ENERGY MANAGEMENT OF MULTIPLE SOURCES FOR ELECTRIC VEHICLES

TIE SIANG FUI

UNIVERSITI TEKNOLOGI MALAYSIA

ENERGY MANAGEMENT OF MULTIPLE SOURCES FOR ELECTRIC VEHICLES

TIE SIANG FUI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

MARCH 2015

Dedicated, in thankful appreciation for support, encouragement, understandings guiding and inspiring to:

My supervisor Dr Tan Chee Wei;
My beloved Father and Mother;
My family members;
Also to all my colleagues and individuals that contributed to this project.

ACKNOWLEDGEMENT

First and foremost, I would like to express my appreciation to *Universiti Teknologi Malaysia, UTM* for giving opportunity to further my master study here. Besides that, I would like to take this opportunity to express my sincere appreciation and heartily gratitude to my supervisor, Dr. Tan Chee Wei for the constant concern, patient guidance and invaluable suggestions throughout the preparation of the project. In particular, I am especially thankful to his for continued patient in helping me to improve my project.

Next, my appreciation also goes to my family who has been so tolerant and supports me all these years. Thanks for their continuing love, emotional support and encouragement that they had given to me especially my parents, who has been an extraordinary mentor.

I would like to express my heartfelt appreciation to all individuals who have directly offered help, support and suggestions, contribution towards the successful completion of this project, especially goes out to all my colleagues in ENCON laboratory of FKE, my lecturer, ex-course mates, friends, industrial individual and whoever involved.

Last but not least, I would like to extend my appreciation to all those who have directly or indirectly played a part in the completion and the success of this thesis. My project would not be carried out so smooth without the aids and guidance from you all. Thanks you so much.

Thank You.

ABSTRACT

This thesis presents the energy management of battery, ultracapacitor (UC) and photovoltaic (PV) power system for Electric Vehicles (EV). The proposed energy sharing control, in which each energy source is connected in parallel to the direct current (DC) bus via a power electronic converter. All energy sources are studied to investigate the different supply characteristics in order to avoid detrimental effects on the energy sources. A total of four control loops are employed in the supervisory system in order to regulate the DC bus voltage. The Proportional-Integral (PI) compensator is used in each control loop to simplify the overall system design. In this work, the Generalized Predictive Controller (GPC) is proposed to control the multiple energy system. The simulation results are then compared with the conventional PI control technique. The energy management strategy is designed according to typical vehicle operation modes based on the state-of-charge of energy storage devices and the total output power. The performance of the EV's energy management using both the PI controller and the GPC is simulated using resistive load and a DC motor drive system through MATLAB/Simulink simulation package. Then, the feasibility of the control system is validated through laboratory scale experimental tests. In the experiment, the dSPACE DS1104 is used to implement PI controller into hardware. The responses of the DC bus are analyzed based on different vehicle operation modes. Results show the proposed parallel energy-sharing control system either in simulation or hardware experiment is able to provide a dynamic response, avoid battery being overstressed by current, the UC charged according to vehicle speed, and the PV tracked the maximum power. However, between the discrete PI and GPC control, the GPC is slightly better than PI control.

ABSTRAK

Tesis ini membentangkan kawalan tenaga perkongsian antara bateri, ultra-kapasitor (UC) dan fotovoltaik (PV) untuk Kenderaan Electrik (EV). Dalam kawalan perkongsian tenaga yang dicadangkan, setiap sumber tenaga akan disambung secara selari kepada bas arus terus (DC) melalui penukar elektronik kuasa. Untuk memastikan prestasi kenderaan, setiap sumber tenaga akan dikaji untuk menyiasat sifat-sifatnya bagi mengelakkan kesan memudaratkan kepada sumber. Sebanyak empat gelung kawalan akan digunakan dalam tenaga kawalan kenderaan elektrik untuk mengawal voltan bas arus terus. Untuk memudahkan proses rekabentuk, kaedah Perkamiran-Berkadaran (PI) telah digunakan dalam setiap gelung kawalan. Kemudian, Kawalan Ramalan Model (GPC) dibangunkan untuk menggantikan kawalan PI. Seterusnya, keputusan simulasi dibandingkan dengan keputusan simulasi yang menggunakan kawalan PI. Strategi pengurusan sumber tenaga dibangunkan mengikut mod operasi kenderaan yang berdasarkan paras voltan setiap sumber tenaga dan jumlah kuasa yang diperlukan. Dengan menggunakan MATLAB/Simulink, prestasi pengurusan tenaga EV yang menggunakan kawalan PI and GPC dikaji. Dalam ujikaji simulasi ini, beban rintangan dan sistem pemacu motor DC digunakan sebagai beban ujian. Kemudian, ujian makmal dengan eksperimen skala digunakan untuk mengesahkan sistem kawalan tersebut. Dalam ujikaji sistem kawalan ini, dSPACE DS1104 telah digunakan untuk melaksanakan pengawal PI ke dalam perkakasan. Seterusnya, sambutan bas DC dianalisis apabila operasi kenderaan mod berubah. Keputusan yang diperolehi dalam MATLAB/Simulink atau ujikaji yang dijalankan menunjukkan kawalan perkongsian tenaga dalam kerja ini mampu mengelakkan bateri daripada tekanan arus elektrik, mengecas UC mengikut kelajuan kenderaan, PV dapat mengeluarkan kuasa maksimum dan berjaya memberi tindak balas fana apabila operasi kenderaan mod berubah. Tetapi di antara kawalan PI and GPC, GPC memberi prestasi yang lebih baik daripada PI.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

