ENERGY MANAGEMENT SYSTEM FOR BATTERY HYBRID ELECTRIC VEHICLE USING SUPERCAPACITOR

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ENERGY MANAGEMENT SYSTEM FOR BATTERY HYBRID ELECTRIC VEHICLE USING SUPERCAPACITOR

AREE WANGSUPPHAPHOL

A thesis submitted in fulfillment of the
requirements for the award of the degree of
Doctor of Philosophy (Electrical Engineering)

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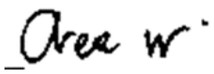
DECLARATION

I hereby declare that this thesis entitled "*Energy Management System for Battery Hybrid Electric Vehicle using Supercapacitor"* is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.



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DEDICATION

This thesis is dedicated to my parents and sisters, who supported me very well in all manners. It is also dedicated to my wife, my sons; DANISH, CHAMIL, and YASEEN, who encouraged me to conduct the reseach until successful.

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ABSTRACT

The propulsion system of battery electric vehicle (BEV) requires high power from the battery during acceleration and supplies high regenerative braking power to the battery while braking. As such, the battery, which is the main energy storage of BEV, consistently has to withstand high dynamic power flow that could shorten its lifespan. To overcome this problem, a hybrid energy storage system (HESS) consisting of the lithium-ion battery (LB) and a supercapacitor (SC) connected via a bi-directional DC-DC converter is proposed for the BEV – which is called as the battery hybrid electric vehicle (BHEV). In this thesis, new energy management control strategies for BHEV are proposed. In order to fully utilize the capability of the SC in capturing the kinetic energy as well as supplying the acceleration power to the BHEV, two methods of calculating the capacitance for the SC which is called the Acceleration-based Design (ABD) and Deceleration-based Design (DBD) are introduced. These methods are based on the principle of conservation of energy which balances the energy stored in the SC and the kinetic energy of the vehicle, and at the same time takes into account the losses involved in charging and discharging processes of the SC. From these two methods, two energy management control strategies are developed and applied to the BHEV. The power and energy flow between the LB, SC and the propulsion load is controlled via a closed-loop control of the SC current; the SC current references are generated based on the ABD and DBD approaches. Simulations of actual-scale BHEV are performed using Matlab/SIMULINK based on the Maximum Acceleration driving cycle and Extra Urban Driving Cycle (EUDC). Performances of the proposed strategies are evaluated in terms of battery peak power reduction, voltage variation improvement, and energy consumption of the battery. Finally, the proposed methods are verified in terms of feasibility and practicability by conducting small-scale experiments and simulations. Based on the results obtained from the simulations and experiments, it is found out that BHEV-DBD gives the best performance in terms of peak battery power reduction, voltage variation improvement and battery energy consumption; compared to the conventional BEV, improvements of up to 46%, 3.5% and 23% respectively, are achieved.

ABSTRAK

Sistem penggerak untuk kenderaan elektrik bateri (BEV) memerlukan kuasa yang tinggi dari bateri semasa memecut dan membekalkan kuasa brek yang tinggi pada bateri semasa brek. Oleh itu bateri, yang merupakan penyimpan utama tenaga untuk BEV, sentiasa menghadapi dinamik kuasa tinggi yang boleh memendekkan jangka hayatnya. Untuk mengelakkan masalah ini, sistem penyimpanan tenaga hibrid (HESS) terdiri dari bateri lithium-ion (LB) dan superkapasitor (SC) yang disambung melalui penukar DC-DC dwiarah dicadangkan untuk BEV – yang dipanggil sebagai kenderaan elektrik bateri hibrid (BHEV). Dalam tesis ini, strategi-strategi kawalan pengurusan tenaga yang baharu untuk BHEV dicadangkan. Untuk mempergunakan kebolehan SC yang memerangkap tenaga kinetik dan juga membekalkan tenaga cepatan dengan berkesan pada BHEV, dua kaedah pengiraan kemuatan SC yang dipanggil sebagai Reka bentuk Berasaskan Pencepatan (ABD) dan Reka bentuk Berasaskan Nyahpecutan (DBD) diperkenalkan. Kaedah ini berasaskan pada prinsip pengekalan tenaga yang mengimbangkan tenaga simpanan dalam SC dan tenaga kinetik kenderaan, dan pada masa yang sama mengambil kira kehilangan semasa proses cas dan nyahcas pada SC. Dari dua kaedah ini, dua strategi kawalan pengurusan tenaga dibangunkan dan diguna pakai untuk BHEV. Pengaliran kuasa dan tenaga di antara LB, SC dan beban penggerak dikawal melalui sistem kawalan gelung untuk arus SC; isyarat rujukan untuk arus SC dijana berasaskan pada pendekatan ABD dan DBD. Simulasi BHEV pada skala sebenar dilakukan menggunakan Matlab/SIMULINK berasaskan kitar panduan Pencepatan maksimum dan kitar pemacuan bandar tambahan (EUDC). Prestasi strategi yang dicadangkan ini dinilai dari segi pengurangan kuasa puncak bateri, penambahbaikan perubahan voltan bateri, dan penggunaan tenaga bateri. Akhir sekali, kaedah dicadang ini disahkan dari segi kesesuaian dan praktikal melalui eksperimen skala kecil dan simulasi. Berdasarkan pada keputusan simulasi dan eksperimen, didapati BHEV-DBD menghasilkan prestasi terbaik dari segi pengurangan kuasa bateri, penambahbaikan perubahan voltan bateri dan penggunaan tenaga bateri; berbanding dengan BEV konvensional, penambahbaikan diperolehi masing-masing sehingga 46%, 3.5% dan 23%.

