be lower than the cutoff frequency of the current loop (inner loop). The cutoff frequency of the current loop is designed at 20 kHz. The magnitude margin is -1.01dB if the system is uncompensated. In this system, $k_{1i} = 1.13$ and $k_{2i} = 2.33 \times 10^4$. The bode-plot shows that the cutoff frequency is 20 kHz, the magnitude margin is 32.1dB. The system is stable.

The current loop PI parameters have been given. The voltage loop PI parameters will be designed in the FCLLM and BPOM based on the current loop PI

parameters. The bode-plots of uncompensated are shown in Figure 4-7 and Figure 4-8. It can be found that the system is unstable in both two modes. As aforementioned, the cutoff frequency of the inner loop should be higher than the cutoff frequency of the outer loop. The cutoff frequency was set at 5 kHz in the research.

k_{1v} is designed at first in the BPOM. $k_{1v} = 98.5$ to make sure the cutoff frequency of the voltage loop is 5 kHz. When k_{1v} is substituted in the FCLLM. The cutoff frequency of the voltage loop is 3.4 kHz, which is lower than 5 kHz. The second part of this section is the k_{2v} design. In this design, $k_{2v} = 3 \times 10^5$. The magnitude margins are 70.1dB (FCLLM) and 50.7dB (BPOM). The system is stable.

Figure 4-7: The bode-plot of voltage loop in the BPOM

Figure 4-8: The bode-plot of voltage loop in the FCLLM

The parameters of current and voltage loops are substituted in FCCLM. The bode-plots of the current and voltage are shown in Figure 4-9 and Figure 4-10. The results show that the cutoff frequency of the current loop is 19.1 kHz and phase margin is 92.2°. The cutoff frequency of the voltage loop is 5.02 kHz and phase margin is 138°, which can meet the design requirement. The PI control parameters have been designed.

Figure 4-9: The bode-plot of current loop in the FCCLM

Figure 4-10: The bode-plot of voltage loop in the FCCLM

This thesis has derived the PI parameter based on the system which was built. If different numbers of energy sources or different type of energy sources are used in MIHC, the PI parameters should be changed correspondingly. For others types of energy source different objective may be needed, different control algorithm may be adopted also.

4.3 Experiment

4.3.1 Experimental platform setup

The prototype of the proposed DSHC and its DSP control system is developed to validate the correctness of the theory and the effectiveness of the control strategy. The system schematic diagram of the prototype is presented in Figure 4-11.

Figure 4-11: Schematic diagram of the DSHC prototype

As can be seen from Figure 4-11, the Ballard Nexa Fuel Cell System (BNFCS), whose dynamic response curves are tested as the report described in Chapter 3, is served as S_1 , while a 10-cell 10Ah lithium battery is chosen as S_2 . The PCB board integrates with the DSHC circuit, interface circuit and TMS320F2808 control system. The programmable electronic load band (KIKUSUI PLZ1004W, 1.5~1500V, 0~200A) is connected to the PCB board to provide preset constant resistance load, which is changing with time. The upper computer that is installed CCS 3.3 and RS232 communication software is responsible for giving operation and control orders to DSP while receiving feedback information from the prototype for supervision. The details on component selection are listed in Table 4-3.

Table 4-3: Performance index of the prototype-used sources and components

v_o	24~42V	D	MBR60H100CTG (60A, 100V)
v_{S1}	26~42V	C_1, C_2, C	ECOS2AA102CA (1000μF, 100V, ESR:182mΩ)
v_{S2}	37~41V	$M_1 \sim M_4$	IRFP4468PBF (290A, 100V)
i_{S1}	0~46A	$D_{buf1},$ D_{buf2}	S5B (5A, 200V)
i_{S2}	0~20A	$C_{buf1},$	0.1μF

		C_{buf2}	
L	$42.25\mu\text{H}$	$R_{buf1},$ R_{buf2}	1.5Ω

Figure 4-12 exhibits experimental installation of the PEM fuel cell/battery hybrid DSHC power supply prototype. The frequency of the PWM control signal input to the MOSFET is 100kHz. v_{oref} of the prototype is set to 30V, i_{lref} for BNFCs is set to 5A. Environmental temperature is 25°C. 99.99% pure hydrogen gas is supplied to the BNFCs with the pressure of 2 bars. Voltages and currents of S_1 , S_2 and converter output are monitored and recorded by the oscilloscope (Tektronix DPO 4034) with 1MHz scan frequency.

Figure 4-12: Photograph of experimental platform

4.3.2 Testing results and discussions

The experiment of the energy management control strategy and DSHC is based on the previous presented platform. All the running states and switching conditions are simulated in the testing process by adjusting the programmable electronic load or turning off the power supply (Li-battery or fuel cell). The experiment parameters are shown in Table 4-4.

Table 4-4: Experiment parameters setting

Items	Value
Fuel cell current	$I_{rfc} = 5A$

Li-battery over voltage protection	$V_{bmax} = 43.5V$
Li-battery low voltage protection	$V_{bmin} = 30V$
Max charging current of Li-battery	$I_{bcmax} = 2.2A$
Max discharging current of Li-battery	$I_{bmax} = 18A$
Max time in BPOM (IF fuel cell works)	$t_{BPO} = 100s$
Max time in FCLLN (Fuel cell protection)	$t_{FCLLN} = 100s$

To illustrate the state of the system, Table 4-5 is given. For convenience, each operation mode is coded in numerical sequences. In the testing result chart, the state of the system is also presented in number sequences.