CO_2 - Carbon dioxide
K_p - Proportional gain, a tuning parameter
K_i - Integral gain, a tuning parameter
K_d - Derivative gain, a tuning parameter
V_i - Voltage input
V_o - Voltage output
V_{uc} - Output voltage of UC
V_{uc_max} - Maximum output voltage of UC
$M_{vehicle}$ - Total weight of the vehicle
C_{uc} - Capacitance of UC
$v_{vehicle}$ - Speed of the vehicle
y_k - Process outputs
$\underset{\rightarrow}{y}_k$ - Predicted future outputs
$\underset{\leftarrow}{y}_k$ - Past output
u_k - Process inputs
u_{k-1} - Process inputs at previous instance
$\Delta\underset{\rightarrow}{u}_{k-1}$ - Optimized future slew rates
$\Delta\underset{\leftarrow}{u}_{k-1}$ - Past slew rates
$\underset{\rightarrow}{r}$ - Future set points
$u_{\max}$ - Upper limit of input constraints
$u_{\min}$ - Lower limit of input constraints

N_1 - Minimum prediction horizon

N_2 - Maximum prediction horizon

M - Control horizon

$R_{i=1,\ldots,\mathrm{m}}$ - Move suppression weights

$W_{i=1,\ldots,\mathrm{n}}$ - Weights on the output residuals

$a_{i=1,\ldots,\alpha}$ - Coefficient of the polynomial matrix in the CARIMA model

$b_{i=1,\ldots,\beta}$ - Coefficient of the polynomial matrix in the CARIMA model

$a(z^{-1})$ - Numerator

$b(z^{-1})$ - Denominator

$T(z^{-1})$ - Design polynomial matrix

v_k - Disturbance effects and measurement noise

Δ - $1 - z^{-1}$

J - Cost function

V_{bus_ref} - Reference of DC bus voltage

I_{UC_ref} - Reference of UC current

I_{load} - DC bus current

I_{batt_ref} - Reference of battery current

I_{UC_D} - UC discharging current

$I_{batt\_feedback}$ - Battery feedback current

I_{L_pv} - PV modules output current

I_{UC_C} - UC charging current

$i_{L\_\max}$ - The achievable inductance’s current

$i_{h\_\max}$ - The achievable output current at high voltage side

V_l - Low voltage

V_h - High voltage

f_s - Converter switching frequency

L_{min} - Minimum inductance values

C_{min} - Minimum capacitance values

ΔV_{out} - Output voltage ripples

Δi_L - Inductor current ripple

D - Duty cycle
E - No-load voltage
E_0 - Battery constant voltage
K - Polarization voltage
Q - Battery capacity
A - Exponential zone amplitude
B - Exponential zone time constant inverse
V_{batt} - Battery voltage
R - Internal resistance
i - Battery current
i_{EPR} - Current in parallel resistance circuit
i_{uc} - Current through the capacitor
E_{cap} - Available energy in UC
E_{max} - Maximum achievable energy storage in UC
I_{pv} - Cell output current
I_{ph} - Photocurrent
I_D - Current diode
V_{pv} - Cell output voltage
I_{sc} - Short-circuit current
V_{oc} - Open-circuit voltage
C_h - Capacitor at high voltage side
C_l - Capacitor at low voltage side
R_{ch} - Internal resistance in capacitor at high voltage side
R_{cl} - Internal resistance in capacitor at low voltage side
H_c - Current feedback gain
H_v - Voltage feedback gain

LIST OF ABBREVIATIONS

GHG - Greenhouse gases
EIA - Energy Information Administration
ICE - Internal Combustion Engine
EV - Electric vehicle
USDE - U.S. Department of Energy
BTU - British thermal unit
ESS - Energy storage system
UC - Ultracapacitor
KERS - Kinetic energy recovery system
HESS - Hybridization of energy storage system
PV - Photovoltaic
PI - Proportional-Integral
GPC - Generalized predictive control
PID - Proportional-integral-derivative
MPC - Model predictive control
MPPT - Maximum power point tracking
DC - Direct current
RTI - Real time interface
ECU - Electronic control unit
P&O - Perturb and observe
DSP - Digital signal processor
AC - Alternating current
SEPIC - Single-ended primary inductance converter
MIPEC - Multiple-input power electronic converter

ZVS	-	Zero-voltage-switching
ANN	-	Artificial neural network
AES	-	Auxiliary energy source
QP	-	Quadratic programming
LP	-	Linear programming
CARIMA	-	Controlled auto-regressive integrated moving average
ARX	-	Auto-regressive eXogenous
RLS	-	Recursive least squares
IncCond	-	Incremental conductance algorithm
MPP	-	Maximum power point
SOC	-	State-of-charge
RC	-	Resistor-capacitor
ESR	-	Equivalent series resistance
EPR	-	Equivalent parallel resistance
CCM	-	Continuous conduction mode
KCL	-	Kirchhoff’s current law
KVL	-	Kirchhoff’s voltage law
RHP	-	Right half-plane
ADC	-	Analog-to-digital converter
MOSFET	-	Metal-oxide-semiconductor field-effect transistor
IGBT	-	Insulated gate bipolar transistor
PCI	-	Peripheral component interconnect
I/O	-	Input output
MIMO	-	Multiple input multiple outputs

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Worldwide emission of greenhouse gases (GHGs) has risen steeply since the industrial revolution from the 18^{th} to the 19th with the largest increase coming after 1945. Human activities such as transportation, electricity, industry, agriculture and others are the main contribution to the GHGs emissions on the earth. From statistical database of the U.S. Energy Information Administration (EIA), transportations consume almost 27% of the total energy consumption in the world and 33.7% of the GHGs emission in 2012, as shown Figure 1.1 and Figure 1.2 [1-4].

