

ENERGY MANAGEMENT SYSTEM FOR THREE-WHEEL LIGHT ELECTRIC
VEHICLE USING MULTI-SOURCES ENERGY MODELS

FARID ARAFAT AZIDIN

THESIS SUBMITTED IN FULFILLMENT FOR DEGREE OF
DOCTOR OF PHILOSOPHY

FACULTY OF ENGINEERING AND BUILT ENVIRONMENT
UNIVERSITI KEBANGSAAN MALAYSIA
BANGI

2016

SISTEM PENGURUSAN TENAGA UNTUK KENDERAAN ELEKTRIK RINGAN TIGA
RODA MENGGUNAKAN PELBAGAI SUMBER

FARID ARAFAT AZIDIN

TESIS YANG DIKEMUKAKAN UNTUK MEMENUHI SEBAHAGIAN DARIPADA
SYARAT MEMPEROLEH IJAZAH
FALSAFAH KEDOKTORAN

FAKULTI KEJURUTERAAN DAN ALAM BINA
UNIVERSITI KEBANGSAAN MALAYSIA
BANGI

2016

DECLARATION

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

18 OGOS 2016

FARID ARAFAT BIN AZIDIN
P50200

ACKNOWLEDGMENTS

First and foremost praise is to Almighty Allah for all his blessings for giving me patience and good health throughout the duration of this PhD research.

I am very fortunate to have Professor Dr. MA Hannan as a research supervisor. I am greatly indebted to his ideas, encouragement, assistance, support, solid guidance and in-depth discussions he shared with me through this research and in the preparation of the thesis. Without his tireless assistance, leadership, and confidence in my abilities, this thesis would not come to its timely completion.

I should like to express my sincere thanks to Professor Dr. Azah Mohamed as Head of Power System Lab and for letting me use all power system instruments towards the successful completion of this PhD degree. I should also like to offer a special thanks to Professor Madya Dr. Hussein Sharif for their insightful comments and solid guidance. Thanks also to my colleagues at the Power Laboratory, UKM for their support and discussions that has helped me during the research.

To Ministry of Higher Education (MOHE) and UTeM, thanks for the financial assistance and space provided for me to do the research.

Love and warmest thanks for my dearest parents; Azidin Bin Mahmud and Sapiah Binti Ahamad Tarmizi, for your do'as, support and encouragements throughout my education years. To my dearest wife, Hamidah Binti Hamzah and my lovely daughter, Farhana Hamizah Binti Farid Arafat, thanks for your do'as, patience, understanding and support for all the duration of doing this research. Finally, to all those who have helped me throughout the duration of this research; families, colleagues and friends, thank you to all of you. All of you have been a source of confidence and inspiration for me.