Table 4-5: State number of the DSHC controller

Mode	CM	SM	FCLLN	LDM	FCLLM	FCOLLM	BPOM
Code	0	1,9	2	3	4	5,8	6,7

As mentioned before, all the actions are activated by adjusting the load conditions or disconnecting the power source. The testing procedure is described by Table 4-6.

Table 4-6: Testing procedure table

Trigger time (s)	Switch Mode	Load changing	Other
0	0→1	disconnected→0A	Press “s” form RS232
60	1→2→3(At 160s)	0A→2.5A	Disconnected Li-Battery
200	3→4	2.5A→3.5A	Reconnected Li-Battery
300	4→5	3.5A→6A	—
400	5→5	6A→12.5A	—
500	5→5	12.5A→8.5A	—
600	5→6	8.5A→8A	Disconnected FC

700	6→6	8A→2A	—
800	6→6	2A→6A	—
900	6→7	6A→6A	Reconnected FC
1000	7→8	6A→8A	—
1100	8→9	8A→disconnected	Power off

The testing results are shown in Figure 4-13 and Figure 4-14.

Figure 4-13 presents the voltage of the load, fuel cell and Li-battery. Figure 4-14 presents the current of the load, fuel cell and Li-battery. The working modes are shown in numerical sequences which are listed in Table 4-5.

In the beginning of the experiment, the controller is switched to standby mode by an external starting command. The voltages of fuel cell and battery are operating of their open circuit voltage. The output current is zero.

Figure 4-13: Voltage waveform of the load, fuel cell and Li-battery

A 2.5A constant current load is connected after 60 seconds. Li-battery is switched off (disconnected) to simulate the failure of Li-battery or SOC alarm. The charging current of the battery is larger than I_{bcmax} (2A) based on the load current. The control system will be switched to FCLLM. Fuel cell will power the load individually. The current of the fuel cell cannot be controlled in this state.

Figure 4-14: Current waveform of the load, fuel cell and Li-battery

When the system time reach to 160 seconds, the running time of FCLLM will be more than 100 seconds ($t_{FCLLM} = 100s$). To protect the fuel cell, the system should switch to LDM as the Li-battery cannot be connected to power the load (The experiment is set to simulate the failure of Li-battery). In LDM, the Li-battery can be charged or replaced to restore the power of Li-battery. In LDM, the monitoring unit will be activated to detect the restoration of the Li-battery.

At 200 seconds ($t = 200s$), the Li-battery is connected, and a 4.5A load is connected also. The system is switched to FCLLM. As the current of fuel cell is less than 2A, the system should switch to FCLLM. In this mode, the fuel cell current is divided into two parts. The first part is 3.65A which is used to power the load. The second part is 1.35A which is used to charge the Li-battery. The current of fuel cell is maintained at 5A.

After another 100 seconds ($t = 300$), the load is increased to 7.6A. The current of fuel cell will be larger than 5A ($I_{r_{fc}} = 5A$) if the load is powered by the fuel cell individually. The system will switch to FCOLLM, fuel cell and Li-battery has to power the load together. The current of fuel cell is maintained at 5A by the current controller which has been presented in the previous section. The extra current (1.5A) of load is provided by the Li-battery. The output voltage of DSHC is maintained at 30V.

The load is changed at 400 seconds and 500 seconds respectively. The output voltage and current of fuel cell are maintained at the reference points. 7.6A, 15A and 8.5A loads are tested. The state of the system is stable.

The fuel cell is disconnected at 600 seconds to simulate the failure of fuel cell. The system is switched to BPOM. The Li-battery powers the load individually. The output voltage is maintained at 30V.

The load is changed at 700 and 800 seconds respectively. The output voltage is maintained at 30V. The state of the system is stable.

The fuel cell is re-connected at 900 seconds. The load is maintained at 6A. The system will detect the restoration of fuel cell. After 100 seconds ($t_{BPO} = 100s$, $t = 1000s$), the system is switched to FCOLLM. The power is provided by the two power sources. The running state of the system is same as previous condition ($t = 300s \sim 600s$).

At 1100 seconds, a stop command is sent by the host PC. All the control signals are disabled. Load current is zero. The main-circuit and control-circuit are still powered. The whole system is switched to SM.

The experiment result demonstrates that the system can be switched in different load conditions based on previous energy management control rules. In FCOLLM and FCLLLM, the current of the fuel cell is maintained at 5A. The fluctuation range of the fuel cell current is less than $\pm 5\%$. The voltage of the load is maintained at 30V except SM and LDM. The fluctuation range of the load voltage is less than $\pm 1\%$.

It can be found that the output current of fuel cell is maintained less than 5A in all the load condition. The overshoot of the fuel cell output power is eliminated (It can be observed at 300s, 400s and 500s during the experiment). Therefore the load impact of the fuel cell is reduced and the mechanical stress of fuel cell membrane is reduced. In addition, it is not recommended the fuel cell operated at the low voltage area, as the polarity of some cell may become negative by the unbalancing of each cell. By adopting the proposed method, the operation point of fuel cell stabilizes in its optimized and safety area. The lifetime and stability of the fuel cell stack is increased. In the experiment, the peak power load demand is provided by the battery as the battery dynamic response is faster than the fuel cell. Because the capacity of the battery is limited, it is charged during light load demand period. The advantages of fuel cell (higher energy density, longer discharging time) and battery (higher power density, faster response) are combined together. The operating point of the fuel cell can be set at a high efficiency area by adopt the proposed method. Furthermore, the operation point of the fuel cell can be set real-time. The operation point can be optimized by adopt some algorithm in different load condition. Further research work can be carried on in this area.

