Fuzzy-PID Controller Modeling and Simulation for Optimization of Cell Equalization in Lithium-ion Batteries for Electric Vehicles

Tulu Megersa Lammecha

A Thesis submitted to

The Department of Mechanical Engineering

School of Mechanical, Chemical and Materials Engineering

Presented in Partial Fulfillment of the Requirement for Master of Science in Automotive Engineering

Office of Graduate Studies

Adama Science and Technology University

January, 2024

Adama, Ethiopia

Fuzzy-PID Controller Modeling and Simulation for Optimization of Cell Equalization in Lithium-ion Batteries for Electric Vehicles

Tulu Megersa Lammecha

Advisor: Dr. Alemayehu wakjira

A Thesis Submitted to the

Department of Mechanical Engineering

School of Mechanical, Chemical and Material Engineering

Presented in Partial Fulfillment of the Requirement for Master of Science in Automotive Engineering

Office of graduate studies

Adama Science and Technology University

January, 2024

Adama, Ethiopia

DECLARATION

I hereby declare that this thesis entitled "**Fuzzy-PID Controller Modeling and Simulation for Optimization of Cell Equalization in Lithium-ion Batteries for Electric Vehicles**" is my own work and has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Tulu Megersa Lammecha

______________________	________________________	________________
Name of the student	Signature	Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Fuzzy-PID Controller Modeling and Simulation for Optimization of Cell Equalization in Lithium-ion Batteries for Electric Vehicles**" prepared under my guidance by Tulu Megersa Therefore, submitted in partial fulfillment of the requirements for Master of Science in Automotive Engineering. Therefore, we recommend the submission of the revised version of the thesis to the department following the applicable procedures.

Dr. Alemayehu Wakjira Huluka	______________________	_______________
Major Advisor	Signature	Date

APPROVAL

I, the advisors of the thesis entitled "**Fuzzy-PID Controller Modeling and Simulation for Optimization of Cell Equalization in Lithium-ion Batteries for Electric Vehicles**" and developed by **Tulu Megersa** hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Alemayehu Wakjira Huluka ____

Major Advisor Signature Date

We, the undersigned, members of the Board of Examiners of the thesis by "Tulu Megersa have read and evaluated the thesis entitled "**Fuzzy-PID Controller Modeling and Simulation for Optimization of Cell Equalization in Lithium-ion Batteries for Electric Vehicles"** and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Automotive engineering.

________________________________ _______________________ _____________________

Chairperson Signature Date

________________________________ _______________________ _____________________

Internal Examiner Signature Date

________________________________ _______________________ _____________________

Eternal Examiner Signature Date

Finally, approval and acceptance of the thesis are contingent upon the submission of its final

Copy to the Office of Postgraduate Studies (OPGS) through the Department of Graduate Council (DGC) and School Graduate Committee (SGC).

____________________________ ______________________ __________________

Department Head Signature Date

____________________________ _____________________ ___________________

School Dean Signature Date

________________________________ _______________________ _____________________

Office of Postgraduate Studies, Dean Signature Date

ACKNOWLEDGMENT

I want to thank God first and foremost for his generosity, for the wisdom and bravery he gave me, for the blessings and protection I experienced while working on my thesis, and I also want to thank His mother. I would like to express my gratitude to Dr. Alemayehu Wakjira, my advisor, for his excellent effort in setting the foundation for my thesis. I now know how to carry out research and present the findings in an easily comprehensible manner thanks to him. It was truly an honor and a delight to work for him. Furthermore, I express my gratitude to Mr. Garibe Chukulu, a PhD candidate student, for his academic expertise, advice, and experience during my master's program and thesis work. This job could not have been finished without your assistance. Lastly, I want to express my gratitude to my families and friends for their important support.

TABLE OF CONTENTS

ACRONYMS

AKF	Adaptive Kalman Filter
BMS	Battery Management System
FLC	Fuzzy Logic Control
HEV	Hybrid Electric Vehicle
OCV	Open Circuit Voltage
SOC	State Of Charge
SOH	State Of Health
PWM	Pulse Width Modulation
DCE	Dissipative Cell Equalization
CCVC	Constant Current Constant Voltage
BPNN	Backpropagation Neural Network
ECM	Equivalent Circuit Model

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

In recent years, electric vehicles have drawn a lot of interest because they offer a more environmentally friendly, efficient, and sustainable form of transportation than traditional fossil fuel-powered vehicles. As the most significant part of the electric car powertrain, lithium-ion batteries need to be accurately monitored and controlled. The mass market manufacture of electric vehicles is still beset with numerous difficulties, such as high battery costs, safety concerns, and lifespan issues. Lifespan of lithium ion battery deteriorate over time because of cell misbalancing during charging and discharge cycle. Researchers have been working on ways to balance the energy levels of individual cells within a battery pack. They have developed a method called active balancing, which involves using CUK circuits to transfer energy between cells and make sure they have similar charge levels. To control energy, transfer process, they have used a type of computer logic called fuzzy logic. It improves time efficiency by more than 30% and energy efficiency by over 11% compared to other methods like the mean difference algorithm in both static (steady) and charge-discharge scenarios. This study describes an active cell balancing method for a series-connected battery pack of lithium-ion cells using a fuzzy-PID controller. The battery model is created using the Equivalent Circuit Model Method; the battery is built on the second-order RC equivalent circuit (ECM, 2RC), which represents the dynamic change in the battery during charge and discharge. The coulomb counting method is used to estimate each cell's SOC, and two MOSFET switches are employed—one is turned on when a cell is being charged, and discharged. The algorithm detects a 10%(55%, 50%, 45%, and 47%) change in the state of charge (SOC) value below this threshold, which prompts the fuzzy-PID controller to use pulse width modulation (PWM) to initiate the CUK equalization circuit and to verify the created model's performance, it is simulated using MATLAB. The balancing mechanism is controlled by a Fuzzy-PID controller that is designed. It is found that the fuzzy-PID controllers responds faster 350 seconds (5.8 min~6 min), 425 seconds (7 min) and 390 seconds (6.5min) to balance four-battery pack state-of-charge batteries during charge state, discharge and static state respectively. For four-battery pack fuzzy-PID controllers take 390 seconds and have an 11.56% faster balancing time than fuzzy logic controller which is shows that a fuzzy-PID control method can self-adapt to save energy (3.48% when compared to the fuzzy logic controller).

Keywords: *Battery modeling, coulomb counting method, Cuk equalization circuit, fuzzy-PID*

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

With the globe moving toward "Green Technologies" in an effort to reduce global warming, almost every country is pushing for the development and use of electric vehicles. Furthermore, the battery of an electric vehicle is considered the engine of the vehicle. This highlights the importance of research and development in terms of battery design and management. The battery management system (BMS), which continuously monitors, controls, and regulates the energy storage and transfer in electric vehicles, guarantees the safety of the battery pack.

A battery management system (BMS) collects data from the battery's sensors, maintains cell balance, regulates the charger to guarantee that the battery is charged properly, guards against overcharging, over-discharging, and other dangerous anomalies, reports the battery's state and temperature, connects to the vehicle, and transfers data to a computer.

BMS charges a cell based on its current state of charge and drains a cell depending on demand and available charge while monitoring and controlling the battery's charging and discharging processes. In a similar vein, maintaining steady cell voltages for every single battery cell helps reduce the loss of battery life. At BMS, there is a particular cell balancing unit.

The temperature is monitored and controlled by the BMS as well. Since no two cells in a multi-cell battery chain are exactly the same, there will always be some variance in the properties, including impedance, temperature characteristics, capacity, state of charge, self-discharge, and impedance. Moreover, uneven draining of a multi rank pack protection integrated circuit (IC) may cause cell imbalance, which may reduce battery life.

This work presents an algorithmic model-based active cell balancing architecture that may self-reconfigure according to the state of charge (SOC) of individual battery pack cells. The most investigated area of current study is reconfigurable battery systems, which are able to adjust their own configuration to achieve optimal performance.

For a very long time, the only batteries suitable for use in portable devices such as mobile computers and wireless communications were nickel-cadmium ones. Although the technology was developed in 1912, the first non-rechargeable lithium batteries were not commercially accessible until the 1970s. During the 1970s oil crisis, Stanley Whittingham, an English scientist, began working on the concept of creating a new kind of battery that could swiftly recharge on its own. He believed that in the end, this will produce energy without the need for fossil fuels. Whittingham attempted to use titanium disulfide and lithium metal as the electrodes, but the batteries shorted out and caught fire as a result, casting doubt on the experiment's safety.

Using lithium cobalt oxide as the cathode, John Goodenough decided to carry out an experiment in the 1980s that doubled the energy potential. This inspired Akira Yoshino to investigate using petroleum coke, and as a result, he found that the battery was far safer without lithium metal. This signaled the beginning of lithium ion battery research.

In the 1990s, lithium ion technology began to gain traction with consumers, making it the battery type with the quickest rate of growth. The first inquiry into the creation of lithium batteries was prompted by concerns about safety with lithium metal batteries. Even though lithium ion has a little lower energy density than lithium metal, it is nevertheless quite safe to charge and discharge when used in compliance with the advised safety protocols.

Various battery types have been utilized as the energy sources for these systems thus far, with the goal of improving their efficiency, low operating temperature, and density. These days, lithium-ion batteries are found in a wide range of electronic products, both big and small, including drones, electric and hybrid vehicles (HEVs), laptops, phones, and drones. When compared to other widely used batteries, lithium-ion batteries have several advantages, including a high energy density, high power density, long life, and high efficiency (Molenda, 2011). Many nations have boosted their spending in EV/HEV, electric vehicle (EA), and hybrid electric vehicle (HEA) research because we will soon run out of fossil fuel supplies(Chen et al., 2019). For EVs and HEVs, the lithium-ion are one of the main power sources of the system.

In electric vehicles nowadays, lead-acid, nickel-metal hydride, and lithium-ion batteries are commonly utilized. Out of the three, lithium-ion batteries have the highest energy density. The lithium-ion battery is also a topic of research because of its great power density, low self-discharge rate, poor memory effect, and environmental concerns. Lithium-ion batteries are used in fuel cell vehicles, hybrid electric vehicles, and electric cars. The extensive usage of lithium-ions, however, may be constrained by a few disadvantages, such as cost, safety, and durability in electronic devices with large battery capacities(Rashid & Osman, 2017).

The Battery Management System (BMS) is the primary line of defense against battery pack disadvantages. State of Charge (SOC), State of Health (SOH), Mileage Agencies, Cell Balancing, Discharge Rate, and Lifetime are all under the control of BMS. One of the key objectives of BMS is cell balancing. When every cell in the battery is precisely at the same state of charge (SOC), the battery is said to be balanced. Numerous factors, such as capacity, internal resistance, self-discharge current, and state of charge, could be causing the battery to be out of balance (Kumar et al., 2022).

Many balancing circuits have been developed over the past ten years(T. T. Nguyen et al., 2014). The main ones for these balancing circuits are the implementation cost, balancing speed, and efficiency limits. They can be broadly separated into two categories: active balancing and passive balancing. The strongest cell in the group must expend more energy for the passive balancing to ensure that all the cells are completely charged. It is affordable and trustworthy. Its rate of balancing is slow and it is incapable of transferring energy. The maximum capacity of the pack is limited by the cell that has the smallest capacity. The active balancing swiftly and effectively distributes energy throughout the pack using electrical circuits. The whole capacity of the pack can be used. But the cost increases as more parts of the balancing circuit are used. The balancing system's cost is a major consideration in EV applications. Reducing the number of components is one option to cut costs, but doing so calls for a more complex balancing control strategy(Gan et al., 2017).

The capacity of the battery pack as a whole is therefore restricted by the unbalanced cells that need to be balanced (also called aberrant cells in this study). These aberrant cells may also diminish the battery pack's lifespan, lower energy usage efficiency, and reduce the usable capacity of the battery pack. Because of this, an essential BMS function for an EV's battery pack is balancing(Piao et al., 2015).

Based on specialists' knowledge of the system, the fuzzy logic controller (FLC) creates a fuzzy logic data base for the operation. FLC can control one balancing topology by adjusting the balancing frequency. It is recommended to swap out the PI controller for an FLC that just makes use of simulation data. The FLC then regulates the balance circuit. It turns out that the FLC has adaptive control over the balancing currents. Large balancing currents can be set in response to large voltage gaps, hastening the balancing process. When the voltage gap is small, moderate balancing currents can be set to reduce energy use. This increases balancing's effectiveness and speed(Cui et al., 2014).

FLC was first proposed by Lotfi A. Zadeh of the University of California, Berkeley in a 1965 study. FLC has many advantages over PID controllers, including ease of design, a hint of human intelligence for the controller, cost effectiveness, the ability to handle non-linearity in the system, the ability to handle it quickly, the high degree of precision achieved, and the lack of a need for mathematical modeling of the system. In FLC, there are basically three important sections: The first thing is the fuzzy block. 2) Inference Framework 3) a block for defuzzification. Fuzzy logic uses linguistic variables to process information instead of numerical ones. However, because the FLC's inputs are given as numerical variables, they must be transformed into language variables. The fuzzifier transforms these crisp sets into fuzzy sets. The fuzzy controller's membership function establishes the fuzzy logic's degree of truth. A set of objects' fuzziness—whether discrete or continuous—is determined by the membership function(Jadhav & Nair, 2019).

This paper proposes two ways based on extended Kalman filters (EKF) and unscented Kalman filters (UKF), respectively, to predict the SoC of a lithium-ion battery used in EVs. The Beijing Driving Cycle is used to verify the parameters of the Thevenin model, which is used to simulate lithium-ion batteries. The parameters of the model are established using experimental data. Next, spatial equations that are iterative are created for estimating SoC. (Zhai et al., 2020) examine the accuracy and convergence of the SoC estimate findings utilizing EKF and UKF.

1.2 Statement of the Problem

Many characteristics of lithium-ion batteries, including their performance may be impacted by cell voltage imbalance, thermal runaway, over- and under-voltage, overcharge and discharge current, and these other factor. One of the most significant issues was cell imbalance, which rapidly depletes battery capacity by causing each battery cell's voltage to change over time (Wu et al., 2021). Cell imbalance is mostly caused by two issues. First, variations in cell impedance values, self-discharge rates, aging rates, and open circle voltages (OCV) result from faults in cell manufacture. Second, diverse conditions are operated in batteries due to uneven heat management, which also affects the state of charge (SOC) of the cell.

As a result, cells with high SOC reach full charge earlier than those with low SOC, and the latter often discharge to full capacity sooner. This can lead to overcharging or over discharging of some cells in specific circumstances, which can result in a variety of abnormal phenomena like fast aging, Li-plating, electrode structure disordering, and even fires and short circuits. To extend the life of the battery pack, battery cells should be equalized on a regular basis to maintain the smallest possible difference between the cells.

Recently, a possible approach that integrates sliding mode, neural network, and fuzzy logic techniques has emerged to manage uncertain and complicated systems. Intelligent control systems that are easy to use, provide accurate control, and can manage dynamic battery changes are known as fuzzy-PID logic controllers. The main focus of this study is fuzzy-PID, which can regulate the state of charge cell difference in lithium ion batteries used in electric vehicles.

1.3 Objective

1.3.1 General Objective

The main goal of this suggested thesis is Fuzzy-PID Controller modeling and Simulation for Optimization of Cell Equalization in Lithium-ion Batteries for Electric Vehicle.

1.3.2 Specific Objectives

The specific objective is as follows:

- To simulate a battery by using analogous circuit modeling.
- To calculate the current state of charge using Coulomb's counting technique.
- To design mechanism of energy transfer between cell (CUK equalization circuit).
- To maximize the cell balance of a lithium-ion battery, an intelligent fuzzy-PID controller for adjusting the fuzzy controller’s membership functions.
- Evaluating the suggested fuzzy-PID controller's performance and contrasting it with the traditional fuzzy-logic controller algorithm.

1.4 Scope of the Study

In order to reduce the amount of time needed for battery pack cell equalization and increase energy efficiency, this work focuses on modeling and simulating fuzzy-PID control equalization of lithium ion for electric vehicles. Using the MATLAB/Simulink platform, lithium ion battery is modeled based on equivalent circuit model and a mathematical model of CUK balancing circuit for a lithium-ion battery is created. Fuzzy-PID controller is designed based on dynamic change of battery during charge-discharge. An equalization cell based on state of charge (SOC) optimization is controlled, using a fuzzy-PID controller.

1.5 Motivation

Recently, the majority of research has been on energy storage in electric vehicles. Electric vehicles use a variety of battery types for energy storage. Modern all-electric cars employ lithium-ion batteries because to their high energy density, low discharge rate, long lifespan, and exceptional efficiency. Beside to these Lithium-ion batteries have drawbacks that can reduce their useful lives in addition to their advantages. These defects include imbalanced cell voltage, thermal runaway, over- and under-voltage, and discharge current. From those cell imbalance is one of the biggest problems since it quickly depletes the battery's capacity by causing the voltage of each individual cell to fluctuate over time (Kumar et al., 2022). I'm motivated to look into battery cell equalization by this. As a result, the BMS needs to have precise and sophisticated features to monitor and manage battery cell imbalance as well as regulate battery over-charge and discharge.

1.6 Significance of the Study

- ✓ Enhanced Battery Performance. By effectively managing the charge imbalance among individual battery cells, the controller can help maximize battery performance, improve energy efficiency, and extend battery lifespan.
- ✓ Optimal Battery Utilization. Balancing the charge among battery cells is essential for ensuring optimal utilization of battery capacity.
- ✓ Safety and Reliability: Lithium-ion batteries are known to be sensitive to charge imbalances, which can result in safety hazards, reduced battery life, and potential failures.
- ✓ Minimizing the inconsistency of batteries.
- ✓ Integration of Advanced Control Techniques:

1.7 Organization of the thesis

The thesis consists of seven chapters, each serving a specific purpose in presenting the research study.

Chapter 1, the introduction, provides an overview of the research. It begins with the background of the study, which contextualizes the research topic by discussing its relevance and the existing knowledge in the field. Following that, the statement of the problem clearly states the research question or issue that the study aims to address. The objectives and scopes section outlines the specific goals and boundaries of the research. The significance of the study explains why the research is important and how it contributes to the field. The motivation section discusses the personal or professional reasons behind choosing this topic. Lastly, the organization of the thesis provides a brief overview of each chapter and how they are structured.

Chapter 2 is a literature review that focuses on reviewing previous studies related to the modeling and simulation of a fuzzy-PID controller for equalizing lithium-ion batteries in electric vehicles. The review summarizes the key theories, concepts, and approaches explored in the literature.

Chapter 3 describes the materials and methods used in the study. It provides a detailed explanation of the materials, tools, software, or equipment employed in the research. Additionally, it outlines the methodology or approach followed to conduct the study, including, simulations, or data collection methods.

Chapter 4 focuses on the modeling of the lithium-ion battery using MATLAB SIMULINK. It delves into the theoretical background of battery modeling and simulation techniques and explains the steps taken to develop the model using the chosen software.

Chapter 5 discusses the design of the balancing circuit and fuzzy-PID controller for the lithium-ion battery. It covers the principles of battery balancing, different circuit topologies, and the design process used to develop the balancing circuit. It explains the theoretical foundations of fuzzy logic and PID control and how these two control techniques are integrated. The chapter also describes the design process used to develop the fuzzy-PID controller.

Chapter 6 presents the results and discussion of the research. It showcases the findings obtained from the research and provides a comprehensive analysis and interpretation of these results.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The expanding greenhouse effect, severe environmental contamination, and depletion of nonrenewable resources make the development of new energy sources imperative. The fast development of electric vehicles (EVs), which is a critical step toward the invention and deployment of new energy sources, is highly prioritized by nations throughout the world. Presently, the bulk of EV power batteries are composed of lead-acid, nickel-cadmium, nickel-hydrogen, and lithium-ion batteries.

Lithium-ion batteries are the main energy source for electric vehicles (EVs) because of their exceptional characteristics, which include high monomer voltage, high energy density, high energy discharge rate, low self-discharge rate, extended cycle life, no memory effect, and high current charging and discharging. Several single batteries coupled in series and parallel are frequently needed for the power battery pack in order to meet the voltage, power, and energy needs of electric vehicles. The unpredictable behavior of the battery, which is brought on by varying internal resistance, uneven capacity, aging, and temperature variations in the surrounding air, jeopardizes the performance, longevity, and safety of the battery pack. To reduce this erratic behavior, it is necessary to understand fair and effective battery equalization control(Shen & Gao, 2019).

2.2 Cell Balancing

By connecting many cells in series to maximize a battery pack's capacity and ensure that all of its energy is used, a technique known as "cell balancing" extends the life of batteries. A part of a battery management system that balances the cells in lithium-ion battery packs used in electric vehicles and energy storage systems (ESS) is called a cell balancer, commonly referred to as a regulator.

Typically, each cell in a battery pack has a different capacity and state of charge. When the cell with the lowest capacity is empty, discharge must stop in the absence of redistribution, even when the other cells are not yet empty. As such, the battery pack's energy delivery capacity is constrained. The difference in cells before and after equalization is displayed on figure 2-1.

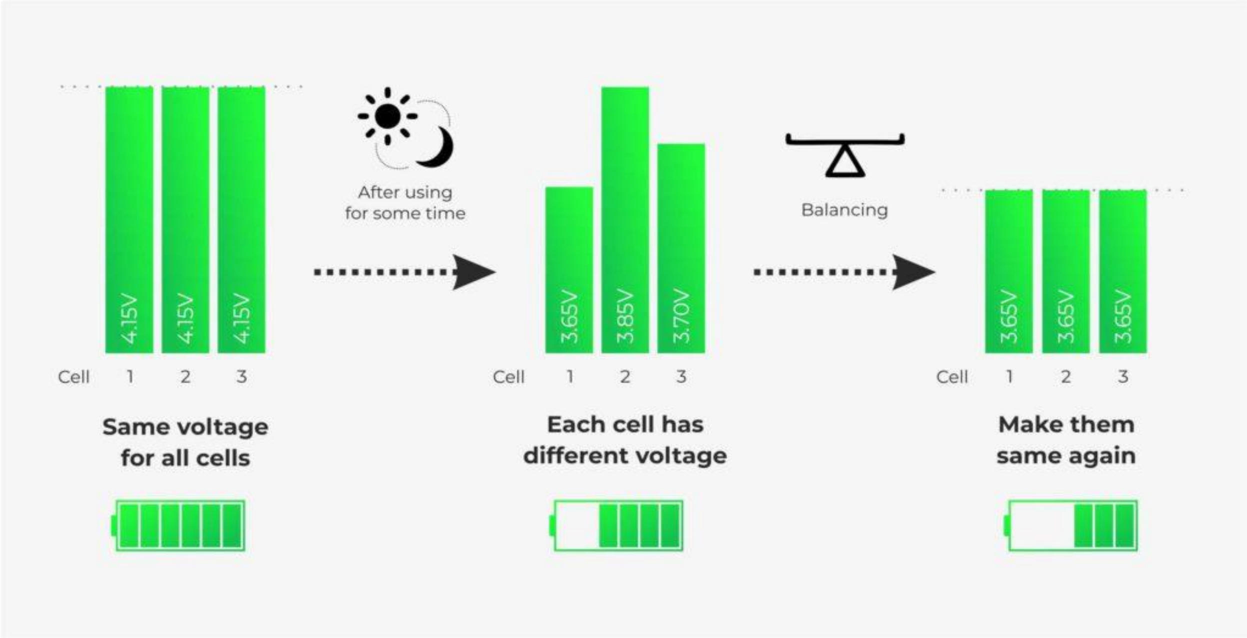


Figure 2-2-1. Cell Balancing (Yang et al., 2020)

Because battery cells are inherently uneven during manufacture and usage, variations in battery packs have a significant impact on battery pack capacity, longevity, and safety for electric vehicles (EVs). The main purposes of cell equalization are to reduce cell variations and increase pack capacity. This research finds that a dissipative cell equalization (DCE) using dissipative resistance is a feasible online equalization method for battery packs in electric vehicles. They then provide online equalization methods for lithium-ion battery packs (CCVCs) based on charging cell voltage curves. These algorithms try to maximize pack capacity by conditioning CCVCs. When the batteries are fully charged, there are ways to balance the voltage and charge level. Battery cells in a pack can have their voltage and state of charge (SOC) balanced using one of two methods: passive or active cell balancing. Passive cell balancing eliminates excess charges from cells with a high charge by using a dissipative characteristic. Active cell balancing uses power electronic switches, inductors, and capacitors to move charges between the cells in order to balance them(Zheng et al., 2014).

2.2.1 Passive Cell Balancing

It is an easy-to-understand cell leveling technique where the cells are released through a dissipative bypass path. This approach offers benefits for implementing an inexpensive system. Because all of a higher-energy cell's surplus energy is lost as heat during discharge, drastically reducing battery runtime, the passive cell balancing method is the least common.

The two types of cell balancing techniques are switching and fixed shunting resistors. The one that keeps the circuit from becoming overly charged is referred to as the fixed shunting resistor and is typically connected to the fixed shunting. The passive balancing circuit uses resistors to manage each cell's maximum voltage without damaging them. Thermal losses may occur to balance a battery in the battery management system due to the energy spent by these resistors. It is therefore shown that the fixed shunting resistor method is inefficient.

The switch shunting resistor cell balancing circuit is the most widely used passive cell equalization technique. It functions in two different modes: sensing and continuous. The continuous mode provides guidance. In the Continuous mode, all switches are meant to turn on or off simultaneously. However, a voltage sensor that operates concurrently in the sensing mode is required for every cell. This cell balancing circuit uses a lot of energy because of the balancing resistor. A circuit for cell balancing is developed for a battery system that requires low current charging or discharging. The resistor used in this circuit for cell balancing uses a lot of energy. The resistor that is utilized in this cell balancing circuit consumes a lot of energy. This circuit is appropriate for a battery system that uses less current when charging or discharging. Figure 2-2 illustrates passive cell balancing using a switched shunt resistor.

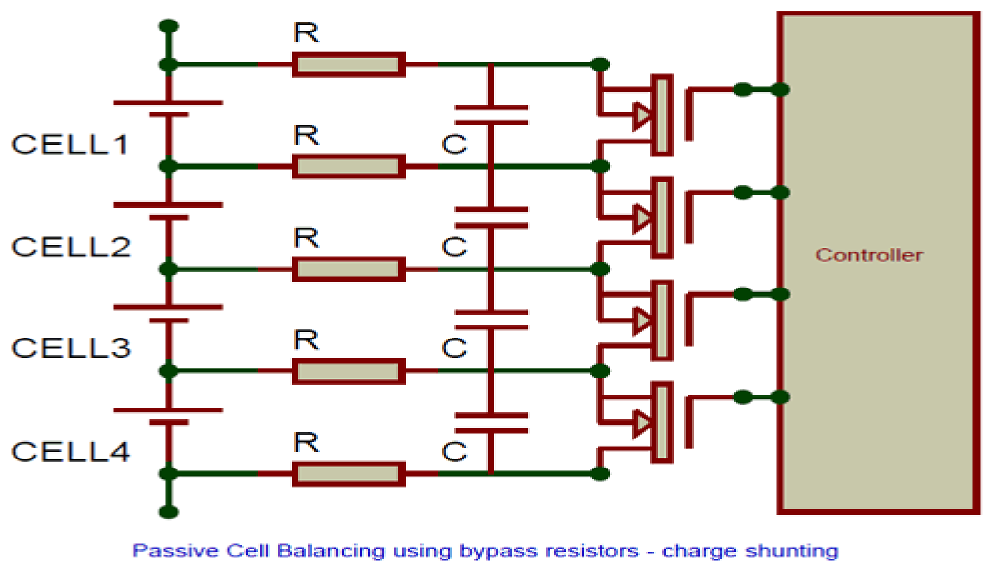


Figure 2-2-2. Passive Cell Balancing (Yang et al., 2020)

Cars and home appliances are using more and more lithium-ion batteries because of their high efficiency, low self-discharge, and high volumetric and gravimetric energy densities. They must be closely observed to ensure that they are functioning within the safe operating parameters that have been assigned to them, as failure to do so may result in explosions and fire hazards. Nevertheless, compared to other batteries, like lead acid batteries, they are more prone to instability due to their large energy carrying capacity. In order to keep consumers safe, a highly developed Battery Management System (BMS) is required. This system will not only lower the batteries' power consumption but also maintain them operating within safe parameters. After modeling batteries using passive components, this paper discusses the essential components needed to build a functional BMS. It also provides simulation to help understand how a BMS operates (Samaddar et al., 2021).

2.2.2 Active Cell Balancing

By employing capacitive or inductive charge, active cell balancing transfers energy from one cell to another. In other words, from a higher charge state cell to a lower charge state cell. The active balancing approach aims to prolong the life or state of charge of a pack of lower capacity cells by transferring energy from the cell in the pack that has more energy than the other. An active cell balancer effectively balances cells by transferring energy from the highest voltage cells to the lowest voltage cells, saving energy that would otherwise be wasted as heat through tiny converter circuits. Active cell balancing solutions come in two flavors: charge shuttling and energy converters. Charge shuttling is the active process of moving charges from one cell to another in order to maintain a constant cell voltage. Energy converters use transformers and inductors to transfer energy between a battery pack's cells. Figure 2-3 on the following page illustrates the use of a switched capacitor for active cell balancing.