ABSTRACT

Hybrid electric vehicles, plug-in hybrid electric vehicles, battery electric vehicles, fuel-cell vehicles are just a few technologies that are being researched worldwide today. Applying renewable energy such as battery, fuel cell and super-capacitor in the electric vehicle is a smart and ideal solution. However, battery as a single-source in electric vehicle has many disadvantages such as limited travel distance and longer charging time. Besides, battery reduces its electrical characteristics through high current flow, high temperature, self-discharge and low battery capacity level. Fuel cell has low power response during sudden energy demand and requires an expensive infrastructure for refueling. In case of light fuel cell vehicle, small tank is practical for exchange tank. In super-capacitor side, it cannot support enough energy for a single powered electric vehicle purposes, however can be used as secondary power supply. Thus, an intelligent energy management system (EMS) of various sources is necessary to counterbalance the drawback of the sources. To solve the problem, the objective of the research is to develop an intelligent EMS which can conduct multi-sources for three wheel light electric vehicle (LEV). A rule-based control algorithm which contains eight states in EMS is designed to control power switches and to ensure sufficient energy is delivered to the load. The work of this research begins by electrical analysis in PSPICE simulation which focuses in circuit design and testing the state condition. A close loop vehicle system implemented with intelligent EMS is designed in MATLAB/Simulink. The simulation model is simulated with a real three wheel scooter specification which has capacity of 5.4 kW DC machine. To show effectiveness of the developed vehicle system, the performance and efficiency of the vehicle simulation is compared with standard drive cycle such as ECE-47 and ECE-15. To justify the simulation model, a scaled-down lab test bench model is designed using dSPACE DS 1104. The LEV model with 18 W load power is implemented in the developed test bench prototype. As a result, the vehicle system specification for the lab test bench model is reduced accordingly to the ratio of load power. The power specifications of the multi-source models such as 30 W for fuel cell, 3 Ah for rechargeable sealed lead acid battery and 100F for super-capacitors have been used. An EMS hardware is designed to offer a bridge between MATLAB/Simulink and dSPACE DS 1104. In the EMS hardware design, the switching relay is used for selection of the sources and current transducers which are used for measuring load current and battery capacity. All input and output signals from the EMS hardware design are connected to the dSPACE DS 1104 for data presentation in graphical user interface. For the uphill simulation test, using ECE-47 drive cycle, multi-source energy models shows that the power effectiveness is 94.6% where as for the battery, as a single-source, it is 84.9%. The lab test bench model also proved that in extension of 33% of speed ECE-47 drive cycle, the energy efficiency of multi-source LEV is 80.2% which is better performance than that of combustion engine energy efficiency of 29.2%. Therefore, the system equipped with an intelligent control algorithm has promising potential in vehicle energy management applications for the future.

ABSTRAK

Kenderaan elektrik jenis hibrid, hibrid masukan-palam, bateri dan sel fuel adalah sebahagian daripada teknologi yang dikaji di seluruh dunia pada masa kini. Penggunaan tenaga keterbaharuan seperti bateri, sel fuel dan pemuat lampau dalam kenderaan elektrik, adalah satu penyelesaian yang pintar dan unggul. Bateri sebagai satu punca dalam kenderaan elektrik mempunyai banyak kekurangan seperti jarak perjalanan terhad dan masa cas yang panjang. Tambahan pula, bateri akan mengurangkan sifat elektriknya dalam keadaan arus elektrik yang tinggi, suhu yang tinggi, nyahcas-kendiri dan paras kapasiti bateri yang rendah. Sel bahanapi pula mempunyai kuasa tindak balas yang rendah dalam keadaan permintaan tenaga tiba-tiba dan juga memerlukan infrastruktur mahal untuk pengisian semula. Bagi kenderaan sel fuel ringan, tangki yang kecil adalah praktikal untuk tangki pertukaran. Untuk pemuat lampau pula, ia tidak mampu membekalkan tenaga kepada kenderaan elektrik punca satu tetapi mampu digunakan sebagai pembekal kuasa sekunder. Oleh itu, satu sistem pengurusan tenaga (SPT) pintar diperlukan untuk memenuhi masalah kekurangan punca tenaga tersebut. Objektif penyelidikan adalah untuk membangunkan SPT yang boleh diaplikasikan pada kenderaan elektrik ringan (KER) tiga roda pelbagai sumber. Satu algoritma kawalan yang mempunyai lapan keadaan dalam SPT dibangunkan untuk mengawal suis kuasa dan memastikan tenaga yang dibekalkan kepada beban adalah mencukupi. Penyelidikan bermula dengan mengenal pasti litar elektrik melalui simulasi PSPICE. Satu sistem gelung tertutup bersama SPT pintar dibangunkan dalam MATLAB/Simulink. Model simulasi adalah mengikut spesifikasi skuter elektrik sebenar dengan kuasa 5.4 kW mesin DC. Untuk menguji kerberkesanan sistem kenderaan tersebut, ianya dibandingkan dengan kitar pandu piawai ECE-47 dan ECE-15. Sebagai pengesahan model simulasi, suatu ujian makmal berskala kecil direka dengan menggunakan dSPACE DS1104. Satu KER prototaip berskala kecil dibangunkan dengan kuasa beban 18 W. Oleh itu, sistem kenderaan juga perlu dikurangkan mengikut nisbah kuasa beban. Spesifikasi kuasa bagi sistem pelbagai sumber tersebut adalah 30 W untuk sel bahanapi, 3 Ah bateri cas semula dan 100 F pemuat lampau. Satu litar elektrik SPT direka untuk dijadikan sebagai perantaramuka MATLAB/Simulink dengan dSPACE DS1104. Dalam litar elektrik SPT, terdapat suis geganti untuk memilih kuasa manakala transduser arus untuk mengukur beban arus dan kapasiti bateri. Semua masukan dan keluaran dari litar elektrik SPT disambungkan kepada keluaran dSPACE DS1104 untuk mempersembahkan data dalam antaramuka pengguna grafik. Dalam ujian simulasi mendaki menggunakan kitar pandu ECE-47, model tenaga pelbagai sumber memberi prestasi 94.6% manakala model bateri adalah 84.9%. Model ujian makmal membuktikan bahawa dengan penambahan kelajuan 33% bagi kelajuan ECE-47, kecekapan kuasa bagi KER pelbagai sumber meningkat ke 80.2%, dan memberikan prestasi yang lebih baik dari enjin pembakaran dengan kecekapan 29.2.0%. Justeru, sistem yang dilengkapi dengan algoritma kawalan pintar mempunyai potensi dalam pengurusan tenaga kenderaan pada masa hadapan.