From the experiment result, it can be observed that the fuel cell and battery current ripple increase when it working at the max output point. Some small over shoot can be found at the load changing moment. Those were caused by the dynamic characterizes of the MIHC and the PCB circuit layout issue. To find more detail on the dynamic response the following result is given.

Figure 4-15: The dynamic response curves of the DSHC

Figure 4-15 shows the current transient responses of the Li-battery and fuel cell when the load current is suddenly changed from 6A to 14A. The fuel cell current can be kept at a constant value (5A) by the proposed control method, and the Li-battery provides the extra current to the load. Because of the hysteresis characteristics of the controller and the sampling device, a 6A pulse is drawn from the fuel cell about 0.05s. Further improvement to keep the overshoot of the fuel cell current during load transients was needed in the further work.

4.4 Conclusion

Experiments of electrical characteristics have indicated that PEM fuel cell has a delay feature both during startup and load changing process, and large transients provided by PEM fuel cell should be reduced for prolonging the operation lifetime of PEM fuel cell. As a result, other energy sources (battery or ultra-capacitor) with relatively higher response rate and a better dynamic performance are needed to assist the PEM fuel cell in the hybrid power supply system. The MIHC has a higher efficiency, fewer component counts, lower cost and the simpler control method. The proposed MIHC is an ideal candidate for this system. In the perspective of mathematics and control theory, the developed DSHC topology has been proven to be able to realize the control target of

regulating both the output voltage of the DSHC and the output current of PEM fuel cell simultaneously.

The control block diagrams in each operation condition are designed. The PI controller (proportional–integral controller) parameters of the DSHC are optimized based on the small signal model which has been built in Chapter 3. A rule-based energy management strategy is designed. The control strategy is designed based on seven working modes. The switching condition of each mode is defined considering the fuel cell efficiency, dynamic behavior and battery characteristic. A testing platform is built to verify the control parameters and the energy management strategy. The load variation is simulated by the programmable E-load.

The testing result shows that the Li-battery can provide the peak current when PEM fuel cell cannot provide enough power to the load (less than the setting rated power). When the load demanded power consumption is under the PEM fuel cell output power, the PEM fuel cell will charge the Li-battery to maintain the output current of PEM fuel cell at a constant rate. The dynamic testing result shows that the transient response time is 5ms. The overshoot of the PEM fuel cell current is 1A (20%).

In Chapters 3 and 4, a MIHC is proposed. The operation principle, small signal model, control parameter optimization and a rule-based energy management strategy are developed. In the next chapter, the regenerative braking function of the MIHC will be presented. A battery management system will also be applied to improve the performance of the system.

CHAPTER 5 Regenerative Braking and Battery Management for Multiple Input Hybrid Power Supply System

5.1 Introduction

One of the most important features of electric vehicles is the ability to recover significant amounts of braking energy [60]. The electric motors in electric vehicles can be controlled to operate as generators to convert the kinetic or potential energy of the vehicle mass into electric energy that can be stored in the ESS and then reused during the next time. On the other hand, it is important that the system must always meet the distinct demand of reducing vehicle speed quickly. Generally, the braking torque required is much larger, especially in heavy braking. That will always cause peak power converted to electrical in a short time. So it is important that design an ESS device which can store the surge energy in a short time [61], [68].

ESS has been a major research area in hybrid electric vehicles for a long time. Among all the energy storage devices, batteries are one of the most widely used. However, using a battery as the sole energy storage system has several issues.

First of all, a battery has higher internal resistance and losses during charging and discharging. These higher losses will limit the performance of the output power and charging power. Secondly, the power density of most available batteries is low. Most of the batteries can be used for a higher discharging rate (Higher than its rated current 2 to 20 times depend on different types of batteries) during the peak power [63], [64]. But it cannot be charged in the same current. A hybrid ultra-capacitors and batteries combined ESS (energy storage system) is proposed in this chapter to improve the system power density. Ultra-capacitors have a better power density but a poorer energy density than batteries. Ultra-capacitors will be used as the major energy regenerative device in the combined system. Another problem for a battery is that the capacity of Li-battery cells will degrade with the charging-discharging cycling increasing.

The differences (e.g. internal resistor, capacity) and different environmental conditions lead battery cell capacities diminish and diverge over time. The proposed hybrid ultra-capacitors and batteries combined ESS can greatly reduce the charging-discharging cycle numbers of the battery and reduce the loss of energy. Furthermore, to improve the performance of the battery and minimal degradation of the battery, a balancing method is adopted in this chapter. Figure 5-1 represents the research works structure of this chapter.

Figure 5-1: Research work structure of Chapter 5

5.2 Regenerative braking

As mentioned above, the energy regeneration function needs a device which can absorb the surge power. As the characteristic of battery, it is unsuitable for storing the regeneration energy recovering.

To solve this problem, this research will use ultra-capacitors as the main device to store the regeneration energy. The power density of ultra-capacitors is higher than batteries. This advantage is valuable for recover the braking energy [62], [63], [65], [66], [67].