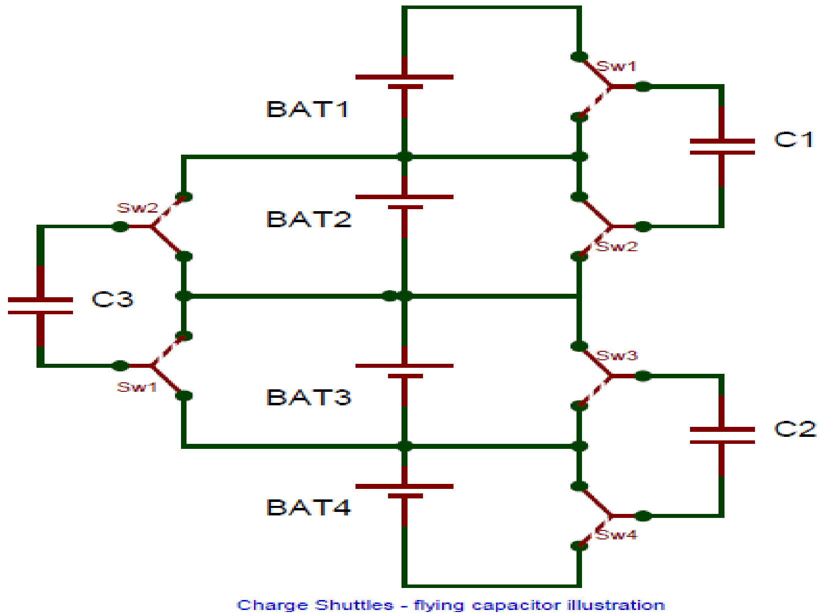


Figure 2-2-3. Active Cell Balancing(Yang et al., 2020)

Ultimately, using an electric vehicle will result in less petroleum goods being available and more demand for assets (EVs). The battery has an impact on the efficiency and range of electric vehicles. The lithium ion (Li-ion) chemistry of batteries can be harmed by deep discharge and overcharging, which can shorten their lifespan and potentially lead to hazardous issues. The Battery administration System (BMS) is composed of three parts: protection, equalization, and administration. When it comes to the longevity of the battery structure, equalization is the most crucial of the three. The process causes a rapid decline in the capacity of the entire pack, which weakens the entire battery system. The situation gets worse when the battery has more cells connected in series and the battery string needs to be charged often. Cell imbalance during charging and discharging is a major issue with battery systems used in EVs. To overcome the imbalance in the cells, cell balancing is used. Cell balancing increases battery life and improves battery safety. This paper discusses several active balancing approaches to increase the battery module's lifespan. The inductor-based balancing technique for 60V battery systems is applied in the MATLAB/Simulink environment based on the comparison, and the outcomes are explained (Duraisamy & Kaliyaperumal, 2020).

The use of lithium ion (Li-ion) batteries has been progressively increasing as a result of environmental concerns. One of the main applications for Li-ion batteries is in electric vehicles

(EVs). Li-ion batteries are much more susceptible to temperature, overvoltage, and under voltage circumstances than conventional batteries. A battery management system (BMS) is used to continuously monitor Li-ion batteries. Techniques for balancing active cells based on transformer switching are covered in this work. Active cell balancing is used to correct imbalances created in the battery pack (SOC) in order to maintain a steady level of charge. A comparison of switching transformer-based active cell balancing pack-to-cell systems is performed to obtain insights.(Pannickottu Nivya & Deepa, 2021).

Electric vehicles (EV) use battery banks comprised of series-parallel combinations of multiple small units to supply the high power demands of the propulsion system. Lithium-ion (Li-ion) batteries are increasingly often used in EVs for energy storage instead of conventional lead acid batteries due to the benefits of higher cell voltage, no memory effect, reduced self-discharge, longer battery life, and lower size and weight. To protect Li-ion battery packs from harm from extreme discharge and overcharging, however, supplementary power balancing circuits are required. In this study, the active circuit for Li-ion battery pack charge balancing is proposed. The recommended charge balancing circuit uses a multi-winding fly back converter with n+ 1 active switch to protect a stack of n number of series linked cells. The performance of the proposed system has been verified using computer modeling in MATLAB with a 4 cell battery pack. The predicted behavior of the system was found to be rather close to the simulation results. (Banerjee et al., 2020).

The potential power delivery of connected battery packs in series and parallel is limited by the string's wickedest cell. Due to practical considerations and industrialized requirements, the terminal voltage and capabilities of each cell vary slightly. During the charging or discharging process, the charge status of the cell strings becomes unbalanced and is prone to losing equalization. The goal of this study is to use an online state of charge (SOC) estimate technique to design an active charge balancing system for lithium-ion battery packs. A Battery Management System (BMS) is modeled to improve the efficiency of rechargeable batteries by controlling the SOC of the cells. The SOC function, which is computed using the Backpropagation Neural Network (BPNN) approach with four switched DC/DC Buck-Boost converters, is used to determine each cell's capacity. According to the simulation results, the developed BMS can synchronize cell equalization by effectively minimizing the SOC estimation error (RMSE 1.20%) (Qays et al., 2019).

Equalization method

This work investigates a Cuk converter-based active cell equalization technique for lithium ion (Li-ion) batteries. The circuit balances eight cells that are connected in series to form a battery pack. Electrical Vehicles (EV) depend heavily on their batteries because battery costs make up the majority of EV costs. A balancing circuit is required to make sure that all of the cells in a battery pack are running at the same voltage level because batteries are constantly being charged and discharged. The Cuk converter balancing method gives a speedy balancing time among the many balancing techniques. The proposed circuit only needs (n) switches, compared to the usual Cuk type's (2n-1) switches, which results in fewer switches and lower losses. The simulation results are used to assess the system's viability. (F. Moghaddam, 2019).

Several switched-capacitor (SC) cell balancing circuits are suggested in this paper for strings of rechargeable super- and battery capacitors. An elementary SC-based cell balancing unit is used as the equivalent resistor to develop the behavioral models of the suggested cell balancing circuits in order to evaluate their balancing performance. The primary difference between the proposed circuits and the SC-based cell balancing circuits now available on the market is that the balancing speed of the recommended circuits is independent of the initial mismatch distribution of cell voltages as well as the quantity of battery cells. The concepts of slow switching limit (SSL), fast switching limit (FSL), and inductive switching limit (ISL) of SC power converters are utilized to offer methods for circuit parameter optimization with the aim of lowering the equivalent resistance. Test and simulation results are presented to demonstrate the viability of the proposed cell balancing circuits(Ye et al., 2016).

Fuzzy logic control cell equalization

This study outlines the development of a lithium-centered Battery Management System (BMS) for electric vehicles (EV). This BMS was developed using fuzzy logic in order to imitate the methods for improving the autonomy and performance of the electric vehicle. The EV was modeled using the driving cycles and powertrain, mimicking its normal real-world operation. With the help of this model, it is now possible to determine the optimal course of action for improving the battery's performance by comparing the State of Charge (SOC) against time under different conditions. The strategy was then implemented using fuzzy logic in the suggested BMS, with a focus on enhancing energy autonomy and performance (Martínez et al., 2017).

Battery equalization technology, a crucial part of the battery management system (BMS), is crucial for maximizing battery energy use, enhancing vehicle efficiency, and extending battery life. Along with the estimate algorithm of equalization reference variables, the common equalizing circuits and equalizing control strategies are introduced. Following a discussion of their benefits and drawbacks, the article evaluates the path of future equalizing technological advancement in comparison to the present. (Yang et al., 2020).

An alternative to the conventional proportional-integral (PI) controller, a fuzzy logic (FL) controller is suggested to improve the balancing capabilities of lithium-ion battery packs. The low-cost multi-switched inductor balancing circuit, or MSIBC, serves as the basis for this. The open circuit voltages (OCVs) of each cell and their variations across the pack are the inputs of the proposed FL controller, and its output is the balancing current. In comparison to the existing PI controller, the FL controller for the MSIBC has the advantage of being able to maintain high balancing currents throughout almost the entire balancing process for different lithium battery types. Because the suggested FL controller completes battery pack balancing much more quickly, more pack capacity can be recovered. This will increase the battery pack's serving time and pack performance for electric vehicles (Cui et al., 2017).

This work provides an enhanced battery pack equalizer (BPE) that uses fuzzy logic controller (FLC) and is based on a DC/DC converter. It is not necessary to use a cell model in the pack to create this BPE. It is reliable and easy to use. According to the simulation results, the BPE with the FLC performs faster and more efficiently than the BPE with the PI controller when it comes to balancing (Cui et al., 2014).

This paper describes how to use a fuzzy logic controller (FLC) to design and implement battery energy management for renewable energy sources, such as solar panels and wind turbines. Energy producing and storage device (ESD) modeling, analysis, and control are best done with MATLAB/Simulink. The FLC was created to control the rate of charging and discharging, prolonging the life of the battery (Jadhav & Nair, 2019).

The battery pack that is connected in series has an imbalance. In order to balance the LFP batteries, this study suggests using a fuzzy logic controller for an active balancing circuit. To obtain the best balancing effect, the proposed fuzzy logic controller might offer balancing currents in an adaptive way. The fuzzy logic controller dramatically boosts balancing speed and efficiency when compared to a PI controller (Cui et al., 2018).

It's critical to understand the continuous and immediate power that batteries can deliver in a number of scenarios, including the quickly evolving electric vehicle market. Our investigation's primary focus is lithium-ion batteries because of their extensive usage in industrial settings. To guarantee the validity and precision of the estimation, a number of research are planned to gather the parameters of lithium-ion batteries. Based on battery state-of-charge (SOC), state-of-health (SOH), and C-rate characteristics, this paper presents a fuzzy logic approach to assess a battery's state-of-function (SOF), or ability to handle continuous and instantaneous loads. The results of experiments and simulations show that the suggested method is appropriate for determining battery SOF(Gan et al., 2017).

Battery groups are frequently utilized in both daily life and business. In addition to speeding up charging, optimal charging can increase battery pack performance and extend battery life. Normally, charges are applied with a steady voltage or current. The charge performance degrades because this kind of technology can't adapt the charge capacity rapidly enough when a storage battery's charging capacity changes. In this paper, a fuzzy PID controller is designed. The battery group can still be charged using the best charging current even when there is a changeable load and interference. The charging controller's viability is supported by simulation results, and the fuzzy PID controller works well. (Xu, 2017).

Lithium ion batteries are a vital type of energy storage, especially in electric cars, because of their enormous capacity. This battery heats up quickly during charging and discharging, which may result in irreversible capacity loss and poor battery performance. This study presents a thermal management system for a lithium ion battery that maintains a regulated temperature process inside the battery pack. Particle swarm optimization (PSO)-based fuzzy logic controller provides a robust control mechanism for the battery temperature management system. Settling time, overshoot, and undershoot are used to measure the system's performance and compare it with the PID and simple fuzzy system in order to validate the results(Hannan et al., 2019).

This study suggests a fuzzy logic-based Li-ion battery model that accounts for temperature influence and state of charge. Because of its versatility and convenience of use, the comparable circuit model for Li-ion batteries has been widely used. However, comparable circuit models now in use rarely account for the temperature effect, which has a significant impact on the performance of electric vehicles (EVs). It is difficult to find a relationship between temperature, state of charge (SOC), and equivalent circuit properties. In this research, we simulate Li-ion batteries using fuzzy logic. The SOC and temperature influence on parameters are stated simultaneously using fuzzy rules in an understandable and straightforward way. The accuracy of the fuzzy logic-based model is shown by simulation and experiment findings, which vary with temperature (Jiani et al., 2014).

It is suggested that non-dissipative equalization based on fuzzy logic control (FLC) be used to lessen the inconsistency of series-connected lithium-ion batteries. The equalization circuit is intended to achieve cell-to-cell equalization for battery packs and paves the way for hardware module-based equalization. With energy transferring inductors, it is a two-stage bidirectional equalization circuit. This work proposes equalization based on state of charge (SOC) using the Extended Kalman Filter (EKF) approach and the Venin equivalent circuit model of a lithium-ion battery. It is advised to use the FLC to reduce energy consumption and equalization time for effective equalization. The FLC technique was created utilizing a series of membership functions to describe the cells' equalization behavior. To verify the benefits of the suggested scheme, a comparison between the proposed FLC and the mean-difference method is conducted (Y. Ma et al., 2018).

An adaptive controller for a battery equalization system for lithium-ion battery packs connected serially is presented in this study. The adaptive neuro-fuzzy technique is implemented using both hardware and software components in the suggested equalization scheme. The adaptive neuro-fuzzy method, when linked with hardware, can be implemented in a way that allows for high-speed response to equalize currents in individual cell equalizers and off-line learning for tracking dynamic reactions on battery packs. The suggested hardware analog controllers provide the output currents that drive the pulse-width-modulation (PWM) signals. For the purpose of training, these output currents are observed via a feedback line. The primary processor uses the adaptive neuro-fuzzy algorithm to provide hardware with adjustable parameters. According to(N. Nguyen et al., 2014), the suggested battery equalization system is flexible and capable of sensing changes in the dynamic reactions of battery cells connected in series.

In order to lessen the consistency of lithium-ion batteries connected in series, this research suggests a non-dissipative equalization method. The series-connected batteries can form a circular energy loop, equalization speed is expedited, and modularization is made easier in an upgraded Buck-Boost equalization circuit. According to the properties of the open-circuit voltage (OCV)-SOC curve for lithium-ion batteries, this article uses voltage and state of charge (SOC) together as equalization variables. The SOC of a lithium-ion battery is computed using a back propagation neural network and a second-order RC equivalent circuit model. To speed up and improve efficiency, fuzzy logic control is employed to dynamically change the equalization current (B. Wang et al., 2020).

This study proposes a new equalization topology that combines a double-layer selector switch with a Cuk equalizer. This design has the advantage of allowing for rapid energy transfer between any numbers of batteries through switch control, thus minimizing the complexity of the energy transmission path. According to the characteristics of the Open Circuit Voltage - State of Charge curve, the piecewise equalization method is adopted, with voltage and State of Charge as equalization variables. The Fuzzy Logic Control algorithm is designed to dynamically adjust the equalization current to reduce equalization time and energy loss. This will help equalize the battery throughout the entire State of Charge range and lessen the influence of inaccurate equalization caused by a single equalization variable. A thorough analysis is conducted on the control technique and topology. Software called Matlab/Simulink is used to create and simulate the model. The experimental results demonstrate that compared with the classic Cuk equalization topology, the equalization topology described in this study can cut the equalization time by 22.17%. Furthermore, the Fuzzy Logic Control method outperforms the mean difference algorithm in terms of time efficiency by over 30% and energy efficiency by roughly 11% in both static and charge-discharge scenarios, indicating the viability of the balancing scheme(Wu et al., 2021).

State of charge estimation method

In order to prolong battery life and maintain the functioning status of the entire battery pack, the BMS can benefit from exact state of charge (SOC) information. This study uses the first-order RC battery model as the research object and thoroughly examines and explains two parameter identification strategies based on the least square method (RLS). The Federal Urban Driving Schedule (FUDS) condition does not suit the model parameters used for the Federal Urban Driving Schedule (HPPC) condition, according to the simulation's results. The model parameters vary through the HPPC situation. To determine the battery's state of charge (SOC), a multi-timescale prediction model is also recommended. In other words, the adaptive unscented Kalman filter (AUKF) is used to predict the battery SOC, and the extended Kalman filter (EKF) is utilized to update the model parameters. Results from experiments conducted at various temperatures demonstrate the superiority of the EKF-AUKF method over other approaches. The algorithm is tested and simulated with various starting SOC faults. The voltage's RSME is within 0.01 V and the SOC's within 1% throughout the entire FUDS operation condition. It suggests that the suggested approach has good robustness and can produce accurate estimation results. Furthermore, the technique can partially remove the sensor accuracy effect, according to simulation findings obtained by introducing noise errors to the current and voltage measurements (Duan et al., 2020).

Optimization of the State-of-Charge (SOC) is a crucial factor in a safe and efficient battery management system. This study provides the highest BMS performance for an electric automobile with a lithium-ion battery. The Kalman filter architecture in this reduces mechanical noise as well as additional voltage and current ripples. The primary objective of this Kalman research project is to determine the necessary sequence, including an appropriate electrical and electronics model, in order to eliminate noise and ripples. Consequently, all existing manufacturers can use the model in its current condition and with its confirmed system architecture, which can be applied to a wide range of problems. From this perspective, we built a design that is faster and more accurate than the Kalman filter design while matching the output source. In light of this, MATLAB Simulink is used to simulate and program the Kalman filter design and its associated electronic components. (Balachander et al., 2021).

This paper suggests a non-dissipative equalization approach to resolve the inconsistency of the series-connected LIB cells. Direct energy transmission between any two individual cells in this configuration is made possible by the dual interleaved inductors in each equalization unit, which increase the equalization speed of a single cell in one equalization cycle by a factor of two. The circuit is compared to three different equalization circuits—the parallel architecture equalization circuit (PAEC), the dual interleaved equalization circuit (DIEC), and the classical inductor equalization circuit (CIEC)—in order to confirm the advantages of the proposed method. The state of charge (SOC) and terminal voltage are both chosen as the equalization criteria in light of the variety of imbalance states. For SOC estimation, the LIB's second-order RC model and the adaptive unscented Kalman filter (AUKF) technique are used. The adaptive fuzzy neural network (AFNN) is used for efficient equalization to further cut down on energy usage and equalization time. According to the experiment's findings, the AFNN algorithm outperforms the traditional mean-difference approach in terms of equalization efficiency, cutting the overall equalization time by around 37.4% and increasing it by about 4.89%. The equalization circuit verification experiment findings, in particular, attest that the suggested equalization structure may significantly speed up equalization progress and minimize equalization loss compared to the other three equalization circuits. (Lei et al., 2022)

2.3 Battery Modeling Algorithm

In this paper, the SoC estimating techniques proposed by academics in the last five years are analyzed critically, along with the main benefits and drawbacks of each technique. Not included here are the techniques that haven't been used frequently recently. The analysis of the various approaches reveals that the most difficult part of obtaining a battery SoC estimation is creating a model that accurately depicts the internal operations of the battery, including the effects of temperature dependencies on internal resistance and capacity fading. The accuracy of SoC estimation may also be affected by factors such as modeling errors, parametric uncertainties, sensor errors, and measurement noise. Self-discharging, aging effects, cell imbalance, capacity fade, and temperature effects are some additional aspects that have an impact on the battery's performance (and thus, the estimation technique). Accuracy and computational complexity must always be traded off in battery modeling, regardless of the technique. (Rivera-Barrera et al., 2017).

LiBs age differently depending on temperature, length, SoC, cycle number, charge rate, and depth of discharge, according to the literature. The accuracy of the SoC estimation is impacted by whether or not these parameters are included in the battery models. The aging phenomenon can be resolved by SoC estimating techniques that update the model parameters continually. The analysis reveals that temperature has an impact on model parameters. For increased SoC estimation accuracy, thermal behavior must therefore be included in the model used for SoC estimation. The model should be as basic as feasible while maintaining an acceptable range of SoC estimation accuracy for real-time electric vehicle applications (Rivera-Barrera et al., 2017).

The ECM is considered to be the ideal model for online estimation, and methods based on artificial intelligence and adaptive filters are offered to precisely estimate the SoC. The main problem with this strategy is that there isn't a chemical or scientific explanation for the tiny movements in the battery. According to reports, the electrochemical model is too complicated to be used for online calculations, even though it might demonstrate the electrochemical mechanism and explain the transfer of charge between two electrodes. Given that EV applications require intensive processing and/or offline learning processes, the review makes it abundantly evident that adaptive filter-based algorithms work better for electric vehicle applications than artificial intelligence-based ones. Artificial intelligence-based optimization approaches are becoming more popular for tackling optimization problems in filter-based procedures due to their ease of use, flexibility, derivation-free process, and avoidance of local optima (Rivera-Barrera et al., 2017).

Further research in this field is required because battery modeling is an essential step towards developing an accurate SoC estimation algorithm, and because the battery modeling techniques proposed in the literature have several limitations regarding aging assessment and are not always sufficiently accurate. During the modeling phase, artificial intelligence, expert systems, and adaptive control technology must be used to build a functional battery. It is imperative to remember that none of the methods we looked at are flawlessly reliable or successful, and that even though they might be full and accurate for certain applications in particular situations, they might not be accurate for other applications. Therefore, it is up to the designer to choose the suitable algorithm, primarily based on his or her understanding of the targeted application. (Rivera-Barrera et al., 2017).

Lithium-ion batteries might be acknowledged as: Systems for storing energy for green technology both high energy and power densities. Accurate battery for development, models in simulation platforms are crucial. Battery-powered system that is effective. This article uses electricity. MATLAB/Simulink was used to create the battery model. Thorough description of the model's structure and lithium-ion battery model Ferro phosphate battery introduction. The model is supported by the outcomes of the experiments. The comparison shows that the created model can accurately forecast current-voltage performance. The model was created for lithium Ferro phosphate batteries, but it is anticipated that it can be used for other battery types as well.(IEEE Industrial Electronics Society. Conference (39th : 2013 : Vienna et al., 2013).

An equivalent circuit model is the most widely used and straightforward technique for illuminating the dynamic behavior of a lithium-ion battery. The literature provides several circuit examples and various approaches to parameterizing the models. In addition to suggesting a second order equivalent circuit, this study explains the parameters identification method using hybrid power pulse characterization (HPPC) testing. The parameter identification and modeling processes take place in the MATLAB/SIMSCAPE environment. This non-linear model captures the dynamic electrical activity of a common vehicle cell. A validation technique is utilized to compare the voltage discrepancies between the estimated voltage profile of the battery cell model and the actual cell measurements. A comparison of measurements and simulations shows good agreement. The current pulse methodology is also provided to validate the ohm resistance values obtained by the optimization procedure in the parameters identification approach. Additionally, studies are conducted to investigate how cell chemistry affects the hypothesized model. (Thanagasundram et al., 2012).

Battery Modeling

The prediction and optimization of some fundamental battery properties, such as charge state, battery lifetime, and charge/discharge characteristic, are made possible with the use of battery modeling. For various application sectors, a wide variety of battery model types have been produced over time.

Various approaches have been proposed for modeling a lithium ion battery, such as the electrochemical, ideal, behavioral, and electric circuit model (ECM) approaches. Five classes can be made out of these techniques.

1. Physics-based models
2. Empirical model
3. Equivalent circuit model (ECM)

4. Electro-chemical model
5. Machine learning models

There are trade-offs between model complexity, accuracy, and parameterization effort when choosing a model from these four groups. Since ECMs accurately capture battery dynamics and require fewer processing resources than alternative techniques, they are frequently employed to control LIBs in battery packs. Since equivalent circuit model (ECM) is simple to utilize in circuit simulators, circuit designers frequently use it. ECM is one of the various battery modeling methodologies that have been published to far (Yu et al., 2020).

For the battery model to generate accurate simulation results for the battery system, it must meet the following criteria:

- Being more straightforward to enable real-time operation.
- Requiring less processing power to conduct simulation testing on the BMS that controls a small number of a pack's parallel and series battery cells.
- Accuracy without complication by using the right model and arrangement.

Physics-based models;-Models based on physics use basic ideas and formulas to explain how the battery behaves. To simulate the performance of the battery, they consider elements including diffusion, heat transport, and electrochemical reactions. These models, which are frequently employed in research and development, necessitate in-depth understanding of the electrochemical characteristics and internal structure of batteries.

Empirical models are data-driven models created using experimental battery performance observations. Regression analysis and statistical approaches are used to link input and output factors and battery behavior. When a fast estimate is needed or comprehensive understanding of the battery's internal operations is unavailable, empirical models are frequently used.

Electrochemical models describe battery activity using mathematical equations derived from electrochemistry principles. They take into account the electrical behavior of the battery, transport phenomena, and chemical reactions that take place at the electrodes. Although they are quite sophisticated and demand a large amount of processing power, electrochemical models offer a thorough insight of battery behavior.

Equivalent circuit model (ECM);-Simplified electrical circuit models that depict battery behavior are called equivalent circuit models, or ECMs. To depict the internal workings of the battery, they combine voltage sources, resistors, and capacitors. Because they offer an excellent balance between computational efficiency and precision, ECMs are frequently utilized in real-world applications.

Machine Learning Models: EV battery models can be created using machine learning methods like random forests, support vector machines, and artificial neural networks. Large databases of battery performance data are used to train these models, which then use the patterns they find to forecast future events. Machine learning algorithms are frequently used to forecast battery health, state of charge, and remaining usable life because they can capture complicated interactions.

In order to explain internal battery conditions, the BMS uses sensors to compute battery metrics (voltage, current, and temperature) as well as the proper battery modeling and estimating approaches. To optimize EV performance and battery life, the charging and discharging algorithms must be developed after the electric and thermal parameters of the battery have been examined. The alarm and safety control module, which must record or get rid of any anomalies in the battery's condition and performance, is another essential part of the BMS.

The four main technologies in a battery management system are:-

1. Battery modeling.
2. Internal state of charge estimation.
3. Battery charging and discharging control.
4. Safety control.

There is a trade-off between model complexity, accuracy, and parameterization effort when choosing a model from these four categories. Because they more accurately capture battery dynamics and need less processing power than alternative techniques, ECMs are frequently employed to regulate LIBs in battery packs. One of the various battery modeling techniques that have been published to date, the equivalent circuit model (ECM), is widely used by circuit designers due to its simplicity of usage in circuit simulators.

For a BMS, the first step is to create the appropriate battery model. The load, age, temperature, and other variables all have an impact on BMS properties like voltage and current while a battery is being charged or drained. While accurate data on the battery's behavior during the charging and discharging cycles must be gathered, it is impractical to get data on the battery's actual activity under all operational conditions for the course of the battery's lifespan. In order to ascertain whether the BMS can operate as intended for the associated battery pack, battery modeling employs an abstract mathematical model of a battery. Research on battery behavior, battery state monitoring, real-time controller design, fault diagnosis, and thermal management is together referred to as "battery modeling."

Since it is believed to be the most widely used method for estimating the SOC, the current integration approach—also referred to as the Coulomb Counting method—is used. It involves monitoring the battery's open circuit voltage at starting to estimate the initial state of charge (SOC) using information from the battery datasheet. Next, by integrating the battery current, an estimate of the amount of charge delivered (or recovered given a charge) by the batteries is obtained. SOC is crucial because, in accordance with the theory of ampere-hour integration, it may accurately represent the energy state. The following is the methodology used to calculate SOC:

$$SOC = \frac{Qc}{Qo} \tag{1}$$

$$SOC = 1 - \frac{Q_T}{Q_O} \tag{2}$$

Qc is the leftover electric quantity, and Qo is the starting electric amount at a certain temperature or the rated charge at a given temperature. The quantity of battery energy that has already been released is denoted by Q_T. The definition of the ampere-hour integral method calculation form is typically used in the calculation procedure. It is impossible to quantify exactly how much electricity a lithium-ion battery releases during a genuine procedure. As a result, its foundation is the discharge current integral accumulative, which represents the quantity of electricity released under the specified conditions.

$$SOC(t) = SOC_O - \int_0^t \frac{\eta I(t)dt}{Q_{rated}} \tag{3}$$

SOC_O Denotes the battery's original state of charge. The efficiency of charging and discharging is indicated by η. Q-rated displays the batteries rated capacity. I(t) shows the value as of that moment. T shows charging when it is less than 0 and discharge when it is more than 0. Lithium-ion batteries have a SOC of 0 to 1. In perfect circumstances, the SOC = 1 for a newly charged battery and = 0 when the charge runs out.

The individual cells inside a battery pack may have distinct states of charge (SOC) during multiple cycles of charging and discharging due to their intrinsically variable capacities. Variations in capacity can be caused by contaminants, aging cells, or exposure to the environment (certain cells may be exposed to extra heat from adjacent sources like motors, electronics, etc.). The accumulation of parasitic loads, such as the cell monitoring circuitry commonly present in a battery management system (BMS), can exacerbate these variances by allowing cells from different production runs to be mixed together.

Optimizing a multi-cell pack's capacity and service life involves balancing each cell to maintain an equal state-of-charge over the widest range feasible given its different capacities. Packs that have multiple cells in series are the only ones that require balancing. Parallel cells will naturally balance because they are physically connected to one another; however, groups of parallel wired cells that are wired in series (also known as parallel-series wiring) must be balanced throughout cell groups.

2.5 Review Summary

Passive equalization, which involves connecting energy-consuming parts like resistors in parallel to each cell, is a reasonably simple circuit to incorporate in a balancing cell. The resistance circuit's matching switch closes when the single cell's voltage is too high, allowing current to pass through the resistor and converting the battery's surplus energy into heat loss. The equalization current of this passive equalization circuit is difficult to manage, and it has numerous other drawbacks. The topic of fixed and switching shunting resistance for passive cell balancing is covered.

Typically, active equalization transfers energy between the cell and the battery pack or between the cell and the cell itself using active components like transformers, inductors, and capacitors. Although this technology significantly increases the rate of energy use and decreases energy waste, there are certain drawbacks, such as a somewhat complex control mechanism. This article review uses a variety of switching devices and control algorithms to control the equalization process.

Numerous equalization control schemes have been developed, as can be seen above, however the necessary level of equalization efficiency is not at required level. Thus, the controller needs to keep an eye on and regulate the battery's current during its charging, discharging, and static phases in addition to providing a real-time state-of-charge estimation. Therefore, it is preferable to use an appropriate equalization control to make it easier to apply the equalization strategy and provide a more precise and quick balance.

2.6 Research Gap

In a battery pack consisting of multiple lithium batteries, the overall capacity of the pack is determined by the battery with the smallest capacity. This means that if there is a significant difference in capacity between the batteries in the pack, it can lead to imbalanced charging and discharging during use. At present, there are three commonly used indicators for battery equalization in lithium battery packs: battery voltage, battery capacity, and Battery State of Charge (SOC).

- Battery voltage-based equalization: This technique equalizes the unusual battery voltage in the battery packs. Numerous studies employ battery voltage as an evaluation index since it is simple to measure and understand(S. Zhang et al., 2020).
- Battery capacity is the basis for the equalization technique, which uses improved capacity utilization as the research goal and battery capacity as the research object. This approach is the most appropriate for equalization since it maintains the battery's capacity over time. However, battery capacity is not appropriate for online balancing because it can only be obtained in static settings. As such, the battery capacity-based technique is no longer in use.
- Battery SOC-based equalization: This method's basic idea is to balance batteries in various states. This control method's hardware circuit is straightforward, and series batteries benefit more from the equalization effect.(X. Ma et al., 2019).

Various scientists work on cell balance utilizing different parameters and control algorithms, according to a survey of the literature. However, they do not use a fuzzy-PID controller for such application. By employing a fuzzy-PID controller for cell equalization, it is possible to optimize the equalization time, energy consumption, and safety of an electric vehicle's lithium-ion battery pack. The fuzzy-PID controller can adaptively adjust the equalization process based on real-time battery conditions, such as cell voltages, and state of charge (SOC). This adaptive control approach can potentially improve the efficiency and effectiveness of the equalization process.

CHAPTER THREE

3. METHODOLOGY

3.1 Introduction

One of the most crucial parts of an electric car is the battery management system. Compared to traditional cars, such those with internal combustion engines, EVs have many benefits, such as efficiency, a high energy density, rapid acceleration, less pollution, and more. However, a significant problem with batteries is their long charging times and gradual deterioration.

