



Faculty of Electrical Engineering

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

Muhammad Sufyan Safwan bin Mohamad Basir

Master of Science in Electrical Engineering

2017

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

MUHAMMAD SUFYAN SAFWAN BIN MOHAMAD BASIR

**A thesis submitted
in fulfilment of the requirements for the degree of Master of Science
in Electrical Engineering**

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2017

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.

Signature :

Name : Muhammad Sufyan Safwan Bin Mohamad Basir

Date :

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.

Thanks to the Zamalah Scheme Universiti Teknikal Malaysia Melaka (UTeM) for the financial support for my study.

Your supports are highly appreciated and very meaningful to me.

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 lengkung 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-transformasi 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.

ACKNOWLEDGEMENTS

First of all, Alhamdulillah thanks to Allah Almighty because of His blessing I would able to finish out my research. In preparing this thesis, I was in contact with many people, researchers, academicians and practitioners. They have contributed towards my understanding and thought. In particular, I wish to express my sincere appreciation to my supervisor, Prof. Madya Dr. Abdul Rahim bin Abdullah for his supports, trust, guidance critics, encouragement and advices throughout this research.

Then, a million thanks towards my co-supervisor Dr. Rahifa binti Ranom for her guidance, advices and motivation. Without their continued support and interest, this research would not have been same as presented here. I am also indebted to Universiti Teknikal Malaysia Melaka Zamalah Scheme and Ministry of Higher Education (MOHE) for scholarship and research grant RAGS/1/2015/TK0/FKE/03/B00091. I also want to thank my parents for their endless support, spirit, motivation and advices for continuing my studies. Behind that entire process they also have contributed, financially.

Next, my fellow postgraduate students from Advanced Digital Signal Processing (ADSP) laboratory should also be recognized for their support and cooperation in completing this thesis. Finally, my sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my family members. Thank you very much.

TABLE OF CONTENTS

	PAGE
DECLARATION	
APPROVAL	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vii
LIST OF FIGURES	viii
LIST OF APPENDICES	xiii
LIST OF ABBREVIATIONS	xiv
LIST OF SYMBOLS	xvi
LIST OF PUBLICATIONS	xviii
CHAPTER	
1. INTRODUCTION	1
1.1 Introduction	1
1.2 Problem Statements	3
1.3 Objectives of Research	5
1.4 Scope of Works	5
1.5 Research Contributions	7
1.6 Organization of Thesis	8
2. LITERATURE REVIEW	10
2.1 Introduction	10
2.2 Energy Storage	10
2.2.1 Types of Battery	11
2.2.1.1 Lead Acid	11
2.2.1.2 Nickel-Metal Hydride	12
2.2.1.3 Lithium-Ion	13
2.2.1.4 Types of Battery Summary	14
2.2.2 IEEE Standards	15
2.2.3 Battery Models	18
2.2.3.1 Electrochemical Model	18
2.2.3.2 Equivalent Circuit Model	20
2.2.3.3 Analytical Model	22
2.2.3.4 Battery Models Summary	24
2.2.4 Battery Charging and Discharging	25
2.2.4.1 Constant Voltage	25
2.2.4.2 Constant Current	27
2.2.4.3 Pulse Charge	28
2.2.4.4 Battery Charging and Discharging Summary	29
2.3 Battery Analysis Techniques	30
2.3.1 Extended Kalman Filter	30

2.3.2	Coulomb Counting	31
2.3.3	Artificial Neural Network	32
2.4	Signal Processing Techniques	34
2.4.1	Periodogram	34
2.4.2	Spectrogram	35
2.4.3	Wavelet Transform	36
2.4.4	S-Transform	37
2.5	Research Gap and Summary	40
3.	RESEARCH METHODOLOGY	43
3.1	Introduction	43
3.2	Battery Signals Modelling	45
3.3	Periodogram	47
3.4	Time-Frequency Distributions	47
3.4.1	Spectrogram	48
3.4.2	S-Transform	49
3.5	Signal Parameters	52
3.5.1	Instantaneous of Means Square Voltage	53
3.5.2	Instantaneous of Direct Current Voltage	53
3.5.3	Instantaneous of Alternating Current Voltage	54
3.6	Signal Characteristics	54
3.6.1	Characteristics for Battery Parameters Estimation	55
3.6.2	Curve Fitting Tools	55
3.7	Performance Measurements of Time-Frequency Distributions	57
3.7.1	Accuracy of the Analysis	57
3.7.2	Computation Complexity of the Analysis	58
3.7.3	Memory Size of the Analysis	58
3.8	System Development	59
3.8.1	Hardware Development	60
3.8.2	Software Development	62
3.9	Experimental Setup	65
3.10	Summary	70
4.	RESULT AND DISCUSSION	71
4.1	Introduction	71
4.2	Battery Signal Analysis	71
4.3	Signal Analysis using Periodogram	75
4.4	Signal Analysis using Time-Frequency Distributions	79
4.4.1	Window Selection for Time-Frequency Distributions	80
4.4.2	Signal Analysis using Spectrogram	88
4.4.3	Signal Analysis using S-Transform	93
4.5	Performance Analysis of the Time-Frequency Distributions	97
4.5.1	Accuracy of the Analysis	98
4.5.2	Computation Complexity of the Analysis	101
4.5.3	Memory Size of Data Processing	103
4.5.4	The Best Time-Frequency Distribution	104
4.6	Parameters Estimation of Battery Signals	106
4.6.1	Characteristics for Lead Acid Battery	106