At the beginning, human use their own strength or animal to transport their goods. Then, transportations start to evolve to steam powered, electric powered and today's internal combustion engine (ICE). Almost 200 year after human discovered the abandon crude oil on earth, now, fossil fuels are the main energy source for propulsion. Therefore, all automotive are designed based on fossil fuel [5, 6]. However, with the drastic growth of power electronic, energy storage devices become cost-effective and it has speed up the electric vehicle (EV) feasibility.

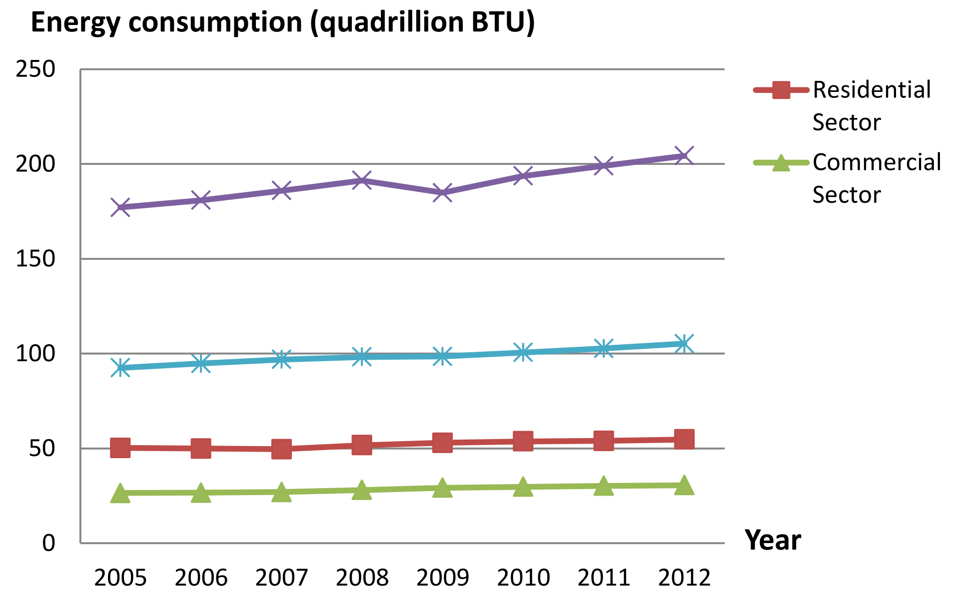

Figure 1.1 Energy consumption (Quadrillion BTU) based on different end-users [1, 4].

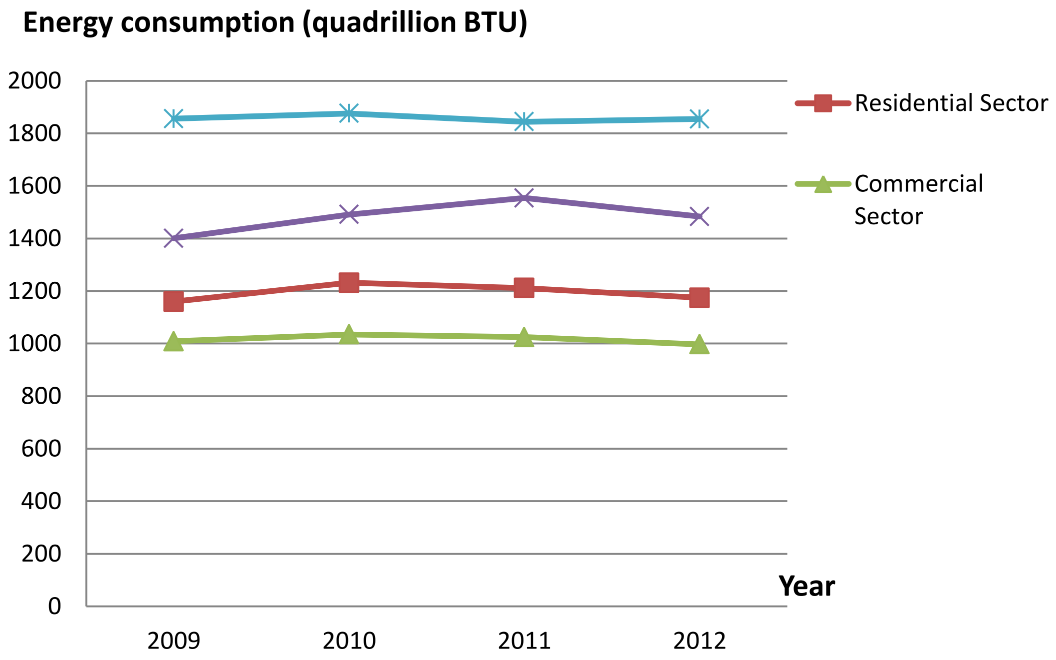

Figure 1.2 The energy-related carbon dioxide emissions (million metric tons CO_2 equivalent) based on different end-users [1, 4].

