LITHIUM-ION CELL BALANCING USING AUXILIARY BATTERY AND DC-DC CUK CONVERTER

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

The lithium-ion battery became more popular to use due to its prominent characteristics such as energy density, power density and high terminal voltage of a single cell. However, if there is power regulation issue during the charging and discharging processes, the performance of the battery will be affected. In this case, the life of the battery will considerably reduce, which may result in undesirable outcomes such as fire or explosion. In order to avoid these issues, Battery Management Systems (BMS) is used to provide proper power regulation. BMS includes substantial subsystems such as SOC estimation, thermal management and cell balancing. This research concentrates on the cell balancing mechanism, which is an essential part of the BMS for extending battery life. The two basic types of cell balancing are passive cell balancing and active cell balancing. The active balancing topology utilized in this research is a Single Switch Capacitor (SSC), capacitor base, in order to perform module balancing and cell balancing inside internal modules. The BMS is based on the pack modularization architecture, where a single capacitor is fitted to transfer the energy from module to module to achieve balancing. While, the internal module balancing is accomplished with the use of a Single Switch Capacitor (SSC), Auxiliary Battery (AB) and Unidirectional DC-DC Cuk Converter (UCC) for boost charging. Finally, the BMS simulation is modelled using MATLAB/SIMULINK to validate the implementation system's results.

ABSTRAK

Bateri litium-ion menjadi lebih popular untuk digunakan kerana ciri-cirinya yang menonjol seperti ketumpatan tenaga, ketumpatan kuasa dan voltan terminal tinggi bagi satu sel. Walau bagaimanapun, jika terdapat isu peraturan kuasa semasa proses pengecasan dan nyahcas, prestasi bateri akan terjejas. Dalam kes ini, hayat bateri akan berkurangan dengan ketara, yang boleh mengakibatkan hasil yang tidak diingini seperti kebakaran atau letupan. Untuk mengelakkan isu ini, Sistem Pengurusan Bateri (BMS) digunakan untuk menyediakan peraturan kuasa yang betul. BMS merangkumi subsistem yang besar seperti anggaran SOC, pengurusan haba dan pengimbangan sel. Penyelidikan ini menumpukan pada mekanisme pengimbangan sel, yang merupakan bahagian penting BMS untuk memanjangkan hayat bateri. Dua jenis asas pengimbangan sel ialah pengimbangan sel pasif dan pengimbangan sel aktif. Topologi pengimbangan aktif yang digunakan dalam penyelidikan ini ialah Kapasitor Suis Tunggal (SSC), asas kapasitor, untuk melaksanakan pengimbangan modul dan pengimbangan sel di dalam modul dalaman. BMS adalah berdasarkan seni bina modularisasi pek, di mana satu kapasitor dipasang untuk memindahkan tenaga dari modul ke modul untuk mencapai keseimbangan. Manakala, pengimbangan modul dalaman dicapai dengan penggunaan Kapasitor Suis Tunggal (SSC), Bateri Bantu (AB) dan Unidirectional DC-DC Cuk Converter (UCC) untuk pengecasan rangsangan. Akhir sekali, simulasi BMS dimodelkan menggunakan MATLAB/SIMULINK untuk mengesahkan keputusan sistem pelaksanaan.

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LIST OF ABBREVIATIONS

AB	-	Auxiliary Battery
BBC	-	Buck Boost Converter
BC	-	Bidirectional DC-DC Converter
BMS	-	Battery Management System
C	-	Capacitance
DC	-	Direct Current
DTSC	-	Double Tiered Switched Capacitor
EV	-	Electric Vehicle
EHV	-	Electric Hybrid Vehicle
F	-	Frequency
FR	-	Fixed Resistor
I	-	Current
ICE	-	Internal Combustion Engine
IMB	-	Internal Module Balancing
M	-	Module
MSI	-	Multi Switched Inductor
MWT	-	Multi winding Transformer
SC	-	Switched Capacitor
SR	-	Shunt Resistor
SOC	-	State of Charge
SOH	-	State of Health
SSC		Single Switched Capacitor
SSI		Single Switched Inductor
UC		Unidirectional DC-DC Converter
UCC		Unidirectional Cuk Converter

