University of Technology Sydney

Centre for Green Energy and Vehicle Innovations

Faculty of Engineering and IT

A NOVEL BATTERY-SUPERCAPACITOR POWER SUPPLY FOR ELECTRIC VEHICLES (EVs) – DESIGN, SIMULATION AND EXPERIMENT

A thesis submitted for the degree of

Doctor of Philosophy

Li SUN

Aug 2017

CERTIFICATION OF ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Aug 2017

ABSTRACT

Most existing electric vehicles (EVs) employ rechargeable batteries alone. As a consequence, they suffer from performance degradation such as power deprivation or battery aging, and have difficulty to cope with the whole spectrum of driving load without compromising durability or safety. A more complex design is therefore, required to address this drawback. More specifically, a Hybrid Energy Storage System (HESS) is proposed to hybridize batteries with other sources possessing higher power density such as a supercapacitor via a smart power converter to electrically regulate each power flow. This unique power sharing capability can effectively reduce power stress that would otherwise be applied to batteries alone, whilst increase the attractiveness of the EV market due to the potential power-boost capabilities. However, the novel HESS increases the cost and weight of the vehicle. This thesis is intended to resolve these conflicts and consists of following three innovative aspects.

1) A four-quadrant, supercapacitor-only drive solution is first investigated, developed and characterized to gain better insights into the unique properties of the supercapacitor and the bi-directional DC-DC converter, during both driving and regenerative braking mode – Chapter 3**.**

2) In order to justify various design trade-offs, a novel Multi Objective Optimization Problem (MOOP) based component sizing algorithm is developed aiming at solving two conflicting objectives – cost and total stored energy in HESS, when considering the presence of a power converter – Chapter 4.

3) Finally, an adaptive power split strategy (PSS) is developed in order to intelligently split load power between batteries and supercapacitors as a function of the ever-changing load profile. A simplified HESS model is first developed in Matlab and then, the real-time PSS is coded using Labview and deployed on a 5kW EV-HESS integrated test rig. Both simulation and experimental results prove its effectiveness in coping with even the harshest driving scenarios in real life – Chapter 5.

Although I specifically present the results for HESS applications, the concept of MOOP, HESS and PSS can be easily tailored for other types of hybridized systems such as series hybrid electric vehicles, battery assisted fuel cell electric vehicles, solar-battery power systems or any dual-source power systems that need to perform load-leveling functions.

ACKNOWLEDGEMENTS

I would like to express my gratitude to all the people who had helped me during my candidature in the University of Technology, Sydney.

First, this thesis will not get started without the vision of my principle supervisor – **Prof. Nong Zhang** – whose critiques and encouragements are essential to shape the key methodologies of this research. Along with my secondary supervisor – **Prof. Jianguo Zhu**, both mentors have placed their faith in me by providing me with an opportunity to pursue a rewarding journey by solving a multi-disciplinary technical challenge.

Second, I would like to thank **Automotive Australia 2020 Cooperative Research Centre**, Commonwealth of Australia for their financial support to this research.

Next, my thank goes to the following industrial partners, and laboratory staffs whose collaboration and expertise is absolutely pivotal to make the final work viable. I am especially grateful to:

- **Kirby Fung** from Qingchi Technologies, whom I had the joy to work with during a few tough overseas travels. Kirby had been working tirelessly to improve the overall converter efficiency within a very tight schedule.
- **Luis Machin** from Amtex Electronics, who had been kind enough to lend expensive factory test facilities and resources to help me successfully prototyping a modified electric scooter.
- **Raja Pillai** from National Instruments, Australia, for the insightful discussion without which, the implementation side of the algorithm would not have been possible.
- **Chris Chapman** from the UTS dynamics lab, who had been an enthusiastic supporter, a coach to this project. He has had the magic to make the rather abstract programming clear and easy to understand. Self-confidence was therefore built up to tackle bigger challenges, and I became more and more

interested in realizing complex functions that could make a difference in the real world. What a thrilling experience!

- **Dr. Paul Walker**, whom I had in-depth discussion with, and whom I always look up as a vivid academic role model during my candidature.
- **Dr. Greg Hunter**, who I had collaborated with. He gave me the faith that true academics are not just paper-driven, but being practical and solve real-world engineering problems as well.
- Other UTS academic, laboratory and workshop staffs such as **Jack Liang**, **Dr. Lei Gang**, **Russell Nicholson**, **Clyde Webster**, **Dr. Holger Roser**, **Peter Tawadros**, **Scott** and **Lawrence Stonard**, etc. have been helpful at various stages of the project development.

Furthermore, I would like to thank my fellow-colleagues **Mohamed Awadallah**, **Yuhong Fang**, **Jianwei Zhang**, **Jiageng Ruan**, etc. My appreciation and gratitude is owed to all involved in the project.

I would also like to thank the three anonymous reviewers from the "IEEE Transaction on Industrial Electronics" and the Associate Editor, **Prof. Leopoldo Franquelo**, for their inspiring comments and warm encouragement without which this work would have never been possible.

Finally, I want to apologize to my son – **Bowen Sun**, my parents – **Jianping and Zhiqiang** who had made tremendous sacrifice during my "dry" and lengthy candidature. I therefore, shall ensure that one day, this research turns into something that people want, and thus make US all proud.

