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Modelling and State-of-Charge Estimation for Ultracapacitors in Electric Vehicles

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Lei ZHANG

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Ph.D. student:
Lei Zhang
E-mail: Lei.Zhang-15@student.uts.edu.au

Supervisor:
Dr. Li Li
E-mail: Li.Li@uts.edu.au

Co-Supervisor:
A.Prof. Youguang Guo
E-mail: Youguang.Guo-1@uts.edu.au

External Supervisor:
Prof. David G. Dorrell
E-mail: dorrelld@ukzn.ac.za

Address:
School of Electrical, Mechanical and Mechatronic Systems
University of Technology, Sydney, 15 Broadway, Ultimo, NSW 2007, Australia

Certificate of Original Authorship

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.

Signature of Student:

Lei Zhang

Date:

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Publications and Conference Contributions

The following publications are part of the thesis.

1. **Published journal papers**

[1] **L. Zhang***, X. Hu, Z. Wang, D. G. Dorrell, Experimental Investigation of Ultracapacitor Impedance Characteristics. *Energy Procedia* **75** (2015) 1888-1894.

[2] **L. Zhang***, X. Hu, Z. Wang, F. Sun, D. G. Dorrell, Fractional-Order Modeling and State-of-Charge Estimation for Ultracapacitors. *Journal of Power Sources* 314 (2016) 28-34.

[3] **L. Zhang***, X. Hu, Z. Wang, F. Sun, D. G. Dorrell, Experimental Impedance Investigation of an Ultracapacitor at Different Conditions for Electric Vehicle Applications. *Journal of Power Sources* **287** (2015) 129-138.

[4] **L. Zhang***, Z. Wang, X. Hu, F. Sun, D. G. Dorrell, A Comparative Study of Equivalent Circuit Models of Ultracapacitors for Electric Vehicles. *Journal of Power Sources* **274** (2015) 899-906.

[5] **L. Zhang***, Z. Wang, F. Sun, D. G. Dorrell, Online Parameter Identification of Ultracapacitor Models Using the Extended Kalman Filter. *Energies* **2014**, 07, 3204-3217.

2. **Journal papers under review**

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[7] **L. Zhang***, X. Hu, Z. Wang, F. Sun, D. G. Dorrell, A Survey of ultracapacitor modeling, estimation and applications. *Journal of Power Sources*, 2016

3. **Published conference paper**

[1] **L. Zhang***, X. Hu, S. Su, D. G. Dorrell, Robust State-of-Charge Estimation of

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Abstract

In order to cope with the global challenges like fossil fuel depletion and environmental pollution, electrified vehicles (EVs) have been widely accepted as an enabling option for future ground mobility. In comparison to conventional combustion engine vehicles, EVs have the advantage of high efficiency, environment-friendly operation and excellent control flexibility. There is a proviso here that the electricity used by the EV is from a green source such as hydro, wind or solar. The energy storage system (ESS) is a key ingredient of an EV, and significantly affects its driving performance and cost-effectiveness. The exploration of a vehicular ESS poses a formidable challenge, because of high power/energy demands and unpredictable driving environments. Li-ion batteries represent a main choice for this use, but suffer the drawbacks of low power density and poor recyclability. Recently, ultracapacitors (UCs), also referred to as supercapacitors (SCs) or electric double-layer capacitors (EDLCs), have gained increasing attention in the energy storage community, thanks to their high power density, high efficiency, fast charge, wide temperature window and excellent recyclability. These advantages make UCs a good augmentation to high-energy ESSs (e.g., fuel cells, lithium-ion batteries). This combination represents a hybrid energy storage system (HESS) that can fully leverage the synergistic benefits of each constituent device. To ensure efficient, reliable and safe operations of UC systems, numerous challenges including modelling and characterization, and State-of-Charge (SOC) estimation should be effectually surmounted. In order to meet the above mentioned challenges, the main research presented in this dissertation includes:

1. A special test rig for UC characteristic investigation has been established. A test procedure is proposed to collect comprehensive test data. A plethora of tests have been conducted on this test rig including capacity calibration, experimental impedance investigation under different temperatures and SOC values, and dynamic cycling including pulse tests and driving-cycle-based tests under different temperatures, resulting in a wide-ranging UC database.

