Faculty of Electrical Engineering

A COMPARATIVE STUDY ON TIME-FREQUENCY DISTRIBUTION TECHNIQUES FOR BATTERY PARAMETERS ESTIMATION SYSTEM

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DECLARATION

I declare that this thesis entitled "A Comparative Study on Time-Frequency Distribution Techniques for Battery Parameters Estimation System" 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 candidature of any other degree.

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APPROVAL

I hereby declare that I have read this thesis and in my opinion, this thesis is sufficient in terms of scope and quality for the award of the Master of Science in Electrical Engineering.

Signature : ……………………………………….

Supervisor Name : Prof. Madya Dr. Abdul Rahim Bin Abdullah

Date : ………………………………………..

DEDICATION

A million praise towards my family, my respectful supervisor, examiner and lecturers and to all my friends for their support and cooperation in helping me to complete this thesis.

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ABSTRACT

Due to the degradation in battery lifetime directly impacts by load performance, reliability and safety operation of the battery cannot be guaranteed. In turn, safety precautions can be taken by monitoring battery performance from charging/discharging signals behaviour. Analyse the battery charging/discharging signals become challenging as the signal characteristic appears at very low frequency. Therefore, fast and accurate analysis in estimating battery parameters for real-time monitoring system should be proposed and developed. This research presents analysis of the battery charging/discharging signals using a spectral analysis technique, namely periodogram and time-frequency distributions (TFDs) which are spectrogram and S-transform techniques. The analysed batteries are lead acid (LA), nickel-metal hydride (Ni-MH) and lithium-ion (Li-ion). From the equivalent circuit model (ECM) simulated using MATLAB, constant charging/discharging signals are presented, jointly, in time-frequency representation (TFR). From the TFR, battery signal characteristics are determined from the estimated parameters of instantaneous of total voltage ($V_{TOT}(t)$), instantaneous of average voltage ($V_{AVG}(t)$) and instantaneous of ripple factor voltage ($V_{RF}(t)$). Hence, an equation for battery remaining capacity as a function of estimated parameter of $V_{RF}(t)$ using curve fitting tool is presented. In developing a real-time automated battery parameters estimation system, best TFD is chosen in terms of accuracy of battery parameters, computational complexity in signal processing and memory size. Advantages in high accuracy for battery parameters estimation and low in memory size requirement makes S-transform technique is selected to be the best TFD. The accuracy of the system is verified with parameters estimation using ECM for each type of battery at a different capacity. The field testing results show that average mean absolute percentage error (MAPE) is around four percent. Thus, implementation of S-transform technique for real-time automated battery parameters estimation system is very appropriate for battery signal analysis.

ABSTRAK

Disebabkan oleh pengurangan jangka hayat bateri kesan langsung dari prestasi beban, kebolehpercayaan dan keselamatan ketika bateri beroperasi tidak terjamin. Sebaliknya, langkah keselamatan boleh diambil dengan memantau prestasi bateri melalui perilaku isyarat pengecasan/menyahcas. Analisa isyarat pengecasan/menyahcas bateri menjadi cabaran kerana ciri-ciri muncul pada frekuensi yang sangat rendah. Oleh itu, analisis yang cepat dan tepat bagi anggaran parameter bateri untuk sistem pemantauan semasa perlu dicadangkan dan dibangunkan. Kajian ini membentangkan analisis bagi pengecasan/menyahcas isyarat bateri menggunakan teknik analisis spektrum, iaitu periodogram dan taburan masa frekuensi (TMF) iaitu spectrogram dan S-transformasi teknik. Analisis bateri adalah bagi asid plumbum (LA), nikel-logam hidrida (Ni-MH) dan litium-ion (Li-ion). Dari simulasi model litar setara (MLS) menggunakan MATLAB, isyarat berterusan pengecasan/menyahcas dibentangkan, bersama, dalam perwakilan masa frekuensi (PMF). Melalui PMF, ciri-ciri isyarat bateri ditentukan daripada anggaran parameter bagi voltan jumlah serta merta (V_J (m)), voltan purata serta merta (V_P (m)) dan voltan faktor riak serta merta (V_{FR} (m)). Oleh itu, satu persamaan baki kapasiti bateri sebagai fungsi bagi anggaran parameter V_{FR} (m) menggunakan alat pengukur lengkuk dibentangkan. Dalam membagunkan sistem anggaran parameter bateri automatik semasa, TMF terbaik dipilih dari segi ketepatan parameter bateri, kerumitan pengiraan dalam pemprosesan isyarat dan saiz memori. Kelebihan dalam ketepatan yang tinggi untuk anggaran parameter bateri dan keperluan memori saiz yang rendah menjadikan teknik S-transfomasi dipilih sebagai TMF terbaik. Ketepatan sistem disahkan melalui anggaran parameter menggunakan MLS bagi setiap jenis bateri pada kapasiti yang berbeza. Ujian prestasi menunjukkan bahawa purata min ralat peratusan mutlak (MRPM) adalah sekitar empat peratus. Oleh yang demikian, sistem anggaran parameter bateri automatik semasa adalah sangat sesuai untuk analisis isyarat bateri.