The sophisticated battery system formed by battery packs with hundreds of battery cells connected in series or parallel is used to meet the high power and voltage needs of electric vehicles. Overcurrent, overvoltage, overcharging, and over discharging are improper battery conditions that deteriorate batteries, speed up their aging process, and—most importantly—present a risk of fire and explosion. For these reasons, a battery management system, or BMS, is required to protect a battery and boost battery efficiency. BMS makes use of battery status data to guard against battery deterioration.

3.2 Materials

The development and simulation of a fuzzy-PID controller for cell equalization in lithium-ion batteries used in electric vehicles is done using the following tools.

Across sectors, there is an increasing need for battery management systems (BMSs) that can ensure maximum performance, safe operation, and optimal longevity under a variety of charge-discharge and environmental situations. To accomplish these objectives, engineers design supervisory control and a feedback algorithm in a BMS is;

- Keep an eye on state of charge and cell voltage.
- Calculate the state of health (SOH) and state of charge (SOC).
- Limit power intake and output for protection against overcharging and heat.
- Manage the charging profile for batteries.
- Maintain each cell's level of charge in balance.
- When required, load the battery pack and isolate it from the source.

This paper describes how engineers develop BMS algorithms and software using Simulink system-level simulations. You can learn more about the dynamic behavior of the battery pack and reduce design errors while exploring software architectures, testing operational situations, and initiating hardware testing early on with Simulink and model-based design. The BMS model serves as the basis for all design and development tasks in Model-Based Design, including formal verification and validation against industry standards, code generation for hardware implementation and real-time simulation, and desktop simulation of the functional aspects of the design.

Building physical prototypes is more expensive, time-consuming, and risky than using MATLAB, Simulink, and Sims Cape for modeling and simulation. We can identify the algorithms or charging strategies that work best for a certain design without having to run the complete system. We might also optimize designs for certain uses and usage patterns in addition to testing scenarios that would be dangerous or challenging to test on real batteries. Through simulation, errors that are overlooked in system-level testing are often discovered. Additionally, our clients can evaluate battery packs and battery management systems for their energy storage systems for residences, offices, and other structures using our models.

3.2.1 MATLAB

The following steps can be used to utilize MATLAB Simulink to model the equivalent circuit of a battery cell and simulate its behavior.

First, identify the cell's equivalent circuit model based on the properties and parameters of the battery cell. The voltage source, internal resistance, capacitance, and other relevant circuit components must all be represented in order to fully depict the behavior of the battery cell. After the circuit model has been created, you may utilize MATLAB Simulink to implement the model by using the required Simulink library blocks and components.

Next, you will connect the pieces to form the complete analogous circuit model of the battery cell. To do this, the voltage source, resistance, capacitance, and other components must be connected correctly in line with the circuit model's description. It is also necessary to configure the model's attributes, including resistance and capacitance, to match the specifics of the battery cell that is being represented.

Once you've completed modeling the battery cells, you may assemble a battery pack by duplicating the model of each cell in the pack. This can be done by encapsulating the different cell models within Simulink subsystems, or by reproducing the battery cell model. The battery cells can be connected either in series or parallel, depending on the desired pack layout. To ensure that cell voltages are equalized, you can additionally add balancing circuits and controllers for optimal performance. These elements can be included in the battery pack model by using the appropriate Simulink blocks and fuzzy-PID control techniques.

Once the battery pack model is constructed, you may configure the model's input signals, like voltage profiles or load currents, to simulate the behavior of the battery pack under various operating conditions. After setting up the variables, including the solver selections and simulation duration, run the simulation. Consequently, the simulation data will be generated, which can then be analyzed to ascertain the state of charge (SOC), voltage response, current flow, and other crucial features of the battery pack. To ensure accurate depiction and desired performance, you can make any necessary adjustments to the model and simulation settings depending on the simulation results. You may construct a battery pack, precisely model a battery cell, and simulate the behavior of the battery pack while accounting for balancing circuits and control algorithms by using the features of MATLAB Simulink. This lets you assess how well the battery pack performs in different operating conditions and optimize it for a range of uses.

Tools Used

- ✓ MATLAB
- ✓ Simulink
- ✓ MATLAB Coder
- ✓ SIMSCAPE
- ✓ Simulink design optimization

3.3 Methods

The project's general and specific objectives must be achieved through the application of several processes or approaches. The multiple steps of the process are summarized and listed in Figure 3.3.1. It illustrates the steps taken to finish the study. A more thorough explanation of the modeling and simulation phase of the methodologies is provided in chapter four.

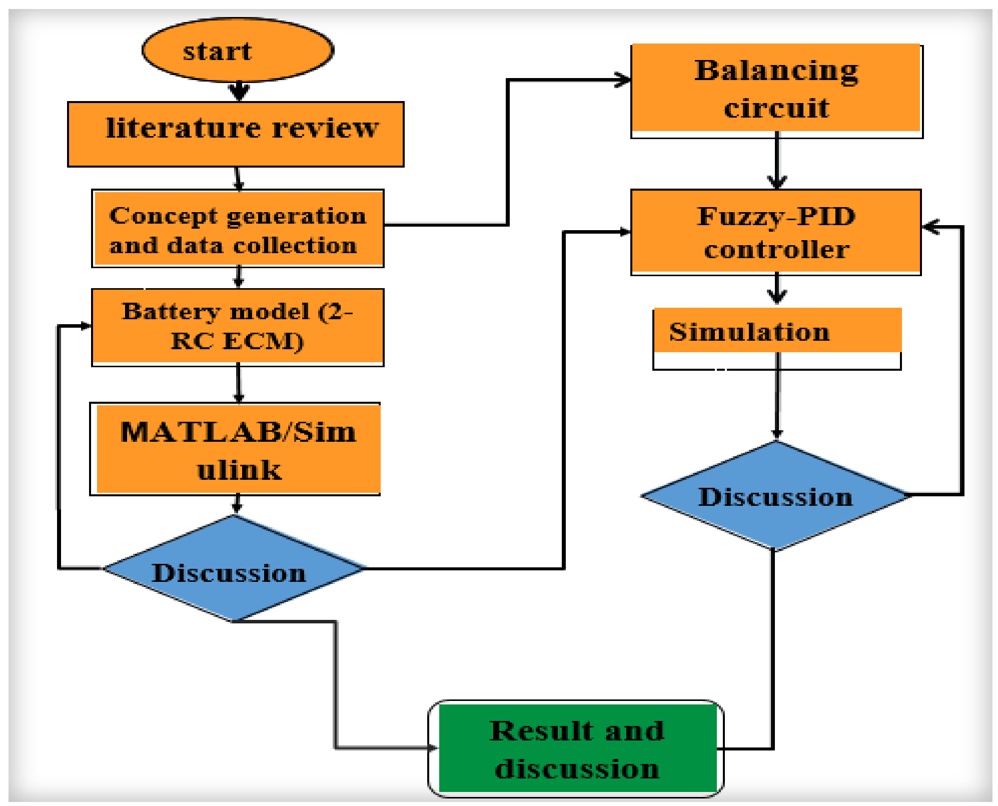


Figure 3-3-1. Procedure of study

3.4 Literature review and problem identification

To gain a comprehensive understanding of the thesis, literature reviews were carried out to identify existing research on the subject, as well as its faults and gaps. The thesis was compiled and examined recent analyses and research in the area of fuzzy-PID controller design and simulation for battery cell equalization.

3.5 Data collection

In order to model battery cells and create fuzzy-PID controllers, the necessary data is collected. Numerous data were collected in order to comprehend the research's current stage. The information is displayed as follows. Therefore, the collected data for modelling and simulation of fuzzy-PID controller is based on the primary and secondary types of Data.

Primary data

The Primary data has been collected for the purpose of this study is from Manufacturer, EEMB Co., Ltd. Battery Model: LIR18650 2600mAh

Specification of lithium ion battery

The required information and technical specifications for the vehicle's current lithium-ion battery have been gathered. Table 3-1 contains all of the lithium ion battery's relevant data.

Parameters	Value
Nominal battery voltage	2.7V
Battery capacity	50 Ah
Inductor L1 and L2	100µH
Capacitor C1 and C2	20µF
Internal resistance	≤70mΩ
Discharge cut-off voltage	3.0V
Maximum voltage charge	4.20±0.05V
Standard charge current	0.52A
Standard discharge current	0.52A
Rapid charge current	1.3A
Rapid discharge current	1.3A
Weight	46.5±1g
Max. Dimension	Diameter(Ø): 18.4mm
	Height (H): 65.2mm
Operating Temperature	Charge: 0 ~ 45℃ Discharge: -20 ~ 60℃
Storage Temperature	During 1 month: -5 ~ 35℃ During 6 months: 0 ~ 35℃

Table 3-1 specification of battery

Secondary data

Secondary data is pre-existing information that has been gathered for a different reason by another party but is still useful for analysis or research. Secondary data in the context of lithium-ion batteries for electric vehicles can include material from earlier research projects, publications, databases, and other publicly accessible sources (Xie et al., 2023). The information is displayed as follows.

SOC	R0/Ω	R1/Ω	C1/F	R2/Ω	C2/F	OCV
0.0487	0.005292	0.4171	23.9764	0.04371	228.6317	2.22364
0.1004	0.005577	0.02978	335.7438	0.06475	23.5916	2.81708
0.1521	0.005646	0.04562	219.224	0.02269	128.5149	2.961
0.1935	0.005662	0.02131	67.6939	0.002178	4590.3958	3.18956
0.2452	0.005677	0.01543	79.322	0.01766	566.2021	3.2132
0.2969	0.005678	0.01374	728.0466	0.01311	130.0763	3.43552
0.3486	0.005685	0.01137	879.686	0.14011	6.5	3.54644
0.4003	0.005685	0.007003	1427.9438	0.01003	266.2991	3.65796
0.452	0.005677	0.00512	1953.125	0.008974	256.8798	3.7624
0.483	0.005685	0.008435	178.1069	0.004103	2437.1954	3.86588
0.545	0.005692	0.007531	162.1747	0.002763	3619.1537	3.97356
0.5967	0.005685	0.006948	1439.327	0.003898	1062.1626	3.98112
0.6484	0.005692	0.003034	549.896	0.006423	1556.886	3.99432
0.7001	0.0056923	0.0059723	267.946	0.0025323	3948.9672	4.00452
0.7518	0.005692	0.002048	4883.5462	0.00558	1792.1147	4.00992
0.8035	0.005692	0.0017538	5701.754	0.005237	1909.5182	4.01244
0.8552	0.005685	0.004931	238.1645	0.0015523	6442.0218	4.0158
0.8966	0.005685	0.004735	2122.3944	0.001449	6903.748	4.02264
0.9483	0.0056846	0.0025569	3911.3418	0.004569	2188.771	4.04376
1	0.0056154	0.04826	110.626	0.005362	1865.136	4.32

Table 3-2 the impedance resistance and impedance capacitance values of lithium-ion batteries for the second-order RC model.

3.6 Concept generation

The idea creation process yields a number of product concepts, from which we create the final designs and specifications. Various concepts are developed for the modeling and construction of battery model and the fuzzy PID controller for the lithium-ion battery of an electric car. This includes controller design, battery modeling, and determining the battery's state of charge; these subjects will be elaborated upon in the upcoming chapter.

3.7 Decision

At this stage, the controller simulation's reaction is evaluated using engineering analysis based on scope and decision techniques. If the results were good, the thesis will proceed to the next phase; if not, the fuzzy-PID controller is modified and optimized again.

CHAPTER FOUR

4. BATTERY MODELLING

4.1 Introduction

Battery models are similar to a route plan for equalization circuit builders. They provide valuable insights into the characteristics and actions of the batteries employed in energy storage systems. Just like a map helps travelers find their way, accurate battery models allow circuit designers to control energy consumption and avoid potential pitfalls like overcharging or over-discharging.

These models offer a wealth of vital information to circuit designers. One crucial piece of information is the State of Charge (SOC). The term "SOC" refers to the battery's remaining capacity, which helps designers estimate remaining energy and create strategies accordingly. It's like being aware of how much gas is left in a car.

Another important consideration is the current flowing into or out of the battery. Determining the rate at which a battery charges or discharges and comprehending the energy flow rely on this current. It's like measuring the water flow of a river to find out how much electricity it can generate.

Another crucial statistic that battery models provide is voltage. It is closely related to SOC and shows the battery's electrical potential. Just as a voltmeter keeps track of the electrical potential in a circuit, voltage data helps estimate the battery's health and power delivery capacity.

Protections against overcharging and over discharging are often included in battery versions. These protections are necessary to ensure the battery's longevity and security. They act as safety barriers to prevent the battery from being overcharged, much like speed limits on roads help prevent accidents.

The chemistry of the battery, temperature, the effects of aging, and discharge/charge behavior are just a few of the factors that must be considered in an accurate battery model. It's like trying to fit all the jigsaw pieces together to make a picture. Circuit designers will be able to make informed decisions throughout the design process if they select or develop an accurate battery model. They may assess the battery's longevity, use less energy, and implement effective battery management strategies. It's like having a reliable compass that directs folks toward safe and reliable battery-operated alternatives.

4.2 Equivalent circuit model (ECM)

Equivalent circuit models, or ECMs, are widely used to represent the dynamic behavior of batteries. These models use resistors and capacitors in an electrical circuit to simulate the properties of the battery. ECMs are widely used primarily because they are straightforward and simple to utilize.

The most basic ECM consists of a single constant voltage source connected in series with an internal resistor. This model is easy to use and provides a simplified explanation of the battery's behavior. It may not be as helpful, though, in analyzing the battery's dynamic performance.

The dynamic behavior of a battery can be better represented by using more complex ECMs. These models also include other parts, such as capacitors, to simulate the internal dynamics of the battery. The capacitors account for the diffusion and polarization effects of the battery. These additional components give the ECM a higher level of sophistication and allow it to more precisely define the battery's performance.

More complex ECMs provide better accuracy, but they can also increase the complexity of parameter estimations and circuit design. Thus, the ECM complexity to be utilized depends on the specific goals of the study and the intended trade-off between simplicity and accuracy.

As a result, several articles introduce 2-RC or 3-RC equivalent circuit models, which are frequently employed in advanced BMS and are especially useful in SOC or SOH estimates. The equivalent circuit, which is utilized to simulate lithium-ion cells here and is shown in Figure 4.4, is constructed using customized Sims cape blocks. The OCV Sims cape block, whose value changes with temperature and cell SOC, represents the open circuit voltage. In this block, the Coulomb integration method is also used to determine the cell SOC. The R0 Sims cape block represents the internal resistance of electrodes, electrolytes, separators, and current collectors. A 3D lookup is necessary since the R0 value changes as a result of the cell's SOC, temperature, and current flow

The MATALAB SIMULINK blocks R1 and C1 make up the first RC couple, which represents the charge transfer process occurring in the negative and positive electrodes. Using the R2 and C2 MATALAB SIMULINK blocks, the second RC pair illustrates the diffusion of lithium ions both inside and outside the active electrode material. R1, C1, R2, and C2 levels are also subject to variation based on temperature and cell state of charge.

The mathematical relationship between the constituent parts of lithium-ion batteries and their V-I characteristics, state of charge (SOC), internal resistance, operating cycles, and self-discharge is demonstrated via a model of lithium-ion batteries. The equivalent circuit model of a lithium-ion battery is a performance model that constructs an electric circuit using one or more parallel combinations of resistance, capacitance, and other circuit elements in order to imitate the dynamic properties of lithium-ion batteries. The electrical equivalent models that are utilized most frequently are constructed via time domain analysis. Open Circuit Voltage (OCV) is the simplest expression for the battery model.

$$v(t) = OCV$$

Figure 4-2-1.Open circuit voltage

When a cell is fully charged, its SO0C is 100%, and when it is entirely drained, its SOC is 0%. The whole capacity, expressed in Ah or mAh, is the amount of charge that has been taken out of the range of 100–0%. The following lists the models used to gauge lithium-ion battery system performance.

4.2.1 Rint model

The most common battery design is seen in Figure 4-2. It consists of an open circuit voltage (OCV) of V0, an equivalent internal resistance Rint, and a hypothetical battery with a terminal voltage of v t. Once the battery is fully charged, the open circuit voltage and the terminal voltage and current, respectively, can be measured in order to calculate the terminal voltage (v (t)) and terminal current (Rint).

When a cell is fully charged, its SOC is 100%, and when it is totally drained, its SOC is 0%. The fee subtracted from 100-0% is total capacity (Q) expressed in mAh or Ah.

$$v(t) = OCV\big(z(t)\big) - i(t)Rint \tag{4}$$

$$\frac{dz}{dt} = -\frac{i(t)}{Q} \qquad (5)$$

$$z(t) = z(t0) - Q\int_{to}^{t} i(T)dT \qquad (5)$$

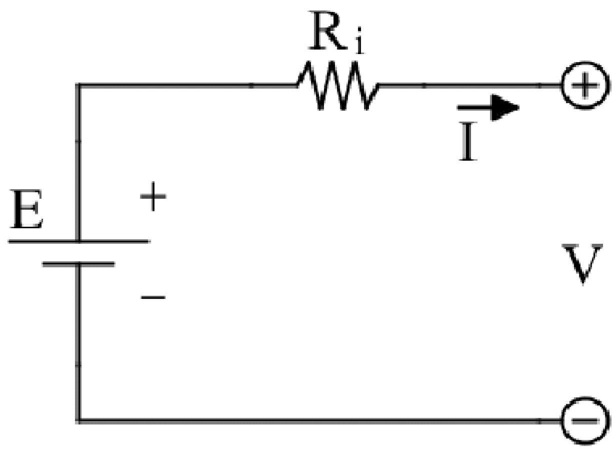


Figure 4-1-2. Rint Model

When a battery is fully charged, its Open Circuit Voltage is higher than when it is discharged. Although the Rint model appears to be relatively simple, it ignores the relationship between temperature, charge state, and electrolytic concentration and internal resistance.

4.2.2 Thevenin battery model

Figure 4-3 displays the schematic for the resistive Thevenin battery model. The two distinct internal resistance types in this model, R0 and R1, respectively, are related to the battery's charging and discharging properties. Both electrical and non-electrical losses are modeled by the internal resistances R0 and R1. Diffusion voltages can also be located closely by using one or more RC parallel branches.

Although transient phenomena like the capacitance effect are not taken into consideration, the model performs better than the Rint model. This model is unsuitable for use in applications involving electric vehicles and electric hybrids because it lacks dynamics. Diffusion voltage, or the gradual drop in voltage to zero during relaxation mode, can be approximated to a high degree using parallel RC branches (Figure 4-3).

$$v(t) = OCV\big(z(t)\big) - i(t)Rint - Vc1(t) \qquad (6)$$

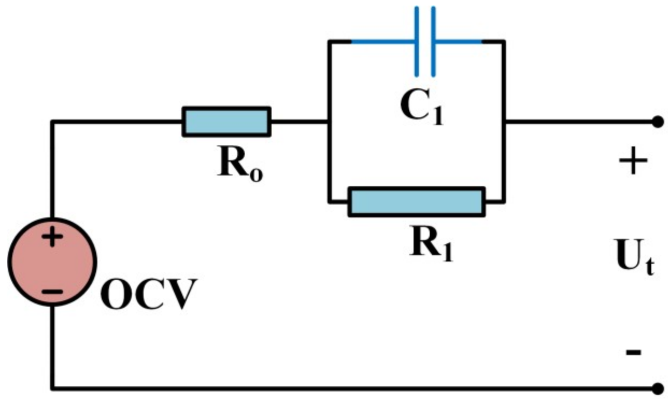


Figure 4-2-2 Thevenin Battery Model

4.2.3 2-RC Equivalent circuit model

To effectively depict the characteristics and behavior of lithium-ion batteries, an analogous circuit model can be utilized. Using a range of circuit components, such as resistors, capacitors, and other parts, this model simulates the dynamic properties of lithium-ion batteries (Raszmann et al., 2017). The analogous circuit model considers several significant factors that impact the performance of lithium-ion batteries, such as:

1. V-I's characteristics; - the voltage-current (V-I) relationship of the battery is a key element of the model. It shows how the current flowing through a battery and its terminal voltage are related. This relationship explains the internal resistance and voltage drop of the battery under different load conditions.
2. State of Charge (SOC): The battery's state of charge (SOC), or the amount of charge remaining in the battery in relation to its full capacity, is taken into consideration by the model. The SOC affects the voltage and capacity of the battery in addition to determining its behavior and efficiency.
3. Internal Resistance: One important model parameter is the internal resistance of the battery. It accounts for the resistance encountered by the battery when it is being charged and discharged. The internal resistance of the battery affects not just the voltage drop and power loss but also the battery's overall performance. The graphic below illustrates how a battery's internal resistance increases during the first 20% of its state of charge and then nearly stabilizes.

During the early stage of discharging a battery, especially when it is at a high state of charge, the internal resistance tends to be lower. This is because the electrochemical reactions within the battery are more efficient, and the electrolyte and active materials are in closer proximity, allowing for better ion transport and lower resistance. However, as the battery discharges and the state of charge decreases, several factors can contribute to an increase in internal resistance. These factors include:

Electrochemical processes: As the battery discharges, the chemical reactions occurring at the electrodes can lead to the formation of passive layers or depletion of active materials. These changes can increase the resistance of the electrochemical interfaces, leading to higher internal resistance.

Ion transport limitations: As the battery discharges, the concentration gradients of ions within the electrolyte can become more pronounced. This can result in increased resistance to ion transport, leading to higher internal resistance.

Structural changes: Some battery chemistries, such as lithium-ion batteries, can experience structural changes within their electrode materials during cycling. These changes, such as particle cracking or electrolyte decomposition, can contribute to an increase in internal resistance

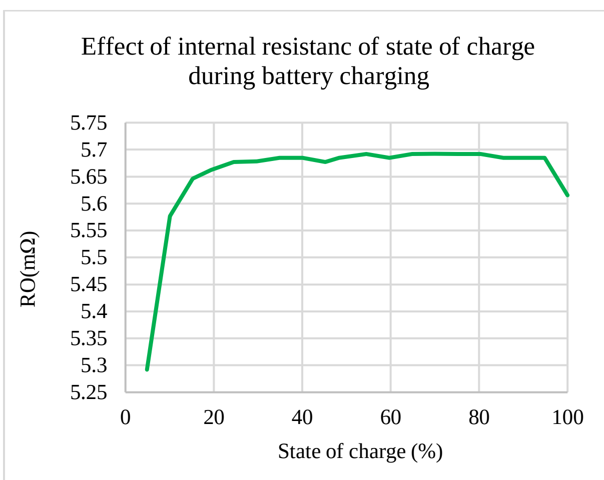


Figure 4-2-3 Effect internal resistances on state of charge

4. Operating Cycles: Lithium-ion batteries experience charge-discharge cycles when in use. The analogous circuit model considers how the battery behaves during operating cycles, accounting for variations in capacity, efficiency, and deterioration over time.

5. Self-Discharge: Self-discharge is a phenomenon that causes lithium-ion batteries to lose charge even when they are not connected to a load. The model includes self-discharge characteristics to explain the gradual decrease in charge over time.

Several parts make up the dynamic equivalent circuit model (Figure 4-2-4), which depicts the dynamic behavior of a battery. Two RC parallel networks (R1, C1, R2, and C2), a series resistance (RS), and a DC voltage source are all included in the model. Each part serves the following purposes:

1. DC voltage source: This shows the open circuit voltage (OCV) of the battery. The voltage of the battery when no current is flowing through it is known as its OCV.
2. Series resistance (RS): The series resistance is an indicator of the internal DC resistance of the battery. It accounts for the losses and voltage dips caused by internal resistance in the battery.
3. R1, C1, R2, and C2 parallel networks (RC): These components explain the transient response of the battery's voltage. The RC networks represent the time constants associated with the internal dynamics of the battery.

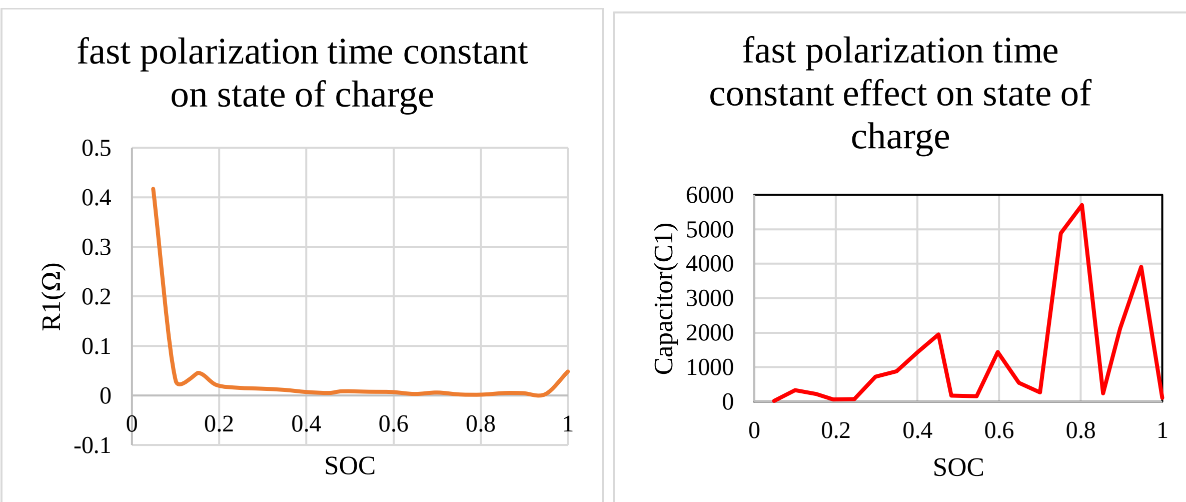
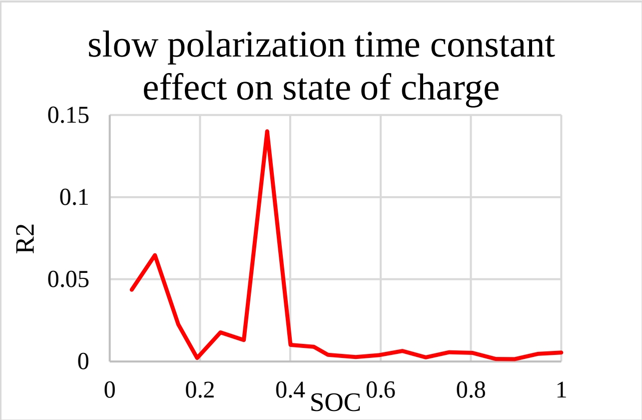


Figure 4-2-4 Dynamic changes in battery performance during transient operations

The dynamic changes in a battery's behavior can be affected by the state of charge. For example, as the battery discharges and the state of charge decreases, the concentration gradients of ions within the battery increase. This can lead to slower diffusion rates and increased resistance to ion transport, resulting in slower dynamic response and potentially longer charge transfer times.

On the other hand, during charging, the state of charge affects the availability of active material and the extent of passivation layers. These factors can influence the dynamic behavior of the battery as it approaches higher states of charge.



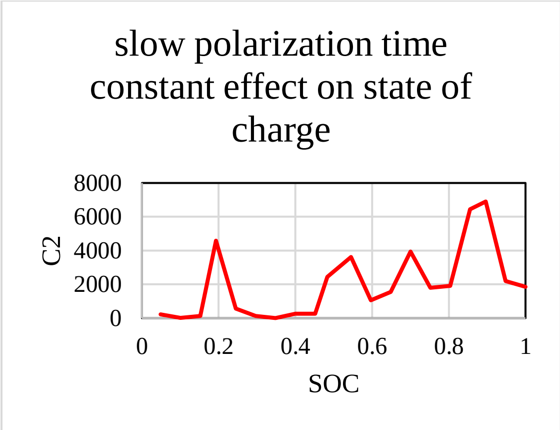


Figure 4-2-5 slow polarizations in a battery's performance over time

The slow polarization characteristics of a battery can also be influenced by the state of charge. As the battery cycles between various states of charge, irreversible side reactions can occur, leading to the formation of passivation layers or degradation of active materials. These slow processes can gradually increase the internal resistance and decrease the battery's overall performance, affecting its energy capacity and power output.

Furthermore, the state of charge at which a battery is stored can also impact slow polarization. High states of charge during storage, especially for extended periods, can accelerate certain degradation mechanisms and lead to increased polarization and reduced battery performance when the battery is eventually put to use.

It's important to note that the specific dynamics and slow polarization characteristics can vary depending on the battery chemistry, design, and operating conditions. Different battery technologies exhibit different time-dependent behaviors, and understanding these phenomena is crucial for optimizing battery performance and lifespan.

4. The terminal voltage (VT), which represents the voltage across the battery terminals, is the model's output. It offers details on the voltage that battery-powered systems can use or measure.

The model also accounts for the rate capacity impact, which is the variation in the battery's usable capacity with current. This effect acknowledges that the current being delivered to the battery when charging or discharging determines how well it transfers energy.

The state of charge (SOC) of the battery can be ascertained by calculating its usable capacity. The SOC of the battery indicates how much of its total capacity is still usable. By taking the SOC and current into consideration, the model's parameters can be adjusted to account for variations in battery performance under different operating situations.

It's important to keep in mind that the SOC and current have an impact on the values of the model parameters, such as resistance and capacitance values. The battery's behavior at different charge and current levels is precisely captured by these variables, allowing the model to represent the battery's dynamic features.

$$v(t) = OCV\big(z(t)\big) - i(t)Rint - Vc1(t) - Vc2(t) \tag{7}$$

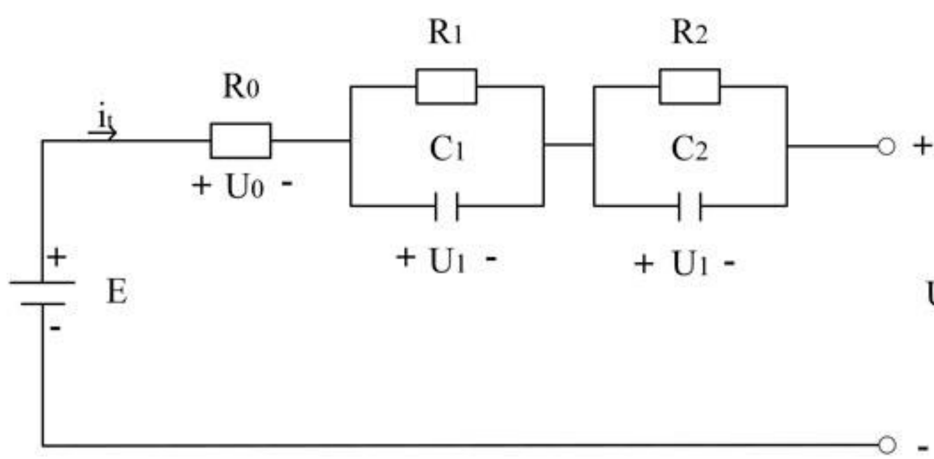


Figure 4-2-6. 2-RC Battery Model

The purpose of the suggested MATLAB/Simulink simulation model in Fig. 4-2-7 is to mimic battery behavior. The model consists of five subsystems: SOC computation, OCV calculation, RC values, Voltages of RC Parallel Networks, and VRS. The battery's terminal voltage (VT) is simulated using a controlled voltage source, and the current value is ascertained using a current measuring block. The initial state of charge (SOC) is known as SOC0, and the real-time SOC is called SOCn.