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a	-	Vehicle acceleration rate
A_f	-	Frontal vehicle area of vehicle
B_m	-	Viscous friction coefficient of motor
C_d	-	Aerodynamic drag coefficient
C	-	Output capacitance of converter
$C_{SC,cell}$	-	Capacitance of a single supercapacitor cell
C_{SC}	-	Actual SC capacitance
$\tilde{d}(s)$	-	Duty ratio in *s*-domain
d	-	Vehicle deceleration rate
E_B	-	Battery energy consumption
F_{ar}	-	Aerodynamic resistance force
F_{gr}	-	Grading resistance force
F_{rr}	-	Rolling resistance force
F_{te}	-	tractive effort
F_{tr}	-	Tractive resistance force
g	-	Gravity acceleration rate
G	-	Overall gear ratio
$i_{SC}(s)$	-	SC current in *s*-domain
$i_{SC}(t)$	-	Time-varying SC current
$i_{SC,ref}(t)$	-	Time-varying SC current reference
$I_{SC,max}$	-	Maximum current of supercapacitor
J_{eq}	-	Equivalent moment of inertia of the motor
J_m	-	Equivalent moment of inertia of motor and flywheel
L	-	Converter inductance
L_a	-	Armature inductance
M_{SC}	-	Supercapacitors mass
M_V	-	Vehicle mass
N_p	-	Number of parallel connection
N_s	-	Number of series connection

$P_i(t)$	-	Time-varying input power of motor
$\acute{P}_l(t)$	-	Time-varying load power
$\mathrm{P_{bat}}$	-	Battery power
$\mathrm{P_i}$	-	Input power of the motor
$\mathrm{P_{dr}}$	-	Driving power
$\mathrm{P_{dy}}$	-	Dynamic power
$\mathrm{P_{SC,max}}$	-	Maximum power of supercapacitor
$\mathrm{P_{tr}}$	-	Tractive load power
$\mathrm{r_C}$	-	Internal resistance of output capacitor
$\mathrm{r_{SC}}$	-	Internal resistance of SC
$\mathrm{r_{SC,cell}}$	-	Internal resistance of a single cell of SC
$\mathrm{r_L}$	-	Equivalent inductive resistance of converter
$\mathrm{r_{wh}}$	-	Wheel diameter of vehicle
R	-	Equivalent resistance at maximum power
$\mathrm{R_a}$	-	Armature resistance
$\mathrm{T_{dy}}$	-	Dynamic load torque
$\mathrm{T_{eq}}$	-	Equivalent load torque transferred through the single gear ratio
$\mathrm{T_{wh}}$	-	Load torque at wheel of the vehicle
$u_{SC}(t)$	-	Time-varying internal voltage of SC
$u_{SCs,ref}(t)$	-	Time-varying internal voltage reference of SC
$v_{SC}(\mathrm{t})$	-	Time-varying terminal voltage of SC
$s_{V,ref}(t)$	-	Time-varying vehicle speed reference
$s_V(t)$	-	Time-varying vehicle speed
$\mathrm{s_{V,max}}$	-	Maximum speed of vehicle
$\mathrm{s_{V,ref}}$	-	Reference speed of vehicle
$\mathrm{V_B}$	-	Battery voltage regulation
μ_{rr}	-	Rolling resistance coefficient
ρ	-	Air density
α	-	Road grading angle
η_{con}	-	Average efficiency of converter
η_{inv}	-	Average efficiency of inverter