4.6.2	Characteristics for Nickel-Metal Hydride Battery	108
4.6.3	Characteristics for Lithium-Ion Battery	109
4.7	Battery Signal Analysis and Parameters Estimation System	111
4.7.1	System Software	111
4.7.2	System Battery Signal Analysis	113
4.7.2.1	Lead Acid Charging/Discharging Signal	113
4.7.2.2	Nickel-Metal Hydride Charging/Discharging Signal	114
4.7.2.3	Lithium-Ion Charging/Discharging Signal	115
4.7.3	Data Logger	116
4.7.4	Battery Characteristics	119
4.8	System Performance Verification	120
4.9	Field Testing	121
4.10	Summary	130
5.	CONCLUSION AND RECOMMENDATIONS	131
5.1	Conclusion	131
5.2	Recommendations	132
	REFERENCES	134
	APPENDICES A-D	162-186

LIST OF TABLES

TABLE	TITLE	PAGE
2.1	Rechargeable batteries performance and characteristics	15
2.2	Signal processing techniques summary	39
3.1	Components in the real-time automated battery parameters estimation system	63
3.2	LA manufacture and rated value	67
3.3	Ni-MH manufacture and rated value	68
3.4	Li-ion manufacture and rated value	69
4.1	Window selection calculation for TFDs	80
4.2	MAPE for simulation results of the batteries parameters	99
4.3	Computational complexity of charging/discharging signals analysis	101
4.4	Memory size of TFRs for every TFD	103

LIST OF FIGURES

FIGURE	TITLE	PAGE
2.1	Battery specific failure criteria stages	17
2.2	Rint equivalent circuit model	21
2.3	Thevenin equivalent circuit model	21
2.4	Hybrid CC/CV method	26
2.5	Pulse charging method	28
3.1	Flow chart of battery signal analysis	44
3.2	Spectrogram resolution	49
3.3	Variation of window length	51
3.4	S-transform resolution	52
3.5	Block diagram for real-time automated battery parameters estimation system	59
3.6	General diagram for the system	61
3.7	Prototype of the system controller	62
3.8	Configuration of battery charging/discharging signals analysis	65
3.9	LA battery test	67
3.10	Ni-MH battery test	68
3.11	Li-ion battery test	69

4.1	Simulation of voltage charging/discharging signal for 12 V LA batteries	72
4.2	Simulation of voltage charging/discharging signal for 12 V Ni-MH batteries	73
4.3	Simulation of voltage charging/discharging signal for 14.8 V Li-ion batteries	73
4.4	(a) 2.0 Ah LA charging/discharging signal and its, (b) power spectrum	76
4.5	(a) 2.0 Ah Ni-MH charging/discharging signal and its, (b) power spectrum	77
4.6	(a) 2.0 Ah Li-Ion charging/discharging signal and its, (b) power spectrum	78
4.7	(a) 5.0 Ah LA charging/discharging signal and its, (b) TFR using spectrogram with window size of 64, (c) $V_{TOT}(t)$, $V_{AVG}(t)$ and $V_{RF}(t)$ using spectrogram with window size of 64	81
4.8	(a) 5.0 Ah LA charging/discharging signal and its, (b) TFR using S-transform with window size of 64, (c) $V_{TOT}(t)$, $V_{AVG}(t)$ and $V_{RF}(t)$ using S-transform with window size of 64	82
4.9	(a) 5.0 Ah LA charging/discharging signal and its, (b) TFR using spectrogram with window size of 4096, (c) $V_{TOT}(t)$, $V_{AVG}(t)$ and $V_{RF}(t)$ using spectrogram with window size of 4096	83
4.10	(a) 5.0 Ah LA charging/discharging signal and its, (b) TFR using S-transform with window size of 4096, (c) $V_{TOT}(t)$, $V_{AVG}(t)$ and $V_{RF}(t)$ using S-transform with window size of 4096	84
4.11	(a) 5.0 Ah LA charging/discharging signal and its, (b) TFR using spectrogram with window size of 8192, (c) $V_{TOT}(t)$, $V_{AVG}(t)$ and $V_{RF}(t)$ using spectrogram with window size of 8192	85
4.12	(a) 5.0 Ah LA charging/discharging signal and its, (b) TFR using S-transform with window size of 8192, (c) $V_{TOT}(t)$, $V_{AVG}(t)$ and $V_{RF}(t)$ using S-transform with window size of 8192	86
4.13	(a) 2.0 Ah LA charging/discharging signal and its, (b) TFR using spectrogram, (c) Instantaneous of total voltage, instantaneous of average voltage and instantaneous of ripple factor voltage	89
4.14	(a) 2.0 Ah Ni-MH charging/discharging signal and its, (b) TFR using spectrogram, (c) Instantaneous of total voltage, instantaneous of average voltage and instantaneous of ripple factor voltage	91

