



Faculty of Electrical Engineering

BATTERY CAPACITY ESTIMATION ANALYSIS BASED ON TIME-FREQUENCY DISTRIBUTION

Rizanaliah binti Kasim

Master of Science in Electrical Engineering

2017

**BATTERY CAPACITY ESTIMATION ANALYSIS BASED ON TIME-
FREQUENCY DISTRIBUTION**

RIZANALIAH BINTI KASIM

**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 entitle “Battery Capacity Estimation Analysis Based On Time-Frequency Distribution” 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 : Rizanaliah Binti Kasim

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 award of Master of Science in Electrical Engineering.

Signature :.....

Supervisor Name : Prof Madya Dr. Abdul Rahim Bin Abdullah

Date :.....

DEDICATION

I dedicate my dissertation work towards my family, my respectful and helpful supervisor, co-supervisor, examiners, collaboration lecturer and all my friends especially from Advanced Digital Signal Processing Group (ADSP) for their support cooperation in helping me to complete this research and thesis.

Thanks to the Ministry of Higher Education (MOHE) and Universiti Teknikal Malaysia Melaka (UTeM) for the financial support for my study.

I also want to give special thanks to my husband Khairul Anuar Bin Md Piah, my mother Rohani Binti Che' Mat, my father Kasim Bin Amid and family for their endless support, motivational and advice to finish my study. They give me strength to gain the knowledge although in hard situation and deepest appreciation for their love and support.

Lastly, your supports are highly appreciated and very meaningful to me for being there for me throughout the entire master program.

ABSTRACT

The rising crude oil prices and awareness of environmental issues led to increasing the development of energy storage system. Due to this reason, rechargeable batteries are beneficial options for energy storage. Improper handling of the battery during the high discharge rate and overcharging will cause the premature failure to the battery. Obtaining an accurate data of battery parameter is important because it will avoid unexpected system interruption and prevent permanent damage to the internal structure of the batteries. This research presents the charging and discharging battery signals analysis using periodogram and time-frequency distribution (TFD) which is spectrogram. The analysis focuses on four types of batteries which are lead acid, nickel-cadmium, nickel-metal hydride and lithium-ion. The nominal voltage for batteries are used 6V and 12V while the capacities is in the range of 5Ah to 50Ah, respectively. The raw data of batteries charging and discharging signals are collected via simulation using MATLAB 2013 for various voltages and battery capacities. Then, the signals are transformed into periodogram and spectrogram. Periodogram represents signal in frequency domain while spectrogram represents signal in time-frequency representation (TFR). The signal parameters that estimated from the spectrogram are instantaneous voltage root mean square (V_{RMS}), instantaneous voltage direct current (V_{DC}) and instantaneous voltage alternating current (V_{AC}). The result shows the decreased voltage signal with an increased battery capacity. The highest voltage signal is at 5 Ah and the lower voltage signal at 50Ah. Besides, the battery capacities can be identified by using formula that have been defined by using the curve fitting tools from MATLAB. An equation is defined based on correlation between voltage alternating current (V_{AC}) and battery capacities (Ah). An experimental test also conducted to capture the real data for battery signals. The outcome of this research shows the application of spectrogram clearly give the information of the performance characteristic of battery at various operating conditions.