LIST OF SYMBOLS

τ	-	Time Constant
T	-	Time Period

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Extensive research and development on green energy has been accomplished over the last three decades, resulting in a plethora of possible new technologies, such as electric vehicles (EVs), solar, and wind power systems. These technologies have the potential to reduce reliance on fossil fuels while also addressing energy, environmental, and economic challenges [1]. As one of the most commonly used and secure energy storage systems, in these applications, the battery plays a crucial role. In comparison to other types of batteries, such as nickel and lead-acid, a rechargeable lithium-ion (Li-ion) battery offers quicker charging rates, longer life spans, and better energy density, according to recent research in battery technology [2].

Li-ion battery is a rechargeable battery where lithium ions migrate from the negative electrode to the positive electrode through an electrolyte during discharge and then back while charging [3]. No sufficient power regulation might occur during the charging and discharging processes of a Li-ion battery. In this case, the battery's life span will be considerably reduced, which may result in undesirable outcomes such as fire or explosion. The imbalances decrease the operational performance of the battery system. If only one Li-ion cell in a battery cell is overcharged or undercharged, it causes permanent damage or speeds cell aging. The Battery management system BMS is employed all the time in order to provide proper power regulation [2], [3].

The BMSs for Li-ion batteries are critical components for their use in a broad range of applications, including EVs. The BMS includes a plenty of significant subsystems such as state of charge (SOC) estimate, thermal control, and cell balancing as shown in figure 1.1. One of the most crucial BMS subsystems that certainly contributes to extending battery life is cell balancing. Furthermore, the mechanism of cell balancing not only effective way to protect cells, but it also distributes energy between cells to constantly maintain energy levels of cells during the operations of charge and discharge [4].

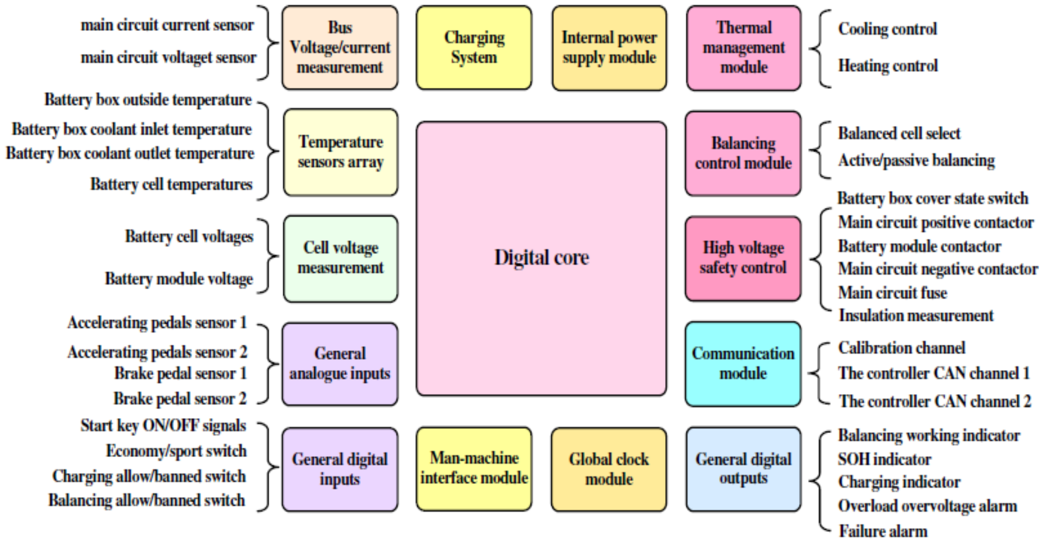

Figure 1.1 Battery Management System [4]

Passive cell balancing and active cell balancing are two basic cell balancing strategies [5]. For accuracy, reliability and safety in a sensitive system such as battery, active cell balancing is mostly employed. Therefore, the focus of this thesis will be on the study of active cell balancing method in Li-ion battery by using single switch capacitor strategy with Auxiliary Battery and Unidirectional Cuk Converter.