The SOC computation subsystem determines the battery's state of charge (SOC). To update the SOC in real-time (SOCn), it incorporates the initial SOC and the measured current over time as inputs. The OCV computation subsystem determines the battery's open-circuit voltage (OCV). It takes the SOC as input and uses a lookup table or predefined relationship to find the equivalent OCV.

The RC values subsystem establishes the resistor (R) and capacitor (C) values for the RC parallel networks in the equivalent circuit model. The current and SOC could cause these figures to fluctuate. The subsystem makes use of lookup tables or calculations to provide the correct values. The Voltages of RC Parallel Networks subsystem is used to calculate the voltages across the RC parallel networks. The computed RC values and the OCV are used as inputs, along with the current and time constants associated with the RC networks, to determine the voltages across each RC parallel network.

The voltage across the series resistance (RS) is determined by the VRS subsystem in the comparable circuit model. Using the current measurement and RS value, one can determine the voltage drop across the internal resistance.

The outputs of the subsystems are combined to form the terminal voltage (VT) of the battery, which is represented by a controlled voltage source. This voltage source is regulated by the series resistance and the expected voltages across the RC parallel networks.

Researchers and engineers can examine how well the battery performs under various current profiles, SOC levels, and circuit topologies by simulating this model using MATLAB/Simulink. The dynamic response of the battery's voltage and state of charge (SOC) may be studied using this simulation, which offers important insights for battery-powered product circuit design and efficient energy management.

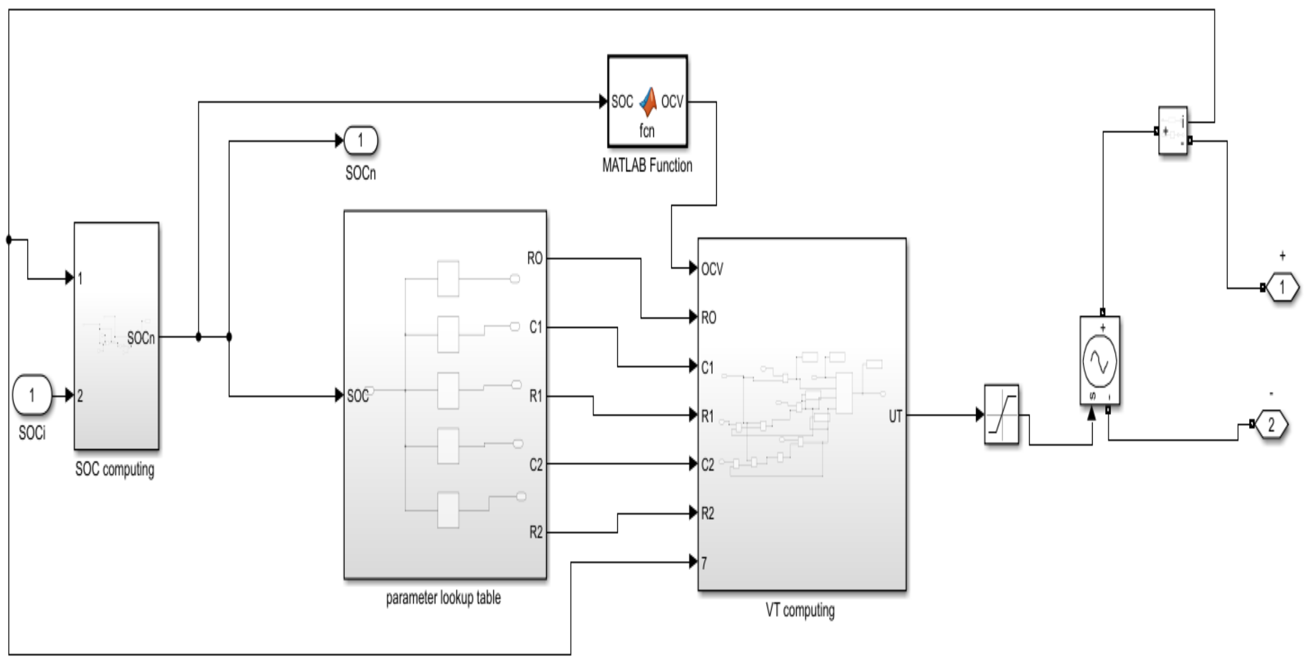


Figure 4-2-7. MATLAB/Simulink 2-RC Battery Model

4.2.4 State of charge estimation

The goal of the SOC computation subsystem in the proposed simulation model is to determine the battery's state of charge (SOC). Its two inputs are the starting SOC (SOC0) and the current measurement. The current measurement indicates the actual current entering or leaving the battery at any given moment. This data can be obtained using a current sensor or measurement instrument connected to the battery circuit.

The value of the SOC at the start of the simulation or at a specific time is known as the initial SOC (SOC0). It provides the initial frame of reference for computations of SOC. The SOC computation subsystem updates the SOC in real-time (SOCn) by combining the current across time. The instantaneous current values at each time step are added during integration to get the total charge transported into or out of the battery. The SOC calculation subsystem dynamically modifies the SOC value by continuously integrating the current measurement over time to track the accumulated charge. This makes it possible to monitor and assess how the battery's state of charge (SOC) changes over time and under different load conditions.

The integration procedure considers the charging and discharging of the battery. When the current is positive (indicating charging), the integration increases the SOC value, indicating a rise in the battery's stored energy. On the other hand, when the current is negative (indicating discharging), the integration decreases the SOC value, which represents the loss of the battery's stored energy.

By including the current measurement and integrating it over time, the SOC calculation subsystem allows the simulation model to track and accurately represent the battery's state of charge in real time. This data is crucial for assessing battery performance, figuring out remaining capacity, and optimizing battery use in a variety of applications.

SOC is found using equation (8), where SOC (i) is the initial SOC, I is the current, and Cn is the useable capacity. The architecture of the SOC compute subsystem is shown in Fig. 4-2. The starting SOC (SOC (ti)) and current (I) are the two inputs of this subsystem, respectively. The battery's impact on rate capacity is represented by a lookup table that illustrates how the usable capacity (Cn) changes with current. The real-time SOC is this subsystem's output.

$$SOC(t) = SOC(t_i) - 1/cn \int_{t0}^{t} i(t)dt \qquad (8)$$

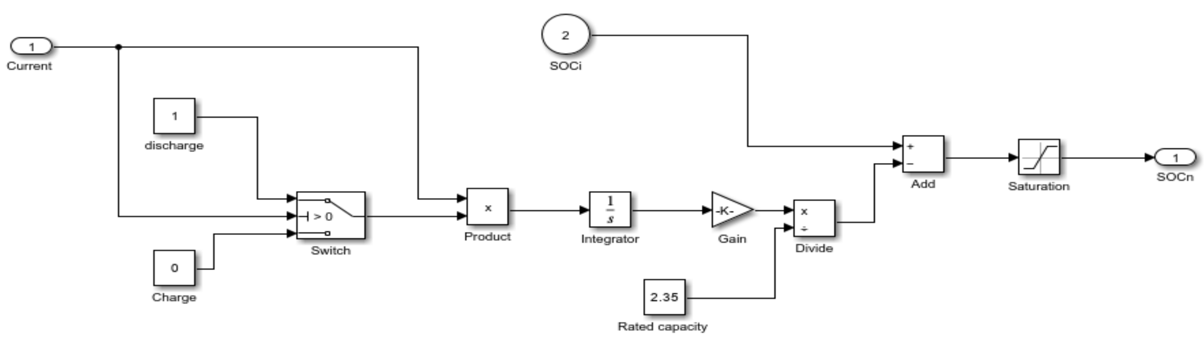


Figure 4-2-8. MATLAB/Simulink, SOC Computation Subsystem

4.2.5 Open circuit voltage (OCV) calculation

The open circuit voltage (OCV) of a battery, which represents the voltage at equilibrium when no current is flowing, is a crucial consideration in battery modeling. The OCV value is affected by the battery's state of charge (SOC).

The mathematical relationship between OCV and SOC in the given simulation model can be understood using polynomial equations. These formulas capture the nonlinear behavior of the OCV-SOC connection, allowing for a more accurate characterization of the battery's voltage characteristics.

A block diagram (Fig. 4-2-9) illustrates the mathematical relationship between OCV and SOC within the OCV calculation subsystem. The block diagram illustrates how the corresponding OCV is calculated using the polynomial equations and the SOC value as an input.

The polynomial equations can be obtained using battery characterization techniques or experimental data. By fitting the polynomial equations to the measured OCV-SOC data points, a mathematical model that can forecast the OCV value for any given SOC within the battery's allowable operating range can be created.

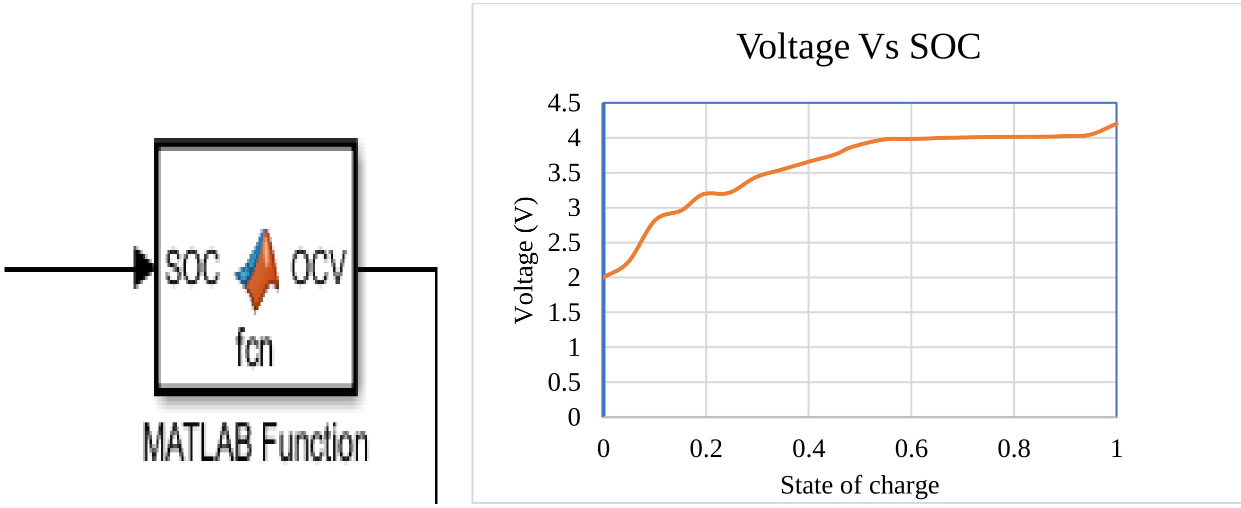


Figure 4-2-9. MATLAB/Simulink, mathematical relationship between OCV and SOC

By integrating the OCV calculation subsystem with its polynomial equations and the SOC input, the simulation model can dynamically calculate the OCV value corresponding to the current SOC. This is an essential component for determining the terminal voltage of the battery and how it will respond to different operating conditions.

4.2.6 Resistance-Capacitor values

The parameters of the RC parallel networks (R1, C1, R2, and C2) in the proposed simulation model depend on the state of charge (SOC) and the current flowing through the battery. These parameter values are computed using a system component called RC values. Figure 4-8 shows a block diagram that determines the parameters of the RC parallel networks using 1-D lookup tables. Using 1-D lookup tables, the SOC and current values are transferred to the appropriate parameter values for R1, C1, R2, and C2.

The useful method of storing and retrieving parameter values using 1-D lookup tables is based on the SOC and current inputs. These tables, which show the link between the RC network parameters and the battery's SOC and current, can be made using analytical models or real data.

Using the provided SOC and current, the lookup tables enable the simulation model to determine the ideal parameter values for the RC parallel networks. In situations where the lookup table may not contain the precise SOC and current values, the interpolation-extrapolation lookup approach is employed. This method predicts the parameter values for the given inputs by using the nearest data points in the lookup table. The output parameter values from the lookup tables are used to configure the RC parallel networks in the simulation model. These networks are essential for capturing the dynamics and transient behavior of the battery's voltage response to variations in current and charge level.

To provide a visual representation for the data from the lookup table, a 3-D graphic is created. This graph illustrates how various combinations of SOC and current impact the RC network's parameter values. This depiction facilitates comprehension of the relationship between the RC network characteristics and the battery's operating conditions.

Using 1-D lookup tables and the interpolation-extrapolation lookup technique, the RC values subsystem in the simulation model dynamically determines the proper parameter values for the RC parallel networks depending on the SOC and current inputs. This makes the simulation results more realistic and makes it possible to see the behavior of the battery in a more realistic way.

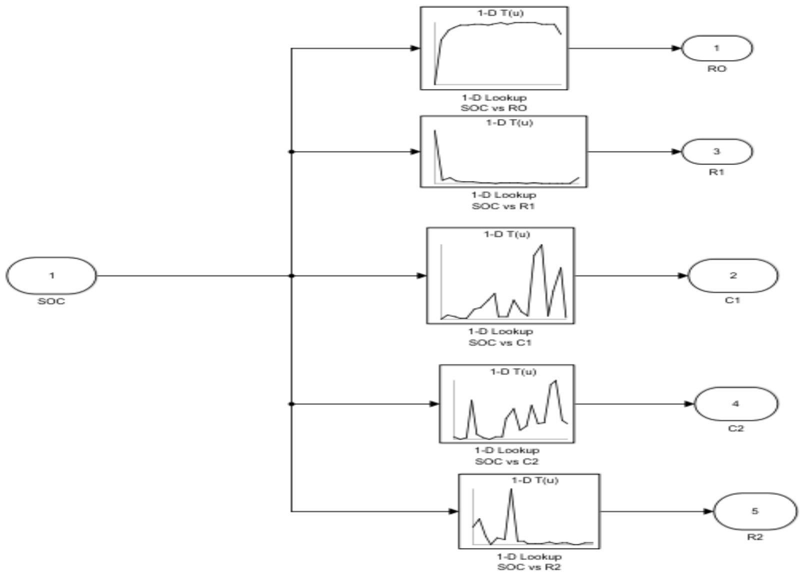


Figure 4-2-10. MATLAB/Simulink, 1-D lookup tables of the RC parallel networks

4.2.7 Voltages of RC Parallel Networks

The subsystem representing the transient response of the battery voltage is identified by analyzing the circuit of an RC parallel network. The circuit component of the RC parallel network is depicted in Fig. 4-2-11. In the s-domain, a mathematical representation of circuits in the Laplace domain, the voltage of the RC parallel network can be expressed as follows:

$$V(s) = H(s) * I(s) \tag{9}$$

Where I(s) is the current flowing through the network, H(s) is the transfer function of the RC parallel network, and V(s) is the voltage across the network after it has undergone Laplace transformation. The transfer function H(s) of an RC parallel network can be expressed as follows:

$$H(s) = 1 / (1 + s * RC) \tag{10}$$

Where s is the complex frequency variable (s = + j), denotes the angular frequency, represents the real part of the complex frequency, and R and C are the network's resistance and capacitance values, respectively.

The transfer function H(s) describes the frequency responsiveness of the RC parallel network; it illustrates the network's behavior at different input signal frequencies. The inverse Laplace transform of V(s) yields the time-domain expression for the voltage across the RC parallel network. The transient response of the battery voltage to changes in the input current over time is represented by this equation.

$$I = \frac{V}{R} + sCV$$

$$V = \frac{1}{s}\left[\frac{I}{C} - \frac{V}{RC}\right]$$

By breaking down the circuit of the RC parallel network and expressing its voltage in the s-domain, one may mathematically explain its behavior. This representation captures the dynamics and transient properties of the battery voltage, which is important to effectively model and simulate the behavior of the battery in response to different load conditions and input currents.

$$V_T = OCV - IR_0 - V_1 - V_2$$

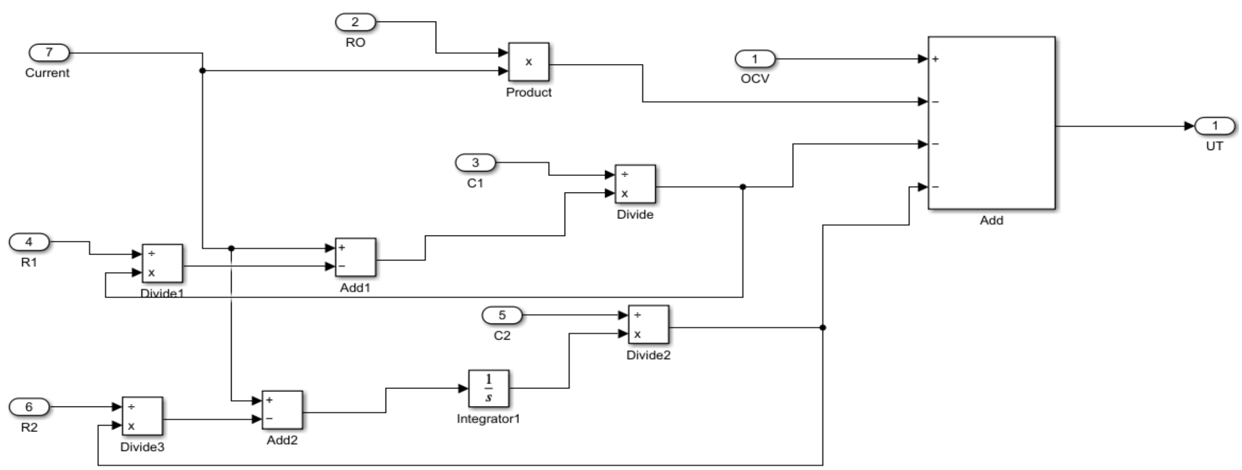


Figure 4-2-11. MATLAB/Simulink, circuit component of the RC parallel network

4.3 Battery packing

A battery pack is a device that stores electrical energy and is used to power an electrical system, such as an energy storage system (ESS) or an electric vehicle (EV). The battery pack is made up of interconnected cells that are utilized as energy storage devices.

To deliver enough power, battery packs must achieve a minimum voltage level that a single cell cannot. To raise voltage, many cells are connected in series with one another. In certain designs, small-capacity cells are utilized. In order to boost capacity and generate the necessary battery energy, cells are connected in parallel. Power is produced by parallel cell connections, which function as one large cell.

Battery packs consist of numerous smaller components called battery modules, also referred to as sub packs. There are less parallel and series connections between the cells in these modules. Because they are at a lower voltage, they are usually handled safely. Modules simplify service when only a few cells need to be changed and doing so doesn't need changing the entire battery. Usually, four to forty modules connected in series make up an EV battery. Figure 4-3-12 displays models for a single cell and a pack of battery cells.

Individual cells inside a battery pack may reach different states of charge during charging and SOC because of their varying capacities. Manufacturing, assembly, combining cells from one production run with another, aging of cells, contaminants, or exposure of specific cells to the environment are the main causes of variations in capacity. Cell pack balancing makes sure that each cell maintains a similar state of charge throughout the greatest range, while having different capacities, in order to maximize the pack's capacity and service life. Since parallel cells are physically connected to one another, only packs comprising multiple cells need to be balanced; however, groups of parallel wired cells connected in series or parallel-series connection also need to be balanced.

The battery management system should keep an eye on each individual cell's condition because operating characteristics like temperature, voltage, and current are frequently recorded across the entire cell pack rather than across individual cells. It might even be able to prevent excessive current spikes brought on by other faults or shorts at the cell level. When charging and discharging, an active cell balancer, on the other hand, will efficiently balance a cell without monitoring the previously described characteristics. Failing to do so may result in catastrophic failures such as thermal runaway, internal gas creation, cell polarity reversal, and others. If you don't, your cells will get permanently damaged. The possibility exists that it will happen. The possibility exists that it will happen. The amount of energy that may be taken out of and added back to the battery is restricted if the cell is not balanced so that the upper and lower cutoff frequencies equal at least the state of the cell with the lowest capacity.

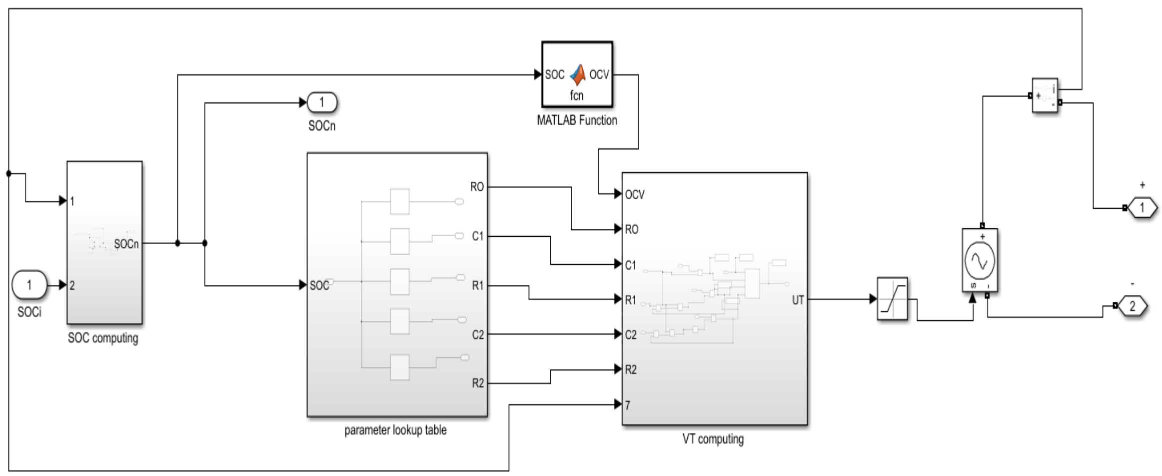


Figure 4-3-12. MATLAB/Simulink, modeling of single cell

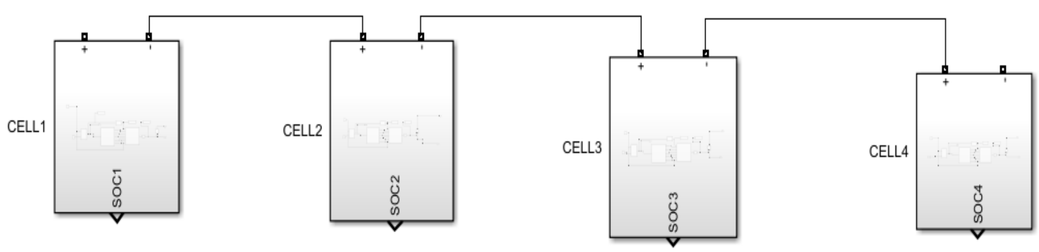


Figure 4-3-13. MATLAB/Simulink, pack of battery cell

CHAPTER FIVE

5. DESIGN OF BALANCING CIRCUIT AND FUZZY-PID CONTROLLER

5.1 Introduction

An electrical or electronic circuit that uses two wires to transfer power or a signal symmetrically is called a balanced circuit. The output of a balanced circuit typically consists of two wires, with one wire output at a 180-degree phase difference from the other wire. This is in contrast to an unbalanced circuit where the voltage is observed in both the common and one wire. High-power or high-electromagnetic interference immunity is achieved by the use of balanced circuits.

The individual cells inside a battery pack may have distinct states of charge (SOC) during multiple cycles of charging and discharging due to their intrinsically variable capacities. Variations in capacity can be caused by contaminants, aging cells, or exposure to the environment (certain cells may be exposed to extra heat from adjacent sources like motors, electronics, etc.). The accumulation of parasitic loads, such as the cell monitoring circuitry commonly present in a battery management system (BMS), can exacerbate these variances by allowing cells from different production runs to be mixed together.

Optimizing a multi-cell pack's capacity and service life involves balancing each cell to maintain an equal state-of-charge over the widest range feasible given its different capacities. Packs that have many series cells just need to be balanced. Parallel cells will naturally balance because they are physically connected to one another; however, cell group balance must be maintained in parallel-series wiring, which connects parallel wired cells in groups.

In battery packs, "cell balancing" is used to ensure that every cell has an identical voltage and state of charge (SOC). Due to variations in production or usage, it is common for some cells in a battery pack's series connection to have relatively fluctuating voltage levels or SOC. Cell balancing helps to correct this imbalance and can extend the longevity, capacity, and general performance of the battery pack by distributing the charge throughout the cells.

Passive and active cell balancing are the two primary varieties. The intrinsic behavior of electrical components, such as resistors or diodes, is used in passive cell balancing. It works by providing several discharge paths for cells with higher voltage levels. The excess charge in these cells is either dissipated as heat or transferred to cells with lower voltage levels. Passive cell balancing is simple and inexpensive, although it may not be as efficient as active balancing.

Active cell balancing: Using extra circuitry and parts, active cell balancing actively moves charge between cells. Switches or DC-DC converters are frequently used to transfer energy from cells with higher voltage levels to cells with lower voltage levels. When balancing cell voltages and SoC, active balancing might be more effective than passive balancing. But putting it into practice is usually costlier and complex.

Numerous cell balancing procedures exist, and figure 5-1 below lists them all.

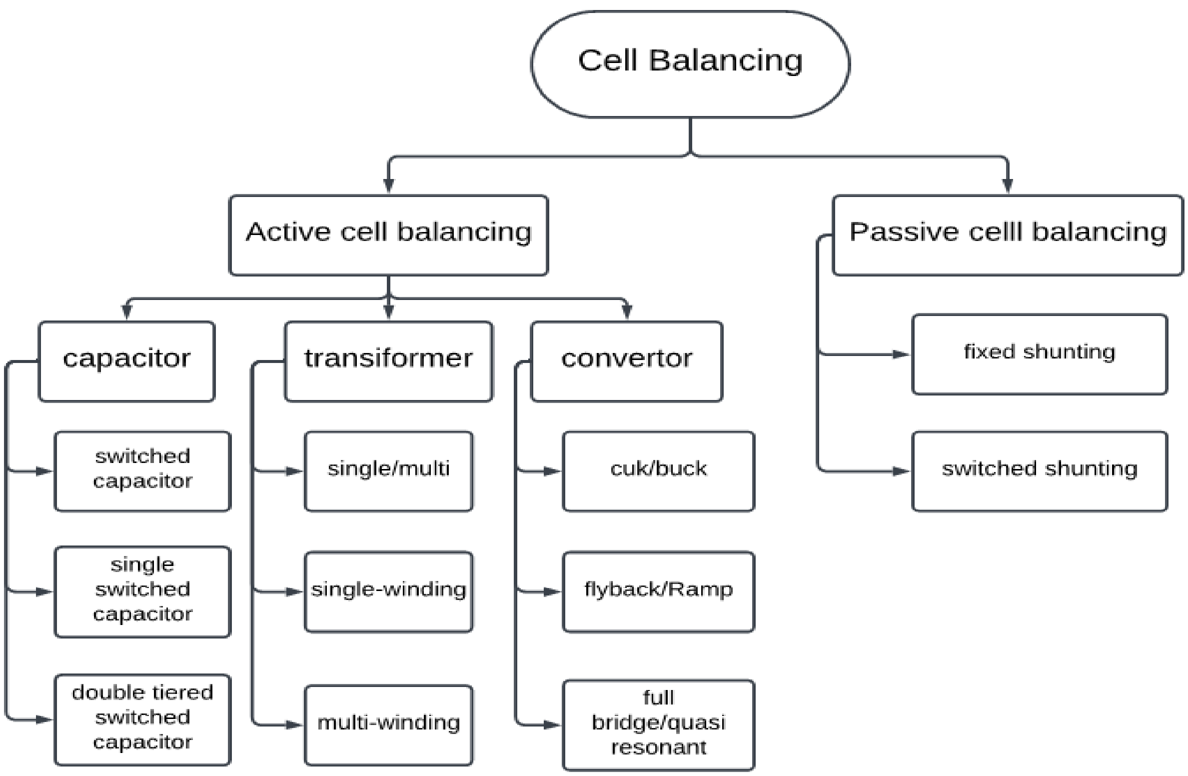


Figure 5-1-1. Classification of Cell Balancing

5.2 Types of balancing circuit

5.2.1 Buck-convertor

A buck converter, often referred to as a step-down converter, is a DC-to-DC converter that boosts current while lowering voltage from its input (supply) to its output (load). It falls within the category of switched-mode power supplies. When it comes to DC-to-DC converters, switching converters (such as buck converters) offer a far higher power efficiency than linear regulators, which are more straightforward circuits that step down voltages by releasing energy as heat but do not increase output current. Buck converters are very useful for jobs like lowering the primary power supply voltage of a computer from its generally 12 V to the lower voltages of 5, 3.3, or 1.8 V that are needed by the CPU, DRAM, and USB. Buck converters have a pretty high efficiency, often exceeding 90%.

The bare minimum of semiconductors in a buck converter is one diode and one transistor, while most contemporary buck converters forgo the diode in favor of a second transistor for synchronous rectification. There might also be an inductor, a capacitor, or a combination of the two. Voltage ripple is usually eliminated by adding filters made of capacitors to the converter's input (supply-side filter) and output (load-side filter). The term "bucks" refers to the inductor's opposition to the supplied voltage.

Buck converters usually use switching frequencies in the region of 100 kHz to a few MHz. Greater switching frequencies can be achieved with smaller inductors and capacitors, but transistor switching causes more frequent efficiency losses.

5.2.2 Boost convertor

A DC-to-DC converter called a boost converter is used to step-up convert the applied DC input. The output voltage of the boost converter is always higher than the input voltage since it boosts (or enhances) the fixed DC input that is delivered to an adjustable DC output voltage. Another name for a boost converter is a step-up chopper or step-up converter. Its output voltage is greater than the input voltage it receives, which is why it is referred to as a "boost". It converts a higher DC input into a lower DC output, doing the opposite function of a buck converter.