ABSTRAK

Kenaikan harga minyak mentah dan kesedaran mengenai isu-isu alam sekitar telah membawa kepada peningkatan pembangunan sistem penyimpanan tenaga. Oleh sebab ini, bateri boleh dicas semula adalah pilihan yang bermanfaat untuk penyimpanan tenaga. Pengendalian bateri yang tidak betul semasa kadar pelepasan yang tinggi dan pengecasan berlebihan akan menyebabkan kegagalan awal pada bateri. Memperolehi data yang tepat mengenai parameter bateri adalah penting kerana ia dapat mengelakkan gangguan sistem yang tidak dijangka dan mencegah kerosakan kekal kepada struktur dalaman bateri. Kajian ini membentangkan analisis isyarat mengecas dan menyahcas bateri menggunakan periodogram dan taburan masa frekuensi (TFD) iaitu spectrogram. Analisis ini memberi tumpuan kepada empat jenis bateri iaitu asid plumbum, nikel-kadmium nikel-logam hidrida dan lithium-ion. Voltan nominal yang digunakan untuk bateri ialah 6V dan 12V manakala kapasiti adalah dalam lingkungan 5Ah hingga 50Ah. Data isyarat mengecas dan menyahcas bateri dikumpulkan melalui simulasi menggunakan MATLAB 2013 untuk pelbagai voltan dan kapasiti bateri. Kemudian, isyarat diubah menjadi periodogram dan spectrogram. Periodogram mewakili isyarat dalam domain frekuensi manakala spectrogram mewakili isyarat dalam perwakilan masa-frekuensi (TFR). Parameter isyarat yang dianggarkan dari spectrogram ialah voltan punca min kuasa dua (V_{PMKD}), voltan arus terus (V_{AT}) dan voltan arus ulang alik (V_{AU}). Hasil daripada keputusan menunjukkan isyarat voltan menurun dengan peningkatan kapasiti bateri. Isyarat voltan yang tertinggi ialah 5A dan isyarat voltan yang rendah ialah 50Ah. Selain itu, kapasiti bateri boleh dianggarkan menggunakan formula yang telah ditentukan menggunakan alat pemasangan lengkung dari MATLAB. Persamaan ditakrifkan berdasarkan korelasi antara voltan arus ulang alik (V_{AU}) dan kapasiti bateri (Ah). Ujian eksperimen juga dijalankan untuk mendapatkan data sebenar untuk isyarat bateri. Hasil kajian ini menunjukkan penggunaan spectrogram dengan jelas memberi ciri prestasi bateri pada pelbagai keadaan operasi.

ACKNOWLEDGEMENTS

Alhamdulillah thanks to Allah Almighty because of His blessing I would able to finish out my research. Peace be upon our Prophet Muhammad S.A.W who has given light to mankind. During in the making of this research I have gain a lot of new knowledge in a practical. First and foremost, I would like to address my gratitude and appreciation to my supervisor P.M. Dr. Abdul Rahim bin Abdullah for his supports, trust, supervision, encouragement and advices throughout this research.

Then, a million thanks towards my co-supervisor En.Zulkifli Bin Ramli for her patience, guidance, support and discussion that further encouraged and helped me a lot in my research. I would like to give appreciation to Ministry of Higher Education (MOHE) and Universiti Teknikal Malaysia Melaka (UTeM) for providing the research grant RAGS /2012/FKE/TK07/1 B0011 to support the financial project.

Next, I would like to thank my beloved husband, children, parents and all my family members for their help and support. My acknowledgement would not complete without my friends, and others from Advanced Digital Signal Processing (ADSP) laboratory who had given me support and cooperation in completing this thesis. Finally, my sincere appreciation also goes to those who directly and indirectly in helping all the way through this research. Thank you to all the parties above, without their helps I can never go through this mission alone. 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	xii
LIST OF ABBREVIATIONS	xiii
LIST OF SYMBOLS	xv
LIST OF PUBLICATIONS	xvii
CHAPTER	
1 INTRODUCTION	
1.1 Introduction	1
1.2 Problem Statements	3
1.3 Objectives of the Research	4
1.4 Scope of Works	5
1.5 Thesis Contributions	6
1.6 Thesis Outline	7
2 LITERATURE REVIEW	
2.1 Introduction	8
2.2 Fundamental of Batteries	8
2.3 Classification of Batteries	10
2.3.1 Primary Batteries	10
2.3.2 Secondary Batteries	10
2.3.2.1 Lead Acid	12
2.3.2.2 Nickel-Cadmium (Ni-Cd)	12
2.3.2.3 Nickel-Metal Hydride (Ni-MH)	13
2.3.2.4 Lithium-ion(Li-ion)	13
2.4 Electrochemical Cells	14
2.4.1 Lead Acid	14
2.4.2 Nickel-Cadmium (Ni-Cd)	15
2.4.3 Nickel-Metal Hydride (Ni-MH)	15
2.4.4 Lithium-ion (Li-ion)	16