η_{m}	-	Average efficiency of motor drive system
η_{mech}	-	Average efficiency of mechanical system
η_{SC}	-	Average efficiency of SC
η_{total}	-	Total efficiency
$\omega(t)$	-	Time-varying angular speed of motor
ω_{m}	-	Angular velocity of the motor
$\omega_{m,max}$	-	Maximum angular speed of motor

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

World energy resources are developed from the plant and animal remainings in the earth's shell, which dwelled millions of years ago, known as the fossil energies. Coal, petroleum, and natural gas are the major forms of the fossil fuels constituting the world's majority energy resources. During the oil crisis in 1973, people became attentive to the fact that fossil energies are the valuable product of the earth. For the last twenty years, the Brent crude oil price on the US market has increased from $17.85 per barrel in January 1996 to the peak at $132.72 in June 2008 and fluctuated between $50-125 ever since [1]. Consequently, the governments and the industries globally, have committed to continuously improve energy economy for all activities: production, distribution and consumption.

In the report of energy consumption by sector in 2009, the energy consumed by the transportation holds the second rank of the primary energy consumption and carbon dioxide emission [2] as shown in Figure 1.1. The carbon dioxide dominates the greenhouse gas emission, and it contributes to the global warming which affects the whole life on earth. Greenhouse gases are not only composed of the carbon dioxide but also other harmful gases such as carbon monoxide, unburned hydrocarbons, nitrogen oxide, sulphur and methane which generate lots of induced costs; for example, health expenses, the cost of replanting forests devastated by acid rain, and the cost of cleaning and fixing surfaces corroded by acid rain. In fact, the induced costs are difficult to assess, and they may include the cost of the damages caused by hurricanes, lost crops due to dryness, damaged properties due to floods, and international aid to relieve the affected populations [3]. In this research, the focus in improving the energy efficiency of the transportation sector, particularly the battery electric vehicle (BEV). Specifically, the aim is to reduce the energy consumption and to improve the performance of energy storage system (ESS).

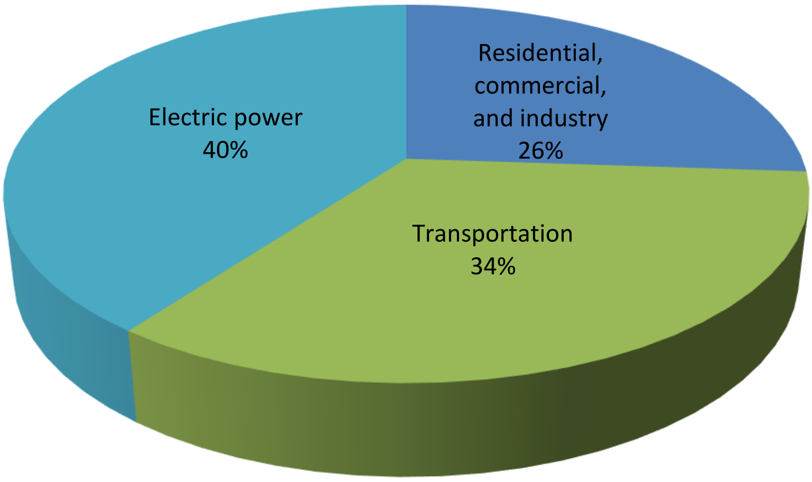

Figure 1.1 Carbon dioxide emission by sector in 2009 [2]

BEVs are vehicles energized by electricity stored in batteries. They offer significant potential in reducing the consumption of petroleum products and reduces the generation of greenhouse gases. The first BEV was launched in the 1830s and commercially traded at the end of the 19^{th} century, but the best time of the electric-powered vehicle was short-lived. By that time, it was recognized that BEV has high running cost and poor performance including short driving range, took long charging period, and short driving durability even in the city. Meanwhile, the internal combustion engine vehicle (ICEV), discovered in 1860, received an abundant attention due to cheap fuel, rapid technology revolution, and reliable assembly production. As a result, the development of BEV was virtually ceased by the early 1930s [3]. However, BEV was reborn as the foregoing reasons during the latter part of the 20^{th} century where they have been technically advanced in design, battery performance, traction motors and inverters [4]. The advantages/disadvantages of BEVs are relatively compared with ICEV as shown in Figure 1.2, in which 0, 1, 2, 3, 4, 5 denotes much worse, worse, similar, better, much better and best, respectively [3].