From the engineering point of view, EV acquires energy conversion efficiency far higher than conventional automotive vehicle or ICE vehicle. According to the U.S. Department of Energy (USDE) in the year of 2012, the highest energy conversion efficiency of ICE vehicle can achieve is only around 15%. In other word, only 15% of total energy contain in fuel is effectively converted to run a car and its other accessories, a major percentage of the fuel is dissipated into heat during combustion [7]. The total energy consumption of the typical ICE vehicle is shown in Figure 1.3 [1, 4]. Another weakness of ICE vehicle is the need of more frequent maintenance than EV. However, as shown in Figure 1.4, EV consumes approximately 81.3% of the energy stored in the energy storage devices to propel the EV. The EV overall operational efficiency can reach up to 67.9% which is around four times more efficient than ICE propelled vehicles [8]. Today, EVs have an average of (7-13 km) range per kWh of stored electricity [9].

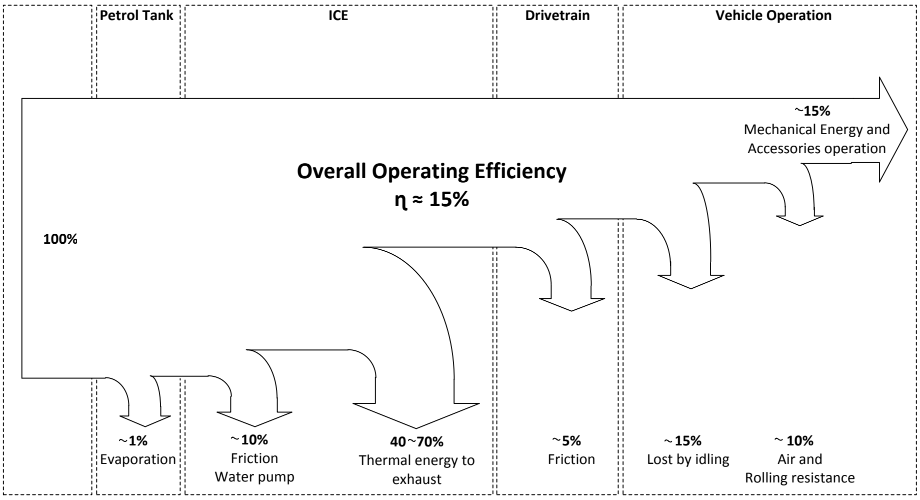

Figure 1.3 The typical energy flow of conventional internal combustion engine vehicle [1, 4].

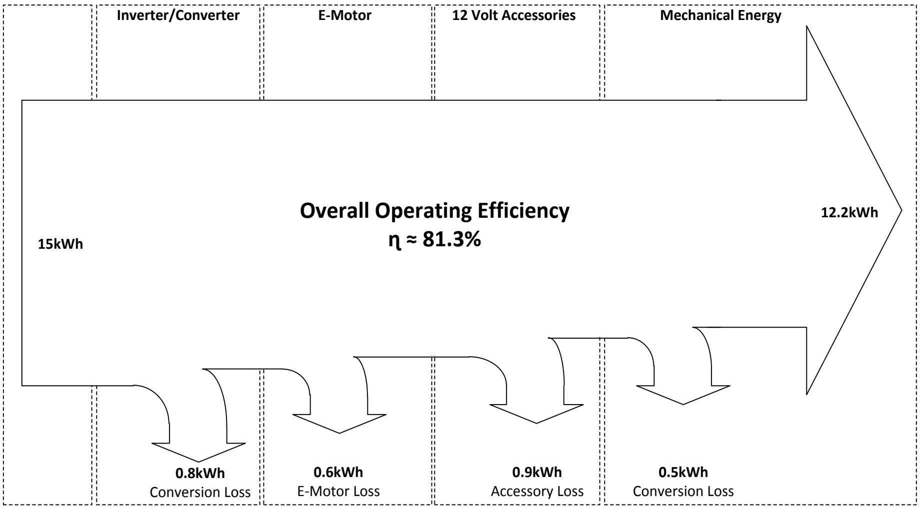

Figure 1.4 EV operating Energy Flow and Efficiency Diagram [1, 4].

Currently, EVs start to get more attention in research and industrial. EVs become the focus to all automobile manufacture for their next version of vehicle. For all automaker, the common challenges of EV manufacturing are the high cost of its component and the short travel distance. The Energy Storage System (ESS) such as battery has contributed more than half of the EV price. ICE vehicle in full tank petrol can travel 4 times of single full charge battery of typical EV [10].in order to make EV comparable with the conventional ICE vehicle, the total cost expensed in EV's service life needs to be lower than the conventional ICE vehicle. Therefore, the major focus in the research of EV nowadays is to prolong the battery life.

Utilizing battery bank in automobile environment increases the difficulty of energy management because vehicle is a dynamic load. Battery's life in automobile tends to degrade faster if current overstress during charging/discharging [1, 4]. Many research done and proposed combination of battery with some high power devices such as the Ultracapacitor (UC) and Flywheel to share and even serve high power charging and discharging for EV [11-15]. Flywheel-based Kinetic Energy Recovery System (KERS) currently is being used in Formula One racing car where there is the need to accelerate immediately. Power capacity of the KERS units can be ranged from 60kW to 120kW. Most of the automobile manufacture already implemented this technology to their car such as Mazda used i-ELOOP, Porche 918 and etc. [16].

In the emerging solar industry, photovoltaic has gone into automobile application in order to obtain a sustainable and environment friendly vehicle. Instead of installing PV system as roof at parking lots, solar panel is installed on the roof on vehicle so called solar panel-embedded roofs. Toyota Prius is the sole vehicles to implement solar panel on its roof. However, the solar panel only serves as powers climate control system in the cabin. Averagely, the space on top of the vehicle is around 16 square feet (1.486 m^2). The space is too small to allow the battery to be fully charged over the course of a day. Instead, at least a week is required. The Ford C-MAX Solar Energi car is incorporate with transparent canopy magnifier on parking lot. This will generate 8 times more energy from the sun and use six or seven hours charging time. Therefore, PV is still considered unpractical in passenger vehicle [17].