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LIST OF ABBREVIATIONS

| | |
|--------|---|
| ADC | Analog/Digital Converter |
| AEV | All Electric Vehicle |
| BC | Battery Capacity |
| BEV | Battery Electric Vehicle |
| BLEV | Battery Light Electric Vehicle |
| CHP | Combined Heat and Power |
| DOD | Depth of Discharge |
| DOE | Department of Energy |
| ECU | Electronic Control Unit |
| EMS | Energy Management System |
| EPR | Equivalent Parallel Resistance |
| ESR | Equivalent Series Resistance |
| ESS | Energy Storage System |
| FC | Fuel-cell |
| FCT | Fully Charged Test |
| FCV | Fuel-cell Vehicle |
| GUI | Graphical User Interface |
| HEV | Hybrid Electric Vehicle |
| HF | Hybridization Factor |
| HFCV | Hybrid Fuel Cell Vehicle |
| ICE | Internal Combustion Engine |
| IGBT | Insulated Gate Bipolar Transistor |
| I/O | Input and Output |
| IPM | Intelligent Power Management |
| LEV | Light Electric Vehicle |
| LV | Light Vehicle |
| MOSFET | Metal Oxide Semiconductor Field Effect Transistor |
| MS-LEV | Multi-Source Light Electric Vehicle |
| NREL | National Renewable Energy Laboratory |
| PCT | Partially Charged Test |
| PD | Power Demand |

| | |
|-------|------------------------------------|
| PEI | Power Electronic Interface |
| PEMFC | Proton Exchange Membrane Fuel Cell |
| PHEV | Plug-in Hybrid Electric Vehicle |
| PO | Pedal Offset |
| PMS | Power Energy Management |
| PV | Photovoltaic |
| PWM | Pulse Width Modulation |
| RTI | Real-Time Interface |
| SC | Super-capacitor |
| SOC | State of Charge |
| UAV | Unmanned Aerial Vehicle |
| UC | Ultra-Capacitor |
| UDDS | Urban Dynamometer Driving Schedule |
| VSP | Vehicle Simulation Program |