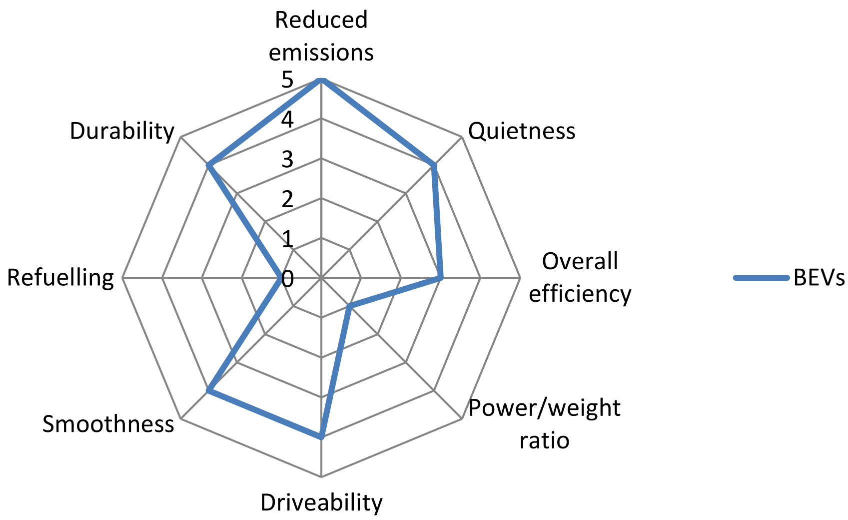

Figure 1.2 Relative comparison of advantages and disadvantages of BEVs over ICEVs [3]

BEVs are the next generation of vehicles after ICEVs and hybrid electric vehicles (HEVs). Figure 1.3 illustrates the significant performance of battery energy and power density for various battery types (e.g., nickel cadmium, lead acid battery and lithium-based battery (LB). As LB offers the highest rating, it is feasible to use LB as the main energy storage in BEVs. Neubauer *et al.* [5] reported that, in order to compete with the ICEV, the battery of BEVs needs to have a specific power of at least 470 W/kg and specific energy of 235 Wh/kg. In addition, BEV drivers require driving in a range of about 20,000 km per year. Consequently, 10+ years of vehicle life and a payback period of 5 years are expected. For a typical driving range of 50 km, a vehicle usually consumes about 2,700 Wh of energy. Thus to travel for 500 km, about 100 kg of LB bank is required, which is equivalent to the energy of one tank of petrol [6], [7].

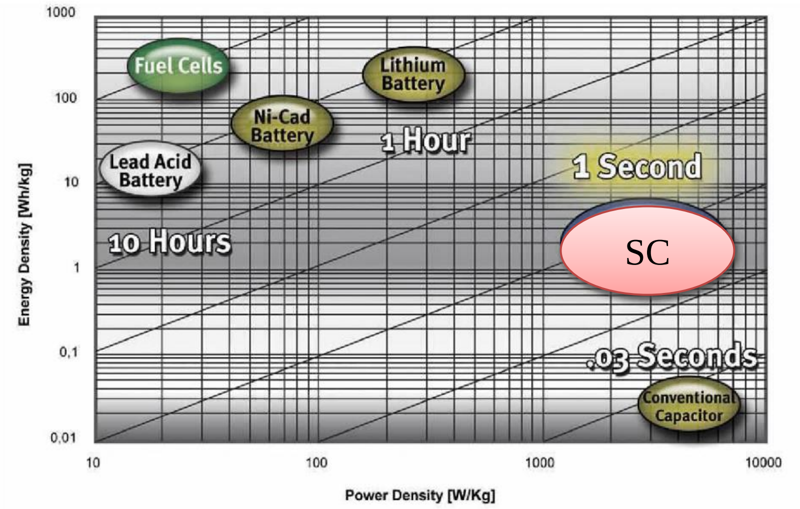

Figure 1.3 The significant performance of energy source/storage [8], [9]