A boost converter is used to increase an input voltage to a higher level based on the demands of the load. This step-up conversion is accomplished by the boost converter by using an inductor to store energy that is then delivered to the load at a greater voltage. Boost converters are widely used in battery-powered electronics when a 5V circuit is needed but two batteries can only supply 3V.

There must be a minimum of two semiconductors, such as a diode and a transistor, and a minimum of one energy storage element, such as an inductor, capacitor, or both. Power MOSFETs, power BJTs, and IGBTs are a few examples of additional semiconductor switches used in boost converter circuits.

5.2.3 Buck-boost convertor

A DC-to-DC converter with an output voltage magnitude that can be either higher or lower than the input voltage magnitude is called a buck-boost converter. A flyback converter functions similarly to a transformer when one inductor is used in place of the other. Two different topologies are used by buck-boost converters. They can both generate output voltages that range from almost zero to much higher than the input voltage in terms of absolute magnitude.

In an inverting topology, the output voltage has the same polarity as the input voltage. This is a switched-mode power supply with a circuit architecture matching both the boost converter and the buck converter. The output voltage can be changed by changing the duty cycle of the switching transistor. The driving circuitry is complicated by the switch's absence of a terminal at ground, which may be a weakness in this converter. However, if the power supply is isolated from the load circuit (for example, if the power source is a battery), this drawback is unimportant because the supply and diode polarity can be easily swapped. When they may be reversed, the switch can be placed on either the supply side or the ground side.

The output voltage, which might be higher or lower than the input value, usually has the same polarity as the input voltage when a buck (step-down) and a boost (step-up) converter are used. Often called a "four-switch buck-boost converter," this type of non-inverting buck-boost converter can use one or more inductors but only one switch, as in the SEPIC and Cuk topologies, or it can use a single inductor that is used for both the boost and buck inductor modes.

5.2.4 CUK convertor

The Cuk type DC-DC converter efficiently steps up or steps down voltage levels. It consists of a capacitor, an inductor, and two switches. The Cuk converter is well known for its ability to provide an output voltage that can be either higher or lower than the input voltage while performing a non-inverting polarity conversion.

A Cuk circuit can be used to equalize the voltages of the different cells in a battery pack in the context of cell balancing in battery management systems. This is important because, if multiple cells are linked in series, the voltages between them may fall out of balance due to differences in the cell's characteristics or the effects of aging. By ensuring that all of the cells operate within their safe voltage ranges, cell balancing extends the battery pack's overall capacity and useful life.

By connecting each individual cell to the input of the Cuk converter, the Cuk circuit can be used in a cell balancing system. Energy is transferred from one cell with a higher voltage to another with a lower voltage by the converter. The duty cycle of the switches in the Cuk converter, which controls the flow of energy, is changed in order to accomplish this procedure.

Cell balancing Cuk converters typically operate in continuous mode, transferring energy between cells continuously. The control algorithm continuously evaluates the voltages of individual cells and adjusts the duty cycle of the switches as needed to maintain a balanced voltage across all cells. By employing a Cuk circuit for cell balancing, battery management systems may prevent individual cells from being overcharged or over discharged and ensure that every cell in the battery pack operates as intended. This raises the durability and overall performance of the battery pack.

The duty cycle of the switches in a Cuk converter can be controlled in a few different ways. One widely used method is pulse width modulation, or PWM. PWM control allows the switches to be quickly turned on and off at a predetermined frequency. By varying the "on-time," or duration of the switches on state, the duty cycle may be adjusted.

An outline of the typical PWM control implementation of a Cuk converter is provided below:

1. Voltage Feedback: In order to modify the duty cycle, one must first measure the output voltage of the converter. This is usually accomplished via a feedback loop that compares the actual output voltage to a reference value.

2. Error Amplifier: The difference between the measured output voltage and the reference value is known as the output voltage error, and it is amplified by an error amplifier. The error amplifier produces an error signal that represents the output voltage difference between the desired and actual output voltages.
3. Comparators: The incorrect signal is then compared to a high-frequency triangular waveform generated by a saw tooth generator. In this comparison, comparators are frequently employed.
4. Pulse Generation: The comparators' output dictates the switching behavior of the converter. When the false signal is larger than the triangle waveform, the comparator outputs a high signal, signaling that the switches should be turned on. When the error signal is lower, the comparator generates a low signal, indicating that the switches ought to be turned off.
5. PWM Signal: The comparators provide the high and low signals to a logic circuit, which produces the PWM signal needed to operate the switches. The duration of the high signal (on-time) dictates the duty cycle of the switches. A longer on-time results in a higher duty cycle, whereas a shorter on-time results in a lower duty cycle.

By using PWM control to alter the duty cycle, the Cuk converter can regulate the energy flow between the input and output. This facilitates step-up or step-down of voltage and eases battery management systems' cell balancing.

5.3 Design of balancing CUK circuit

The CUK converter serves as an interface between the DC supply and the battery cells. It is a type of DC-DC converter that can step up or step down the voltage to match the requirements of the battery cells. The CUK converter can efficiently transfer power from the DC supply to the batteries by controlling the duty cycle of its switches.

The SOC (State of Charge) controller block is responsible for monitoring and regulating the charging and discharging of the battery cells. In this system, the fuzzy-PID (Proportional-Integral-Derivative) controller is used as the SOC controller. The SOC controller takes the feedback signal from the battery charge controller, which has been filtered, and generates a pulse width modulated (PWM) signal based on the current feedback from the buck converter.

The solid-state switch array block consists of switches that control the charging and discharging of specific battery cells. The PWM signal generated by the SOC controller is used to gate the input DC source to the specific cells through these charging and discharging switches. By selectively enabling or disabling the switches, the solid-state switch array block regulates the flow of energy between the CUK converter and the battery cells.

The SOC controller block is a novel block included in the proposed system. Based on each cell's unique state of charge, the algorithmic controller selects an unbalanced cell from the pack and controls cell switching to gate the signal from the CUK converter. If the SOC of every single cell is higher than the SOC average, the discharging switch will get a powerful pulse to conduct the switch. The draining switch's inverted output will be received by the charging switch.

A solid-state switch array, seen in Figure 5-5, controls the charging and discharging of individual cells through the use of a CUK converter, two bi-directional switches, and two switches. The recommended strategy moves charge to the undercharged cell in the battery pack from the other overcharged cells. The SOC controller and the bi-directional switches enable this. The SOC controller receives its input from the SOC of each individual cell.

By comparing the SOCs of individual cells with the average SOC of all the cells, the SOC controller employs an equalization algorithm to produce two output signals that are complimentary to one another. Output 1 governs the charging network and output 2 controls the discharging network. Since the two sets of outputs are complimentary, the overcharged cells will be triggered to release their excess charge, and the undercharged cells will be gated for charging. Consequently, charge shifts from an overcharged cell to an undercharged cell via the bi-directional switches.

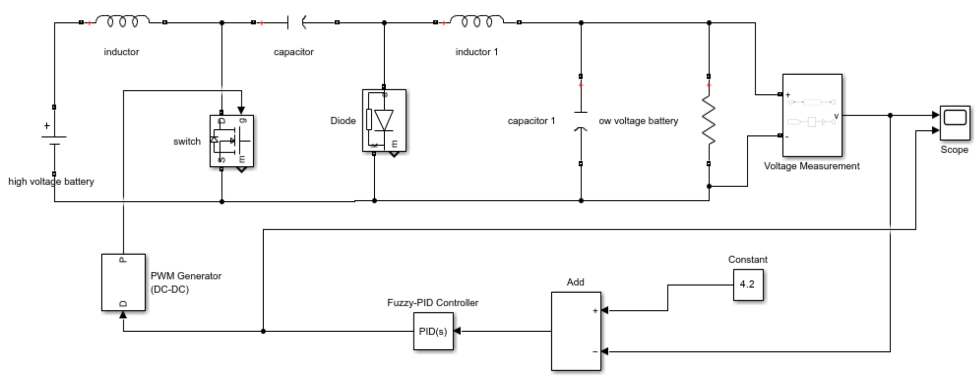


Figure 5-5-2. Cuk convertor working system

5.3.2 Working principle of Cuk convertor

A non-isolated UK converter consists of two inductors, two capacitors, a switch (often a transistor), and a diode. You may see its schematic in picture 5-6. The output voltage is the opposite of the input voltage since the converter is inverting.

The input voltage source (Vs) and the output voltage source (Vt) are converted into current sources, respectively, by the two inductors L1 and L2. An inductor can be considered a current generator on a short time scale since it sustains a constant current. The parasitic resistance would be the only thing restricting the current if the capacitor were connected directly to the voltage source, which would result in a significant energy loss. Utilizing an inductor as a current source allows one to bypass resistive current limiting and the associated energy loss.

The current flow pattern when every cell is charging from the source is shown in Figure 5-5: DC supply: switch; L1; S1; batteries; S2; batteries; S3; batteries; S4; batteries. In this phase, all four cells are receiving power from the source. Now, there is a discrepancy because Battery 1's SOC is increased but Batteries 2, 3, and 4's SOCs remain low. In this case, Batteries 2, 3, and 4 receive the excess charge from Battery 1 in two stages. The current flow in each case is explained below, and this is covered in Steps I and II (Figures 5-5 and 5-6, respectively). The SOC controller sends switch control signals when required as a result of regular contact with the cells, switches, and CUK converter. The electrical path between the CUK converter and the cells is verified by this control signal.

Step I

In the event that Battery B1 has a greater energy charge than the remaining cells, this imbalance will be corrected using the method outlined below. The CUK converter switch is not in the S1 position. There is less energy stored in the inductor than in Battery B1 when switch S1 is turned on. Battery 1's energy drives the inductor through switch. The current flow path is Battery B1 –L1 - switch - Battery B1. In this instance, only Battery 1 is connected to the path, which results in Battery B1 is discharge. After the inductor L1 is more activated than the battery B1 charge, the step II operation will start.

Step II

Through the conduction of the discharging switch S6 and the charging diode, the inductor L1 will be discharged to the capacitor C1 and inductor l2. Step II operation occurs when the inductor L2 energy exceeds the battery energy and the CUK converter switch S1 is in the off position. Battery B1 is not charging; only Batteries B3 is drawing energy from the stored inductance L2 through the diode. The present flow path is (L1 – C1 - diode - L 2 – S6 – B3). By alternating between turning on and off the switches, each of the other cells maintains balanced cell charging through the fuzzy-PID control approach.

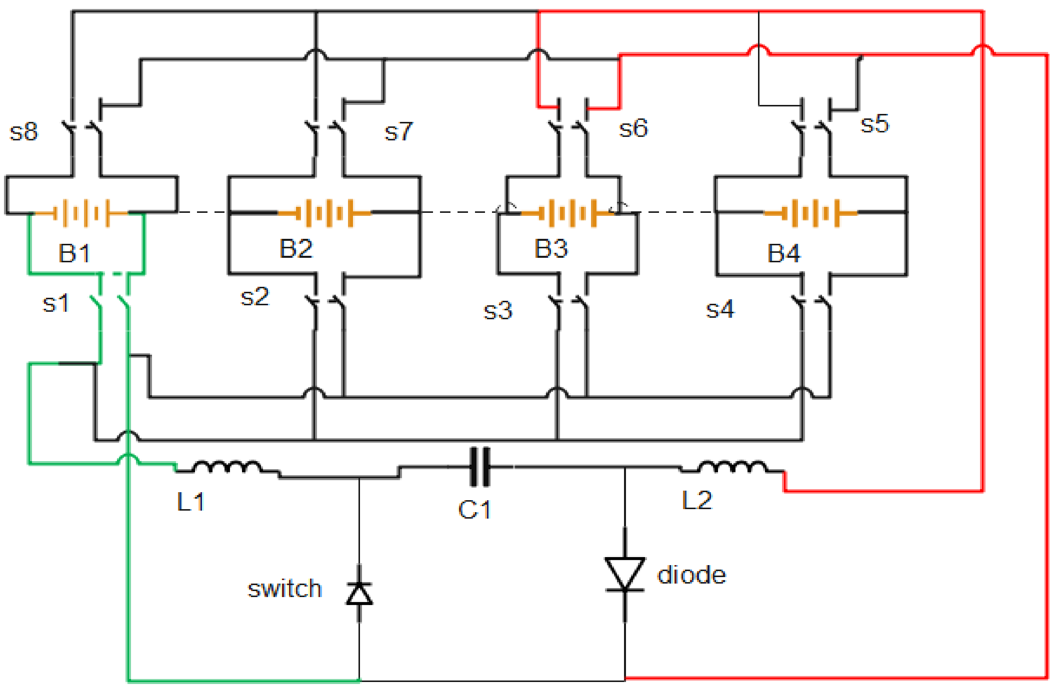


Figure 5-5-3. Cuk Convertor circuit

During T ON [0 ≤ t ≤ DT]

When the Cuk converter is turned on, the diode is off, acting as a closed switch, and the capacitor C1 is already charged to a constant voltage (Vt). The Cuk converter operates as a closed switch. An energy charge is transferred to Inductor 1 as a result of current passing through it.

Subsequently, the charged inductor 1 transfers energy to the inductor 2 and capacitor 2. Energy is transmitted to capacitor 2 and inductor 2 after a voltage drop brought on by the discharge of capacitor 1 (C1). Inductor 1 reduces its current because of synchronous energy transfers to capacitor 2 and inductor 2. The switch is turned OFF and the diode is switched ON to allow for commutation after a predetermined amount of time. By turning off the switch, the current that was going through inductor 1 is now going through the diode, which allows the energy that has been stored in inductor 1 to keep moving.

When the diode is turned on and the switch is turned off, energy transfer still occurs. The residual energy from inductor 1 is sent to inductor 2 and capacitor 2 via the diode, wherein inductor 2 stores the energy in its magnetic field and capacitor 2 charges.

The required voltage conversion and energy transfer can be achieved by maintaining a steady energy flow between inductor 1, capacitor C1, capacitor 2, and inductor 2 as the switch and diode alternate between respective states.

By Kirchhoff's voltage law in input loops

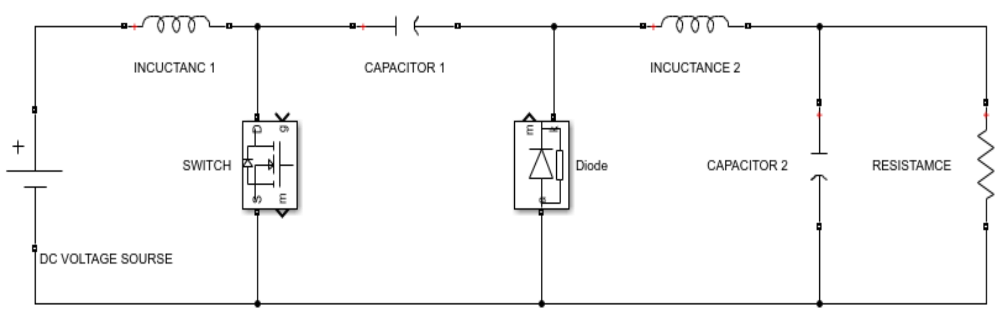


Figure 5-5-4. Energy Transfer Principle of Cuk Convertor Circuit

$$Vs - V_{L1} = 0$$

$$t_1 = \frac{L1\Delta I_{L1}}{Vs} \tag{11}$$

$$\Delta I_{L1} = \frac{Vst_1}{L1}$$

By Kirchhoff's voltage law in output loops

$$V_{C1} + Vo - V_{C2} = 0$$

$$t_1 = \frac{L1\Delta I_{L2}}{Vc1+Vo} \tag{12}$$

$$\Delta I_{L2} = \frac{(Vc1 + Vo)t_1}{L_2}$$

During T OFF [DT ≤ t ≤ T]

Inductor 2 releases energy to the load, inductor 1 charges capacitor 1, and the switch becomes OFF, acting as open, and diode is ON throughout the OFF time (see figures 5-3).

By Kirchhoff's voltage law in input loops

$$V_S - V_{L1} - V_{C1} = 0$$

$$t_2 = \frac{-L1\Delta I_{L1}}{Vs - V_{C1}} \tag{13}$$

$$\Delta I_{L1} = \frac{-(Vs - V_{C1})t_2}{L_1}$$

Equating value of ΔI_{L1} from equation 11 and 12and put t1 = DT AND t2 = (1-D) T

$$V_{C1} = \frac{Vs}{1-D} \tag{14}$$

By Kirchhoff's voltage law in output loops

$$V_{L2} - V_o = 0$$

$$t_2 = \frac{-L2\Delta I_{L2}}{Vo} \tag{15}$$

$$\Delta I_{L2} = \frac{-Vot_2}{L_2}$$

$$V_O = \frac{-L2\Delta I_{L2}}{t_2} \tag{16}$$

Equating value of ΔI_{L2} from equation 12, 3- and 13

$$V_{C1} = \frac{-Vo}{D} \tag{17}$$

From equation 14 put $V_{C1} = \frac{Vs}{1-D}$

$$V_O = \frac{-DVs}{1-D} \tag{19}$$

By power balancing equation assume no loss in all components

$$P_{in} = P_{out}$$

$$V_s I_s = V_O I_O \tag{20}$$

$$I_s = \frac{D}{1-D} I_O$$

From ΔI_{L1} T = t_1+t_2

$$T = \frac{L1 \Delta I_{L1}}{Vs} * \frac{1}{D}$$

$$\frac{1}{f} = \frac{L1 \Delta I_{L1}}{D * Vs} \tag{21}$$

$$\Delta I_{L1} = \frac{DVs}{f * L_1}$$

$$\Delta I_{L2} = \frac{DVs}{f * L_2} \tag{22}$$

Change of ΔV_{c1} in capacitor 1

During T OFF I_{c1}average = I_{c1}=I_s

$$\Delta V_{c1} = \frac{Is(1-D)}{f * C_1} \tag{23}$$

Change of ΔV_{c1} in capacitor 2

$$\Delta C_2 = \frac{DVs}{8f^2 * L_2 C_2}$$

$$L_{c1} = L_1 = \frac{R(1-D)^2}{2Df} \tag{24}$$

$$L_{c2} = L_2 = \frac{R(1-D)}{2f}$$

$$C_{c1} = C_1 = \frac{D}{2fR}$$

$$C_{c2} = C_2 = \frac{1}{8fR} \tag{25}$$

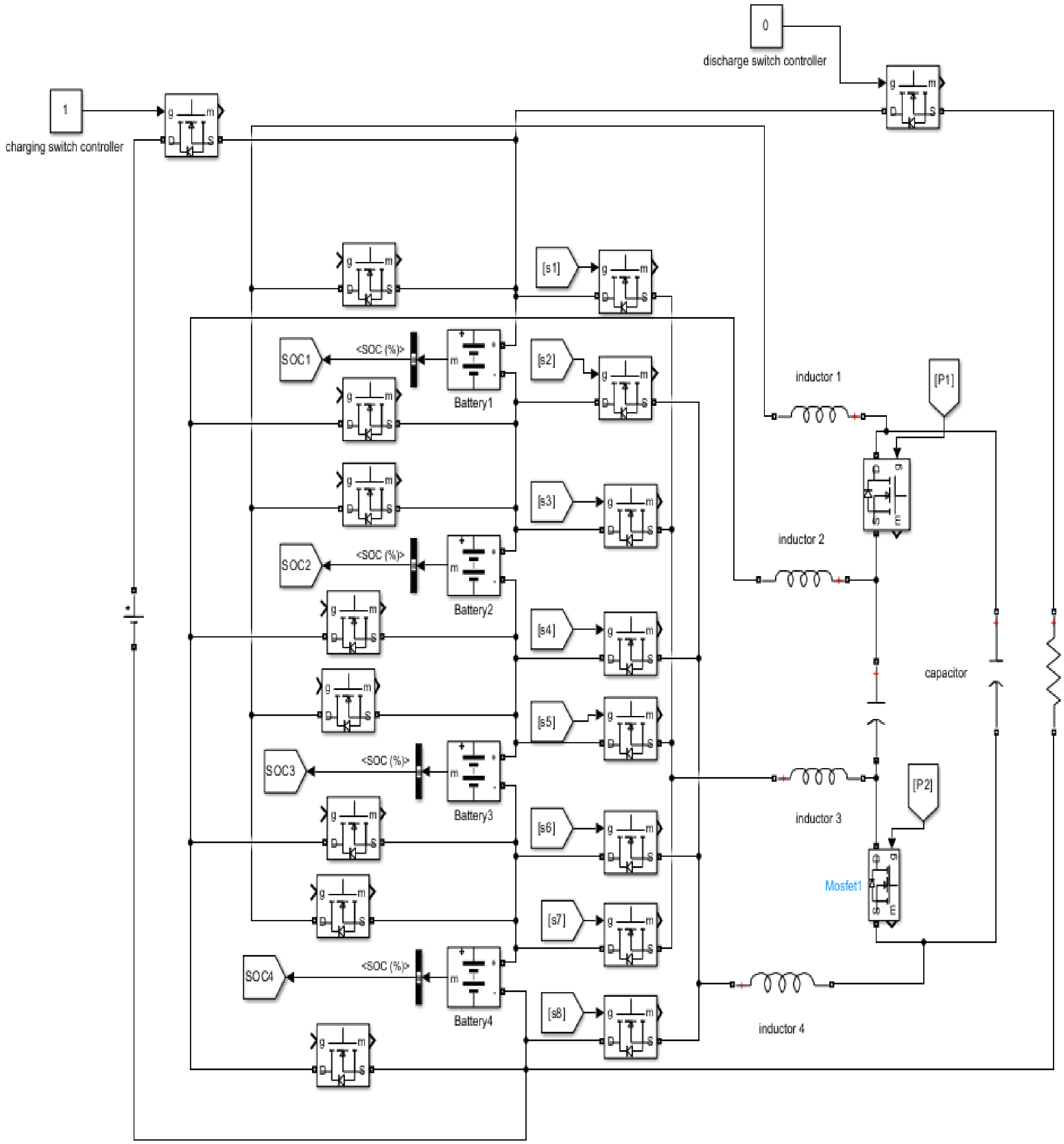


Figure 5-5-4. MATLAB/Simulink, Pack of Battery Cell with Balancing Circuit

5.4 Design of Fuzzy-PID Controller

5.4.1 Introduction

A fuzzy PID controller is a proportional-integral-derivative controller that controls errors in industrial systems by utilizing fuzzy logic software concepts. PID controllers are frequently used in automation to modify process controls, such as valves, by accumulating errors over time. Compared to a typical PID controller, a fuzzy PID controller can produce more accurate results in non-linear scenarios. Fuzzy systems are based on a kind of programming logic that aims to address the fuzzy areas of process uncertainty more successfully than normal controls.

Control systems need to include a built-in method for bringing an out-of-range value back into an acceptable range. By dividing the variability into discrete values and allocating predefined actions to those values, the typical PID controller may respond to it in an on/off manner at particular times in the process. This approach is somewhat analogous to a digital process analysis technique. A fuzzy PID controller, on the other hand, does not have a set point at which action is always done; instead, it calculates deviation along an analog range with an optimal value and increasingly less optimal values.

The architecture of both a regular PID controller and a fuzzy PID controller makes use of historical data to forecast future behavior. The initials in PID actually stand for the following: D represents future error states, I for past errors, and P for current faults. Fuzzy systems try to assign errors to different membership sets for a variety of logical conditions and define errors in terms of their persistence. This enables the rate of change for regaining control of a system to be set by a fuzzy PID controller. This rate of change, which is based on the principles of inference, suggests the best course of action based on the accumulation of data and incorrect states.

The equalization procedure consists of three stages: cell equalization, establishing the equalization threshold, and controlling the equalization system. They are shown in Figure 6-3. Prior to limiting the maximum difference to no more than 10%, it is imperative to ascertain whether the variation between the cells inside the module is excessive. After computing the difference between the SOC values of each individual cell, this is done.

Stage 1: figuring out how charged the battery is and modifying the threshold. This essay's equalization target is the cell's SOC, and implementing the equalization approach requires exactly obtaining the SOC. It is well known that the SOC may be estimated quickly, accurately, and easily using the coulomb counting technique. For the cell differential turn-on threshold to be reached, the consistency SOC of the cells usually needs to be at least 10%. The SOCavg of the pack cells is then calculated.

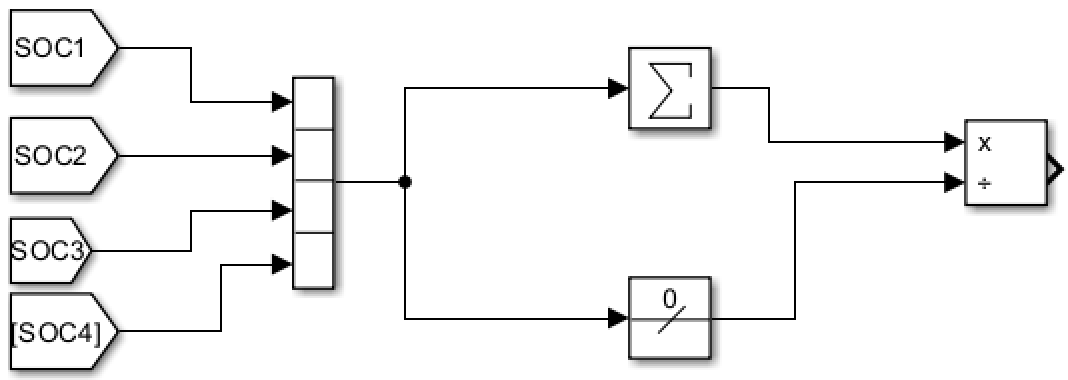


Figure 5-1-5. MATHLAB Simulink of state of charge average calculation

$$\text{SOCavg} = 1/\text{n} \sum_{j=1}^{n} \text{SOCi} \quad (27)$$

Where n is the total number of cells in the battery pack and i represents individual cells within each module. Calculate the difference between the average SOC values of the modules: Take the absolute difference between the average SOC values of each module. This will give you the difference in SOC levels between the modules.

Compare the difference with the maximum allowable difference: Compare the calculated difference between the average SOC values with the maximum allowable difference threshold, which in this case is set to 10%. If the calculated difference exceeds 10%, it indicates that the difference between the batteries in the modules is too great. It is required to equalize between the cells when the difference is too great, which can significantly cut down on the equalization time.

By following these steps, you can determine whether the difference between the batteries in the modules exceeds the specified threshold and take appropriate actions, such as initiating equalization processes or maintenance procedures, as necessary.

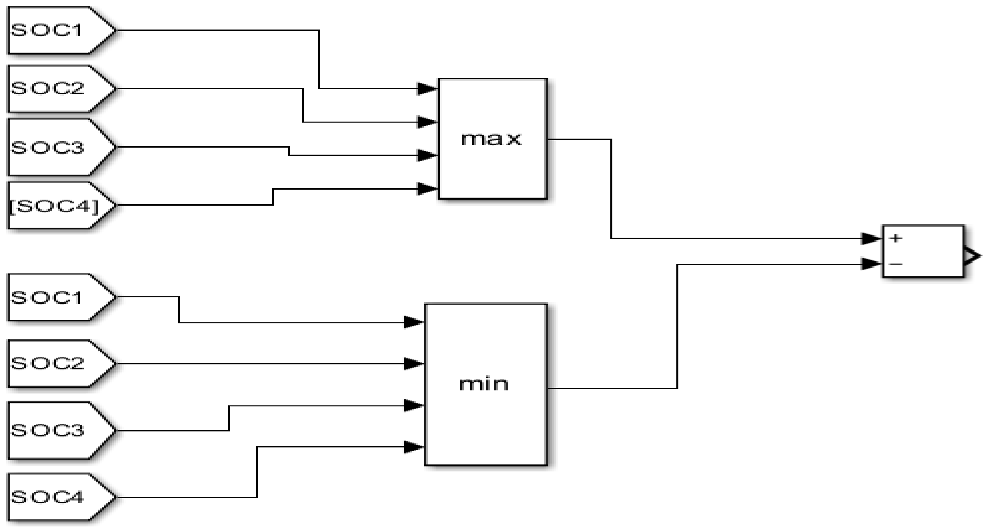


Figure 5-1-6. MATHLAB Simulink of state of charge difference calculation

Stage 2-Cell Equalization.

It is possible to equalize the pack module and the cell at the same time. After calculating the difference and average SOC between the cells, the fuzzy-PID based control algorithm turns on the appropriate switches Sn, starting the battery packs' equalization process and continuing it until the cells are approximately equalized.

Battery monitoring module collected the state charge of all battery cell, the MATLAB/Simulink calculate the average and difference of state charge of all four battery cell. Depend on SOC difference and average the fuzzy-PID controller triggering the switch of balancing circuit. The comparators provide the high and low signals to a logic circuit based on SOC cell difference, which produces the PWM signal needed to operate the switches. The duration of the high signal (on-time) dictates the duty cycle of the switches. A longer on-time results in a higher duty cycle, whereas a shorter on-time results in a lower duty cycle.

By using PWM control to alter the duty cycle, the Cuk converter can regulate the energy flow between the input and output. This facilitates step-up or step-down of voltage and eases battery management systems' cell balancing. The diagram on next page shows the process of energy transfer and fuzzy-PID controller system.