LIST OF SYMBOLS

| | |
|-----------------------|--|
| R_1, R_2, R_3 | Resistors network circuit |
| C_1, C_2, C_3 | Capacitors network circuit |
| C_b | Battery capacitance |
| R_p | Self-discharge resistance |
| R_{1C}, R_{1D}, C_1 | Represent voltage drop during charge and discharge |
| R_{SC}, R_{SD} | Resistance of the electrolyte and resistance of the battery plates |
| T | Battery temperature |
| R | Universal gas constant |
| F | Faraday's constant |
| P_{H_2} | Partial pressures of hydrogen |
| P_{O_2} | Partial pressures of oxygen |
| P_{H_2O} | Partial pressures of water |
| J_a | Actual current density of the cell (A/m ²) |
| J_{max} | Typical values range of 500-1500 mA/cm ² |
| N | Number of cells in the stack |
| L | Voltage Loss |
| P_{std} | Standard pressure |
| Q_{SC} | Energy stored in SC |
| I_L | Light generated current |
| I_o | Initial current |
| K | Boltzmann constant |
| q | Electron charge |
| $V_{SC,OC}$ | Open circuit voltage in SC |
| d | Distance between plates |
| ε | Permittivity |
| q_{SC} | SC charge |
| C_{SC} | SC capacitance |
| i_{SC} | Charging current flow |

| | |
|------------------|--|
| $V_{SC,max}$ | Maximum SC voltage |
| $V_{SC,min}$ | Minimum SC voltage |
| R_{SC} | Line resistance |
| $V_{SC,i}$ | Initial SC voltage |
| $V_{SC,f}$ | Final SC voltage |
| t_{on} | Length of the ON state of the switch |
| D_C | Duty cycle |
| i_L | Inductor current |
| t_{off} | Length of the OFF state of the switch |
| $MAX_{capacity}$ | Maximum battery energy in Ampere hour |
| AH_{used} | Energy usage in Ampere hour |
| P_{EM} | Peak power of the electric motor |
| P_{ICE} | Peak power of the ICE (internal combustion engine) |
| V_{Batt} | Battery open voltage |
| R_{int} | Battery internal resistance |
| t_{S5} | Switching control for battery |
| V_{FC} | FC open voltage source |
| $V_{FC act}$ | FC actual voltage when reach transient time |
| t_{S3} | Switching control for FC |
| V_{SC} | SC open voltage source |
| R_p | Parallel internal resistance in SC |
| R_s | Series internal resistance in SC |
| t_{S1} | Switching control for SC |
| $V_{S1_{on}}$ | SC voltage at start S1 active switching |
| $V_{S1_{off}}$ | SC voltage at final S1 off switching |
| V_{batt} | Battery constant load voltage |
| V_0 | Battery no load voltage |
| K | Polarized voltage constant |
| Q | Battery capacity |

| | |
|---------------|--|
| N | Numbers of the cell |
| A_v | Exponential voltage |
| \ln | Natural logarithm |
| i_{fc} | FC current |
| E_{fc} | Generated energy of FC |
| RC | Time-constant formed by resistor and capacitor |
| E_{SC} | SC consumed energy |
| V_f | SC final voltage |
| n_s | Number of capacitors in series |
| n_p | Number of capacitors in parallel |
| ESR | Equivalent series resistance |
| $V_{SC\max}$ | SC maximum voltage |
| I_{dsc} | Constant discharge current |
| E_{batt} | Energy from Battery |
| E_{FC} | Energy from FC |
| E_{SC} | Energy from SC |
| I_{ref} | Reference current |
| $Speed_{ref}$ | Reference speed of vehicle / Drive cycle reference |
| $Speed_{act}$ | Actual speed of vehicle |
| k_p, k_i | Proportional and integrator gain |
| I_a | Armature current |
| r | Tyre radius |
| m | Vehicle mass |
| A | Frontal area |
| d | Air density |
| C_d | Drag coefficient |
| μ_r | Rolling coefficient |
| g | Gravity acceleration |
| α | Angle slope |

| | |
|----------------------|--|
| V_{out} | Measured current in output voltage |
| I_{PN} | Primary nominal rms current |
| I_P | Primary current, measuring range |
| $u_1(t)$ | Signal from pedal offset through A/D converter |
| T_1 | Timer relay for SC |
| $u_2(t)$ | Signal from current load through A/D converter |
| T_2 | Timer relay for FC |
| C | Tangent of Current/voltage graph |
| $i(t)$ | Battery current to the load |
| $DutyCycle_{offset}$ | Additional offset value of duty cycle |
| T_e | Electromechanical torque |