Nowadays, the demand in high specific power and high specific energy is partially fulfilled by the advancement in LB technology, in which a specific energy of around 400 Wh/kg, and the specific power of approximately 500 W/kg can be achieved (as shown in Figure 1.3). However the extremely high power requirements during acceleration and deceleration whereby the battery needs to supply very large power to the propulsion load and need to absorb enormous amount of regenerative braking energy can cause problems to LB in BEV [10], [11]. Under these extreme operating conditions, the battery's internal resistance increases due to the increase in temperature, thus decreases the energy efficiency and the lifecycle of the battery [12], [13], [14]. The LB used in the simulation work of this thesis has the maximum discharge current limit up to 7.5 times (600 A) of the standard charging current (C), 80 A, for supplying acceleration power. However, it has the maximum charging ability of only 2C for recapturing energy from regenerative braking as shown in Appendix G. Thus, the energy from deceleration cannot be recovered 100%. The energy is then dissolved by means of friction using mechanical braking, in general. The mechanical braking does not only cause of the heat dissipation but also diffuse hazard particles to the surrounding environment that affect the people and the vehicle parts and components themselves. The heat source in a BEV can also come from the battery that supplies and receives high peak power to and from the propulsion load respectively. The high temperature of the battery requires good heat ventilation system to maintain its operation, otherwise, the internal resistance can increase rapidly [14].

To solve these problems, energy management system, which is widely used in many industrial firms for improving energy performance, is implemented. The aim of energy management system is to establish an efficient system and necessary steps to improve energy performance. This method can be applied to all kinds of energy consumption units [15]. Lately, surge of interest in the applications of energy management system to BEV can be seen; by proposing hybrid energy storage system (HESS) between LB and supercapacitor (SC) [16], [17], [18], [19], [20], [21], [22]. These studies presented the advantages of HESS in terms of power and energy availability, battery life extension, lower battery temperature, lower energy loss, economical implementation, etc. The other type of HESS used in BEV is a combination of battery and a mechanical flywheel [23], [24]. However, the implementation of a flywheel as energy storage is not only complex and inefficient, but also is not safe [25]. Therefore, currently, the HESS consisting of LB and SC is generally accepted as the most suitable and safest solution for BHEV applications [26], [24], [27], [28].

SC is an electrochemical double layer capacitor having high specific area of activated porous carbon to contain a large amount of electric [29]. It has a low specific energy density in the vicinity of 5Wh/kg but possesses a high specific power around 10 kW/kg [30]. Compared to LB, the specific energy density of SC is lower; however, it has much higher specific power density. The outstanding performance of SC is the extremely long life cycle, which is about one million cycles [31]. It is anticipated that the application of LB and SC in HESS for BEV, which is called battery hybrid electric vehicle (BHEV), will become an ultimate solution for solving the deteriorated battery problem found in BEV, thus, enhancing the vehicle performance.

1.2 Issues related to Hybrid Energy Storage System

There are two primary concerns related to the energy management system for BHEV using SC: first is the configuration schemes used for the HESS and, second is the energy management control strategy between the energy storages. The first issue has been studied by many researchers, and in general, two types of configurations have been proposed: a single bidirectional DC-DC converter connecting to either SC or battery [32], [11], [33], [34], [35] and multiple bi-directional DC-DC converters connecting to SC and battery [34], [36], [37], [22], as shown in Figure 1.4. A single converter connected to the SC allows variation in the DC bus voltage according to the state of charge (SOC) of the battery, while with multiple converter schemes the DC bus voltage is basically fixed. If the DC bus voltage is to be fixed using a DC-DC converter, losses caused by the converter used for the battery has to be considered. The configuration scheme used in this study considers the presently available technology in which the DC bus voltage (i.e. input to the propulsion inverter) is allowed to vary from the maximum to half of the rated voltage [38]. The trade-off between the loss in a converter for maintaining DC bus voltage and the loss of propulsion inverter fed by the high voltage variation (direct connection of the battery to the inverter) can be considered equal since they are both controlling the same amount of power between the battery and the propulsion load. Furthermore, a single converter scheme is more reliable than that of multiple converters configuration. For instance, a vehicle can become inoperative if one of the converters in the multiple converter scheme is broken.