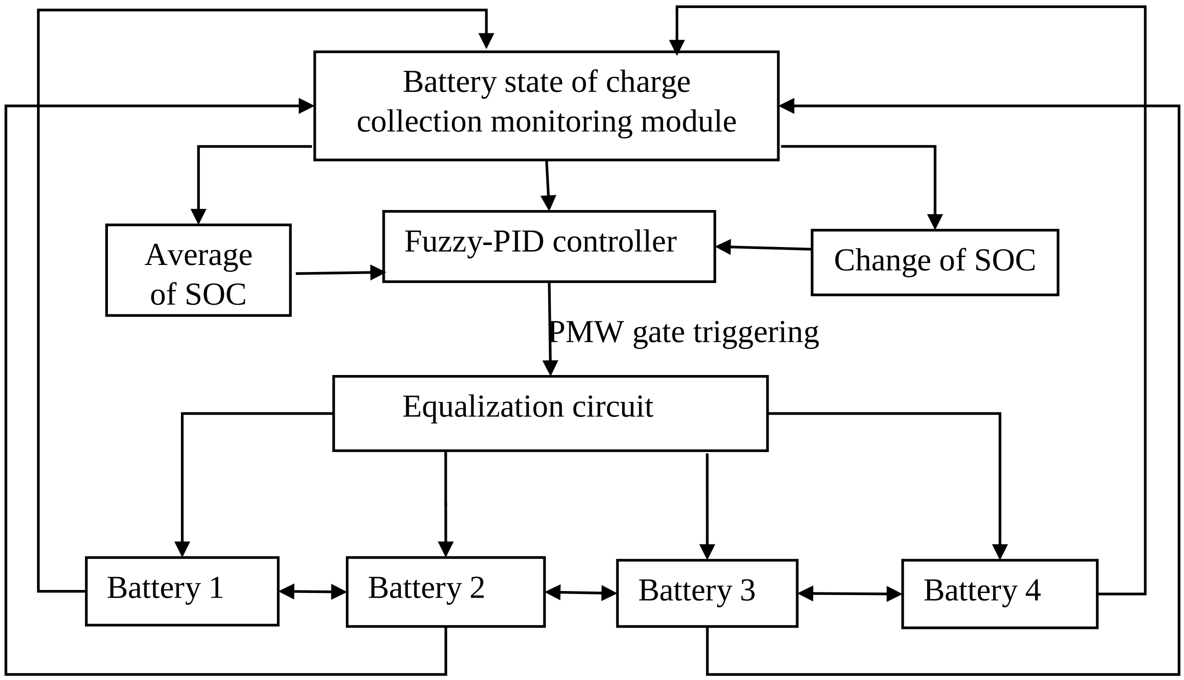


Figure 6 1-3. Diagram of Fuzzy-PID Control Design

The benefits of fuzzy logic control and PID control are combined in fuzzy-PID (Proportional, Integral, and Derivative) control. It is frequently employed in many different applications, such as battery balancing systems. The process of bringing each cell or part of a battery pack's charge or voltage levels into balance is known as battery balancing.

The fuzzy-PID controller guarantees an efficient battery balancing procedure by continuously monitoring and modifying the energy transfer rate, hence minimizing needless energy losses. It optimizes energy use to reach a balanced state across all cells by dynamically adapting to changing variables, such as alterations in cell properties, load conditions, and temperature.

$$\varepsilon = \sqrt{\sum_{i}^{n} (\frac{SOCi - SOCavg}{n})^2} \tag{28}$$

$$\eta = \frac{\Delta Qch}{\Delta Qdis} \tag{29}$$

In the battery pack, SOCi and SOC represent the average charge state and the charge state of each monomer, respectively. The energy charged by equilibrium is denoted by ΔQch, while the energy released by equilibrium is denoted by ΔQdis.

5.4.2 Control rule design

This study's fuzzy controller is a one-dimensional, two-input, single-variable controller. The battery's status must be accurately reflected in the fuzzy controller's input. In view of the concerns brought up in the literature, this study selects the average state of charge of cells ((SOC)) and the state of charge differential between batteries (SOC) as input values [Rivera-Barrera et al., 2017]. When the SOC difference is greater, a larger equalization current is required to raise the equalization speed; when the SOC difference is smaller, the opposite is true. When SOC is higher, larger balancing currents can be utilized without damaging a drained battery; however, when SOC is lower, this is not the case.

Fuzzification, database, rule base, fuzzy inference machine, and defuzzification comprise the majority of the five components that comprise the fuzzy-PID controller. By including a scaling factor, the Fuzzy-PID technique overcomes the limitation of an immutable fuzzy control domain by allowing the domain to grow or shrink in response to a real-time change in the parameters.

The scaling factor can be used to amplify or attenuate the influence of the fuzzy constraints or objectives. By adjusting the scaling factor, the optimization algorithm can prioritize certain constraints or objectives over others based on the problem requirements or preferences. A larger scaling factor increases the importance of the corresponding fuzzy constraint or objective, while a smaller scaling factor reduces its significance.

The selection of appropriate scaling factors is crucial in fuzzy optimization as it affects the convergence behavior and solution quality. It requires careful consideration and domain knowledge to determine the scaling factors that appropriately balance the trade-offs between different constraints and objectives in the optimization problem.

A technique for understanding the values of an input vector and allocating matching values to the output vector based on different sets of fuzzy rules is called the Fuzzy Inference System (FIS). This method involves mapping an input to an output using fuzzy logic. This mapping process is the basis upon which the system decides and establishes patterns.

5.4.3 Creating Linguistic Variables

The equilibrium current is used as the output to calculate the average value of the charge state (SOC) of a cell bank, represented by the letter "e," and the difference between the charge states of its surrounding cells, represented by the letter SOCec. The linguistic variables S, M, and L—which stand for small, medium, and big, respectively—are employed in this fuzzy logic system.

The domain for the charge state variable, e, is defined as [0-100], indicating a range from 0 to 100. The linguistic terms S, M, and L are associated with fuzzy membership functions that assign degrees of membership to different values within this range. Figure below shows average SOC MFs of the fuzzy input variables of the proposed optimal fuzzy-PID controller.

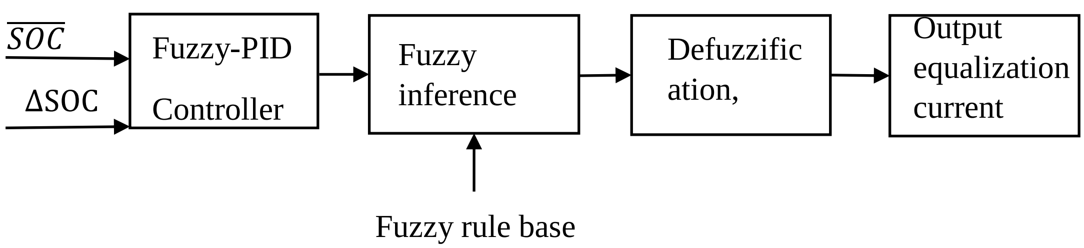


Figure 5-3-7. Diagram of Fuzzy Inference System

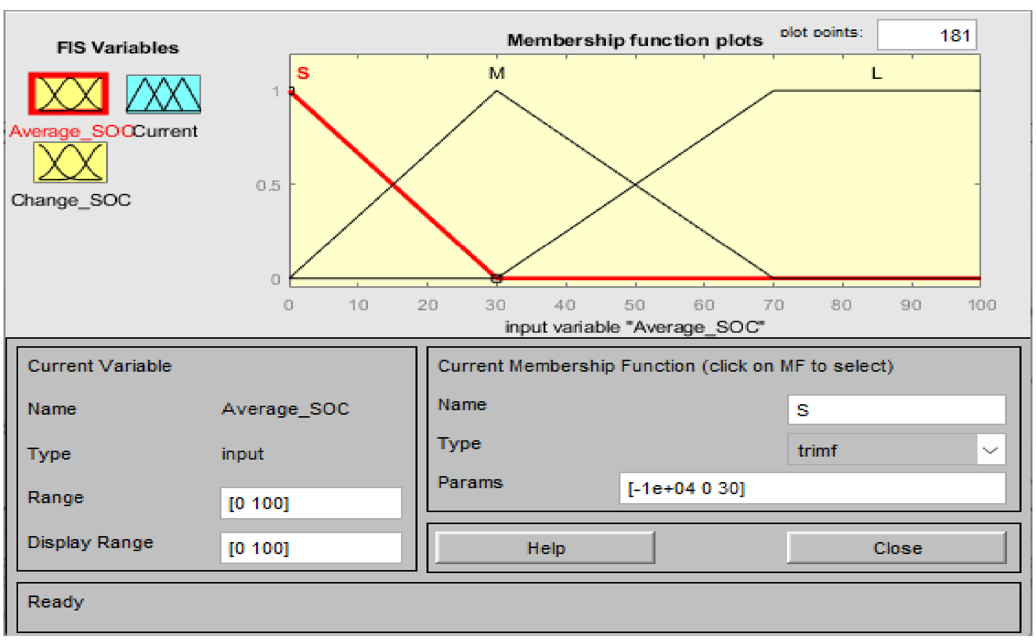


Figure 5-3-8. Creating member function of input variables (average SOC)

In the given context, the change value of SOC (charge state of the cell bank) is categorized using fuzzy domain linguistic phrases. The linguistic terms for the change value are "Very Tiny" (VS), "Small" (S), "Medium" (M), "Large" (L), and "Very Large" (VL). These linguistic phrases represent different degrees or magnitudes of change in the SOC within the specified range of [0-10]. For example, if the change value of SOC is close to zero, it would be categorized as "Very Tiny" (VS). As the change value increases, it transitions through the linguistic terms "Small" (S), "Medium" (M), "Large" (L), and finally "Very Large" (VL) to indicate progressively larger changes in the SOC.

However, it's important to note that the specific shapes and parameters of the membership functions associated with these linguistic phrases, which define the degree of membership for different change values, are not provided. These membership functions determine how the input values of the change value of SOC are mapped to the linguistic terms (VS, S, M, L, and VL) and their respective degrees of membership.

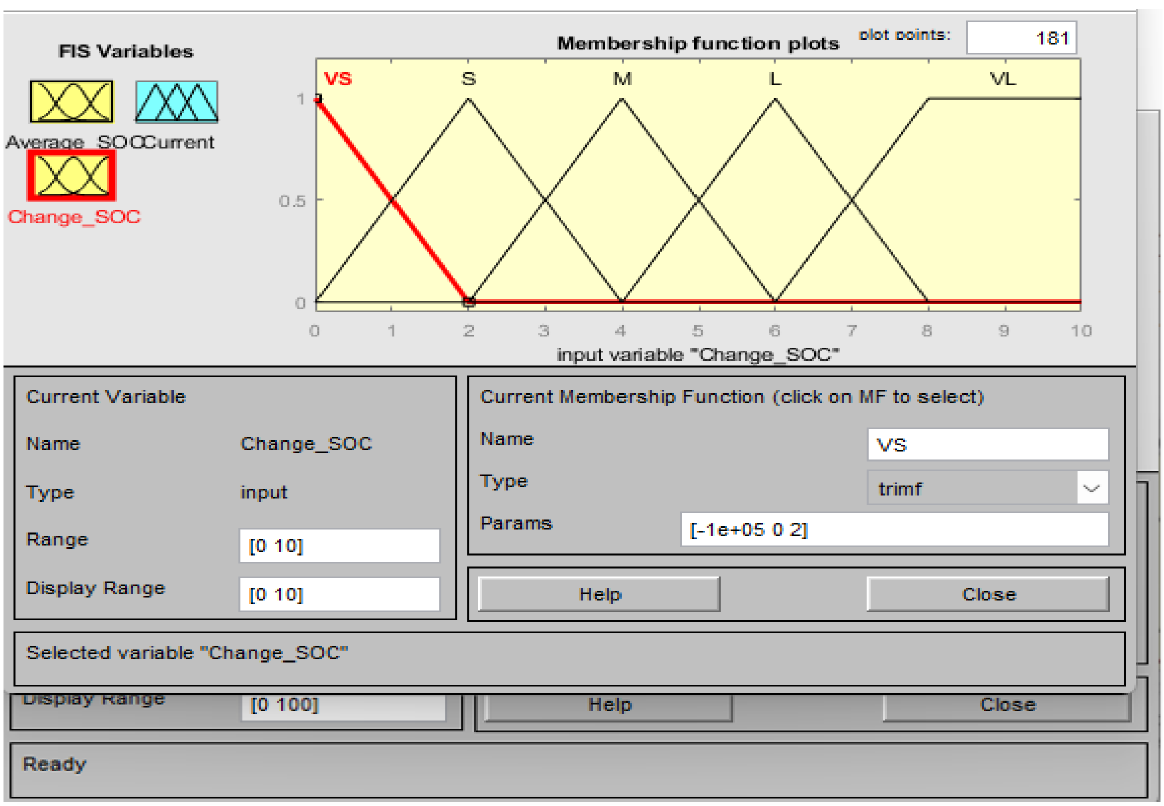


Figure 5-3-9. Creating member function of input variables (change SOC

5.4.4 Creating Membership Functions

Linguistic terms are used in fuzzy logic to describe qualitative or subjective concepts. These terms are represented by membership functions, which assign a degree of membership to each element of a universe of discourse. Membership functions indicate how well an element belongs to a particular linguistic term. The two common types of membership functions used in fuzzy logic are triangular and trapezoidal functions.

Triangular Membership Function: This function takes the shape of a triangle and is defined by three parameters - the left foot, the peak, and the right foot. The membership value starts at zero, increases linearly from the left foot to the peak, remains at unity (maximum) at the peak, and then decreases linearly from the peak to the right foot.

Trapezoidal Membership Function: This function takes the shape of a trapezoid and is defined by four parameters - the left foot, the left shoulder, the right shoulder, and the right foot. The membership value starts at zero, increases linearly from the left foot to the left shoulder, stays at unity (maximum) between the left shoulder and the right shoulder, and then decreases linearly from the right shoulder to the right foot.

These membership functions are often used to represent fuzzy sets and fuzzy logic systems. By applying these functions to numerical data, you can determine the membership degree of each data point to a particular linguistic term.

In practice, the selection of the membership function often involves a combination of domain knowledge, data analysis, and experimentation. It may be helpful to analyze the data distribution and consider the characteristics of the linguistic terms being used to determine which membership function is most suitable for a specific application.

In this system, the balanced current (I) is defined within a theoretical domain of [0-5]. The linguistic variables associated with the fuzzy domain are VS, S, M, L, and VL, representing "Very Small," "Small," "Medium," "Large," and "Very Large," respectively. These linguistic terms describe the meaning or interpretation of different values of the fuzzy variables.

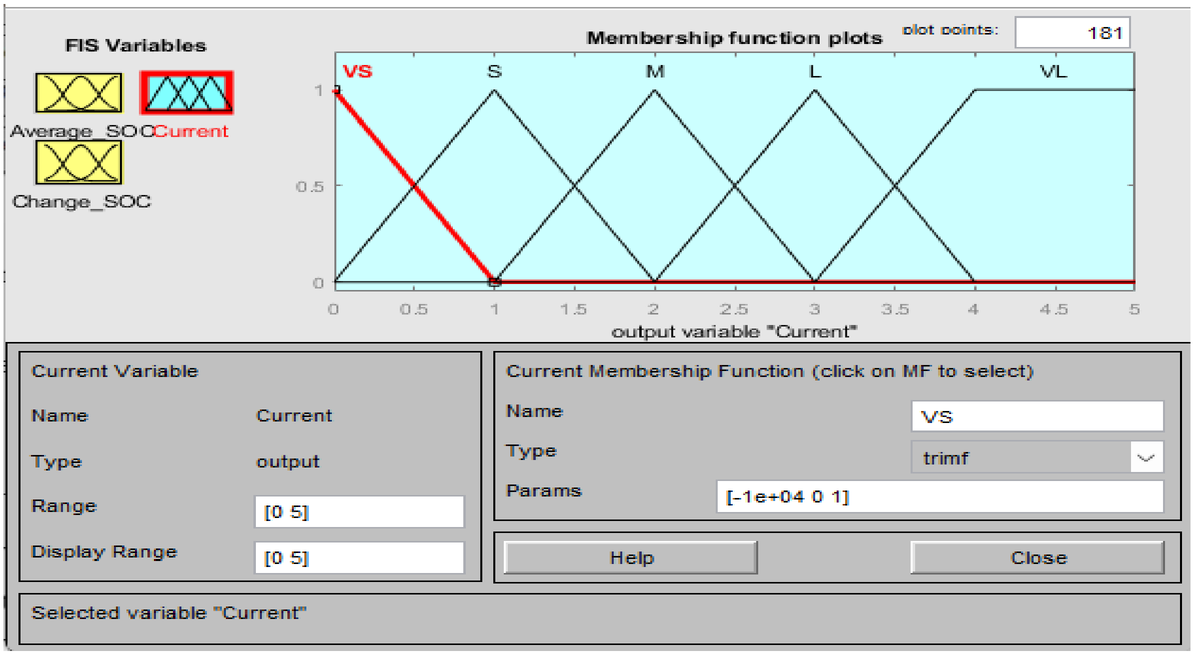


Figure 5-4-10. Creating member function of output variables (current)

5.4.5 The Fuzzy Logic Rule Base

The rule base of a FLC should be designed with more attention since it determines the satisfactoriness of the given controller for the application needed. A general procedure used while designing a fuzzy logic rule base includes the following

1. Define the Input and Output Variables: Identify the input variables (linguistic terms) that represent the system's inputs and the output variable (linguistic terms) that represents the desired output or control action.
2. Determine the Universe of Discourse: Specify the range or domain of each input and output variable. This defines the boundaries within which the variables can take their values.
3. Linguistic Term Selection: Determine the linguistic terms (e.g., "low," "medium," "high") that will be used to describe the input and output variables. These terms should be intuitive and meaningful in the context of the application.
4. Define the Membership Functions: Choose appropriate membership functions (triangular, trapezoidal, Gaussian, etc.) for each linguistic term associated with the

input and output variables. These functions describe the degree of membership of an element in a linguistic term.

5 Generate Rule Base: Create rules that define the relationship between the input variables and the output variable. Each rule consists of an antecedent (input conditions) and a consequent (output action). These rules are typically expressed in an "if-then" format using linguistic terms.
6 Determine Rule Weights (optional): Assign weights to individual rules to prioritize their influence on the system's decision-making process. This step is optional and is used when certain rules need to have more significance than others.
7 Rule Base Refinement: Review and refine the rule base to ensure it captures the desired control behavior accurately. Consider domain knowledge, expert input, and iterative testing to improve the rule base's performance.
8 Rule Base Evaluation and Tuning: Evaluate the rule base's performance using simulation or real-world data. Fine-tune the rules and membership functions based on system behavior and desired control outcomes.

The fuzzy rule control table is shown in Figure 6-5, with the following access controls:

- Use the intermediate current figure for equalization when both average SOC and difference SOC are bigger to avoid the battery pack overcharging;
- It is possible to employ a minor current equalization when average SOC is large and difference SOC is minimal.
- High current equalization can be utilized to accelerate equalization when average SOC is small and difference SOC is significant.

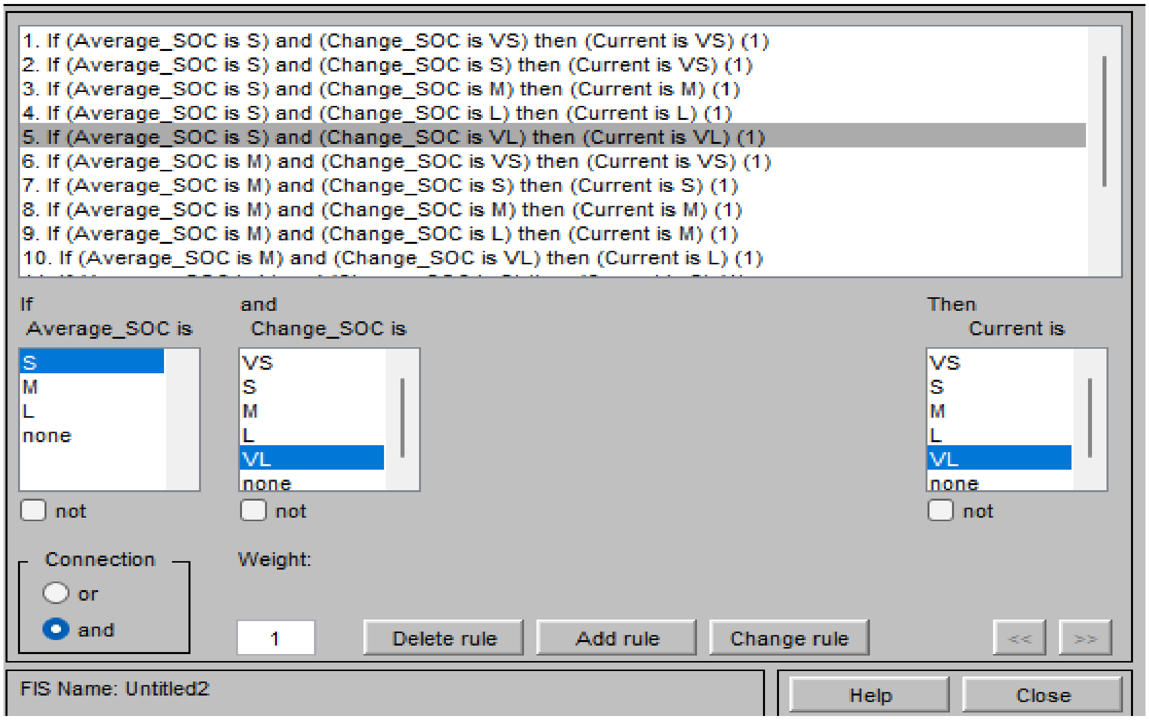


Figure 5-5-11. Fuzzy logic rule base

The fuzzy-PID controller's output controls the MOSFET in the equalization circuit. On and off, with the frequency of the switch chosen as the output to regulate the charge balance situation. The equalization current generally raises as the switching period (TS) increases.

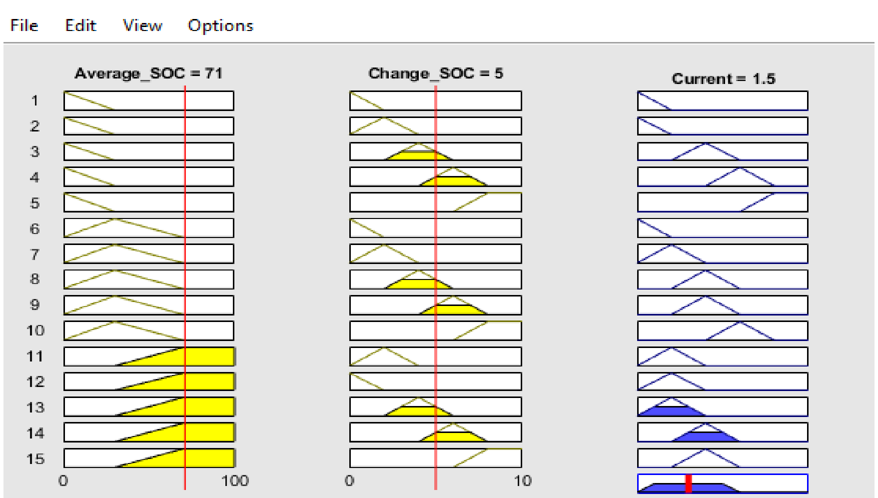


Figure 5-5-12. Rule Viewer of Fuzzy-PID Control input and output

According to the above analysis, the input of the fuzzy controller can be obtained in MATLAB.

Table 6-1;-input and output of fuzzy rules

I		ΔSOC				
		VS	S	M	L	VL
SOC	S	VS	VS	M	L	VL
	M	VS	S	M	M	L
	L	S	S	S	M	M

Table 5-1 Input and Output of Fuzzy Rules

The output surface plot is shown in Figure 6-5-9.

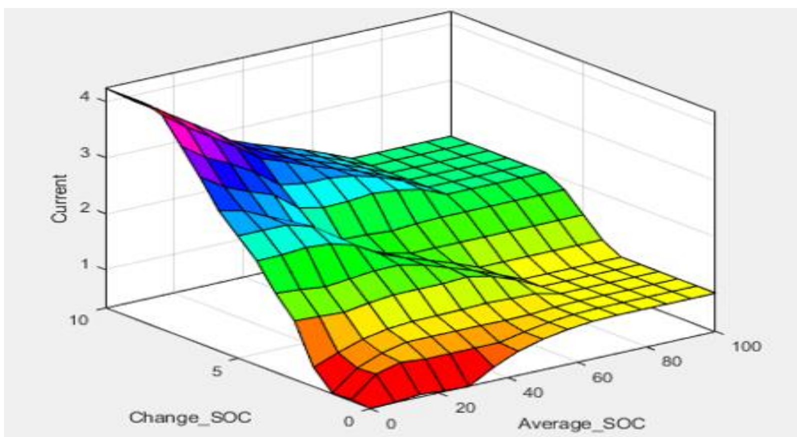


Figure 5-5-13. Surface Area of Fuzzy-Control

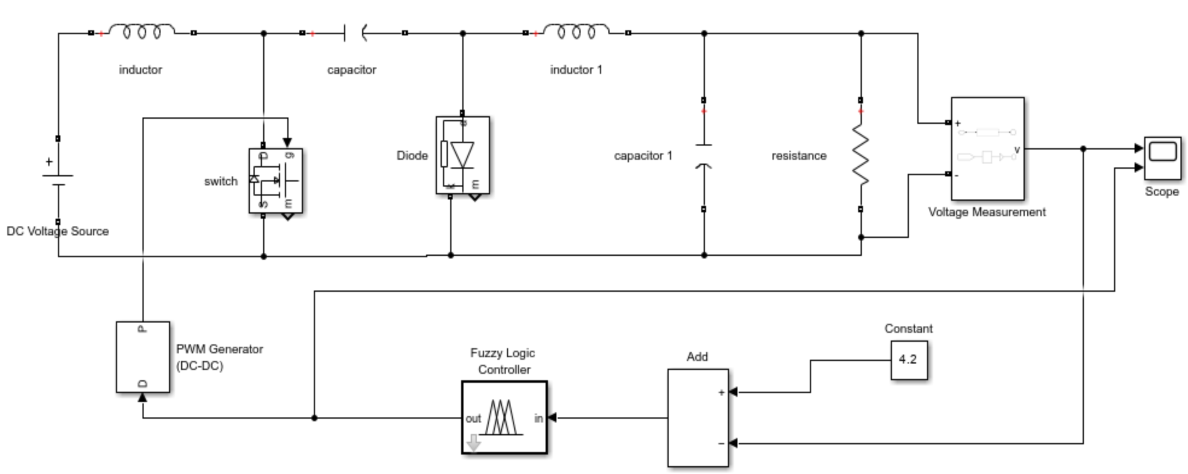


Figure 5-5-14. Fuzzy-logic Control with equalization circuit with fuzzy logic

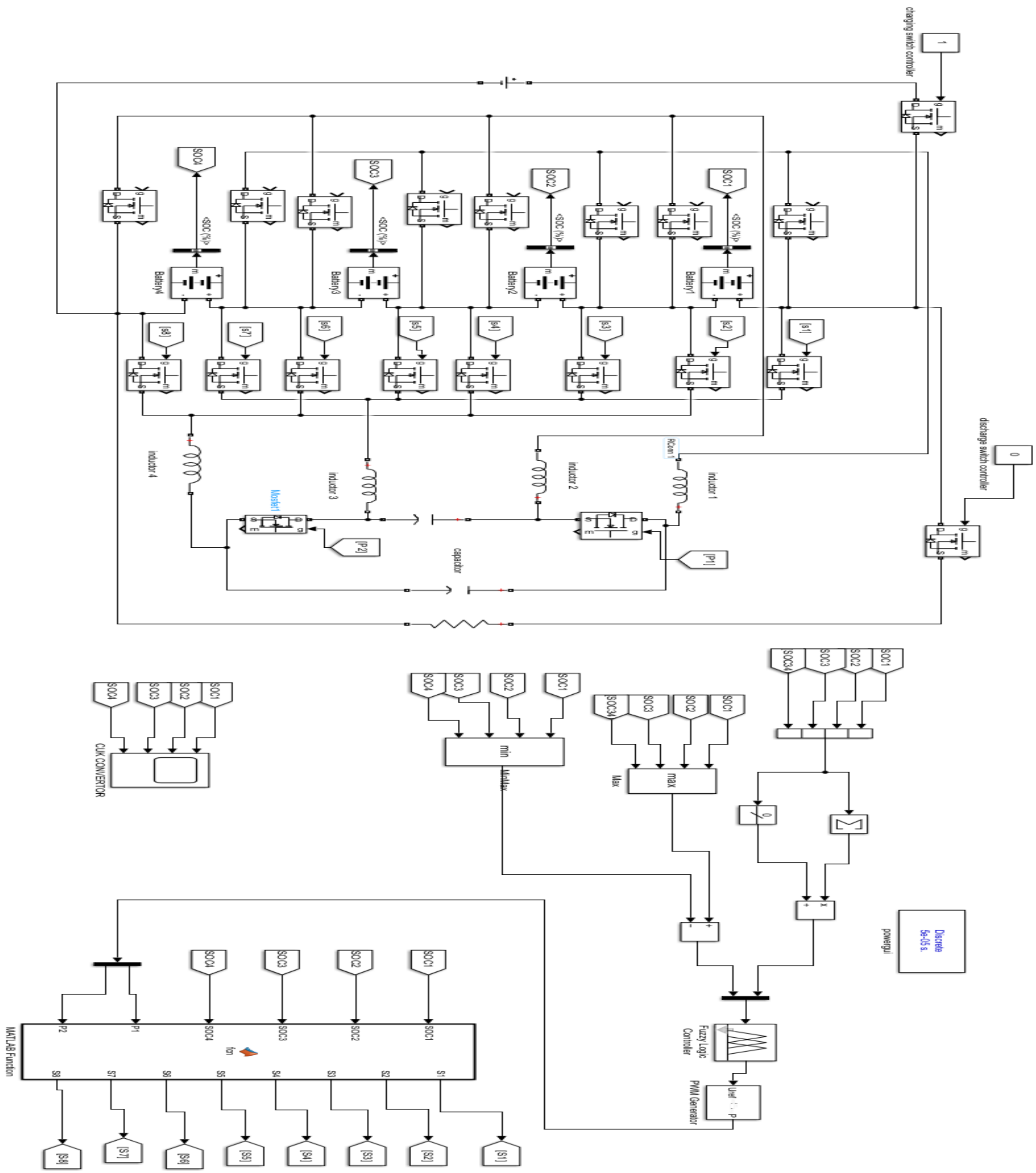


Figure 5-5-15. Fuzzy-PID controller on over all controlling system

5.5 PID controller

Self-regulating systems that rely on feedback loops, or the process of bringing a system's output back to its input, have existed since antiquity. These days, these systems are an essential part of contemporary technology. One of the first attempts to formally define control loops using feedback may be found in James Clark Maxwell's more than 150-year-old article On Governors.

In the context of control systems, a controller that makes decisions based only on predefined input values and ignores feedback is known as an open-loop control system. Contrarily, a closed-loop controller has continuous feedback built in, allowing for real-time modifications to enhance precision, stability, and resilience. This makes it more suitable for achieving desired control objectives in a variety of scenarios.

The most widely used type of closed-loop control system at the moment is the proportional-integral-derivative (PID) controller. These controllers keep an eye on a system's output and adjust it as needed to bring it into compliance with a predefined goal condition or desired set point for the system or process in question. PID controllers are incredibly versatile, relatively inexpensive, and easy to implement, which allows them to be used in a wide range of systems, from analog and digital electronics to hydraulics and pneumatics.