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LIST OF ABBREVIATIONS

ADSP	-	Advanced Digital Signal Processing
AI	-	Analogue Input
ANN	-	Artificial Neural Network
AO	-	Analogue Output
BEVs	-	Battery Electric Vehicles
BMS	-	Battery Management System
CC	-	Constant Current
CV	-	Constant Voltage
DAQ	-	Data Acquisition
DFT	-	Discrete Fourier Transform
DIO	-	Digital Input/Output
DOD	-	Depth of Discharge
DSP	-	Digital Signal Processing
DVVPCS	-	Duty-Varied Voltage Pulse-Charge System
ECM	-	Equivalent Circuit Model
ECT	-	Electrochemical–Thermal
EKF	-	Extended Kalman Filter
FFT	-	Fast Fourier Transform
FT	-	Fourier Transform
GMRAE	-	Geometric Mean Relative Absolute Error
GND	-	Ground
GUI	-	Graphical User Interface
HEV	-	Hybrid Electric Vehicle
Hz	-	Frequency Unit, Hertz

IEEE	-	Institute of Electrical and Electronics Engineers
LA	-	Lead Acid
Li-ion	-	Lithium-Ion
MAPE	-	Mean Absolute Percentage Error
Mbyte	-	Megabyte
MPE	-	Maximum Percentage Error
MRA	-	Multi-Resolution Analysis
NC	-	Normally Close
NI	-	National Instruments
Ni-MH	-	Nickel-Metal Hydride
NO	-	Normally Open
OSWS	-	One Sample Window Shift
PC	-	Pulse Charge
PDAE	-	Partial Differential-Algebraic Equation
PEV	-	Plug-In Electric Vehicle
RMSPE	-	Root Mean Square Percentage Error
SAPV	-	Stand-Alone Photovoltaic
sMAPE	-	Symmetric Mean Absolute Percentage Error
SOC	-	State of Charge
SOD	-	State of Discharge
STFT	-	Short-Time Fourier Transform
TFD	-	Time-Frequency Distribution
TFDs	-	Time-Frequency Distributions
TFR	-	Time-Frequency Representation
USABC	-	United States Advanced Battery Consortium
VB	-	Visual Basic
VFPCS	-	Variable Frequency Pulse Charge System
VS	-	Visual Studio
WT	-	Wavelet Transform

LIST OF APPENDICES

LIST OF SYMBOLS

σ	-	Function of time and frequency
Δf	-	Fundamental frequency bandwidth
η_{s1}	-	Local value of the surface overpotential
$w(\tau - t)$	-	Shifted window
A_t	-	Actual value
c_{max}	-	Solubility limit
C_{TH}	-	Equivalent capacitance
E_0	-	Battery constant voltage
E_0	-	Open circuit voltage
$E_t/V_0/V_t$	-	Terminal voltage
f	-	Frequency
f_1	-	Fundamental frequency
f_r	-	Frequency resolution
f_s	-	Sampling frequency
F_t	-	Measured value
H_2SO_4	-	Sulphuric acid
I	-	Superficial current density
I_{flut}	-	Charging current
I_L	-	Load current
it	-	Actual battery charge
I_{TH}	-	Thevenin current
K	-	Polarization resistance
$LiCoO_2$	-	Lithium cobalt oxide