The proposed Multiple Input Hybrid Converter (MIHC), as discussed in Chapters 3 and 4, is modified to include the regenerative braking function. A Matlab simulation and its result will be given in this chapter. In the last part of

Figure 5-5: Heavy braking mode (Charging)

5.2.2 Control system design and simulation

Circuit analyses and control system

There are two control modes for different operation conditions. The system will select the corresponding control modes based on the driver's commands. Figure 5-6 shows the outline structure of the control system. The following part will represent the two control modes respectively.

Figure 5-6: Outline structure of the control system

Driving mode

In the driving mode, the targets of the control system are three: p_{fc} (power of PEM fuel cell), i_{ba} (current of battery) and v_o (voltage of output). Figure 5-7 represents the control block diagram. 4 PI loops are built. The function of PI_1 is to control the PEM fuel cell power. PI_2 will use to limit the current of battery. The PI_3 is the output voltage controller. It will decide the total time of all three power switches. The output of PI_3 will be separated to three parts D_{fc} , D_{ba} and D_{cap} by the PWM distributor. The PI_4 controller is an internal controller which is used to control the voltage of the output capacitor C_2 . All the output of PI controllers will

be connected to a saturation function. The function of the saturation function is to prevent the overflow of the controller. Figure 5-8 represents the waveform for driving the power switches.

Figure 5-7: Schematic of closed loop control method in driving mode

Figure 5-8: Switching waveform in driving mode

The output of PI_3 is D_{buck} . Eq. (5-1) shows the operation in the PWM distributor. All the output of PI controller will be normalized before being sent to the

distributor.

$$\begin{cases} D_{fc} = D_{buck} \times PI_1 \\ D_{ba} = D_{buck} \times (1 - PI_1) \times PI_2 \\ D_{cap} = D_{buck} \times [1 - PI_1 - (1 - PI_1) \times PI_2] \end{cases} \quad (5-1)$$

The boost duty cycle D_{boost} is decided by the PI_4 loop directly, and its reference is the output voltage multiply with a coefficient μ (In the simulation this coefficient is 1.2).

Figure 5-8 represents the switching sequence of four switches. As shown in Figure 5-8, each switch (S_3 , S_4 and S_7) will turn on at different timing in one switching cycle. t_{d1} and t_{d2} are the dead time zone to prevent any two switches from being closed at the same time.

Regeneration mode

In the regeneration mode, two variables are controlled, which are the braking current and the charging current of the battery. As represented by Figure 5-4 and Figure 5-5, in the regenerative braking, the motor will work at the generator side. The braking current will be absorbed by the ultra-capacitors. Figure 5-9 represents the simplified equivalent circuit when the system running at the regenerative braking.

Figure 5-9: The equivalent circuit during the regeneration

The braking current is maintained by the boost converter (S_6 , C_3 , L_2) and the charging current is controlled by adjusting the duty cycle of S_2 . The duty cycle of S_6 is called D_{brake} and duty cycle of S_2 is D_{cha} .

Based on the power electronic technology for a given load and a fixed D_{brake} , the bus capacitor voltage v_{c2} is constant when the system in the steady state. When the load power consumption is suddenly increased at the same D_{brake} , the bus capacitor voltage (v_{c2}) will decrease as the dynamic characteristic of the circuit and effect of the internal resistance (in a real system this is very important). The bus capacitor voltage will fluctuate in the next few seconds and settles down to the steady state. The battery charging current can be controlled with the above rules.

Figure 5-10 represents the power flow black diagram when the system in the regeneration mode. During the braking, to meet the requirement of brake force, a brake current command will be set. The average of braking current (i_{brake}) is controlled to reach the reference value by adjusting D_{brake} (S_6). In a normal battery powered hybrid system, when the braking current (i_{brake}) is fixed, the bus capacitor voltage v_{c2} is uncontrollable because of Eq. (5-2). But in the proposed circuit, the load of the boost will change in each switching cycle by adjusting D_{cha} (S_2). As mentioned previously, the bus capacitor voltage v_{c2} will be reduced by increasing D_{cha} (The ultra-capacitor will absorb more energy for the bus capacitor which cause the bus capacitor voltage to drop). The bus capacitor voltage v_{c2} is controllable if the system applies an appropriate controller to adjust D_{cha} . Moreover, according to Eq. (5-3) expressing, the charging current of the battery will depend on the bus capacitor voltage v_{c2} , so the charging rate of battery (i_{ba}) can be controlled indirectly by D_{cha} .

Figure 5-10: Power flow black diagram in the regeneration mode

$$i_{ba} v_{ba} = i_{brake} v_{motor} \quad (5-2)$$

$$\underbrace{i_{ba}}_{\text{controlled indirectly}} v_{ba} + \underbrace{i_{uc}}_{D_{cha}} v_{uc} = \underbrace{i_{brake}}_{D_{brake}} v_{motor} \quad (5-3)$$

Figure 5-11: Schematic of closed loop control method for regeneration

Two separated PI controllers are used to maintain the i_{brake} and i_{ba} . As no shorting or charging problem exists during the switching, the dead time is not required. Figure 5-11 represents the control schematic when the system works at regeneration mode.