When EV comes to Hybridization of Energy Storage System (HESS), EV energy management plays an important role in order to distribute the required power to main ESS, auxiliary ESS and load. In short, the combination of ESS or hybridization of energy source has to be made carefully. Secondly, a suitable energy management method is crucial in order to extend the battery life, since battery is the main source and main cost of the EV.

1.2 Objectives

The main purpose of the research is to develop an unprecedented parallel energy-sharing control system for battery based hybrid source system. Ultracapacitor (UC) and photovoltaic (PV) module is used as auxiliary energy sources in this research. In order to supply EV propulsion system, the DC energy source from batteries, UC and PV work closely with each other to regulate the output bus voltage. The objectives of this research are:

1. To model the power converter of EV energy management using the proportional-integral (PI) controller and Generalized Predictive Control (GPC).
2. To simulate the energy management algorithm for parallel energy-sharing utilizing battery, UC, and PV in resistive load and DC motor drive system.
3. To compare and analyze the energy management system performance between PI controller and the GPC using simulation approach only.
4. To verify experimentally the multiple energy management system using PI controller only.

1.3 Problem Statement

The price of crude oil has risen from as low as USD 2 per barrel to as high as USD 108 per barrel in 2014 [18]. This situation gave the disadvantage to conventional gasoline vehicle to maintain its existent in future generation. In energy transition like this, EV gains the advantage to enter automobile industry. However, currently half of the EV price is from its energy storage device alone. Reducing battery capacity is able to reduce the total price of the EV but it also reduces the vehicle's performance and the travel distance. Hence, hybridization of energy storage is a promising solution to above mentioned issues. One of the disadvantages of battery is its low power density. So, battery is not allowed to be overstressed on its current during charging/discharging, because this would reduce the battery's life cycle. To protect the battery from being damaged, the hybridization architecture and suitable energy management is the concern during the predesigned stage.

Proportional-integral-derivative (PID) control is the typically used conventional compensator in power converters. PID cannot satisfy the requirement of the EV energy management control because of vehicle's fast dynamic response. Many modern high-performance control techniques, such as adaptive control, fuzzy control, artificial neural network and expert system should be used in the EV's controller. In this research, a new model predictive control (MPC) is chosen to control the multiple energy management to investigate the response of the current control. It is expected to achieve smooth and stable current output at the dc bus of the multiple energy sources by using the proposed control technique.

1.4 Scope of Research

This research focuses on the controller design and energy management for the battery-UC-PV hybrid system. The optimal energy source capacity and supervisory vehicle control, optimal hybridization degree design, design of inverter and electric motor propulsion are not the scope of this research. Therefore, hybridization degree is based on the energy source that is available in the laboratory. The energy management of three parallel energy sources in EV is designed to meet the following requirements:

1. The ability of battery, UC and PV to deliver optimal power to the load simultaneously or individually
2. The capability of battery and UC to compensate each other when peak load or peak regeneration is needed, providing that
   a) peak power overstress in battery is avoided
   b) maintain UC's optimal energy level in every mode of powering
3. The competency of PV to provide optimal power to charge the battery and UC at any time when sunlight is accessible

The proposed control system is simulated in Matlab/Simulink environment and the feasibility of the proposed solution is closely examined through experiments.

1.5 Methodology

First, literature review on power electronic converter topology, Hybridization of Energy Storage System (HESS), Proportional-Integral-Derivative (PID) control loop, Generalized Predictive Control (GPC) algorithm, PV Maximum Power Point Tracking (MPPT) and energy management algorithm are studied. All literature articles are obtained from conference papers, journal papers, online articles, books or electronic book and reading material from library. This helps to strengthen the fundamental understanding of the energy management techniques, power converter topologies with its control, power tracking algorithms and energy storage systems. Next, the power stage design and power electronic components optimization will be carried out. A bidirectional DC-DC converter will be designed and simulated using MATLAB/Simulink software. The input voltage of the converter is 48 V and the output voltage bus is 80 V. All components are design based on the converter operating range as in practical implementation. This is followed by the simulation of the Energy Storage System (ESS) which include the UC, lead acid battery and PV, module in MATLAB/Simulink. The Bidirectional DC/DC converter and the boost converter are designed using the average model method. After obtaining the component parameter values from the power stage design, those parameters will be verified through simulation. Then, the output responses of the ESS and also the power converters are studied.

In the design stage, the power converter’s loop compensator is obtained. From the readily available boost converter’s transfer function, the proportional-integral (PI) inner current control loop and outer voltage control loop of converter are derived. Through MATLAB/Simulink environment, the PI controller's parameter, K_p and K_i, are obtained according to the hardware requirement. After that, the proposed MPC is designed and simulated to compare the system's response with the PI controller. Next, PV Maximum Power Point Tracking (MPPT) algorithm is simulated to ensure that the PV is able to produce the optimal power supply at all weather conditions. Then, the simulation of parallel combined ESS integrated with power converter is made. The response of the vehicle is emulated through combination of resistive load. For acceleration mode, resistive load will be stepped down by a switch. Similarly, the resistive load will be stepped up by the switch to emulate the braking mode. For coasting mode and parking mode, a constant load and no load will be used respectively. Next, the resistive load is replaced by a DC motor drive system in order to test both charging and discharging responses of each energy sources in the proposed energy management algorithm.