They are currently extensively employed in many industrial and scientific domains, such as manufacturing, photonics, sensors, material science, and nanotechnology.

5.5.1 PID working principle and building blocks

A PID controller's objective is to generate a control signal that enables the system to dynamically close the distance between its output and the desired set point. Let's think about the next illustration. After looping back and evaluating the system's output, y(t), against the set point, r(t), the comparator generates the time-dependent error signal, e(t) = r(t) - y(t). This error signal is subsequently reduced by the loop filter and used to generate the control signal u (t), which drives the system's output and initiates closed-loop functioning.

Therefore, as shown in Figure 2, it is crucial to consider not only the current error but also its accumulation over time (represented by the integral) and its future tendency (shown by the derivative at time t). These procedures are always followed in an effort to decrease error.

The three primary components of the PID controller loop filter—the derivative, integral, and proportional terms—are utilized to reduce mistakes in the majority of scenarios.

The total of the three distinct contributions can be used as a broad quantitative representation of the complete control function: A typical PID controller was designed using the deviation of E and the deviation rate of Ec as input variables. Additionally, the output variable served as U's control quantity for managing the perform structure. The control parameters for Kp, Ki, and Kd were input by the operator. The three input, one output mode was built.

The current difference between the system's measured output and set point serves as the basis for the proportional term, denoted by the letter P. This term helps to return the system's output to the set point and reduces the rising time of the corrective signal by providing a correction proportionate to the amplitude of the error. The larger the mistake with a fixed Kp, the larger up (t), or the larger the correction made by the proportional term. Since the P term always requires a non-zero error in order to produce its output, it is unable to cancel the error on its own. Under steady-state system conditions, equilibrium with a steady-state error is reached.

An adjustment proportionates to the error's history, or time integral, is applied by the integral term, denoted by the letter I. For example, if the error persists over time, the integral term will increase and the output of the system will be corrected more severely. Unlike the proportional term, the integral term allows the controller to generate a non-zero control signal even in the absence of an error at that moment. This feature allows the controller to precisely bring the system up to the desired set point.

With an increase in the value of the integral gain coefficient, the cumulative mistake over time contributes more to the control signal. This suggests that in the event of a steady-state error, an integral term with a large gain coefficient will force the control signal to eliminate the error more quickly than a smaller integral term.

Increasing the integral term too much, however, might lead to an oscillating output if too much error is gathered. This will cause the control signal to overshoot and oscillate at the set point. This phenomenon is known as an integral windup.

The derivative term (shown by D) provides control over the error tendency, or future behavior, by applying a correction proportional to the temporal derivative of the mistake. This reduces the rate at which the error changes, improving the control loop's stability and responsiveness. Predicting changes in the error signal is the goal. For instance, the derivative action aims to correct the error if it shows an upward trend instead of waiting for it to get larger (a proportionate action) or persist for a longer period of time (an integral action).

Practical PID implementations occasionally omit the derivative action because of its great sensitivity to the quality of the input signal. In the event of a particularly noisy control signal, when the reference value swings rapidly, the derivative of the error tends to become quite large. This results in an abrupt adjustment from the PID controller that could lead to oscillations or instability in the control loop.

As a mitigation strategy to improve stability, prior low-pass filtering of the error signal is commonly used; however, only a limited amount of filtering is possible because low-pass filtering and derivative control cancel one another.

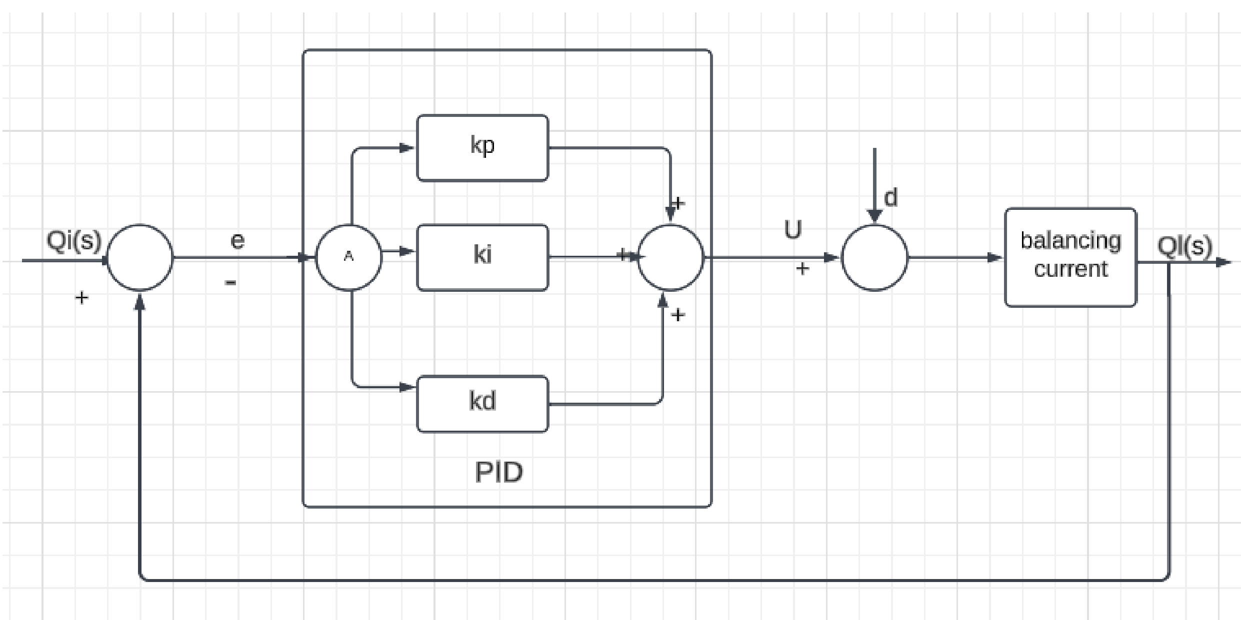


Figure 6-6-13. PID controller systematic diagram

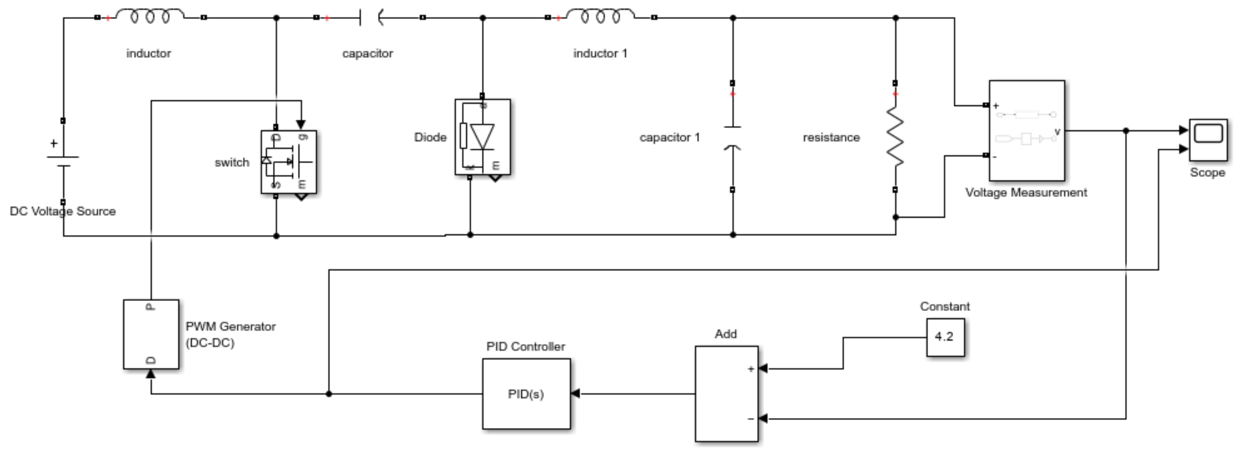


Figure 6-6-164. Cuk convertor with PID Controller

Derivation of an initial set of parameters (Tuning)

One of the main advantages of PID controllers is its application without the need for a detailed model or system understanding. Heuristic calibration techniques have made it possible to generate coefficients based just on simple experimental tests that are performed directly on the process. But first, fine-tuning the PID parameters can be difficult.

A beginning set of coefficients can be found using a variety of well-proven methods, many of which include measuring certain open-loop features of the system

The phrase "open-loop" refers to a system's behavior in which an input signal is given and the output is just measured without being communicated back to the input, as was indicated in the introduction. The input signal can be any signal that is appropriate for the system being controlled, such as a sine wave, ramp, step function, or other. After that, the output of the system is recorded as a function of time, allowing for the examination of its response properties, such as its natural frequency, time constant, and damping ratio.

Three steps are usually involved in the overall technique to obtain starting parameters:

1. Measure some of the distinctive characteristics, such as the process delay and the oscillation period of the system output, after obtaining the open-loop response of the system.

2. Using the measured parameters as a guide, determine the approximate values of the gain coefficients Kp, Ki, and Kd.
3. Adjust the PID gain coefficients for robustness, speed, or noise reduction.

PID (Proportional-Integral-Derivative) controllers are widely used in industrial control applications due to their simplicity, comprehensible control algorithm, and cost-effectiveness [31]. The goal of designing a PID controller is to ensure that the output signals of a controlled plant can accurately track a reference signal provided as an input, with the ability to minimize the steady-state error to negligible levels.

By tuning the parameters of the PID controller (proportional gain, integral gain, and derivative gain), it is possible to achieve precise of the reference signal and minimize the steady-state error. The tuning process involves finding the optimal combination of these parameters through techniques such as trial and error, manual tuning, or automated methods like Ziegler-Nichols or model-based approaches. After automatically tuning the following gain reached for optimal performance.

No.	Gain	Values
1	Kp	0
2	Ki	12076575.98
3	Kd	0

5.6 Modeling and Design of Selector

When designing a selector for a fuzzy and PID controller, the goal is to combine the outputs of both controllers in a way that optimally utilizes their strengths. This can be achieved by creating a hybrid controller that takes advantage of the fuzzy logic controller's ability to handle complex and nonlinear systems, while also leveraging the PID controller's ability to provide precise and stable control.

1. Identify the control objectives: Understand the specific control objectives you want to achieve with your system. This could include tracking a set point, rejecting disturbances, minimizing overshoot, etc.

2. Design the fuzzy controller: Develop a fuzzy logic controller that captures the system's behavior and can generate appropriate control signals based on the current state and inputs. Define fuzzy sets, membership functions, rules, and the inference mechanism to map inputs to outputs.
3. Design the PID controller: Develop a PID controller that can provide proportional, integral, and derivative actions to regulate the system's response. Tune the PID parameters (proportional gain, integral gain, and derivative gain) to achieve the desired control performance.
4. Define the selection criteria: Determine the conditions under which you want to switch between the fuzzy and PID controllers. This could be based on error magnitude, rate of change of error, or any other relevant system variables.
5. Implement the selector: Create a logic or decision-making mechanism that evaluates the selection criteria and determines whether to use the fuzzy controller or the PID controller. This can be done using simple threshold-based conditions or more complex algorithms, depending on the specific requirements.
6. Combine the outputs: Once the selector has determined which controller to use, combine the output signals of the selected controller with appropriate scaling factors or weightings. This can be achieved through simple addition or more advanced techniques like model predictive control.

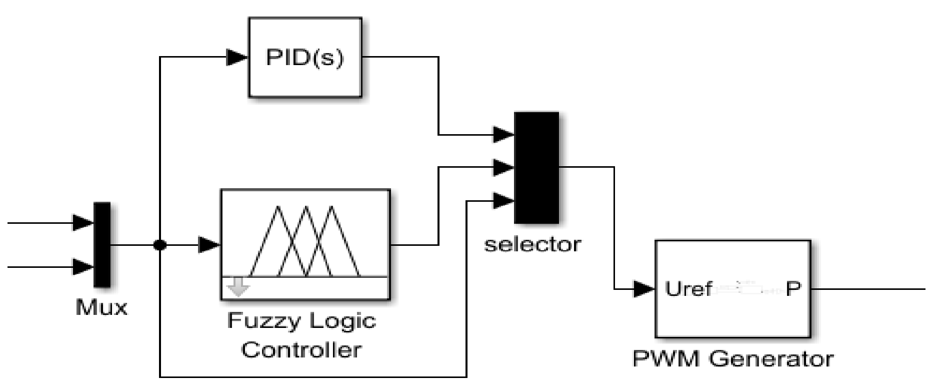


Figure 6-7-15. Design a selector for a fuzzy and PID controller

```
% Define the error threshold for controller selection
Large Error Threshold = 1%
% assuming you have already computed the error value
Error = ... % Calculate the error value here
% Controller selection based on error magnitude
If abs (error) > large Error Threshold
% large error, select Fuzzy controller
Controller = fuzzy Controller; % Replace "fuzzy Controller" with your actual fuzzy controller
Else
 % Small error, select PID controller
 Controller = PID Controller; % Replace "PID Controller" with your actual PID controller
End
```

In the provided code, an error threshold is defined to determine whether the error is large or small. If the absolute value of the error is greater than the threshold, the Fuzzy controller is selected. Otherwise, the PI controller is selected. The error threshold is a predetermined value that serves as a criterion to determine whether the error is large or small. It is typically chosen based on the system's characteristics, control objectives, and the desired behavior of the hybrid controller. The threshold value can be adjusted to strike a balance between the fuzzy logic controller's ability to handle complex and nonlinear systems and the PID controller's strength in providing precise control.

The absolute value of the error is compared with the error threshold. The absolute value is used to ensure that both positive and negative errors are considered. If the absolute value of the error is greater than the threshold, it indicates a large error, and the fuzzy logic controller is selected. The fuzzy logic controller can handle complex and nonlinear systems by using linguistic variables and rules to represent and control the system's behavior. It provides flexibility in capturing expert knowledge and experience in designing the control rules and membership functions.

Otherwise, if the absolute value of the error is less than or equal to the threshold, it indicates a small error, and the PID controller is selected. The PID controller is known for its ability to provide precise and stable control. It calculates the control action based on the error between the desired set point and the actual system output, using the proportional, integral, and derivative terms. The

PID controller's output is effective in fine-tuning the control action to achieve accurate control in response to small errors.

By using the error threshold to switch between the fuzzy logic and PID controllers, the hybrid controller combines the strengths of both controllers. When the error is large, indicating a complex or nonlinear system behavior, the fuzzy logic controller takes control to handle the system's challenges. On the other hand, when the error is small, indicating a relatively stable system behavior, the PID controller takes control to provide precise and stable control.

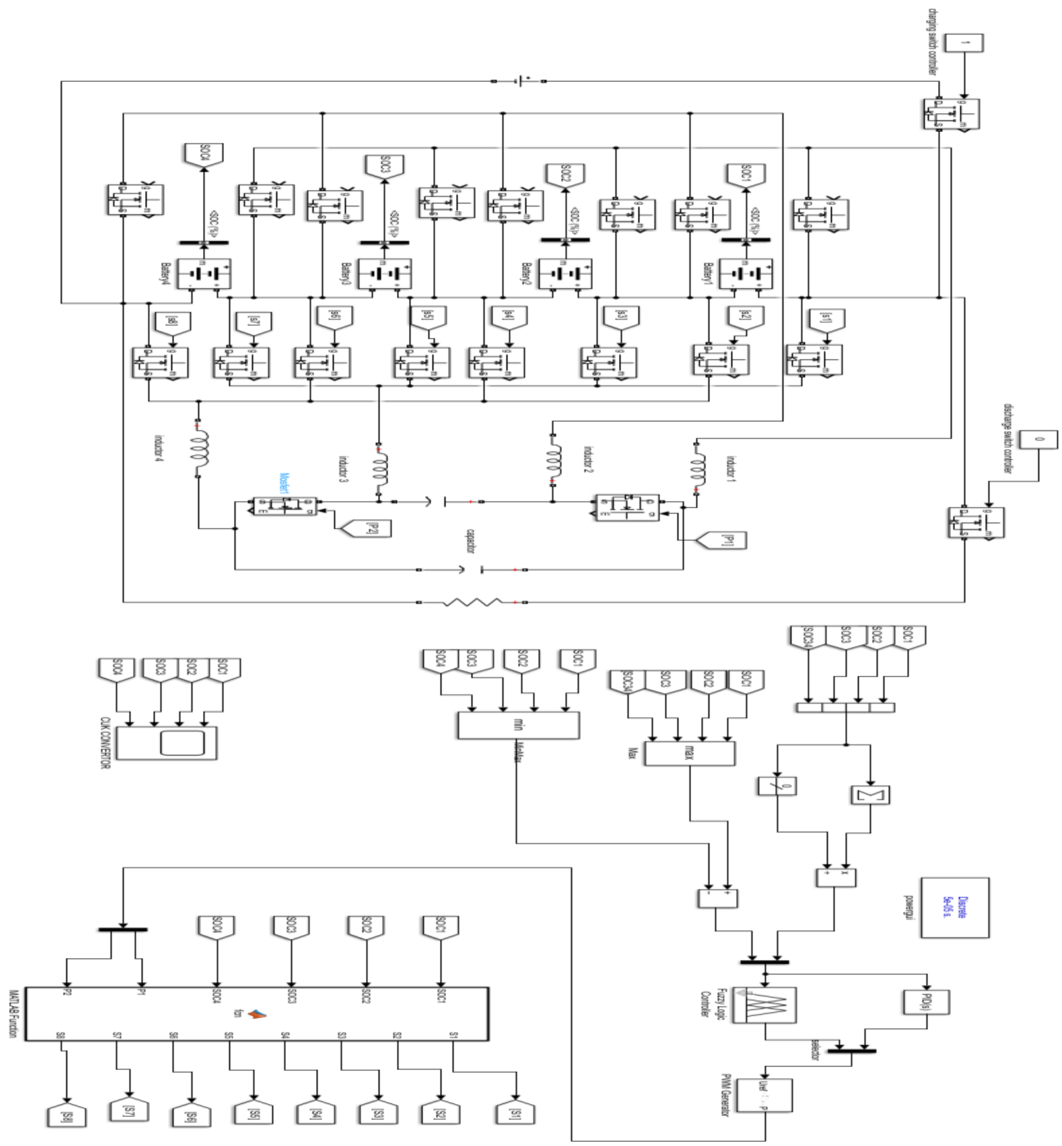


Figure 6-7-16. MATLAB/Simulink selector function on controlling system

CHAPTER SIX

6. RESULTS AND CONCLUSION

6.1 Introduction

The two primary factors that contribute to cell imbalances in lithium-ion batteries are (i) manufacturing errors that result in uneven charge levels, and (ii) working condition, which is multiple charging and discharging cycles that result in uneven charge levels. Such imbalances cannot tolerate overcharging, which could cause a battery explosion, or over-discharging, which could shorten a battery's lifespan. Cell balancing must therefore be a part of the battery's two independent charging and draining phases. The battery monitor determines when to finish charging or discharging the battery by comparing each cell's state to the voltage regulation point while the battery is being charged.

Stronger cells are slightly overcharged and weaker cells are somewhat undercharged as a result. This causes weaker cells to deteriorate more quickly, which affects the battery pack as a whole. The stronger cells retain some of their charge during the discharge cycle, while the weaker cell discharges more quickly. Thus, weaker cells degenerate again as a result of excess discharge. These problems can be resolved with a controller or efficient cell balancing technique that increases battery longevity and safety.

6.2 Results

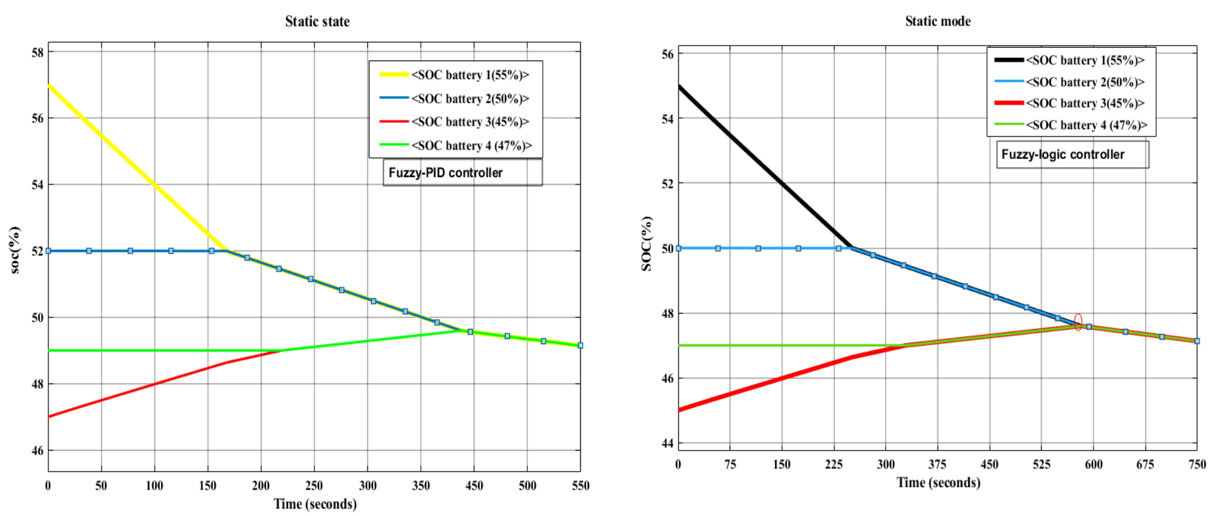
Scenario 1: The battery pack in Static state (no load)

In static mode or no-load conditions, batteries undergo self-discharge over time. Self-discharge is the gradual loss of charge that occurs due to internal chemical reactions within the battery. The self-discharge rate depends on the battery chemistry and temperature. It is important to consider self-discharge when estimating the available capacity of a battery pack that has been in static mode for an extended period. In some cases, battery packs may still consume a small amount of power in static mode, even without any external load. This power consumption is often associated with internal circuitry, control systems, or auxiliary components within the battery pack. It is generally a low level of power compared to active load conditions.

Before the equalizing process, there was a considerable variation in the state of charge (SOC) levels inside the pack of cells, with a maximum SOC difference of 10%. The initial state of charge (SOC) values of the cells ranged from 45% to 55%, indicating an imbalance in their cycles of charging and discharging. To address this imbalance, an equalizing procedure was initiated and ran for ten minutes.

During the equalization procedure, the charge was distributed among the cells using the equalizing circuits. These circuits were operational for between 0% and 50% of the 10 kHz pulse duration, with a duty cycle of 0 to 0.75. The equalizing circuits made sure that every cell got the right amount of charge to bring their SOC levels closer together by carefully regulating the duty cycle.

After the equalizing procedure, the cells' SOC levels were balanced, as seen in figure 6-2 below. The SOC levels were found to be surprisingly close to each other, with 47.56%, 47.31%, 47.53%, and 47.54% of the values obtained from the scope for each individual cell. This demonstrates that a high degree of uniformity and balance among the cells was successfully achieved by the equalizing process



a b

Figure 6-2-1 a) Fuzzy- PID during Static mode. b) Fuzzy-logic during static mode

From above result, it appears that the fuzzy-PID controller is more efficient than the fuzzy-logic controller in terms of the equalizing procedure for a four-cell battery pack. The efficiency is demonstrated by the considerable decrease in the highest state of charge (SOC) difference, which decreases from 10% to just 0.25% as shown in Figure 6-2a. The fuzzy-PID controller takes around

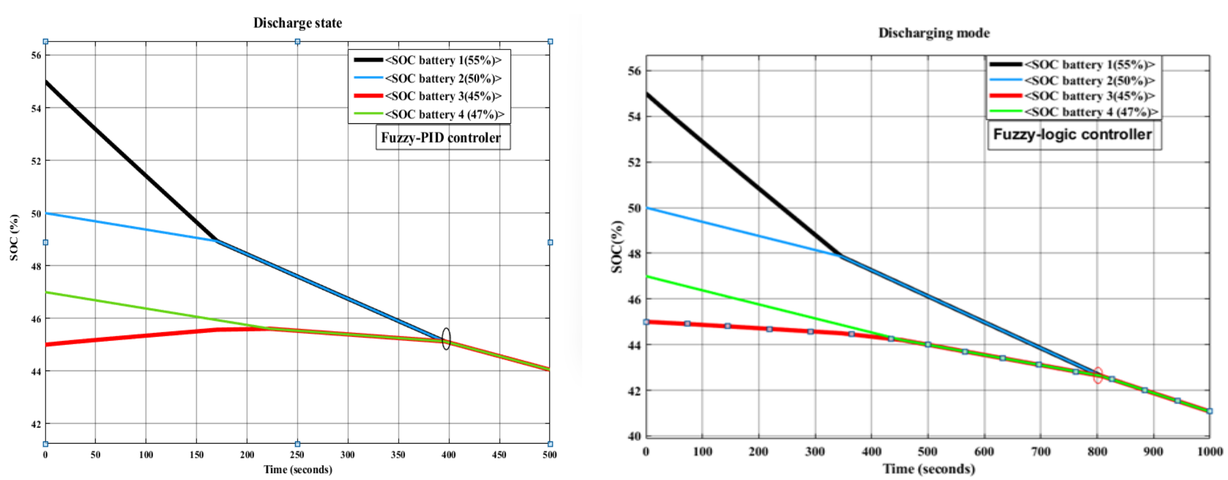
415 seconds (approximately 7 minutes) to balance the four-cell battery pack, while the fuzzy-logic controller takes around 575 seconds (approximately 10 minutes) to achieve the same result for four battery cell. Therefore, the fuzzy-PID controller is more efficient because it requires less time to balance the battery pack compared to the fuzzy-logic controller.

Scenario 2: The battery pack on discharging state

Balancing a battery pack during discharging mode refers to the process of equalizing the state of charge (SoC) of individual cells or modules within the pack. Balancing helps ensure that each cell or module is discharged evenly, preventing any cell from being over-discharged or reaching a critically low SoC. balancing a battery pack during discharging helps optimize its capacity utilization, extend overall pack life, and maintain safe operation.

In this case, a battery pack's cells are equalized during discharge by means of a fuzzy-PID controller. The cells had starting SOC values of 47%, 50%, and 45%, with a maximum SOC error of 10%.

The equalization process employing the fuzzy-PID controller produced impressive results, as seen in figure 6-2 below. At the beginning of the process, the SOC values of the battery pack's cells varied, with a maximum initial SOC error of 10%. This may indicate a significant imbalance within the cell population. However, after nearly ten minutes of equalization, the largest SOC error has been reduced to just 0.06%, indicating that the cells' SOC levels have been correctly balanced.



a b

Figure 6-2-2 a) Fuzzy- PID during discharging mode. b) Fuzzy-logic during discharging mode

As we see on above graph, the fuzzy-PID controller is more efficient than the fuzzy-logic controller in achieving cell equalization in less time. The fuzzy-PID controller takes 390 seconds (6.5 minutes), as shown in Figure 6-2a, to balance the four battery cells and effectively distribute energy across them to bring them closer to uniform state of charge (SOC) levels.

The fuzzy-PID controller's efficiency in attaining cell equalization is attributed to its ability to modify the equalization procedure on the fly based on the cells' SOC values. This adaptive behavior allows the controller to optimize the energy distribution process and achieve a more uniform SOC across the battery cells.

In contrast, the fuzzy-logic controller takes 14 minutes, as shown in Figure 6-2b, to balance the four battery cells during discharging. This longer time can be indicative of the fuzzy-logic controller's less efficient performance in achieving cell equalization compared to the fuzzy-PID controller in this specific scenario.

In another case, fuzzy-PID controller is more energy-efficient than the fuzzy-logic controller in achieving cell balancing. The fuzzy-PID controller achieves balancing at 45% of state of charge, while the fuzzy-logic controller achieves it at 42.8% of state of charge as shown above figure.

Achieving cell balancing at a higher state of charge (45% in this case) indicates that the fuzzy-PID controller can distribute energy more effectively among the cells, resulting in a more efficient use of energy. This higher state of charge at which balancing is achieved suggests that the fuzzy-PID controller can maintain a higher overall energy capacity in the battery pack.

In contrast, the fuzzy-logic controller achieves balancing at a lower state of charge (42.8%), which implies that it may not distribute energy as optimally as the fuzzy-PID controller. This lower state of charge at which balancing occurs may result in a slightly lower overall energy capacity in the battery pack.

Upon completion of the equalization procedure, the controller's close to ideal SOC values (45.28, 45.30, 45.32, and 45.34 for the relevant cells) demonstrate a high level of precision in its operation. Thanks to the smallest SOC variance among the cells, a pack's energy capacity is optimized and potential issues like overcharging or underutilizing specific cells are avoided.

Overall, the results highlight how crucial it is for battery management systems to employ cutting-edge control techniques like fuzzy-PID. SOC equalization that is successful improves not only the performance and efficiency of the battery pack but also its overall longevity and durability. Such accurate management techniques are critical to the development of robust and optimal energy storage systems for a range of applications, from renewable energy storage to electric vehicles.

Scenario 3: The pack on charging state

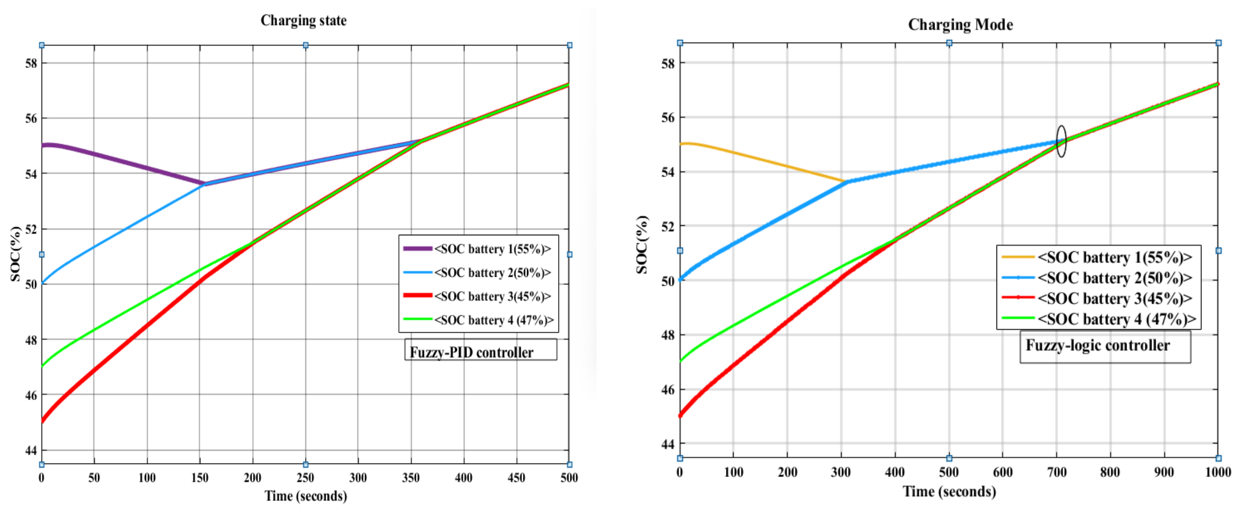
Balancing a battery pack during charging mode involves equalizing the state of charge (SoC) of individual cells or modules within the pack. The objective of balancing is to ensure that all cells reach their maximum capacity without any cell being overcharged. Top balancing and charge distribution involves periodically interrupting the charging process and equalizing the SoC of the cells by discharging the higher SoC cells and charging current is directed to cells with lower SoC. This can be achieved by adjusting the charging algorithm or using a charging system that allows individual cell monitoring and control. By directing more charging current to cells with lower SoC, the pack can be balanced during the charging process.