1.2 Problem Statement

Due to the limitations of existing manufacturing technology, cells within a battery pack are not identical in terms of voltage, capacity and internal resistance. Overcharging or Over-discharging phenomena of the cells inside the battery, represents the consequence of an imbalance in the parameters. Thus, it has an impact on the battery pack's performance and longevity, as well as the risk of a fire or explosion [6]. In order to solve this problem, Battery Management System (BMS) is employed. BMS is an electronic system that protects the battery system from harm such us power regulation issues [7]. Cell Balancing/Battery Equalization is very important subsystem in BMS that improves battery life by equalizing charges between the cells.

The cell balancing mode can be classified into passive balancing (dissipative) and active balancing (non-dissipative) relative to the amount of excess energy dissipated in the form of heat [5]-[7]. With a parallel resistor, passive cell balancing releases surplus energy as heat. This equalization approach is easy, convenient, adaptable, low-cost, and compact in size, but it has drawbacks such as energy waste, which makes thermal management more difficult [8]. In contrast, active cell balancing transfers energy between cells in order to eliminate the heat. But with this approach the redistribution of energy between cells with different SOCs still brings energy losses. However, if battery systems do not include a balancing technique, one or more cells will restrict both charging and discharging operations, lowering useable energy [9]. Therefore, developing a precise active cell balancing approach that can improve the battery system is crucial.

1.3 Hypothesis

Several hypotheses of this research include:

(a) Providing a convenient method to transfer energy inside the battery from cell to cell and from module to module. Thus, there will not be any risk of energy dissipation.

(b) Improving the performance of the BMS system in general by increasing the charging speed.

(c) Developing new manufacturing technology that is more practical and economic.

1.4 Objectives

The main objectives of this research are:

(a) To design and simulate a new innovative cell balancing approach by combining Single Switched Capacitor, Auxiliary battery, and Unidirectional DC-DC Cuk converter for balancing of cells in Li-ion battery using MATLAB/SIMULINK.

(b) To validate Single Switched Capacitor only for active cell balancing method in Li-ion battery using MATLAB/SIMULINK.

(c) To improve the state of charge SOC and balance speed between cells using the combination of Single Switched Capacitor, Auxiliary battery, and Unidirectional DC-DC Cuk converter.

1.5 Research Scope

The scope of this work includes:

(a) Focus on using Single Switched Capacitor with Auxiliary Battery and Unidirectional DC-DC Cuk Converter topology.

(b) Focus on active cell balancing using Single Switched Capacitor only for Li-ion battery.

(c) MATLAB/Simulink is utilized to obtain the accurate simulation results.

1.6 Expected Contributions

This research is expected to contribute the following matters:

(a) This research will introduce an innovative balancing method which efficiently lead to prolong the batteries life span and reduce the aging of cells.

(b) The non-dissipation method that used in this research will reduce undesirable results such as fire or explosion that may occur battery systems.

(c) The losses of energy will decrease, whereas the capacity of battery will increase in this method. Thus, it is expected to play a major role in increasing the demand on clean energy sources and abstain on fossil fuels.

REFERENCES

[1] N. Ghaeminezhad, Q. Ouyang, X. Hu, G. Xu, and Z. Wang, "Active Cell Equalization Topologies Analysis for Battery Packs: A Systematic Review," IEEE Trans. Power Electron., vol. 36, no. 8, pp. 9119–9135, 2021, doi: 10.1109/TPEL.2021.3052163.

[2] M. Caspar, T. Eiler, and S. Hohmann, "Systematic Comparison of Active Balancing: A Model-Based Quantitative Analysis," IEEE Trans. Veh. Technol., vol. 67, no. 2, pp. 920–934, 2018, doi: 10.1109/TVT.2016.2633499.

[3] J. Carter, Z. Fan, and J. Cao, "Cell equalisation circuits: A review," J. Power Sources, vol. 448, no. April 2019, p. 227489, 2020, doi: 10.1016/j.jpowsour.2019.227489.

[4] L. Lu, X. Han, J. Li, J. Hua, and M. Ouyang, "A review on the key issues for lithium-ion battery management in electric vehicles," J. Power Sources, vol. 226, pp. 272–288, 2013, doi: 10.1016/j.jpowsour.2012.10.060.