2.5	Battery Terminology	16
2.5.1	Capacity	16
2.5.2	Cut-off Voltage	17
2.5.3	C-rates	17
2.5.4	Depth of Discharge (DOD)	18
2.5.5	Internal resistance	18
2.5.6	State of Charge	18
2.6	Mathematical Battery Model	19
2.6.1	The Discharge Model	20
2.6.2	The Charge Model	23
2.7	Identification of the Parameter Batteries	26
2.8	Signal Processing Technique	27
2.8.1	Periodogram	28
2.8.2	Wavelet Transform (WT)	30
2.8.3	Spectrogram	31
2.9	Summary	34
3	RESEARCH METHODOLOGY	
3.1	Introduction	36
3.2	Battery Model	38
3.3	Battery Charging and Discharging Signals	42
3.4	Periodogram	43
3.5	Time-Frequency Distribution	45
3.5.1	The Need of Time-Frequency Distribution	45
3.5.2	Spectrogram	47
3.6	Signal Parameters	50
3.6.1	Instantaneous RMS Voltage	50
3.6.2	Instantaneous Direct Current Voltage	51
3.6.3	Instantaneous Alternating Current Voltage	51
3.6.4	Signal Processing Procedure	52
3.7	Formula Generation	54
3.8	Battery Test System	54
3.9	Summary	56
4	RESULTS AND DISCUSSION	
4.1	Introduction	57
4.2	Battery Charging and Discharging Signals	58
4.2.1	Lead Acid	58
4.2.2	Nickel-Cadmium (Ni-Cd)	59
4.2.3	Nickel-Metal Hydride (Ni-MH)	61
4.2.4	Lithium-ion (Li-ion)	62
4.3	Signal Analysis Using Periodogram	63
4.4	Battery Signal Analysis Using Time-Frequency Representation	68
4.5	Battery Signal Parameters	73
4.5.1	Instantaneous RMS Voltage (V_{RMS})	73

4.5.2	Instantaneous Voltage Direct Current (V_{DC})	76
4.5.3	Instantaneous Voltage Alternating Current (V_{AC})	78
4.6	Parameter Estimation Curve for Instantaneous V_{RMS} , V_{DC} and V_{AC}	82
4.7	Formula Generation	87
4.8	Experimental Result	89
4.8.1	Battery Charging and Discharging Signal Battery	89
4.8.2	Battery Signal Analysis Using Time-Frequency Representation	91
4.8.3	Signal Parameter Estimation	93
4.8.3.1	Instantaneous Voltage Root Mean Square (V_{RMS})	93
4.8.3.2	Instantaneous Voltage Direct Current (V_{DC})	95
4.8.3.3	Instantaneous Voltage Alternating Current (V_{AC})	97
4.9	Summary	99
5	CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH	
5.1	Conclusion	100
5.2	Recommendation	102
	REFERENCES	103
	APPENDIX A	117
	APPENDIX B	120
	APPENDIX C	123
	APPENDIX D	126

LIST OF TABLES

TABLE	TITLE	PAGE
2.1	Explanation of the Equation quantities	21
2.2	Discharge and Charge equation for the four types of batteries	25
4.1	Periodogram data	66

LIST OF FIGURES

FIGURE	TITLE	PAGE
2.1	Components of a cell	9
2.2	Schematic representation of the operation of charging and discharging a battery	11
2.3	Typical battery discharge curve	20
2.4	Hysteresis phenomenon	22
2.5	(a) Raw signal (b) Periodogram of Proton Exchange Membrane Fuel cell.	29
2.6	(a) An ideal ECG signal in time (b) Continuous Wavelet	31
2.7	a) Signal Open Circuit Switches Fault (S_{11}) b) Time-frequency representation (TFR)	33
3.1	The flow chart of the research	37
3.2	A rechargeable battery equivalent circuit model in MATLAB/SIMULINK	39
3.3	Example discharge curve	41
3.4	Model of battery charging and discharging	42
3.5	Nickel-Cadmium battery a) Raw signal in time domain b) Periodogram which shows the magnitude of the distribution in the frequency domain	44
3.6	Flowchart of time-frequency technique	45
3.7	Battery charging and discharging for lithium-ion battery	46
3.8	Periodogram of lithium-ion	46