4.15	(a) 2.0 Ah Li-Ion charging/discharging signal and its, (b) TFR using spectrogram, (c) Instantaneous of total voltage, instantaneous of average voltage and instantaneous of ripple factor voltage	92
4.16	(a) 2.0 Ah LA charging/discharging signal and its, (b) TFR using S-transform, (c) Instantaneous of total voltage, instantaneous of average voltage and instantaneous of ripple factor voltage	94
4.17	(a) 2.0 Ah Ni-MH charging/discharging signal and its, (b) TFR using S-transform, (c) Instantaneous of total voltage, instantaneous of average voltage and instantaneous of ripple factor voltage	95
4.18	(a) 2.0 Ah Li-Ion charging/discharging signal and its, (b) TFR using S-transform, (c) Instantaneous of total voltage, instantaneous of average voltage and instantaneous of ripple factor voltage	97
4.19	MAPE of LA, Ni-MH and Li-ion batteries for TFDs	100
4.20	MAPE for average batteries parameters estimation	100
4.21	Average of computational complexity used for batteries signal analysis	102
4.22	Average of memory size used for batteries signal analysis	104
4.23	Comparison of the TFDs in term of accuracy, computational complexity and memory size of the analysis	105
4.24	Battery storage capacity from 1.0 Ah to 10.0 Ah of simulation result for LA battery using (a) spectrogram, (b) S-transform	107
4.25	Battery storage capacity from 1.0 Ah to 10.0 Ah of simulation result for Ni-MH battery using (a) spectrogram, (b) S-transform	109
4.26	Battery storage capacity from 0.5 Ah to 3.5 Ah of simulation result for Li-ion battery using (a) spectrogram, (b) S-transform	110
4.27	(a) System GUI, (b) Real-time automated battery parameters estimation system	113
4.28	(a) 2.0 Ah LA charging/discharging signal and its, (b) Power Spectrum, (c) Instantaneous of total voltage, instantaneous of average voltage and instantaneous of ripple factor voltage	114
4.29	(a) 2.0 Ah Ni-MH charging/discharging signal and its, (b) Power Spectrum, (c) Instantaneous of total voltage, instantaneous of average voltage and instantaneous of ripple factor voltage	115

4.30	(a) 2.0 Ah Li-ion charging/discharging signal and its, (b) Power Spectrum, (c) Instantaneous of total voltage, instantaneous of average voltage and instantaneous of ripple factor voltage	116
4.31	Record data	117
4.32	Recorded parameters for battery signal analysis	118
4.33	Input data loader	119
4.34	GUI for battery parameters estimation	119
4.35	Comparison between Actual, Simulation and System for LA battery (a) Instantaneous of total voltage, (b) Instantaneous of average voltage, (c) Instantaneous of ripple factor voltage using S-transform	121
4.36	(a) Experimental of voltage charging and discharging signal for 12 V LA with 2.3 Ah, 4.5 Ah and 7.2 Ah batteries, (b) TFR using S-transform for 2.3 Ah battery, (c) Instantaneous of total voltage, instantaneous of average voltage and instantaneous of ripple factor voltage	123
4.37	(a) Experimental of voltage charging and discharging signal for 12 V Ni-MH with 1.3 Ah, 1.8 Ah and 2.7 Ah batteries, (b) TFR using S-transform for 1.3 Ah battery, (c) Instantaneous of total voltage, instantaneous of average voltage and instantaneous of ripple factor voltage	125
4.38	(a) Experimental of voltage charging and discharging signal for 14.8 V Li-ion with 0.75 Ah, 3.0 Ah and 3.4 Ah batteries, (b) TFR using S-transform for 0.75 Ah battery, (c) Instantaneous of total voltage, instantaneous of average voltage and instantaneous of ripple factor voltage	128
4.39	MAPE of simulation and experimental	129

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

APPENDIX	TITLE	PAGE
A	Parameters of equivalent circuit model	162
B	Control unit for hardware development	171
C	Parameters of batteries signals analysis	174
D	Comparison of batteries parameters between simulation and experimental	184

LIST OF SYMBOLS

σ	-	Function of time and frequency
Δf	-	Fundamental frequency bandwidth
η_{sl}	-	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_i	-	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

$m-WO_3$	-	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.
- 4) Shamsudin, N.H., Misdar, N.A., Abdullah, A.R., **Basir, M.S.S.M.** and Selamat, N.A., 2015. Speed Warning System Using Solar Power. *Journal of Theoretical and Applied Information Technology*, 80(3), p.431.
- 6) Shamsudin, N., Iszhal, N., Abdullah, A.R., **Basir, M.S.S.M.** and Sulaima, M., 2015. An Improved Crossover Genetic Algorithm with Distributed Generator (DG)

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