[5] Michael, R. P. Sujatmiko, T. Abuzairi, M. Rizkinia, and T. A. Kurniawan, "Design of overcharging protection and passive balancing circuits using dioda for lithium-ion battery management system," 2019 16th Int. Conf. Qual. Res. QIR 2019 - Int. Symp. Electr. Comput. Eng., pp. 20–23, 2019, doi: 10.1109/QIR.2019.8898267.

[6] M. H. Hashim, M. S. Jamaluddin, M. H. S. Hun, M. J. A. Aziz, and N. M. Nordin, "Lithium-Ion Cell Balancing Using Auxiliary Battery and DC/DC Unidirectional Converter," pp. 52–57, 2021, doi: 10.1109/cencon51869.2021.9627298.

[7] M. Daowd, M. Antoine, N. Omar, P. Van Den Bossche, and J. Van Mierlo, "Single Switched Capacitor Battery Balancing System Enhancements," pp. 2149–2174, 2013, doi: 10.3390/en6042149.

[8] W. Luo, J. Lv, W. Song, and Z. Feng, "Study on passive balancing characteristics of serially connected lithium-ion battery string," ICEMI 2017 - Proc. IEEE 13th Int. Conf. Electron. Meas. Instruments, vol. 2018-Janua, pp. 489–495, 2017, doi: 10.1109/ICEMI.2017.8265862.

[9] V. Vardwaj, V. Vishakha, V. K. Jadoun, S. Jayalaksmi, and A. Agarwal, “Various Methods Used for Battery Balancing in Electric Vehicles: A Comprehensive Review,” 2020 Int. Conf. Power Electron. IoT Appl. Renew. Energy its Control. PARC 2020, pp. 208–213, 2020, doi: 10.1109/PARC49193.2020.236594.

[10] D. Doughty and E. P. Roth, “A general discussion of Li Ion battery safety,” Electrochem. Soc. Interface, vol. 21, no. 2, pp. 37–44, 2012, doi: 10.1149/2.F03122if.

[11] Y. Chen et al., “A review of lithium-ion battery safety concerns: The issues, strategies, and testing standards,” J. Energy Chem., vol. 59, pp. 83–99, 2021, doi: 10.1016/j.jechem.2020.10.017.

[12] S. F. Tie and C. W. Tan, “A review of energy sources and energy management system in electric vehicles,” Renew. Sustain. Energy Rev., vol. 20, pp. 82–102, 2013, doi: 10.1016/j.rser.2012.11.077.

[13] S. Shete, P. Jog, R. K. Kumawat, and D. K. Palwalia, “Battery Management System for SOC Estimation of Lithium-Ion Battery in Electric Vehicle: A Review,” 2021 6th IEEE Int. Conf. Recent Adv. Innov. Eng. ICRAIE 2021, vol. 2021, 2021, doi: 10.1109/ICRAIE52900.2021.9703752.

[14] W. Vermeer, G. R. Chandra Mouli, and P. Bauer, “A Comprehensive Review on the Characteristics and Modeling of Lithium-Ion Battery Aging,” IEEE Trans. Transp. Electrif., vol. 8, no. 2, pp. 2205–2232, 2022, doi: 10.1109/TTE.2021.3138357.

[15] N. S. Choi, Y. Yao, Y. Cui, and J. Cho, “One dimensional Si/Sn - Based nanowires and nanotubes for lithium-ion energy storage materials,” J. Mater. Chem., vol. 21, no. 27, pp. 9825–9840, 2011, doi: 10.1039/c0jm03842c.

[16] J. Wehbe and N. Karami, “Battery equivalent circuits and brief summary of components value determination of lithium ion: A review,” 2015 3rd Int. Conf. Technol. Adv. Electr. Electron. Comput. Eng. TAEECE 2015, pp. 45–49, 2015, doi: 10.1109/TAEECE.2015.7113598.

[17] M. Naguib, P. Kollmeyer, and A. Emadi, “Lithium-ion battery pack robust state of charge estimation, cell inconsistency, and balancing: Review,” IEEE Access, vol. 9, pp. 50570–50582, 2021, doi: 10.1109/ACCESS.2021.3068776.

[18] Y. Ren and Z. Wang, “Review of Low Temperature Reliability of Lithium-ion Battery,” pp. 222–228, 2022.