3.9	TFR-Spectrogram	47
3.10	Spectrogram resolution	49
3.11	The flow of figure for the signal processing technique	53
3.12	Experimental setup of Charging and Discharging Batteries system	55
4.1	Voltage charging and discharging signals of lead acid battery at: a) 6V with 15Ah b) 6V with 35Ah c) 12V with 35A	59
4.2	Voltage charging and discharging of a Ni-Cd at: a) 6V with 15Ah b) 6V with 35Ah c)12V with 35Ah	60
4.3	Voltage charging and discharging for a Ni-MH at: a) 6V with 15Ah b) 6V with 35Ah c)12V with 35Ah	61
4.4	Voltage charging and discharging signals for a Li-ion battery at; a) 6V 15 Ah b) 6V 35Ah c) 12V 35Ah	62
4.5	The output voltage signal of batteries in time domain and its corresponding signal in frequency domain (periodogram) for 6V and 12V with 10Ah and 20Ah	65
4.6	Periodogram result for all battery: a) 6V with 10 and 20Ah b) 12V with 10 and 20Ah	67
4.7	Time-Frequency representation for lead acid at a) 6V with 15Ah (b) 6V with 35Ah (c) 12V with 35Ah	69
4.8	Time-Frequency Representation of a Ni-Cd battery at: a) 6V with 35Ah b) 6V with 35Ah c) 12V with 35 Ah	70
4.9	Time-frequency representation for a Ni-MH at: a) 6V with 15Ah b) 6V with 35Ah c) 12V with 35Ah	71
4.10	Time-Frequency Representation of a Li-ion battery at: a) 6V with 35Ah b) 6V with 35Ah c) 12V with 35 Ah	72
4.11	Instantaneous V_{RMS} for Lead Acid	74
4.12	Instantaneous V_{RMS} for Ni-Cd battery	74
4.13	Instantaneous VRMS for Ni-MH battery	75
4.14	Instantaneous V_{RMS} for Li-ion battery	75
4.15	Instantaneous V_{DC} for Lead acid battery	76

4.16	Instantaneous V_{DC} for Ni-Cd battery	77
4.17	Instantaneous V_{DC} for Ni-MH battery	77
4.18	Instantaneous V_{DC} for Li-ion battery	78
4.19	Instantaneous V_{AC} for Lead acid battery	79
4.20	Instantaneous V_{AC} for Ni-Cd battery	79
4.21	Instantaneous V_{AC} for Ni-MH battery	80
4.22	Instantaneous V_{AC} for Li-ion battery	81
4.23	Parameter estimation curve for the instantaneous V_{RMS} , V_{DC} and V_{AC} for a lead acid battery at nominal voltage of 6V and battery capacities of 5 to 50Ah	83
4.24	Parameter estimation curve for the instantaneous V_{RMS} , V_{DC} and V_{AC} for a lead acid battery at nominal voltage of 12V and battery capacities of 5 to 50Ah	83
4.25	Parameter estimation curve for the instantaneous V_{RMS} , V_{DC} and V_{AC} for a Ni-Cd battery at a nominal voltage of 12V and battery capacities of 5 to 50Ah	84
4.26	Parameter estimation curve for the instantaneous V_{RMS} , V_{DC} and V_{AC} for Ni-MH battery at nominal voltage of 6V and battery capacities at 5 to 50Ah	84
4.27	Parameter estimation curve for the instantaneous V_{RMS} , V_{DC} and V_{AC} for Ni-MH battery at nominal voltage of 12V and battery capacities at 5 to 50Ah	85
4.28	Parameter estimation curve for the instantaneous V_{RMS} , V_{DC} and V_{AC} for a Ni-Cd battery at a nominal voltage of 6V and battery capacities of 5 to 50Ah.	85
4.29	Parameter estimation curve for the instantaneous V_{RMS} , V_{DC} and V_{AC} for a Ni-Cd battery at a nominal voltage of 12V and battery capacities of 5 to 50Ah.	86
4.30	Parameter estimation curve for the instantaneous V_{RMS} , V_{DC} and V_{AC} for a Li-ion battery at nominal voltage of 6V and battery capacities of 5 to 50A	86
4.31	Battery capacity estimation of (a) Lead Acid (b) Ni-Cd (c) Ni-MH d) Li-ion	88