After completing all simulations, the experimental hardware will be implemented to test the studied energy management with PI control. The dSPACE RTI1104 as Real Time Interface (RTI) is used to control experiment hardware through MATLAB/Simulink environment. Hardware implementation consist of ESSs, power converters, gate driver circuit, voltage transducer, current transducer, load circuit and protection circuit. Finally, the voltage output and the current output response of the experimental hardware testing can be observed through oscilloscope or Control Desk which is the dSPACE experiment software for electronic control unit (ECU) development. The results of the experiment will be analyzed.

1.6 Outline of Thesis

This thesis consists of six chapters that are organized and described as follows:

Chapter 1 describes the background of transportation role on environment impact and comparison between conventional ICE vehicle and EV. The chapter also discusses the potential problems faced by EV energy management system, the objectives of the thesis, the scope of the thesis and the methodology used.

Chapter 2 presents types of DC/DC power electronic topologies for EV application. Some reviews on converter's characteristic are explained in this section. In addition to that, the way of hybridization ESS in EV application is reviewed too. The types of energy management algorithm and control in EV and PV are also discussed. The controls of EV's energy management are differentiated into two categories. They are high level supervisory control and low level component control. Then, power converter control methods through proportional-integral (PI) and model predictive control (MPC) are review in this chapter. The MPPT algorithm on PV is reviewed last.

Chapter 3 details the power stage design which considering all vehicle’s operating conditions. The calculated value of output capacitor, inductor, and system voltage are reported in this chapter. The optimized calculation of components in small scale EV is described. The ESS which consists of battery, UC and PV is modeled in this chapter. In addition, the boost converter modeling and bidirectional DC/DC converter modeling is also explained. Based on the modeling, the parameters loop compensator of the PI controller and GPC algorithm are designed. Then, perturb and observe (P&O) MPPT algorithm is simulated for the PV.

Chapter 4 discusses system simulation of energy management through continuous PI control, discrete PI control and GPC algorithm. This includes simulation results and evaluation of the performances on resistive load and DC motor drive system.

Chapter 5 covers all the experimental set-up. The power circuit and gate drivers are briefly explained in this chapter. The implementation of the proposed system using DS1104 DSP is also outlined. Hardware result of discrete PI control is presented here. Discussions and analysis of the results are also presented.

Chapter 6 draws the conclusion for the thesis and highlights the academic contributions obtained throughout this research. Suggestions for possibility of future work in this area of study are outlined.

REFERENCES

1. Tie, S.F. and C.W. Tan, *A review of energy sources and energy management system in electric vehicles.* Renewable and Sustainable Energy Reviews, 2013. **20**(0): p. 82-102.
2. Baumert, K.A., T. Herzog, and J. Pershing, *Navigating the Numbers: Greenhouse Gas Data and International Climate Policy*. 2005: World Resources Institute.
3. Schmidt, R. *Information technology energy usage and our planet*. in *Thermal and Thermomechanical Phenomena in Electronic Systems, 2008. ITHERM 2008. 11th Intersociety Conference on*. 2008.
4. Siang Fui, T. and T. Chee Wei. *A review of power and energy management strategies in electric vehicles*. in *Intelligent and Advanced Systems (ICIAS), 2012 4th International Conference on*. 2012.
5. Rodrigue, J.-P. and C. Comtois, *The Geography of Transport Systems*. Third Edition ed. Transportation and Energy. Vol. 8. 2013, New York: Routledge. 416.
6. Zuttel, A., A. Borgschulte, and L. Schlapbach, *Hydrogen as a Future Energy Carrier*. 2008, Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA.
7. Chau, K.T. and C.C. Chan, *Emerging Energy-Efficient Technologies for Hybrid Electric Vehicles.* Proceedings of the IEEE, 2007. **95**(4): p. 821-835.
8. Soylu, S., *Electric Vehicle - Modelling and Simulations*. 2011, Croatia: InTech. 478.
9. *Energy: High Impedance Batteries*. 2005 22/09/05 [cited 2014 26 December]; Available from: http://www.meridian-int-res.com/Energy/Battery.htm.

10. *Questions and Answers on Electric Vehicles*. 2014 [cited 2014 19/11/2014]; Available from: http://www.ucsusa.org/clean_vehicles/smart-transportation-solutions/advanced-vehicle-technologies/electric-cars/model-e-faq.html#bf-toc-3.
11. Ortuzar, M., J. Moreno, and J. Dixon, *Ultracapacitor-Based Auxiliary Energy System for an Electric Vehicle: Implementation and Evaluation.* Industrial Electronics, IEEE Transactions on, 2007. **54**(4): p. 2147-2156.
12. Schaltz, E., A. Khaligh, and P.O. Rasmussen, *Influence of Battery/Ultracapacitor Energy-Storage Sizing on Battery Lifetime in a Fuel Cell Hybrid Electric Vehicle.* Vehicular Technology, IEEE Transactions on, 2009. **58**(8): p. 3882-3891.
13. Lukic, S.M., et al. *Power Management of an Ultracapacitor/Battery Hybrid Energy Storage System in an HEV*. in *Vehicle Power and Propulsion Conference, 2006. VPPC '06. IEEE*. 2006.
14. Camara, M.B., et al., *Design and New Control of DC/DC Converters to Share Energy Between Supercapacitors and Batteries in Hybrid Vehicles.* Vehicular Technology, IEEE Transactions on, 2008. **57**(5): p. 2721-2735.
15. Camara, M.B., et al., *DC/DC Converter Design for Supercapacitor and Battery Power Management in Hybrid Vehicle Applications—Polynomial Control Strategy.* Industrial Electronics, IEEE Transactions on, 2010. **57**(2): p. 587-597.
16. *Kinetic Energy Recovery System*, in *Wikipedia*. 2014, Wikipedia.
17. Shahan, Z. *Ford C-Max Solar Energi Concept Car Coming To CES 2014*. 2014.
18. *World Oil Crisis: Driving forces, Impact and Effects*. 2008; Available from: http://www.world-crisis.net/oil-crisis.html.
19. Luo, F.L. and H. Ye, *Advanged DC/DC Converters*. 2004: CRC Press. 761.
20. Schupbach, R.M. and J.C. Balda. *Comparing DC-DC converters for power management in hybrid electric vehicles*. in *Electric Machines and Drives Conference, 2003. IEMDC'03. IEEE International*. 2003.
21. Maclaurin, A., et al. *Control of a flywheel energy storage system for rural applications using a Split-Pi DC-DC converter*. in *Electric Machines & Drives Conference (IEMDC), 2011 IEEE International*. 2011.