[19] V. Mohanapriya, V. Manimegalai, B. Sharmila, M. Sinivasan, M. Vadivel, and S. Veera Rithik, "Estimation of State of Charge of Battery," Proc. 5th Int. Conf. Trends Electron. Informatics, ICOEI 2021, pp. 279–284, 2021, doi: 10.1109/ICOEI51242.2021.9452992.

[20] K. W. E. Cheng, B. P. Divakar, H. Wu, K. Ding, and H. F. Ho, "Battery-management system (BMS) and SOC development for electrical vehicles," IEEE Trans. Veh. Technol., vol. 60, no. 1, pp. 76–88, 2011, doi: 10.1109/TVT.2010.2089647.

[21] F. Wenjie, Z. Zhibin, D. Ming, and R. Ming, "On-line Estimation Method for Internal Temperature of Lithium-ion Battery Based on Electrochemical Impedance Spectroscopy," 2021 Electr. Insul. Conf. EIC 2021, pp. 247–251, 2021, doi: 10.1109/EIC49891.2021.9612262.

[22] L. Yin, G. Du, and X. Liu, "Impact of ambient temperature on the self-heating effects in FinFETs," J. Semicond., vol. 39, no. 9, pp. 763–766, 2018, doi: 10.1088/1674-4926/39/9/094011.

[23] C. C. Chuang, C. J. Yao, and S. T. Wu, "Study on Fast Charging Method of Series Connected Lithium-Ion Battery Strings with Intelligent Control," 2020 Int. Conf. Fuzzy Theory Its Appl. iFUZZY 2020, pp. 1–6, 2020, doi: 10.1109/iFUZZY50310.2020.9297813.

[24] P. Shen, M. Ouyang, L. Lu, J. Li, and X. Feng, "The co-estimation of state of charge, state of health, and state of function for lithium-ion batteries in electric vehicles," IEEE Trans. Veh. Technol., vol. 67, no. 1, pp. 92–103, 2018, doi: 10.1109/TVT.2017.2751613.

[25] P. A. Topan, M. N. Ramadan, G. Fathoni, A. I. Cahyadi, and O. Wahyunggoro, "State of Charge (SOC) and State of Health (SOH) estimation on lithium polymer battery via Kalman filter," Proc. - 2016 2nd Int. Conf. Sci. Technol. ICST 2016, no. 2, pp. 93–96, 2017, doi: 10.1109/ICSTC.2016.7877354.

[26] A. Zilio and P. Mattavelli, "A flexible Multi-Active Half-Bridge converter for active balancing of series-connected Li-Ion cells," IECON Proc. (Industrial Electron. Conf., vol. 2021-Octob, 2021, doi: 10.1109/IECON48115.2021.9589854.

[27] M. Raber, D. O. Abdeslam, A. Heinzelmann, and A. Ramirez, "Performance estimation of a cell-to-cell-type active balancing circuit for lithium-ion battery

systems," IEEE Int. Symp. Ind. Electron., pp. 1005–1010, 2017, doi: 10.1109/ISIE.2017.8001383.

[28] A. Kelkar, Y. Dasari, and S. S. Williamson, "A Comprehensive Review of Power Electronics Enabled Active Battery Cell Balancing for Smart Energy Management," 2020 IEEE Int. Conf. Power Electron. Smart Grid Renew. Energy, PESGRE 2020, pp. 1–6, 2020, doi: 10.1109/PESGRE45664.2020.9070666.

[29] I. C. Guran, L. A. Perisoara, A. Florescu, and D. I. Sacaleanu, "4-Cell Passive Battery Management System for Automotive Applications," 2021 IEEE 27th Int. Symp. Des. Technol. Electron. Packag. SIITME 2021 - Conf. Proc., pp. 338–341, 2021, doi: 10.1109/SIITME53254.2021.9663604.

[30] L. A. Perişoară, I. C. Guran, and D. C. Costache, "A Passive Battery Management System for Fast Balancing of Four LiFePO4 Cells," 2018 IEEE 24th Int. Symp. Des. Technol. Electron. Packag. SIITME 2018 - Proc., pp. 390–393, 2019, doi: 10.1109/SIITME.2018.8599258.

