ROBUST ESTIMATION OF THE STATE OF CHARGE IN A LITHIUM-ION BATTERY FOR A BATTERY MANAGEMENT SYSTEM

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A DISSERTATION SUBMITTED TO THE SCHOOL OF POSGRADUATE STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF ENGINEERING (M.ENG) DEGREE IN ELECTRICAL AND ELECTRONICS ENGINEERING IN THE DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING, COLLEGE OF ENGINEERING, COVENANT UNIVERSITY, OTA, OGUN STATE, NIGERIA

SEPTEMBER, 2022

ACCEPTANCE

This is to attest that this dissertation is accepted in partial fulfillment of the requirements for the award of the degree of **Master of Engineering (M.Eng)** degree in Electrical and Electronics Engineering in the Department of **Electrical and Information Engineering,** College of Engineering, Covenant University, Ota, Nigeria.

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(Secretary, School of Postgraduate Studies) **Signature and Date**

Prof. Akan B. Williams
(Dean, School of Postgraduate Studies) **Signature and Date**

DECLARATION

I, OMILOLI, KOTO ANDREW (20PCK02300) declares that this research was carried out by me under the supervision of Dr. Ayokunle A. Awelewa of the Department of **Electrical and Information Engineering,** College of Engineering, Covenant University, Ota, Nigeria. I attest that the dissertation has not been presented either wholly or partially for the award of any degree elsewhere. All sources of data and scholarly information used in this dissertation are duly acknowledged.

OMILOLI, KOTO ANDREW

Signature and Date

CERTIFICATION

We certify that this dissertation titled **"ROBUST ESTIMATION OF THE STATE OF CHARGE IN A LITHIUM-ION BATTERY FOR A BATTERY MANAGEMENT SYSTEM"** is an original research work carried out by **OMILOLI, KOTO ANDREW (20PCK02300)** in the Department of Electrical and Information Engineering, College of Engineering, Covenant University, Ota, Ogun State, Nigeria under the supervision of Dr. Ayokunle A. Awelewa. We have examined and found this work acceptable as part of the requirements for the award of **Master of Engineering (M.Eng)** degree in **Electrical and Electronics Engineering.**

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Prof. Akan B. Williams
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DEDICATION

To my loving father, Chief Engr. Koto Andrew Omiloli

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LIST OF ABREVIATIONS AND SYMBOLS

A/S	Alternative Supply
AEVs	All Electrical Vehicles
Ah	Ampere Hour
ANN	Artificial Neural Network
AEKF	Adaptive Extended Kalman Filter
BMS	Battery management system
CC_I	Constant Current
CC	Coulomb Counting
DEKF	Double Extended Kalman Filter
DKF	Dual Kalman Filter
DST	Dynamic Distress Test
EVs	Electrical Vehicles
EM	Electrochemical Model
ECM	Equivalent Circuit Model
EKF	Extended Kalman Filter
FL	Fuzzy Logic
FUDS	Federal Urban Driving Schedule
FLSMO	Fuzzy Logic Sliding Mode Observer
GLD	Gas Liquid Dynamics
HPPC	Hybrid Power Pulse Characterization
IEKF	Improved Extended Kalman Filter
KF	Kalman Filter
LiB	Lithium-ion battery
$LiFePo_4$	Lithium iron phosphate
LMI	Linear Matrix Inequality
MAE	Mean Absolute Error
MLP	Multi-Layer Perception
MSE	Mean Square Error
MCPSO	Mixed-Swarm based Cooperative Particle Swarm Optimization

MI	Multi- innovation
NMC	Nickel Manganese Cobalt Oxide
OCV	Open Circuit Voltage
PHEVs	Plug in Electrical Vehicles
PID	Proportional Integral Derivative
PF	Particle Filter
RC	Resistance Capacitor
RUL	Remaining Useful Life
RDT	Remaining Dischargeable Time
RMSE	Root Mean Square Error
SMO	Sliding Mode Observer
SOT	State of Temperature
SOC	State of Charge
SOH	State of health
SOF	State of function
SOB	State of balance
UPF	Unscented Particle Filter
UDDS	Urban Dynameter Driving Schedule
η	Coulombic efficiency
Δ	Change
∂	Partial derivative
$\vert$	such that
$\hat{x}$	predicted state
$\bar{x}$	corrected state
A^T	transpose of A
Σ	sum
$\bar{y}$	mean

ABSTRACT

The hazardous effect fossil-based systems have on the planet requires transition to nonpolluting energy sources which lithium-ion batteries (LiBs) fall. An implication is, the state of charge (SOC), must be determined to provide an indication for the available energy left in LiBs. However, there exists the difficulty in measuring the SOC, more so existing methods for SOC estimation are not robust to accommodate battery parameter sensitivity to disturbance. Hence, in this research battery models coupled with SOC estimation techniques, namely Extended Kalman Filter (EKF), Linear Matrix Inequality (LMI) and Sliding Mode Observer (SMO), are developed and implemented to solve the observability problem. Model validation was carried out via primary data while the secondary data was used for validating the state estimators using charge/discharge voltage and current inputs. Performance results showed the LMI and SMO, yielded RMSE and MAE values equal to zero (0), offering a superior accuracy than the EKFs having RMSE values in range of [0.00000861, 0.00680] and MAE in range of [0.00000214, 0.00410]. In addition, by means of a modified priori estimate and a compensating proportional gain, an improved extended Kalman filter (EKF_{mod}) for the estimation task was carried out. Amongst the improved estimators, the fourth order EKF_{mod} had an accuracy of six (6) decimal places with the smallest error bound of ±2.05%. In terms of robustness, the SMO and LMI algorithms demonstrated capability in disturbance rejection from measurement input data at battery temperature of 0^oC having both RMSE and MAE values of zero (0) in contrast to the EKF having lesser metrics values. Furthermore, a hybrid (EKF-SMO) estimator developed showed a 93% decrease from the EKF performance metrics and faster convergence. This research recommends the selection of battery models, and the estimators should be a trade-off between model complexity, accuracy, and present computation power.

Keywords: Lithium-ion Battery, Extended Kalman Filter, Sliding Mode Observer, State of Charge, Linear Matrix Inequality, Robust.