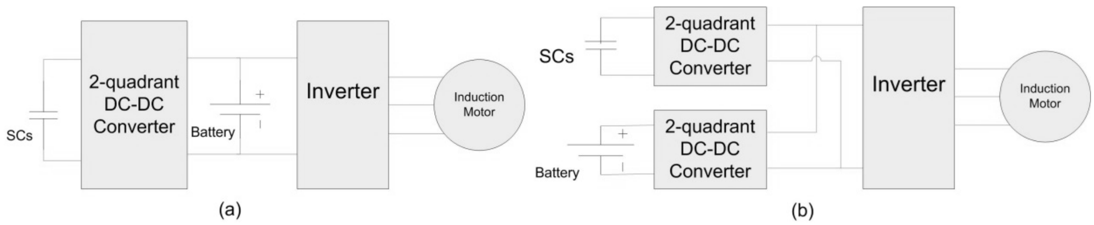

Figure 1.4 Connection scheme of HESS (a) single converter scheme and (b) multiple converter scheme

The second concern related to the energy management system is the energy management control strategy, which can be categorized into two approaches, i.e. rule-based energy management control strategy and optimization-based energy management control strategy. Zhang *et al.* [39] have analysed the energy management control strategy for BHEVs and found that rule-based energy management control strategy is an exclusive strategy and can be commercially implemented. Although it is computationally efficient and easy to implement, optimal solution is however not guaranteed. On the other hand, the optimization-based energy management control strategy, which finds solution optimally, has been widely studied, however very difficult or almost impossible to be implemented in real-time driving environment. With the aim of obtaining a practical and optimal energy management control strategy for BHEVs, currently the researchers are focusing on developing optimum rule-based energy management control strategies and reducing the computational burden during optimization processes. At the moment, these techniques are still in the developing stages and are not yet used in BHEVs. In this thesis, energy management control strategy based on deterministic (heuristic) rule-based control strategy is chosen. In developing this strategy, human expertise, engineering intuition and powertrain characteristics are exploited. The deterministic rule-based energy management control strategy is suitable for the real-time control implementation for BHEV since it requires less demanding computational requirement and easy to implement. The advantages and disadvantages of rule-based and optimization-based energy management control strategy are discussed in Chapter 2. From this point of view, a new control strategy based on deterministic rule-based energy management control strategy is considered in this thesis.

1.3 Problem Statement

The main problem associated with deterministic rule-based energy management control strategy for BHEV using single converter scheme, as presented in literature, is in the real-time generation of the correct SC current reference. An extreme (too high) SC current reference generated by a controller can cause a full discharge of SC stored energy before the end of an acceleration is reached. In contrast, a too low reference resulted in an ineffective utilization the stored energy in the SC. In order to maximize the utilization of the SC in BHEV, not only the current has to be controlled properly, but at the same time a suitable capacitance value of the SC has to be determined analytically. Inappropriate determination of the capacitance may underutilize (or over-utilize) the SC thus render ineffective operation of the proposed rule-based energy management control strategies.

1.4 Thesis Objectives

The work in this thesis proposes two new methods of SC capacity calculations and hence two deterministic rule-based energy management control strategies for HESS of a BHEV. The hybridised energy storage between LB and SC is based on a single converter scheme. The two methods are named as acceleration-based design (ABD) and deceleration-based design (DBD). The former calculates the SC capacity by using the principle of conservation of energy that balances the vehicle kinetic energy with the stored energy in the SC during acceleration, taking into account the discharge losses. The latter calculates the capacity of the SC based on the balanced energy during braking (deceleration), taking into account SC charging losses. The proposed energy management control strategies generate the SC reference currents using ABD and DBD approaches, from the *v-i* relationship of a capacitor that is obtained from energy conservation law of vehicle kinetic energy and SC stored energy. In these strategies, the SC is used to assist the main energy storage (i.e. the battery) in supplying the energy and power to the propulsion load. The control performances of the proposed techniques are simulated and experimented as presented in Chapter 5. The improvements are demonstrated in terms of battery peak power reduction, DC bus voltage variation reduction, and a better energy saving compared. The specific objectives of this research are listed as follows:

(i) To formulate the capacity of SC auxiliary energy storage based on ABD and DBD to obtain the best performance of HESS. This is achieved by using the principle of conservation of energy during acceleration or deceleration.

(ii) To design and develop two new control strategies to control the SC current based on acceleration and deceleration of the vehicle, taking into account the charging and discharging losses of the SC.