2. The impedance characteristics of UCs are experimentally investigated under different temperatures and SOC values. The results show that the impedance is highly sensitive to temperature and SOC; and the temperature effect is more significant. In particular, the coupling effect between the temperature and SOC is illustrated, and the high-efficiency SOC window is highlighted.

3. For UC modelling, three commonly used equivalent circuit models are systematically examined in terms of model accuracy, complexity and robustness in the context of EV applications. A genetic algorithm (GA) is employed to extract the optimal model parameters based on the Hybrid Pulse Power Characterization (HPPC) test data. The performance of these models is then evaluated and compared by measuring the model complexity, accuracy, and robustness against “unseen” data collected in the Dynamic Stress Test (DST) and a self-designed pulse (SDP) test. The validation results show that the dynamic model has the best overall performance for EV applications.

4. Online parameter identification of UC models is researched. The extended Kalman Filter (EKF) is proposed to recursively estimate the model parameters using the DST dataset, in which the dynamic model is used to represent the UC dynamics. The effectiveness and robustness of the proposed method is validated using another driving-cycle-based dataset.

5. A novel robust *H*-infinity observer is presented to realize UC SOC estimation in real-time. In comparison to the state-of-the-art Kalman filter-based (KF-based) methods, the developed robust scheme can ensure high estimation accuracy without prior knowledge of process and measurement noise statistical properties. More significantly, the proposed *H*-infinity observer proves to be more robust to modelling uncertainties arising from the change of thermal conditions and/or cell health status.

6. A novel fractional-order model is put forward to emulate the UC dynamics. In contrast to integer-order models, the presented fractional-order model has the merits of better model accuracy and fewer parameters. It consists of a series resistor, a constant-phase-element (CPE), and a Warburg-like element. The model parameters are optimally extracted using GA, based on the time-domain Federal Urban Driving Schedule (FUDS) test data acquired through the established test rig. By means of this fractional-order model, a fractional Kalman filter is synthesized to recursively estimate the UC SOC. Validation results show that the proposed fractional-order modelling and state estimation scheme is accurate and outperforms the current practice based on integral-order techniques.

7. An optimal HESS sizing method using a multi-objective optimization algorithm is presented, in which the primary goal is reducing the ESS cost and weight while prolonging battery life. To this end, a battery state-of-health (SOH) model is incorporated to quantitatively investigate the impact of component sizing on battery life. The wavelet-transform-based power management algorithm is adopted to realize the power coordination between the battery and UC packs. The results provide prudent insights into HESS sizing with different emphases.

Key words: electrified vehicles; ultracapacitor; extended Kalman filter; *H*-infinity observer; fractional-order modelling; hybrid energy storage system

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Nomenclature

Global abbreviations used in this thesis

EV = Electrified vehicle
BEV = Battery electric vehicle
HEV = Hybrid electric vehicle
PHEV = Plug-in hybrid electric vehicle
UC = Ultracapacitor
SC = Supercapacitor
EDL = Electric-double-layer
ESS = Energy storage system
HESS = Hybrid energy storage system
UMS = Ultracapacitor management system
SOC = State-of-Charge
SOH = State-of-Health
EKF = Extended Kalman filter
KF = Kalman filter
GA = Genetic algorithm
HPPC = Hybrid Pulse Power Characterization
DST = Dynamic Stress Test
FUDS = Federal Urban Driving Schedule
SDP = Self-designed Pulse
UDDS = Urban Dynamometer Driving Schedule
EoL = End-of-Life
ANN = Artificial neural network
PDE = Partial differential equation
ODE = Ordinary differential equation
RMS = Root-mean-squared
EIS = Electrochemical impedance spectroscopy

LMI = Linear Matrix Inequality

ARE = Algebraic Ricaati Equation

FOC = Fractional-order calculus

GL = Grünald-Letnikov

GLD = Grünald-Letnikov derivative

RL = Riemann-Liouville

CPE = Constant-phase-element

DP = Dynamic programming

MPC = Model predictive control

WT = Wavelet-transform

NSGA = Non-dominated sorting genetic algorithm