22. Amjadi, Z. and S.S. Williamson. *Novel controller design for a Luo converter electric vehicle energy management system*. in *Electric Power and Energy Conference (EPEC), 2010 IEEE*. 2010.

23. Garcia, O., et al., *Automotive DC-DC bidirectional converter made with many interleaved buck stages.* Power Electronics, IEEE Transactions on, 2006. **21**(3): p. 578-586.

24. Amjadi, Z. and S.S. Williamson, *Power-Electronics-Based Solutions for Plug-in Hybrid Electric Vehicle Energy Storage and Management Systems.* Industrial Electronics, IEEE Transactions on, 2010. **57**(2): p. 608-616.

25. Ferreira, A.A., et al., *Energy Management Fuzzy Logic Supervisory for Electric Vehicle Power Supplies System.* Power Electronics, IEEE Transactions on, 2008. **23**(1): p. 107-115.

26. Jih-Sheng, L. and D.J. Nelson, *Energy Management Power Converters in Hybrid Electric and Fuel Cell Vehicles.* Proceedings of the IEEE, 2007. **95**(4): p. 766-777.

27. Lukic, S.M., et al., *Energy Storage Systems for Automotive Applications.* Industrial Electronics, IEEE Transactions on, 2008. **55**(6): p. 2258-2267.

28. Kohler, T.P., D. Buecherl, and H. Herzog. *Investigation of control strategies for hybrid energy storage systems in hybrid electric vehicles*. in *Vehicle Power and Propulsion Conference, 2009. VPPC '09. IEEE*. 2009.

29. Matsuo, H., et al., *Characteristics of the multiple-input DC-DC converter.* Industrial Electronics, IEEE Transactions on, 2004. **51**(3): p. 625-631.

30. Solero, L., A. Lidozzi, and J.A. Pomilio, *Design of multiple-input power converter for hybrid vehicles.* Power Electronics, IEEE Transactions on, 2005. **20**(5): p. 1007-1016.

31. Zhenhua, J. and R.A. Dougal, *A Compact Digitally Controlled Fuel Cell/Battery Hybrid Power Source.* Industrial Electronics, IEEE Transactions on, 2006. **53**(4): p. 1094-1104.

32. Camara, M.B., et al. *DC/DC converters control for embedded energy management — Supercapacitors and battery*. in *IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society*. 2010.

33. Danwei, L. and L. Hui, *A ZVS Bi-Directional DC/DC Converter for Multiple Energy Storage Elements.* Power Electronics, IEEE Transactions on, 2006. **21**(5): p. 1513-1517.

34. Lei, W. and L. Hui, *Maximum Fuel Economy-Oriented Power Management Design for a Fuel Cell Vehicle Using Battery and Ultracapacitor.* Industry Applications, IEEE Transactions on, 2010. **46**(3): p. 1011-1020.

35. Bennett, J., et al. *PID Tuning Via Classical Methods*. 2007 [cited 2014; Available from: https://controls.engin.umich.edu/wiki/index.php/PIDTuning.

36. Goodwin, G.C., S.F. Graebe, and M.E. Salgado, *Control System Design*. 2000, Upper Saddle River, NJ, USA: Prentice Hall PTR.

37. F.Franklin, G., A. Emami-Naeini, and J.D. Powell, *Feedback Control of Dynamic Systems*. 1993, Inc. Boston, MA, USA: Addison-Wesley Longman Publishing Co.

38. Linder, A. and R. Kennel. *Model Predictive Control for Electrical Drives*. in *Power Electronics Specialists Conference, 2005. PESC '05. IEEE 36th*. 2005.

39. Kouro, S., et al., *Model Predictive Control - A Simple and Powerful Method to Control Power Converters.* Industrial Electronics, IEEE Transactions on, 2009. **56**(6): p. 1826-1838.

40. Kuen, H.Y., *Adaptive-Model Based Self-Tuning Generalized Predictive Control of A Biodiesel Reactor*, in *Faculty of Engineering*. 2011, University of Malaya: Kuala Lumpur.

41. Serrao, L., *A Comparative Analysis of Energy Management Strategies for Hybrid Electric Vehicles*, in *Machine Design*. 2009, Ohio State University: Ohio State University. p. 240.

42. Xuejun, L., *An Improved Perturbation and Observation Maximum Power Point Tracking Algorithm For PV Panels*, in *Electrical and Computer Engineering*. 2004, Concordia University Montreal: Quebec, Canada.