$m\text{-}WO_3$	-	Mesoporous tungsten oxide
N	-	Signal length
N_s	-	Sample shift
N_w	-	Window length
Pb	-	Lead
PbO_2	-	Lead dioxide
Q	-	Battery capacity
$Q_{remaining}$	-	Remaining capacity
R_0/R_i	-	Internal resistance
SO_4	-	Sulphate substance
T	-	Signal period
t	-	Time
THD	-	Total harmonic distortion
T_i	-	Discharging time under current
T_r	-	Time resolution
$u(t)$	-	Charge or discharge mode
U_1	-	Theoretical open-circuit potential
U_L	-	Battery loading voltage
V_{AC}	-	Alternating current voltage
$V_{AC}(t)$	-	Instantaneous of alternating current voltage
$V_{AVG}(t)$	-	Instantaneous of average voltage
V_{DC}	-	Direct current voltage
$V_{DC}(t)$	-	Instantaneous of direct current voltage
V_{exp}	-	Exponential zone voltage
V_{flut}	-	Predefined voltage
V_{full}	-	Fully charged voltage
$V_{RF}(t)$	-	Instantaneous of ripple factor voltage
V_{RMS}	-	Mean square voltage
$V_{RMS}(t)$	-	Instantaneous of means square voltage
$V_{TOT}(t)$	-	Instantaneous of total voltage
$w(t)$	-	Observation window
$x(t)$	-	Time domain signal

LIST OF PUBLICATIONS

A. Journal

1) **Basir, M.S.S.M**., Abdullah, A.R., Ranom, R., Kasim, R. and Selamat, N.A., 2016. Experimental Verification of Lead Acid Battery Parameters Estimation. Middle-East Journal of Scientific Research, 24 (4), pp. 151-1158.

2) **Basir, M.S.S.M**., Abdullah, A.R., Ranom, R., Kasim, R., Selamat, N.A. and Shamsudin, N.H., 2016. Experimental Verification of Nickel-Metal Hydride Battery Parameters Estimation. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, 8 (2), pp. 47-52.

3) Kasim, R., Abdullah, A.R., Selamat, N.A., **Basir, M.S.S.M**. and Ramli, M.Z., 2016. Nickel-Cadmium battery analysis using spectrogram. *Journal of Engineering and Applied Sciences*, 11 (6), pp. 3975-3979.

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Installation for DNR Restoration in Reducing Power Losses. *International Review on Modelling and Simulations (IREMOS)*, 8 (5), pp. 566-575.

B. Conference

1) Selamat, N. A., **Basir, M. S. S. M**., Abdullah, A. R., Yusoff, M. R., and Shamsudin, N. H., 2016. Experimental Verification of Lithium Ion Battery Parameters Estimation. *The 1st Asian Conference on Railway Infrastructure and Transportation (ART), Jeju, Korea, 19 -20 October 2016*.

2) Shamsudin, N.H., **Basir, M.S.S.M**., Abdullah, A.R., Sulaima, M.F. and Shair, E.F., 2015, August. Losses minimization in network reconfiguration for fault restoration via a uniform crossover of genetic algorithm. In *Technology Management and Emerging Technologies (ISTMET), 2015 International Symposium on* (pp. 330-334). IEEE.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The increased utilization of renewable energy and mobility equipment leads batteries to be more pervasively used as the energy storage tank. The type of batteries is differentiated by the materials used and the common types of batteries are lead acid (LA), nickel-metal hydride (Ni-MH) and lithium-ion (Li-ion) (Micea et al., 2011). The LA battery is commonly selected as a backup for appliances such as automotive lighting and ignition application. This type of battery is not suitable for portable appliances but is still selected due to its low investment cost. To overcome the limitations of LA batteries, Ni-MH battery is invented. This battery is widely used in appliances such as portable cameras and is considered more environmental friendly with high storage and energy densities (Hussein and Batarseh, 2011). Nevertheless, with the superiority in high power and energy density, stable physical properties and long shelf life, Li-ion battery has become an alternative source to fulfil the necessary load (Gao et al., 2015). Li-ion battery is known to be the best among other types of batteries and is capable of transmitting power for a variety of applications either as backup or for portable equipment.

Different types of battery transmit different amount of power which depends on the duration of charging or discharging cycle. The cycle can be categorized into three, namely short, medium and long. The capability of the batteries in transmitting the power for a longer