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NOMENCLATURE

Global abbreviations used in this thesis

HEV	Hybrid Electric Vehicle
EV	Electric Vehicle
ESS	Energy Storage System
HESS	Hybrid Energy Storage System
ICE	Internal Combustion Engine
SOC	State Of Charge
BP	Battery Pack
SC	Supercapacitor
SP	Supercapacitor Pack
PC	Power Converter
EMS	Energy Management Strategy
PSS	Power Split Strategy
MOOP	Multi Objective Optimization Problem
P_{LOAD}	Load Power (W)
P_{SP}	Supercapacitor Power (W)
P_{BP}	Battery Power (W)

Chapter 1 Notation

EPA	Environmental Protection Agency
DCT	Dual Clutch Transmission
VCU	Vehicle Control Unit
TCU	Transmission Control Unit

Chapter 2 Notation

ESR	Equivalent Series Resistance
NTC	Negative Temperature Coefficient
PTC	Positive Temperature Coefficient
RB	Rule Based
ECMS	Equivalent Consumption Minimization Strategy
SVM	Support Vector Machine

Chapter 3 Notation

OCL	Overhead Contact Lines
NiMH	Nickel-Metal Hydride
EMF	Electromotive Force
VSD	Variable Speed Drive
V_1	Cut-off voltage of the supercapacitor bank (V)
V_2	Fully charged DC voltage of the supercapacitor bank (V)
C	Total capacitance of the supercapacitor bank (F)
E	Total energy stored within the supercapacitor bank (J)
M	Total Mass of the scooter and driver (kg)
S_1	Scooter end speed (m/s)
S_2	Scooter initial speed (m/s)
V_{scap}	Supercapacitor terminal voltage (V)
I_{scap}	Supercapacitor current (A)
V_m	Scooter motor back EMF (V)
I_m	Scooter motor current (A)
V_o	Converter output voltage (V)
P_m	Net motor(generator) power (W)
R_a	Armature resistance
P_{in}	Total electromotive input power (W)
P_{dc}	Converter output power (W)
P_{scap}	Supercapacitor power (W)
EFF_m	Power conversion efficiency over motor energy conversion stage
EFF_{dc}	Power conversion efficiency over DC-DC energy conversion stage
EFF_{regen}	Power conversion efficiency over regenerative energy conversion stage
$EFF_{overall}$	Overall power conversion efficiency

Chapter 4 Notation

HCR	Hybridized Cost Ratio
LiFPO4	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
MOOP	Multi-Objective Optimization Problem
NCM	Nickel-Cobalt-Manganese

PCOA	Parallel Chaos Optimization Algorithm
ZVC	Zero Voltage Switching
W	Total weight of HESS (kg)
W_b	Weight of battery pack (kg)
W_{sc}	Weight of supercapacitor pack (kg)
W_{pc}	Weight of power converter (kg)
E	Total stored energy of HESS (kWh)
E_b	Stored energy of battery pack (kWh)
E_{sc}	Stored energy of supercapacitor pack (kWh)
P	Total power capacity of HESS (kW)
P_b	Power capacity of battery pack (kW)
P_{sc}	Power capacity of supercapacitor pack (kW)
P_{pc}	Power capacity of power converter (kW)
X	Total cost of HESS (AUD)
X_b	Cost of battery pack (AUD)
X_{sc}	Cost of supercapacitor pack (AUD)
X_{pc}	Cost of power converter (AUD)
m	Curb weight of the vehicle excluding the weight of HESS (kg)
P2W	Power to weight ratio of the vehicle (kW/kg)
Φ_b	(Weight) Specific energy of battery pack (Wh/kg)
Φ_{sc}	(Weight) Specific energy of supercapacitor pack (Wh/kg)
θ_b	(Weight) Specific power of battery pack (kW/kg)
θ_{sc}	(Weight) Specific power of supercapacitor pack (kW/kg)
θ_{pc}	(Weight) Specific power of power converter (kW/kg)
C_b	(Weight) Specific cost of battery pack (AUD/kg)
C_{sc}	(Weight) Specific cost of supercapacitor pack (AUD/kg)
C_{pc}	(Weight) Specific cost of power converter (AUD/kg)
V_{dc}	DC link voltage (V)
J	Multi-objective optimization function vector [(kWh), (AUD)]
J_E	Multi-objective optimization function vector – minimum system energy (kWh)
J_C	Multi-objective optimization function vector – minimum cost (AUD)
$P_{\_min}$	Minimum total power of HESS (kW)

P_{sc_min}	Minimum total power of supercapacitor (kW)
P_{b_min}	Minimum total power of battery (kW)
E_{sc_min}	Minimum energy stored in SP (Wh)
$P2W_{\_min}$	Minimum P2W ratio
$W_{\_max}$	Maximum weight of the overall HESS (kg)

Chapter 5 Notation

AI	Artificial Intelligence
DFT	Discrete Fourier Transform
EMS	Energy Management Strategy
FIR	Finite Impulse Response
LPF	Low Pass Filter
PAPR	Peak-to-Average Power Ratio
PAVR	Peak-to-Average Velocity Ratio
I_{SP}	Output current of the SP (A)
I_{BP}	Output current of the BP (A)
I_{LOAD}	Load current (A)
R	Ratio of area
$f_{\_c}$	Cut-off frequency (Hz)
F_r	Tyre rolling resistance (N)
F_d	Aerodynamic drag force (N)
η	Total electricl energy conversion efficiency
M	Vehicle mass (kg)
C_r	Aerodynamic drag coefficient
A	Frontal area (m^2)
ρ	Air density (kg/m3)
C_d	Rolling resistance coefficient
R_w	Wheel radius (m)
V	Vehicle velocity (km/hr)