Simulation and results

Table 5-1: Simulation parameters and summary of output results

v_o (Set)	24V	Fuel cell voltage	60V
Battery voltage	48V	Switching frequency	50kHz
Load R	1ohm	Simulation time	0.016s
L_1	10 μ H	L_2	1mH
C_2	50 μ F	C_3	10 μ F
Ultra-capacitor	20F	Battery current limitation	1.5A
Fuel cell power limitation	80W	Output battery current	1.48A
Output power of Battery	70W	Output power of FC	80W
Output power of Load	550W	Output power of Ucap	400W

To verify the above control system and the control strategy, a simulation program is built. The simulation of this system is based on Matlab/SimPowerSystem. As mentioned previously, there are two working states depending on different modes. In the driving mode, the entire three devices (fuel cell, battery and UC) will provide power to the load. As it is complex to simulate a PEM fuel cell, this simulation concentrates on the Ohmic polarization of the PEM fuel cell. So the fuel cell is simulated by a DC voltage source in series with a resistor. Table 5-1 lists the parameter and result when the circuit working at driving mode.

Figure 5-12: Simulation results of power distribution in driving mode

Figure 5-13: Simulation results of output voltage in driving mode

Figure 5-12 and Figure 5-13 represent the simulation results. As we can get from Figure 5-12 (a) (b) the average output current and power of the battery and the PEM fuel cell are steady. The power of the PEM fuel cell and the current of the battery are limited within the reference values. From Figure 5-12 (c) and (d), the ultra-capacitor provides most of the dynamic power (more than 70%) during this simulation. The output voltage v_o is regulated at 23.5V – 24V.

During the regeneration mode, the energy is flowing from the motor to the ultra-capacitor and the battery. The reference value of braking current is 20A. The initial voltage of the ultra-capacitor is 10V. The initial motor voltage is 24V. The limitation of battery charging current is set at 2A. Figure 5-14 shows the charging currents of battery and ultra-capacitor and the brake current.

(a) Brake current (A)

(b) Battery charging current (A)

(c) Ultracapacitor charging current (A)

Figure 5-14: Regeneration simulation results

The results show that the brake current can be controlled in its reference working point by the proposed control method. The battery charging current is limited within the safety operation area by adjusting the D_{cha} which effects the charging current distribution between the ultra-capacitor and the battery. As more energy is recycled, the energy recovery system becomes more efficient.

5.3 Battery management system for MIHC

As mentioned before, the Li-battery has been considered as a large capacity single power source in the previous chapters. But the performance and characteristic of series connected Li-Battery is different from a single battery cell. A typical Li-battery pack consists of several cells in series, with one or more cells in parallel. While common, those configurations are not as efficient as they could be, because any capacity mismatch between series-connected cells reduces the overall pack capacity [73-76]. In fact, cell-to-cell differences in temperature, capacity and series impedance are a major concern as more cells are required in a pack.

Li-battery cells experience two primary kinds of mismatch. SOC mismatch occurs when initially equal capacity cells gradually diverge to contain different amounts of charge. Capacity or energy(C/E) mismatch occurs when cells with different initial capacities are used together.

SOH introduction

State of Health (SOH) [77], [78] is a "measurement" that reflects the general condition of a battery and its ability to deliver the specified performance as

compared to a fresh battery. It takes into account such factors as charge acceptance, internal resistance, voltage and self-discharges.

During the lifetime of a battery, its performance or "health" tends to deteriorate gradually due to irreversible physical and chemical changes, which take place with usage and with age until eventually the battery is no longer usable or dead.

The SOH is an indication of the point which has been reached in the life cycle of the battery and a measure of its condition relative to a fresh battery.

One safety operation rule for charging and discharging a Li-battery

A battery stack is built by connecting the individual cell in parallel and series. The charging process cannot be continued when one cell (usually the cell with the lowest capacity) is completely charged although some cells are not. The discharging process must stop when one cell (usually the cell with the lowest capacity) is empty, although the others still have some charge left.

The imbalance of SOC

The discharging and charging cycle of a Li-battery with the imbalance SOC is described in Figure 5-15. Base on the safety operation rule, the weakest cell (the SOC of this cell is smaller than others). It is indicated as $Cell_{(x)}$ in Figure 5-16 in the battery stack that the weakest cell will be fully discharged first. In the next charging cycle, the weakest cell cannot be fully charged as the stronger cells have been fully charged firstly. The performance of the Li-battery pack will depend on the weakest cell [79], [80], [81].

Figure 5-15: Imbalance of SOC

Figure 5-16: Simulation results of SOC imbalance discharging and charging cycle

The SOH of the weakest cell decreases faster compared with the other cells. The performance of the Li-battery pack decreases faster when to the weakest cell performance decreases. The efficiency of the Li-battery pack is lower compared with a SOC matched battery Li-battery.

The imbalance of capacity

The discharging and charging cycle of a Li-battery with the imbalance capacity is described in Figure 5-17. The weakest cell (the capacity of this cell is smaller than others) in the battery stack will be fully discharged first. The weakest cell will be fully charged first. The performance of the Li-battery pack will depend on the weakest cell. Figure 5-18 represents this [79], [80-83].

Figure 5-17: Imbalance of capacity

Figure 5-18: Simulation results of capacity imbalance discharging and charging cycle

As the same reason for SOC imbalance, the performance of the Li-battery pack depends on the weakest cells. The efficiency of the Li-battery pack is lower compared with a SOC matched Li-battery [73], [76].