4.32	Experimental result for charging and discharging battery of a Lead Acid at 12V with 2.3Ah and 12V with 7.2Ah	89
4.33	Experimental result for charging and discharging battery of Ni-MH at 12V with 1.8Ah and 12V with 2.7Ah	90
4.34	Experimental result for charging and discharging battery of Li-ion at 12V with 3.0Ah and 12V with 3.4Ah	91
4.35	Time-frequency representation for Lead Acid a) 12V with 2.3Ah b) 12V with 7.2Ah.	92
4.36	Time-frequency representation for Ni-MH at a) 12V with 2.7Ah (b) 12V with 1.8Ah	92
4.37	Time-frequency representation for Li-ion at a) 14.8V with 3.0Ah (b) 14.8V with 3.4Ah	93
4.38	Instantaneous V_{RMS} parameter estimation of Lead acid battery 12V with 2.3Ah and 12V with 7.2Ah	94
4.39	Instantaneous V_{RMS} parameter estimation for Ni-MH battery at 12V with 1.8Ah and 12V with 2.7Ah	94
4.40	Instantaneous V_{RMS} parameter estimation for Li-ion battery at 14.8V with 3.0Ah and 14.8V with 3.4Ah	95
4.41	Instantaneous V_{DC} parameter estimation of Lead acid battery at 12V with 2.3Ah and 12V with 7.2Ah	96
4.42	Instantaneous V_{DC} parameter estimation for Ni-MH battery at 12V with 1.8Ah and 12V with 2.7Ah	96
4.43	Instantaneous V_{DC} parameter estimation for Li-ion battery at 14.8V with 3.0Ah and 14.8V with 3.4Ah	97
4.44	Instantaneous V_{AC} parameter estimation of Lead acid battery at 12V with 2.3Ah and 12V with 7.2Ah	97
4.45	Instantaneous V_{AC} parameter estimation for Ni-MH battery at 12V with 1.8Ah and 12V with 2.7Ah	98
4.46	Instantaneous V_{AC} parameter estimation for Li-ion battery at 14.8V with 3.0Ah and 14.8V with 3.4Ah	98

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	The example of Lead Acid battery	117
B	The examples of Nickel-Cadmium battery	120
C	The examples of Nickel-Metal Hydride battery	123
D	The examples of Lithium-ion	126

LIST OF ABBREVIATIONS

A	-	Ampere
Ah	-	Ampere hour
e	-	Electron
EKF	-	Extended Kalman filter
Exp	-	Exponential
FFT	-	Fast Fourier transform
FT	-	Fourier transform
H ⁺	-	Proton
H ₂ O	-	Water
H ₂ SO ₄	-	Sulphuric acid
Hz	-	Frequency unit, Hertz
Li-ion	-	Lithium-ion
LiCoO ₂	-	Lithium cobalt oxide
LiMn ₂ O ₄	-	Lithium manganese oxide

LiNiO ₂	-	Lithium nickel oxide
LiPF ₆	-	Lithium hexafluorophosphate
LiC ₆	-	Lithium graphite
Ni-CD	-	Nickel Cadmium
Ni-MH	-	Nickel-Metal Hydride
Ni(OH) ₂ /NiOOH	-	Nickel hydroxide/ nickel oxyhydroxide
O ₂	-	Oxygen
Pb	-	Lead
PbO ₂	-	Lead dioxide
SOC	-	State Of Charge
STFT	-	Short Time Fourier Transform
TFD	-	Time-frequency distribution
TFR	-	Time-frequency representation
V _{AC}	-	Voltage alternating current
V _{DC}	-	Voltage direct current
V _{RMS}	-	Voltage root means square
WT	-	Wavelet transform
Zn-MnO ₂	-	Zinc-manganese dioxide