[31] P. T. Krein and R. S. Balog, "Life extension through charge equalization of lead-acid batteries," INTELEC, Int. Telecommun. Energy Conf., pp. 516–523, 2002, doi: 10.1109/intlec.2002.1048705.

[32] B. Yildirim, M. Elgendy, A. Smith, and V. Pickert, "Evaluation and Comparison of Battery Cell Balancing Methods," Proc. 2019 IEEE PES Innov. Smart Grid Technol. Eur. ISGT-Europe 2019, 2019, doi: 10.1109/ISGTEurope.2019.8905588.

[33] L. Valda and K. Kosturik, "Comparison of Li-ion active cell balancing methods replacing passive cell balancer," Int. Conf. Appl. Electron., vol. 2015-October, pp. 267–270, 2015.

[34] C. Pascual and P. T. Krein, "Switched capacitor system for automatic series battery equalization," Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC, vol. 2, pp. 848–854, 1997, doi: 10.1109/apec.1997.575744.

[35] Y. Ye and K. W. E. Cheng, "An automatic switched-capacitor cell balancing circuit for series-connected battery strings," Energies, vol. 9, no. 3, 2016, doi: 10.3390/en9030138.

[36] A. C. Baughman and M. Ferdowsi, "Double-tiered switched-capacitor battery charge equalization technique," IEEE Trans. Ind. Electron., vol. 55, no. 6, pp. 2277–2285, 2008, doi: 10.1109/TIE.2008.918401.

[37] A. F. Moghaddam and A. Van Den Bossche, “An Active Cell Equalization Technique for Lithium Ion Batteries Based on Inductor Balancing,” Proc. 2018 9th Int. Conf. Mech. Aerosp. Eng. ICMAE 2018, pp. 274–278, 2018, doi: 10.1109/ICMAE.2018.8467685.

[38] H. Liu and C. Xia, “An efficient battery balancing scheme in electric vehicle,” ICMREE 2013 - Proc. 2013 Int. Conf. Mater. Renew. Energy Environ., vol. 2, pp. 541–544, 2013, doi: 10.1109/ICMREE.2013.6893730.

[39] L. R. Yu, Y. C. Hsieh, W. C. Liu, and C. S. Moo, “Balanced discharging for serial battery power modules with boost converters,” ICSSE 2013 - IEEE Int. Conf. Syst. Sci. Eng. Proc., pp. 449–453, 2013, doi: 10.1109/ICSSE.2013.6614708.

[40] X. Lu, W. Qian, and F. Z. Peng, “Modularized buck-boost + Cuk converter for high voltage series connected battery cells,” Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC, pp. 2272–2278, 2012, doi: 10.1109/APEC.2012.6166139.

[41] T. H. Wu, C. S. Moo, and C. H. Hou, “A battery power bank with series-connected buck-boost-type battery power modules,” Energies, vol. 10, no. 5, pp. 1–12, 2017, doi: 10.3390/en10050650.

[42] A. F. Moghaddam and A. Van Den Bossche, “A Battery Equalization Technique Based on Ćuk Converter Balancing for Lithium Ion Batteries,” 2019 8th Int. Conf. Mod. Circuits Syst. Technol. MOCAST 2019, pp. 8–11, 2019, doi: 10.1109/MOCAST.2019.8741779.

[43] J. W. Shin, G. S. Seo, C. Y. Chun, and B. H. Cho, “Selective Flyback balancing circuit with improved balancing speed for series connected Lithium-ion batteries,” 2010 Int. Power Electron. Conf. - ECCE Asia -, IPEC 2010, pp. 1180–1184, 2010, doi: 10.1109/IPEC.2010.5543502.

[44] M. Daowd, N. Omar, P. van den Bossche, and J. van Mierlo, “A review of passive and active battery balancing based on MATLAB/Simulink,” Int. Rev. Electr. Eng., vol. 6, no. 7, pp. 2974–2989, 2011.

[45] Moghaddam, Ali Farzan, and Alex Van den Bossche. "Flyback converter balancing technique for lithium based batteries." *2019 8th International Conference on Modern Circuits and Systems Technologies (MOCAST)*. IEEE, 2019.