The difference between SOC imbalance and capacity imbalance is the SOC at the charging terminal point. The imbalanced cell cannot be fully charged if the battery stack is SOC imbalance. The imbalanced cell will be fully charged firstly if the battery stack is capacity imbalance. This has been represented in Figure 5-16 and Figure 5-18. For both case, the performance of the weakest cell will decrease faster as compared with others as the working condition of the weakest cell is worse than others.

It can be found that the stronger cells' energy cannot be fully released in the above simulation result. The total capacity of the Li-battery pack is reduced due to these two types of imbalance. A series connected Li-battery pack will exhibit

both types of imbalance over the course of its operational life, and if the imbalance is allowed to propagate, it can eventually limit the pack performance or shorten system life. The cell balancing system of the battery system plays a key role in improving battery performance and prolonging battery life.

In the previous MIHC system, the Li-battery pack is used to absorb the kinetic energy during braking. Furthermore, the Li-battery pack is used to maintain the current of the fuel cell when the system releases the energy to the load. The capacity of the Li-battery and the charging-discharging current of the Li-battery are very critical parameters for the system. To solve the imbalance of the SOC and capacity of the Li-battery, a balancing circuit is designed. There are two types of balancing method. It can basically be divided into two main groups: passive cell balancing and active cell balancing [84].

Passive cell balancing [84] uses a resistor to discharge the cell with the highest cell voltage so that charging can be continued until all the cells are fully charged. This method is only suitable during the charging process and not efficient due to power dissipation and energy waste. With active cell balancing, charge can be transferred between the cells in a battery stack using a short time storage element, which can be either a capacitor or an inductor.

Active balancing method ([74], [84], [85]) is used in this research to improve the efficiency of the hybrid system.

Figure 5-19 shows the basic operation circuit for managing the Li-battery stack.

Figure 5-19: The equivalent circuit for battery management circuit

There are two steps for completing a balancing cycle.

Step 1: $S_{(x-1)L}$ is closed, the energy of $Cell_{(x-1)}$ is discharged to the inductor. The equivalent circuit of step 1 can be expressed by Figure 5-20.

Step 2: $S_{(x-1)L}$ is opened; $S_{(x)H}$ is closed. The inductor energy is used to charge the $Cell_{(x)}$. The energy of $Cell_{(x-1)}$ transfers the energy to the $Cell_{(x)}$. In this schematic $Cell_{(x-1)}$ represents the strongest cell and $Cell_{(x)}$ represents the weakest cell. The electric charge is moved from the stronger cell to the weaker cell.

Equivalent circuit of Step 1

Equivalent circuit of Step 2

Figure 5-20: Operation principle of the battery management circuit

The Li-battery performance can be improved by applying this circuit to the Li-battery.

When the voltage of a cell is close to charging protection voltage, the charge can be transferred to the other cells, and the charging process can be continued. With this method, each cell could be completely charged, although it would take much more time, depending on the charging current, the balancing current, the SOC, and the capacity of each cell.

When the voltage of a cell is close to discharging protection voltage, the charge can be transferred to this cell, and the discharging process can be continued. With this method, the battery stack can be discharged until all the cells are completely discharged (depending on the discharge current, the balancing current, the SOC, and the capacity of each cell).

In this research, the evaluations of capacity and SOC are based on the voltage of each cell. Because the method used to measure the SOC and capacity of the battery is not the focus in this research, it is assumed that the voltage difference of each cell represents the battery performance.

Simulation

To verify the above balance method, a simulation platform [79], [82] was set up using Matlab simulink. Figure 5-21 described the simulation block diagram.

Figure 5-21: Simulation block diagram of the battery management system

The SOC, capacity and SOC-capacity imbalance were simulated. The SOC-capacity imbalance charging and discharging cycles are shown and discussed in the following section.

The testing setting parameters are described in Table 5-2

Table 5-2: Simulation parameters setting for the battery management system

Cell Num	1	2	3	4	5	6	7	8	9	10	11	12
Cap	1.60	1.43	1.56	1.51	1.63	1.63	1.63	1.63	1.63	1.63	1.63	1.63

SoC	95	87	100	100	80	92	100	100	100	100	100	100
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The battery capacity is 1.63Ah. The discharging current is 2.5-2.7A. The charging current is 1.5A. A continual charging-discharging cycle is applied to test the performance of the battery management system.

Figure 5-22: SOC comparison of controlled and un-controlled charging-discharging

Figure 5-22 illustrates the SOC of each cell, when a charging-discharging testing cycle is applied to the Li-battery stack. It can be found that the un-controlled SOC curves are scattered as compared with controlled SOC curves. Some cells cannot be fully charged or discharged during every testing cycle if the Li-battery worked at the un-controlled state. The capacity of the battery will be wasted due to the imbalance of Li-battery stack. The SOC difference of each cell will become smaller when the proposed balanced method is used.

Figure 5-23: Voltage variation comparison of controlled and un-controlled charging-discharging

Figure 5-23 illustrates the voltage of each cell, when a charging-discharging testing cycle is applied to the Li-battery stack. The voltage difference of each cell will be reduced when the balance method is enabled in each testing cycle.