43. AmpedRealtor. *Model S - Charging Less Already?* 2013; Available from: http://www.teslamotors.com/en_AU/forum/forums/model-s-charging-less-already.

44. *Thermal Management*, in *Battery and Energy Technologies*. 2005, Electropaedia: United Kingdom.

45. University, B. *Safety of Lithium-ion Batteries*. 2014; Available from: http://batteryuniversity.com/learn/article/safety_of_lithium_ion_batteries.

46. Upadhyay, C. and H. Chandwani, *Ultracapacitor - Future of Regenerative Storage in Electric Vehicle.* International Journal of Electrical and Electronics Engineering (IJEEE), 2013. **2**(2): p. 41-48.

47. Lidozzi, A. and L. Solero. *Power balance control of multiple-input DC-DC power converter for hybrid vehicles*. in *Industrial Electronics, 2004 IEEE International Symposium on*. 2004.

48. Hasaneen, B.M. and A.A.E. Mohammed. *Design and simulation of DC/DC boost converter*. in *Power System Conference, 2008. MEPCON 2008. 12th International Middle-East*. 2008.

49. Tremblay, O., L.A. Dessaint, and A.I. Dekkiche. *A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehicles*. in *Vehicle Power and Propulsion Conference, 2007. VPPC 2007. IEEE*. 2007.

50. *WP 1.5 Battery Modeling*, S.H. Jensen, C.N. Rasmussen, and G. Yang, Editors. 2012, EDISON Consortium.

51. Hansen, A.D., et al., *Models for a Stand-Alone PV System*. 2000, Risø National Laboratory, Roskilde. p. 78.

52. Vural, B., et al. *A dynamic ultra-Capacitor model for vehicular applications*. in *Clean Electrical Power, 2009 International Conference on*. 2009.

53. Uzunoglu, M. and M.S. Alam, *Modeling and Analysis of an FC/UC Hybrid Vehicular Power System Using a Novel-Wavelet-Based Load Sharing Algorithm.* Energy Conversion, IEEE Transactions on, 2008. **23**(1): p. 263-272.

54. Thounthong, P., et al., *Analysis of Supercapacitor as Second Source Based on Fuel Cell Power Generation.* Energy Conversion, IEEE Transactions on, 2009. **24**(1): p. 247-255.

55. Knopf, H., *Analysis, Simulation , and Evaluation of Maximum Power Point Tracking (MPPT) Methods for a Solar Powered Vehicle*, in *Electrical and Computer Engineering*. 1999, Portland State University. p. 177.

56. Jamri, M.S. and T.C. Wei, *Modeling and control of a photovoltaic energy system using the state-space averaging technique.* American Journal of Applied Sciences, 2010. **7**(5): p. 682-691.

57. B., S.M., R. R., and M. B.L., *Design and Modeling of Standalone Solar Photovoltaic Charging System.* International Journal of Computer Applications, 2011. **18**(2): p. 41-45.

58. Orozco, M.I.A., et al., *Maximum Power Point Tracker of a Photovoltaic System Using Sliding Mode Control*, in *International Conference on Renewable Energies and PowerQuality (ICREPQ'09)*. 2009, European

Association for the Development of Renewable Energies, Environment and Power Quality: Valencia, Spain.

59. *YingLi Solar*. 2014; Available from: http://www.yinglisolar.com.
60. Armstrong, P.M., et al. *A reconfigurable PV array scheme integrated into an electric vehicle*. in *Hybrid and Electric Vehicles Conference 2013 (HEVC 2013), IET*. 2013.
61. Erickson, R.W., *Fundamentals of Power Electronics*. 2000, Secaucus, NJ, USA: Kluwer Academic Publishers.
62. Zhang, J., *Bidirectional DC-DC Power Converter Design Optimization, Modeling and Control*, in *Electrical Engineering*. 2008, Virginia Polytechnic Institute and State University: Blacksburg, Virginia.
63. Yan, X., *Control Strategies and Power Electronics in a Low-cost Electric Vehicle Propulsion System Employing a Brushless DC Machine*, in *Faculty of Technology*. 2000, Northern Territory University: Northern Territory University.
64. Hwa, W.J., *Parallel Energy Sharing Control for Fuel Cell-Battery-Ultracapacitor Hybrid Electric Vehicle*, in *Fakulti Kejuruteraan Elektrik*. 2012, Universiti Teknologi Malaysia: Johor Bahru, Malaysia.
65. Arrieta, O., R. Vilanovam, and P. Balaguer, *Procedure for Cascade Control Systems Design Choice of Suitable PID Tunings*. International Journal of Compunters, Cummunications & Control, 2008. **III**(3): p. 235-248.
66. Feng, G., et al., *Study on Global Optimization and Control Strategy Development for a PHEV Charging Facility*. Vehicular Technology, IEEE Transactions on, 2012. **61**(6): p. 2431-2441.
67. Fadali, H., *Fuel Cell Distributed Generation: Power Conditioning, Control and Energy Management*, in *Electrical and Computer Engineering*. 2008, University of Waterloo: Waterloo, Ontario.
68. Jamil, Y., *Laporan Kursus Pendek CHICHE project 629*. 1995, Universiti Teknologi Malaysia.
69. *LEM*. [cited 2014; Available from: http://www.lem.com/hq/en/content/view/261/200/.
70. dSPACE. *DS1104 R&D Controller Board*. 2010; 7.0:[Available from: http://www.dspace.com/en/pub/home/products/hw/singbord/ds1104.cfm.