LIST OF SYMBOL

A	-	Ampere
Ah	-	Ampere hour
E_0	-	Battery constant voltage
t	-	Time
f	-	Frequency
f_l	-	Fundamental frequency
f_r	-	Frequency resolution
f_s	-	Frequency sampling
it	-	Actual battery charge
K	-	Polarization constant (V/Ah) or polarization resistance
N	-	Number of signal length
N_s	-	Number of samples
N_W	-	Number of window length
Q	-	Battery capacity
$S(t,f)$	-	Time-frequency distribution
$S_x(t,f)$	-	TFR of signal
T_r	-	Time resolution
V	-	Voltage
$V_{AC}(t)$	-	Voltage alternating

V_{dis}	-	Battery voltage during discharge process
$V_{DC}(t)$	-	Voltage direct current
$V_{RMS}(t)$	-	Instantaneous RMS voltage
$w(t)$	-	Window function
$x(t)$	-	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.1151-1158.
- 2) Kasim, R., Abdullah, A.R., Selamat, N.A., and Mohammad Basir, M.S.S., 2016.
Nickel-Cadmium Battery Analysis Using Spectrogram. *Australian Journal of Basic and Applied Sciences*, 11(6), pp. 3975–3979.
- 3) Kasim, R., Abdullah, A.R., Selamat, N.A., Baharom, M.F. and Ahmad, N.H.T.H., 2015. Battery Parameters Identification Analysis Using Periodogram. In *Applied Mechanics and Materials* (Vol. 785, pp. 687-691). Trans Tech Publications.
- 4) Kasim, R., Abdullah, A.R., Selamat, N.A., Abidullah, N.A. and Zawawi, T.N.S.T., 2015. Lead Acid Battery Analysis Using Spectrogram. In *Applied Mechanics and Materials* (Vol. 785, pp. 692-696). Trans Tech Publications.

- 5) Kasim, R., Abdullah, A.R., Selamat, N.A. and Bahari, N., 2015. Lithium-ion Battery Parameter Analysis Using Spectrogram. *Australian Journal of Basic and Applied Sciences*, 9(12), pp.76-80.

- 6) Abdullah, A.R., Kasim, R., Selamat, N.A., and Ramli, M.Z., 2015. Nickel-metal Hydride Battery Analysis Using Spectrogram. *Australian Journal of Basic and Applied Sciences*, 10(15), pp. 6448–6452.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Batteries are one of the most successful creations in the history of mankind (Erdinc et al., 2009) . It plays an important role in future technology since it potentially to be applied as devices to store energy. Besides, it could not only used to store energy from various source and release the load during demand, but it also, supply enough power for the demand of electricity (Schainker, 2004). Many of today's technologies are powered by batteries such as portable electronic, uninterruptible power supply (UPS), renewable energy, and cars (Li et al., 2015). The battery used for each device is different, depending on the power requirements and for what they are used (Birkl and Howey, 2013).

Batteries are generally, divided into two categories, namely, non-rechargeable (or primary cell) and rechargeable (or secondary cell). A non-rechargeable battery is designed to be used once and discarded after it is depleted. Meanwhile, a rechargeable battery can be charged multiple times to refill its store of energy (Divya and stergaard, 2009).

Rechargeable batteries store energy by holding different electrochemically active materials together. Rechargeable batteries generate and store free electrons (electrical potential energy) for long periods of time and release them when needed (Subburaj and Bayne, 2014). Rechargeable batteries are characterized (in addition to their ability to be recharged) by high power density, good low-temperature, and high discharge rate. Their energy densities are generally lower than those of non-rechargeable batteries (Chuang, 2015).