Figure 5-24: Coulomb counting comparison of controlled and un-controlled charging-discharging

Figure 5-25: Statistical results of coulomb counting comparison

Figure 5-24 and Figure 5-25 illustrate the coulomb counting of each cell, during charging-discharging testing cycle, the total coulomb counting of the Li-battery will increase when the Li-battery is balanced. It can be found that the capacity (or the total energy) of the Li-battery is increased from the statistical results.

5.4 Experiment and analysis

Figure 5-26 is the system of the Li-battery. A protection card and a balancing board were installed in the Li-battery system. As the battery management card does not have the data logging device. The experiment of battery is simulated in the lab by the programmable E-load.

Figure 5-26: The photo of the Li-battery management system

The function of the protection card is used to prevent Li-batteries from over-current, short circuit and over-temperature. The protection card will cut off

the battery automatically when the charging or discharging current of battery is out of control. The balancing board is built based on the previous presented method. A MCU (micro-controller-unit) is used to monitor the voltage of each cell and control the switch array.

Figure 5-27: The discharging curves of each cell without BMS

A host PC is used to monitor the state of the each cell. The Li-battery is discharged at the same constant current rate in both controlled and uncontrolled conditions. Figure 5-27 and Figure 5-28 represent the results of these two experiments. In Figure 5-27, since the current is the same throughout all cells, the voltage of the cell with the smallest capacity (or SOC or both) is the first one which reaches the discharging voltage limit. The discharging process has to stop immediately. In Figure 5-28, it can be found that the dispersion of the cell voltage is reduced when the battery control method is adopted. The discharging time of the Li-battery pack has been increased when the proposed control method is adopted. The capacity (capacity efficiency) will increase when the proposed battery control method is used.

Figure 5-28: The discharging curves of each cell with BMS

Figure 5-29 shows the experiment platform of the hybrid system. The experimental platform includes three parts: two power sources, hybrid module and electric vehicle (E-bike). The proposed MIHC includes three power sources. Because of the limitation of experiment environment (the size of available PEM fuel cell in the lab is larger) and a PEM fuel cell and Li-battery hybrid system has been tested in the proposed MIHC in the previous chapter. Only two powers sources are installed in the E-bike.

Figure 5-29: The experiment platform of the E-bike

The input power sources are two, which include an ultra-capacitor and a Li-battery. The hybrid control module is composed of the MIHC (regenerative braking function is added), energy management controller and data logging device. The previous mentioned battery management device is used to improve the performance of the battery.

Figure 5-30: Lab testing results of the regeneration braking

Figure 5-30 is the waveform of the regeneration braking in the lab environment.

Channel 2 (purple) represents the ultra-capacitor current. Channel 3 (orange) represents the battery current. Channel 4 (yellow) represents the braking current. In the beginning of the waveform, the charging current of the battery and the ultra-capacitor are constant and steady. This part is used to simulate the constant current deceleration. The reference signal is changed in the middle of the waveform. This part is used to simulate the braking state. The requirement of the braking current is higher. The braking current is absorbed by the ultra-capacitor. The charging current of the battery is maintained at 5A. This experiment is done in the lab environment. The motor is powered by the external pedaling. The main purpose of this testing is used to verify that the braking current, charging current of battery are stable when the previous proposed system is applied.

Figure 5-31: The experiment results of the E-bike (discharging)

Figure 5-31 and Figure 5-32 represent the experiment results when the system is tested on the road. Figure 5-31 represents the results when the system operating at discharging mode (The energy is delivered to the motor). For

extreme working conditions, the e-bike accelerates from 0km/h to 25km/h at 75s. When a motor is first energized, the rotor is not moving, and a very high current equivalent to the stalled current (25A) will flow. If this starting current applies to the battery, the battery stack may be damaged and the lifetime of the battery will be reduced. It can be noted in Figure 5-31, the MIHC maintains the discharging current of the Li-battery within 5A. The ultra-capacitor provides the peak current (At 75s and 310s). The surge current was absorbed by the ultra-capacitor as designed. From 100s to 250s, the MIHC detected that the power demands of the e-bike was reduced. The energy of the Li-battery was used to charge the ultra-capacitor and it will be discharged for the next surged power demand. The capacity and lifetime of the Li-battery will be decreased when the discharging current is set at a high discharge rate. In this proposed hybrid system, the Li-battery energy efficiency and lifetime are improved due to the discharging current is optimized at the normal discharge rate.

Figure 5-32: The experiment results of the E-bike (braking)

Figure 5-32 represents the regenerative braking testing result (The energy flowed back to the battery and ultra-capacitors). As stated above, the

ultra-capacitor is used to absorb the braking energy and limit the charging current of the battery. During the brake or deceleration period, the MIHC work at the braking mode. The charging current of the Li-battery is limited at 3A by the MIHC. All other energy was recovered by the ultra-capacitor. During the braking, it can be found that some saw-tooth waveform was added on the battery and ultra-capacitor charging current. Because the braking energy is many times than the normal working condition, the current ripple of inductor has been increased. The overshoot of the PI controller will become higher as noise has been increased. This can be solved by applying a higher value inductor. The ultra-capacitor absorbs the braking energy as its power density is higher than the Li-battery. The efficiency of the system is improved as more kinetic energy is recovered to electrical energy compared with a single Li-battery system.