(iii) To model, design and simulate a real-scale BHEV using Matlab/SIMULINK . The controllers are to be designed based on the averaged and linearised model of the system, while the verification is to be based on a large-signal model of the system, consisting of the battery, SC, bi-directional DC-DC converter and motor drive system connected to the vehicle propulsion load.

(iv) To develop and build a small-scale (laboratory-scale) inertial propulsion system to study on the feasibility, effectiveness and practicability of the proposed control strategies. Experimental results are to be compared with the results obtain from the simulation of the small-scale model.

1.5 Scopes of Work

The modelling, design, simulations and experiments conducted in this thesis are confined within the following scopes:

(i) The energy management control strategies for BHEV developed in this thesis is designed for a typical subcompact car (B-segment). Nonetheless, applications to other class of cars or vehicles can be readily applied with minor changes.

(ii) Modelling and simulation work conducted for the real-scale and small-scale are performed using Matlab/SIMULINK with standard toolboxes. These include the controller design using the averaged and linearized models, as well as the large-signal simulation model for controller verifications.

(iii) The controllers for small-scale experiments are developed using DS1104 controller board from dSPACE. The C-codes are generated using Rapid Control Prototyping (RCP) technique and monitored and recorded using *ControlDesk* software from dSPACE.

(iv) Due to the hardware and equipment constraints, verifications of the proposed strategies in terms of feasibility and practicability is performed using small-scale experimental set-up. However, due to the relatively much smaller amount of energy involved compared to the actual scale, losses in the converters of the small-scale system becomes significant. These limitations are discussed in Chapter 5 of the thesis.

(v) Three different duty cycles are used to test and analyze the effectiveness of the proposed strategies: maximum acceleration driving cycle, Extra Urban Driving Cycle (EUDC) and Urban Dynamometer Driving Schedule (UDDS). The actual-scale simulation results for the UDDS are presented in Appendix H.

1.6 Thesis Contributions

This research contributes to the determination of proper capacity of the SC and its respective energy management control strategies, known as ABD and DBD. The contributions of the thesis are summarized as follows:

(i) The development of two novel techniques in calculating the capacity of the SC that include the charging and discharging losses. Determining the suitable capacitance for the SC is important to ensure that the SC is not under-utilized (or over-utilized) that can result in inefficient energy management control.

(ii) The design and development of two novel deterministic rule-based energy management control strategies for controlling the SC current in BHEV. The complexity in the modelling and generating the SC reference current is removed by using a simplified *v-i* model of the SC. The improvements in terms of battery peak power reduction, battery voltage variation reduction, and battery energy consumption reduction are achieved and presented.

(iii) The construction of averaged and linearized model of the system for controller design and development of complete large-signal model of the system for controller performance verifications.

(iv) The development and construction of the small-scale experimental set-up which is equivalent to the simulated actual-scale of BHEV. The small-scale experiments are conducted mainly to study on the feasibility and practicability of the proposed control strategies.

1.7 Thesis Organizations

This thesis is organized into six chapters. Their contents are described as follows:

(i) Chapter 1 delivers a brief introduction to the study. It covers the background, thesis objectives, problem statement and scope of the work, thesis contributions, and thesis organisations.

(ii) Chapter 2 reviews electric vehicle and energy management systems and electric vehicle architectures. The modelling of an electric vehicle, battery and SC hybrid energy storage systems and converter topologies for an energy sources are also presented. Finally, overview on the previous energy management control strategies are presented.

(iii) Chapter 3 explains the acceleration-based design and deceleration-based design of the energy management control strategies for BHEV. In this chapter, the description of the BHEV, acceleration-based design strategy, deceleration-based design strategy, and current control of the SC are presented.

(iv) Chapter 4 presents hardware design and development. The experimental setup of the small-scale inertial propulsion system for hybrid energy storage between battery and SC is described. The descriptions on the dSPACE DS1104 controller board, gate driver circuit, power bi-directional DC-DC converter, 2-quadrant DC motor drive system, battery bank and SC bank are also given in details.

(v) Chapter 5 reports the simulation results (for small-scale and actual-scale) and experimental results (for small-scale) of the proposed control strategies in terms of battery peak power reduction, battery voltage variation reduction, and battery energy consumption reduction. Results are presented, discussed and compared.

(vi) Chapter 6 summarises the work in this thesis and highlights the contributions of this research. Several suggestions are provided for possible directions of future work.