5.5 Conclusion

In this chapter, a further research for MIHC is carried out. The regenerative braking function is added in this chapter. The results of simulation show that the power distribution can be controlled by adjusting the duty cycle ratio D_{ba} , D_{fc} and D_{cap} . The Li-battery discharging current is limited below its rated operation range when the load is at the peak power demand, the ultra-capacitor would provide the extra-power to the load. In this way, the reliability of the Li-battery is improved and the lifetime of the Li-battery is prolonged. During regenerative braking mode, two parameters must be controlled. One is the braking current which is used to adjust to the regenerating torque; the other one is the battery charging current used to protect the battery from damage.

In the second part of this chapter, an optimized balancing method of Li-battery pack is studied. An active balanced battery management method based on the coupled inductor is applied in the Li-battery stack. The simulation result shows that the imbalanced capacity or SOC of the Li-battery can be compensated when the balancing method is adopted. The energy efficiency of the Li-battery is increased by about 15-20%. The discharging time of Li-battery is 1950 seconds when the system does not install the battery management card. The

discharging time increases to 2250 seconds when the battery management card is used.

An E-bike is used to build the platform to test and verify the MIHC and battery management method. The testing result indicated that the dynamic load power is provided by the ultra-capacitor, and the output current of Li-battery is limited within 5A. The braking energy is absorbed by the ultra-capacitor when the braking current exceeds the battery maximum charging rate (3A). The lifetime of the Li-battery is prolonged and the efficiency of the regenerative braking is increased.

CHAPTER 6 Conclusions and Future Works

6.1 Conclusions

In this thesis, a hybrid power supply system was studied and a MIHC was developed. The general condition of the MIHC was analyzed. The small signal model of the DSHC was derived. The control parameters and a rule-based energy management strategy were designed. The regenerative braking and battery management method were investigated.

6.1.1 MIHC for hybrid power supply system

A MIHC topology suitable for medium power electric vehicle is proposed and implemented in a hybrid system employing PEM fuel cell as the main power source and battery as the auxiliary energy storage system or battery as the main power source and ultra-capacitor as the auxiliary power source in this study. The small-signal model of the proposed MIHC is also built based on state-space average method. After that, the close-loop transfer feedback control scheme is represented. The energy distribution among fuel cell, battery and ultra-capacitor is made variable by adjusting the duty cycle ratio among the switches; the advantage of this duty cycle control method is that it is simple, effective and easy to implement. To validate the effectiveness of the novel topology, a hardware prototype is realized. The system operation modes are analyzed and defined with the actual situations considered. The experiment results have shown that the new MIHC has better response characteristic and exhibits excellent performance in realizing the control objectives.

The PEM fuel cell current is controlled to remain at nearly constant when the load vary while the battery provides the extra-current for the load. So hence the proposed control strategy can compensate the low dynamic response characteristic of fuel cell and improve its efficiency.

6.1.2 Regenerative braking and battery management

In the further research, the regenerative braking and battery management method were studied in this thesis. The regenerative braking function was

added in the modified MIHC. When the hybrid system delivers power to the load, the system is controlled based on the control method which has been proposed in Chapters 3 and 4. A braking energy recovery control method is adopted when the hybrid system is braking. The proposed braking energy recovery control method controls the charging current of the battery and the braking current of the system. During regenerative braking, the battery charging current is controlled at a limited range. Most of the regenerative current is absorbed by the ultra-capacitor. In this way, the battery can be prevented from inrush charge current damage, and its lifetime can also be prolonged.

The mismatch of each battery is another issue to affect the performance of the hybrid system. In the last part of this thesis, the battery equalization management system was studied and integrated in the testing platform. The simulation and experiment results have validated that the developed battery equalization management system is an effective method to extend the battery capacity and improve the battery stack charging and discharging performance. The energy capacity of the battery can be increased by 15-20%.

The advantages of a fuel cell hybrid system include improving the system performance and fuel economy. But the energy storage system is also a problem which, inevitably, will increase the cost and lead to the complexity of the system, thus, it will weak the system stability. This thesis developed a high efficiency hybrid energy storage system based on battery or battery and ultra-capacitor. Experimental verifications with an electric bicycle hybrid system bench in the laboratory have evidently shown that the proposed energy storage system has improved the performance of the whole system and validated the proposed energy control management strategy.

6.2 Recommendations for further studies

The research assumes the performance of PEM fuel cell is steady. In practice, the PEM fuel cell is a complex power supply and its performance will change with humidity, temperature, water management etc. however, fuel cell systems can run stably and adjustably with appropriate control method to avoid large transient power demand.

The future work includes the control strategy considerations of the PEM fuel cell based on a multi source hybrid converter. The fuel cell controller and hybrid controller can adjust control their corresponding strategies dynamically by considering the states of the fuel cell and hybrid system.

The accurate prediction of the SOC and the SOC level controlling are difficult for the complex electrochemical reaction of the battery and effects of temperature, discharging current and internal resistor and so on. The SOC of the battery is an important parameter which provides available capacity details of a battery for the battery equalizer system to balance the cell with appropriate current. A reasonable balancing system will enlarge the stack capacity and prolong its lifetime. Therefore, It is valuable to find a high precision algorithm to predict the SOC.

Though the developed system has been installed on an E-bike to verify the validity of MHIC, there is still a long way to go in order to apply it on industrial automobiles or other larger capacity hybrid systems. The designed PCB must be modified to carry more current for the load and the electromagnetic compatibility has to be reconsidered.

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Appendix 3: Schematic of Battery management board