The example that is given explains how a battery pack with four cells goes through the process of cell equalization. This equalization process was intended to provide a balanced state of charge (SOC) among the cells. Throughout the process, current was used to charge the batteries. At the beginning of the equalization process, the cells' initial SOC levels varied. Cells 1 through 4 had SOC values of 45%, 47%, 50%, and 55%, in that orders. The maximum SOC difference of 10% at this moment indicated a serious cell imbalance between any two cells.

Nonetheless, there was a noticeable improvement in reducing the SOC differences following the equalization process. Notably, the largest SOC variation between any two cells decreased to a mere 0.15%. The SOC values of the cells likewise converged to a considerably tighter range, with Cell 1 reaching 54.63%, Cell 2 reaching 54.76%, Cell 3 reaching 54.78%, and Cell 4 reaching 54.75%.

This outcome demonstrates how successfully the equalization process distributed charge more evenly throughout the battery pack. After a substantial initial difference, the SOC levels of the cells are now quite close to each other. This improved balance is crucial for the battery packs overall performance, longevity, and safety to be optimized.

In order to prevent overcharging or over-discharging, a balanced SOC distribution must be achieved, guaranteeing that every cell operates within its optimal range. Additionally, a balanced SOC increases the overall efficiency and energy storage capacity of the pack while reducing the strain on individual cells.



a b

Figure 6-2-3.a) Fuzzy- PID during charging mode. b) Fuzzy-logic during charging mode

As shown from above figure, fuzzy-PID controller is more efficient than the fuzzy-logic controller during the charging time in terms of balancing a battery pack. The fuzzy-PID controller takes 350 seconds (5.8 minutes) to balance the battery pack, as shown in Figure 6-3, while the fuzzy-logic controller takes 12 minutes.

This result suggests that the fuzzy-PID controller is able to distribute the charging energy more effectively among the battery cells, achieving a balanced state in a shorter amount of time compared to the fuzzy-logic controller. The efficiency of the fuzzy-PID controller in balancing the battery pack during charging can be attributed to its ability to adaptively modify the equalization procedure based on the state of charge (SOC) of the cells, optimizing the energy distribution process. On the other hand, the fuzzy-logic controller takes a longer time to balance the battery pack during charging, indicating potentially less efficient energy distribution among the cells.

6.3 Energy utilization

The energy utilization of a fuzzy-PID controller in battery balancing refers to how effectively the controller manages the energy transfer between cells during the balancing process. The main goal of a battery balancing system is to transfer energy from cells with higher charge or voltage levels to cells with lower charge or voltage levels, thereby equalizing the state of charge (SOC) or state of voltage (SOV) across all cells. A fuzzy-PID controller optimizes the energy utilization in battery balancing by dynamically adjusting the energy transfer rate based on the system's operating conditions. It uses fuzzy logic to account for the inherent uncertainties and nonlinearities in the battery system, while the PID control component fine-tunes the energy transfer based on error signals (e.g., the difference between the desired and actual SOC/SOV).

The battery pack's initial state (before equalization) has a SOC range of 10% and a ε of 3.76. This is compared to the SOC state of each cell after static equalization by fuzzy-PID controller in Fig. 6-3, a comparison diagram. However, after equalization, the SOC range is 0.25%, ε and η are 0.078 and 87.52%, respectively. It is evident that the fuzzy-PID controller's energy usage rate is increased by 3.48% when compared to the mean difference algorithm.

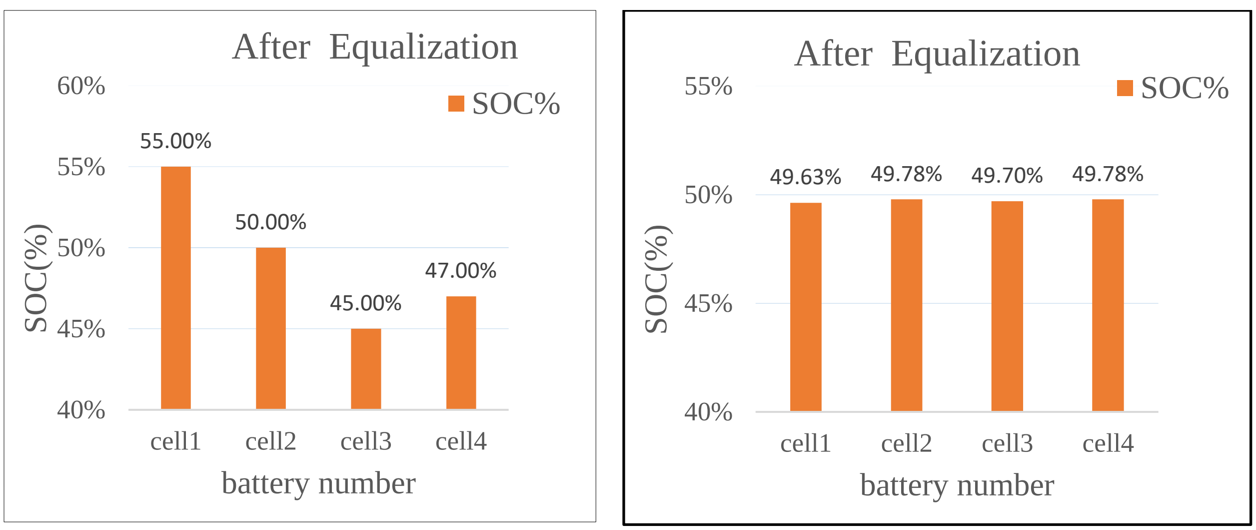


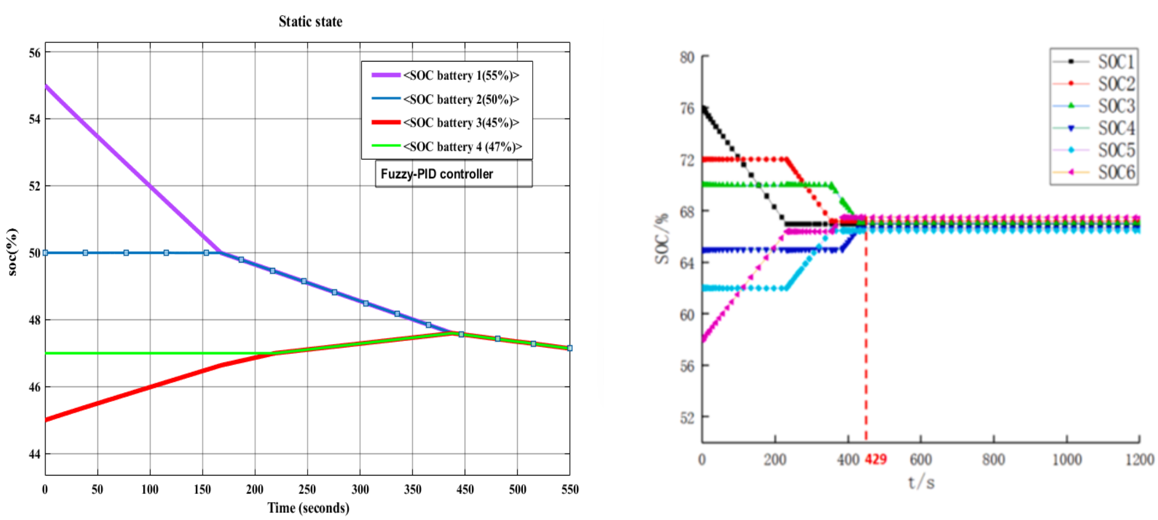
Figure 6-3-1. SOC changes before and after equalization.

6.4 Performance verification

1. Equalization in Static mode (no load)

The equilibrium performance of the fuzzy-PID controller is verified by comparing it with the fuzzy-logic controller between adjacent cells that uses the Cuk circuit as an energy transfer converter(Wu et al., 2021). This is done using the Cuk circuit as the basis for the energy transfer between arbitrary cells as is stated in this work.

Figures 6-4 (a) and (b) respectively, depict the specific changes in SOC values of each monomer used in the comparison, which is based on fuzzy-PID and fuzzy-logic. The battery pack can be balanced using the fuzzy-logic controller approach in 429 seconds, whereas the fuzzy-PID control can balance the battery pack in 400 seconds, as illustrated in Fig. 6-4. This means that the fuzzy-PID controller has a 6.75% faster balancing time.

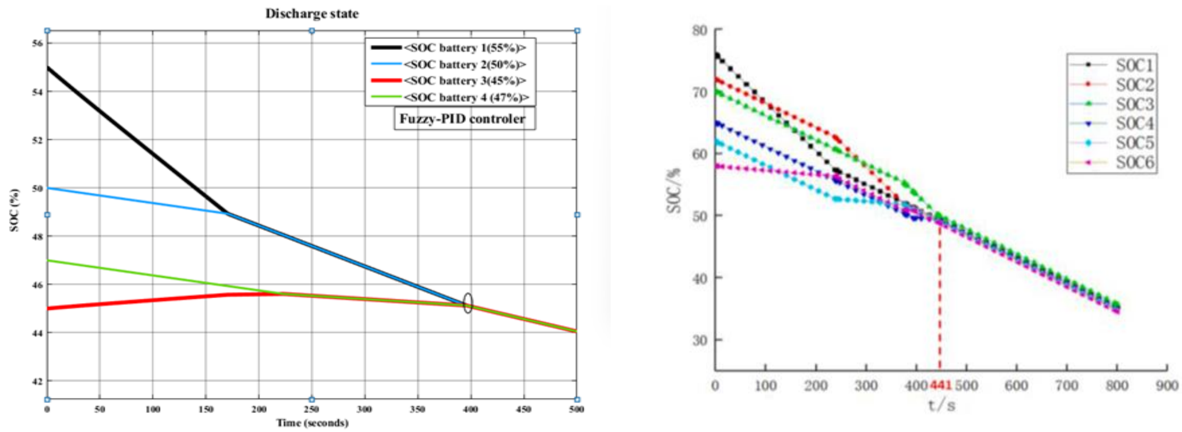


(a) Fuzzy- PID based (b) fuzzy logic based

Figure 6-4-1 static equilibrium

2. Equalization in discharge mode

The SOC variation curves of discharge equalization based on fuzzy-logic controller and fuzzy-PID controller are shown in Fig. 6.5 (a) and (b) respectively. The battery pack can be balanced using the fuzzy-logic controller approach in 441 seconds, whereas the fuzzy-PID control can balance the battery pack in 390 seconds, as illustrated in Fig. 6-5. This means that the fuzzy-PID controller has an 11.56% faster balancing time.

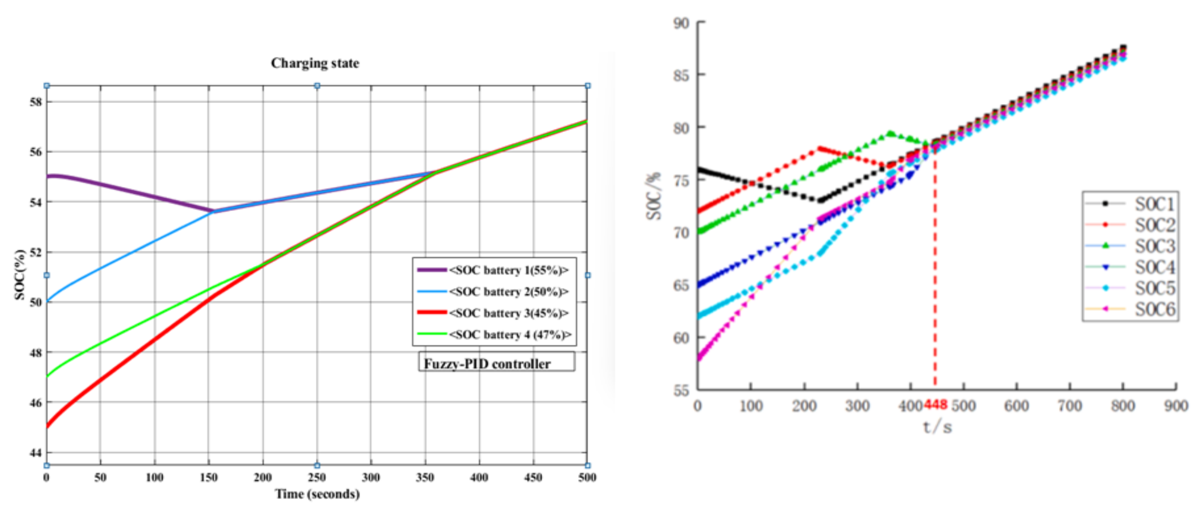


(a) Fuzzy- PID based (b) fuzzy logic based

Figure 6-5-1 Discharge Equalization

3. Equalization in charge mode

The SOC variation curves of charge equalization based on fuzzy-logic controller and fuzzy-PID controller are shown in Fig. 7.6 (a) and (b) respectively. The battery pack can be balanced using the fuzzy-logic controller approach in 448 seconds, whereas the fuzzy-PID control FLC algorithm can balance the battery pack in 350 seconds, as illustrated in Fig. 7-6. This means that the fuzzy-PID controller has a 21.875% faster balancing time.



(a) Fuzzy- PID based (b) fuzzy logic based

Figure 6-6-1 Charge Equalization

6.5 Conclusion

Better state of charge (SOC) balance amongst the cells is just one benefit of the equalization process described in the scenario for the battery pack. First off, by reducing the SOC differences across cells, the equalization process helps to maximize the battery pack's overall capacity utilization. When there are significant SOC anomalies, some cells may be used excessively, while others may be used insufficiently. By balancing the SOC levels and ensuring that every cell contributes evenly to the overall energy delivery and storage, the battery pack may make better use of its full capacity.

Furthermore, a more uniform state of charge distribution can increase the precision and reliability of the battery pack's state of charge estimation. Finding the battery's available energy and predicting its remaining life depend on the SOC calculation. Uneven SOC levels can lead to inaccurate or inconsistent SOC estimation, which can compromise battery reliability and performance. The equalization procedure lowers these estimation errors, enabling more precise battery pack control and monitoring by the energy management system.

Equalization also leads to an increased SOC balance, which may improve overall health and longevity of the battery pack. Because cells with higher SOC levels may age and experience more stress, SOC imbalances may accelerate the degeneration of cells. When the SOC levels are balanced, the cells function more reliably, reducing stress on individual cells and encouraging more even wear and tear. This could extend the battery pack's overall lifespan and maintain its performance over time.

Fuzzy-PID (Proportional-Integral-Derivative) controllers can be used for cell balancing in a number of scenarios, including static conditions, discharging, and charging. By fusing the advantages of traditional PID control with fuzzy logic control, fuzzy-PID controllers provide dependable and adaptive control strategies.

In the context of cell balancing, fuzzy-PID controllers can help maintain a balanced state of charge (SOC) among the cells in a battery pack. To ensure that every cell reaches a comparable SOC level, the controller may dynamically adjust the charging voltage or current while monitoring each cell's state of charge (SOC). By keeping an eye on the SOC differences and modifying the control settings, it can effectively distribute the charging energy across the cells and avoid overcharging or undercharging of particular cells.

Fuzzy-PID controllers can modify the discharge voltage or current during discharging, much like they can during charging, to prevent some cells from losing power faster than others. By continuously monitoring the SOC levels and dynamically adjusting the discharge parameters, the controller can ensure that each cell contributes equally to the overall discharge process. This keeps the SOC distribution in check and keeps certain cells from being used excessively or insufficiently.

When the battery pack is not actively charging or discharging, or when it is static and not in use, fuzzy-PID controllers can still be utilized to balance cells. To balance the SOC dispersion, they can regularly make small adjustments to the cells' SOC levels. This is important because self-discharge or even small changes in cell characteristics can eventually generate SOC imbalances, even in static settings. As a result, it can prevent these imbalances from occurring and preserve a more balanced SOC distribution.

Fuzzy-PID controllers have the advantage of being able to adapt to changing conditions and uncertainty. Although the PID control element provides feedback-based control to respond to deviations from the optimal state of balance, fuzzy logic permits the creation of adaptable rules that consider many circumstances and factors. By mixing these two control techniques, fuzzy-PID controllers may effectively manage the intricacies and variations observed in cell balancing scenarios.

To continuously tune the duty cycles and equally tune the equalizing currents, the fuzzy-PID controllers based on the analysis of the equalizing circuit implemented by the modified Cuk converter. The equalizing speed and cell protection indices, which are represented by the average state charge of all adjacent cell pairs and state charge differences, respectively, are used to assess the overall performance of the suggested equalizers. Expert experience and knowledge, along with cell characteristics, are used to build membership functions and a rule database for the suggested fuzzy-PID controllers. The suggested fuzzy-PID controllers are shown to have a quicker equalizing time, better adaptability, and a higher energy efficiency than the traditional fuzzy controllers through simulations.

Ultimately, the safety of the battery pack is increased by a balanced SOC distribution. Differences in voltage between cells that have significantly different SOC levels could lead to overcharging or over discharging, which could cause capacity loss or thermal runaway, among other safety concerns. The equalization process prevents excessive voltage differentials and the associated safety issues by ensuring that every cell operates within a more constrained SOC range.

6.6 Recommendation

Because of all of their benefits—which include high energy densities, low self-discharge, and great efficiency—batteries are becoming more and more common in cars and homes. But it's crucial to understand that batteries can provide safety threats like fire and explosion hazards if they're not made precisely and accurately or if they're not used in the right circumstances. Battery producers must follow stringent quality control procedures during the manufacturing process in order to allay these worries. This entails making certain that battery components are assembled precisely and accurately, handling chemicals safely, and doing extensive testing to find any potential flaws or weaknesses. It is possible to considerably lower the likelihood of safety issues by putting strict manufacturing standards into place. Additionally, maintaining safe operating conditions and improving power utilization in battery packs need the use of highly automated Battery Management Systems (BMS). To make sure the battery works within safe bounds, a BMS keeps an eye on a number of characteristics, including voltage, temperature, and state of charge. Additionally, it aids in maintaining the equilibrium of the individual cells inside a battery pack, avoiding the potentially dangerous overcharging or over discharging of cells.

6.7 Future work

It is important to keep in mind that a fuzzy-PID controller's exact performance and efficiency for cell balancing will depend on several factors, such as the controller's design, the battery pack's properties, and the control settings.

In this paper, the primary focus lies in the theoretical modeling and simulation of the fuzzy-PID controller. The design principles and algorithms utilized for achieving cell equalization are thoroughly discussed, considering the dynamic behavior of the battery cells. The modeling phase aims to ensure balanced charging and discharging among the individual cells within the lithium-ion battery pack.

In the future, the paper suggests the inclusion of experimental studies that involve implementing the fuzzy-PID controller on actual lithium-ion battery cells. Controlled charging and discharging cycles should be performed, and relevant data such as voltage and current measurements should be collected and analyzed. The experimental analysis will provide valuable insights into the controller's behavior, stability, and performance under various operating conditions, thereby strengthening the overall understanding of its effectiveness in achieving cell equalization in electric vehicle battery management systems and Fuzzy-PID controllers may be used in conjunction with other cell balancing techniques, such as active or passive balancing circuits, to further enhance the balancing performance in specific situations.

REFERENCES

Balachander, K., Amudha, A., & Naveen, K. T. (2021). Battery Management System for E-Vehicle using Kalman Filter. *Journal of Physics: Conference Series*, *1979*(1). https://doi.org/10.1088/1742-6596/1979/1/012018

Banerjee, D., Giri, A., & Saha, S. S. (2020). Active Cell Balancing of Li-Ion Batteries for Electric Vehicles. *SSRN Electronic Journal*, 1–6. https://doi.org/10.2139/ssrn.3495810

Chen, W., Liang, J., Yang, Z., & Li, G. (2019). A review of lithium-ion battery for electric vehicle applications and beyond. *Energy Procedia*, *158*, 4363–4368. https://doi.org/10.1016/j.egypro.2019.01.783

Cui, X., Shen, W., Zhang, Y., & Hu, C. (2017). A fast multi-switched inductor balancing system based on a fuzzy logic controller for lithium-ion battery packs in electric vehicles. *Energies*, *10*(7), 1–18. https://doi.org/10.3390/en10071034

Cui, X., Shen, W., Zhang, Y., & Hu, C. (2018). Fuzzy logic controller for battery balancing system for lithium-iron phosphate battery pack. *Proceedings of the 2017 12th IEEE Conference on Industrial Electronics and Applications, ICIEA 2017*, *2018-Febru*, 1723–1728. https://doi.org/10.1109/ICIEA.2017.8283117

Cui, X., Shen, W., & Zheng, J. (2014). *An Improved Battery Pack Equalizer Based on a*. 27–32.

Duan, W., Song, C., Chen, Y., Xiao, F., Peng, S., Shao, Y., & Song, S. (2020). Online parameter identification and state of charge estimation of battery based on multitimescale adaptive double kalman filter algorithm. *Mathematical Problems in Engineering*, *2020*. https://doi.org/10.1155/2020/9502605

Duraisamy, T., & Kaliyaperumal, D. (2020). Active cell balancing for electric vehicle battery management system. *International Journal of Power Electronics and Drive Systems*, *11*(2), 571–579. https://doi.org/10.11591/ijpeds.v11.i2.pp571-579

Gan, L., Yang, F., Shi, Y. F., & He, H. L. (2017). Lithium-ion battery state of function estimation based on fuzzy logic algorithm with associated variables. *IOP Conference Series: Earth and Environmental Science*, *94*(1). https://doi.org/10.1088/1755-1315/94/1/012133

Hannan, M. A., Young, Y. S., Hoque, M. M., Ker, P. J., & Uddin, M. N. (2019). Lithium Ion Battery Thermal Management System Using Optimized Fuzzy Controller. *2019 IEEE Industry Applications Society Annual Meeting, IAS 2019, September*. https://doi.org/10.1109/IAS.2019.8912339

Hofmann, T., Westhoff, D., Feinauer, J., Andrä, H., Zausch, J., Schmidt, V., & Müller, R. (2020). Electro-chemo-mechanical simulation for lithium ion batteries across the scales. *International Journal of Solids and Structures*, *184*(xxxx), 24–39. https://doi.org/10.1016/j.ijsolstr.2019.05.002

IEEE Industrial Electronics Society. Conference (39th : 2013 : Vienna, A., Technische Universität Wien, Austrian Institute of Technology, IEEE Industrial Electronics Society, & Institute of Electrical and Electronics Engineers. (2013). *IECON 2013-39th Annual Conference of the IEEE Industrial Electronics Society : proceedings : Austria Center Vienna, Vienna, Austria, 10-14 November, 2013*. 1729–1734.

Jadhav, A. D., & Nair, S. (2019). Battery Management using Fuzzy Logic Controller. *Journal of Physics: Conference Series*, *1172*(1). https://doi.org/10.1088/1742-6596/1172/1/012093

Jiang, J., Trundle, P., Ren, J., Cheng, Y.-L., Lee, C.-Y., Huang, Y.-L., Buckner, C. A., Lafrenie, R. M., Dénommée, J. A., Caswell, J. M., Want, D. A., Gan, G. G., Leong, Y. C., Bee, P. C., Chin, E., Teh, A. K. H., Picco, S., Villegas, L., Tonelli, F., … García-Díaz, V. (2010). We are IntechOpen , the world ' s leading publisher of Open Access books Built by scientists , for scientists TOP 1 %. *Intech*, *34*(8), 57–67. https://doi.org/10.1007/s12559-021-09926-6%0Ahttps://www.intechopen.com/books/advanced-biometric-technologies/liveness-detection-in-biometrics%0Ahttp://dx.doi.org/10.1016/j.compmedimag.2010.07.003

Jiani, D., Zhitao, L., Youyi, W., & Changyun, W. (2014). A fuzzy logic-based model for Li-ion battery with SOC and temperature effect. *IEEE International Conference on Control and Automation, ICCA*, 1333–1338. https://doi.org/10.1109/ICCA.2014.6871117

Kumar, S. N., R, S. K., M Tejaswini S, V. H., & Professor, A. (2022). A Comparative Analysis of Cell Balancing Techniques For Battery Management System. *International Research Journal of Engineering and Technology*. www.irjet.net

Lei, X., He, J., Fan, L., & Wang, G. (2022). *Active Equalization Strategy for Lithium-Ion Battery Packs Based on Multilayer Dual Interleaved Inductor Circuits in Electric Vehicles*. *2022*.

Ma, X., Qiu, D., Tao, Q., & Zhu, D. (2019). State of charge estimation of a lithium ion battery based on adaptive kalman filter method for an equivalent circuit model. *Applied Sciences (Switzerland)*, *9*(13). https://doi.org/10.3390/APP9132765

Ma, Y., Duan, P., Sun, Y., & Chen, H. (2018). Equalization of Lithium-Ion Battery Pack Based on Fuzzy Logic Control in Electric Vehicle. *IEEE Transactions on Industrial Electronics*, *65*(8), 6762–6771. https://doi.org/10.1109/TIE.2018.2795578

Martínez, D. A., Poveda, J. D., & Montenegro, D. (2017). Li-Ion battery management system based in fuzzy logic for improving electric vehicle autonomy. *2017 3rd IEEE Workshop on Power Electronics and Power Quality Applications, PEPQA 2017 - Proceedings*, *May*. https://doi.org/10.1109/PEPQA.2017.7981677

Moghaddam, A. F., & Van den Bossche, A. (2019). A ćuk converter cell balancing technique by using coupled inductors for lithium-based batteries. *Energies*, *12*(15). https://doi.org/10.3390/en12152881

Moghaddam, F. (2019). A Battery Equalization Technique Based on Cuk Converter Balancing for Lithium Ion Batteries. *2019 8th International Conference on Modern Circuits and Systems Technologies (MOCAST)*, 1–4. https://doi.org/10.1109/MOCAST.2019.8741779

Molenda, J. (2011). Li-ion batteries for electric vehicles. *Annales UMCS, Chemistry*, *66*(1). https://doi.org/10.2478/v10063-011-0004-z

Nguyen, N., Oruganti, S. K., Na, K., & Bien, F. (2014). An adaptive backward control battery equalization system for serially connected lithium-ion battery packs. *IEEE Transactions on Vehicular Technology*, *63*(8), 3651–3660. https://doi.org/10.1109/TVT.2014.2304453

Nguyen, T. T., Tran, V. L., & Choi, W. (2014). Development of the intelligent charger with battery State-Of-Health estimation using online impedance spectroscopy. *IEEE International Symposium on Industrial Electronics*, 454–458. https://doi.org/10.1109/ISIE.2014.6864656

Pannickottu Nivya, K., & Deepa, K. (2021). Active cell balancing for a 2s Lithium ion battery pack using flyback converter and push-pull converter. *IOP Conference Series: Materials Science and Engineering*, *1070*(1), 012097. https://doi.org/10.1088/1757-899x/1070/1/012097

Piao, C., Wang, Z., Cao, J., Zhang, W., & Lu, S. (2015). Lithium-Ion Battery Cell-Balancing Algorithm for Battery Management System Based on Real-Time Outlier Detection. *Mathematical Problems in Engineering*, *2015*. https://doi.org/10.1155/2015/168529

Qays, O., Buswig, Y., & Anyi, M. (2019). Active Cell Balancing Control Method for Series-Connected Lithium-Ion Battery. *International Journal of Innovative Technology and Exploring Engineering*, *8*(9), 2424–2430. https://doi.org/10.35940/ijitee.i8905.078919

Rashid, M., & Osman, J. (2017). Design and Implementation of Battery Management System for Electric Bicycle. *MATEC Web of Conferences*, *01111*. https://www.matec-conferences.org/articles/matecconf/abs/2017/11/matecconf_etic2017_01111/matecconf_etic2017_01111.html

Raszmann, E., Baker, K., Shi, Y., & Christensen, D. (2017). Modeling stationary lithium-ion batteries for optimization and predictive control. *2017 IEEE Power and Energy Conference at Illinois, PECI 2017*. https://doi.org/10.1109/PECI.2017.7935755

Rivera-Barrera, J. P., Muñoz-Galeano, N., & Sarmiento-Maldonado, H. O. (2017). Soc estimation for lithium-ion batteries: Review and future challenges. In *Electronics (Switzerland)* (Vol. 6, Issue 4). https://doi.org/10.3390/electronics6040102

Samaddar, N., Senthil Kumar, N., & Jayapragash, R. (2021). Passive cell balancing of li-ion batteries used for automotive applications. *Journal of Physics: Conference Series*, *1716*(1). https://doi.org/10.1088/1742-6596/1716/1/012005

Shen, M., & Gao, Q. (2019). A review on battery management system from the modeling efforts to its multiapplication and integration. *International Journal of Energy Research*, *43*(10), 5042–5075. https://doi.org/10.1002/er.4433

Song, Z., Yang, X. G., Yang, N., Delgado, F. P., Hofmann, H., & Sun, J. (2021). A study of cell-to-cell variation of capacity in parallel-connected lithium-ion battery cells. *ETransportation*, *7*, 100091. https://doi.org/10.1016/j.etran.2020.100091

Thanagasundram, S., Arunachala, R., Makinejad, K., Teutsch, T., & Jossen, A. (2012). *A Cell Level Model for Battery Simulation*. *November*, 1–13.

Tomasov, M., Kajanova, M., Bracinik, P., & Motyka, D. (2019). Overview of battery models for sustainable power and transport applications. *Transportation Research Procedia*, *40*, 548–555. https://doi.org/10.1016/j.trpro.2019.07.079

Wang, B., Qin, F., Zhao, X., Ni, X., & Xuan, D. (2020). Equalization of series connected lithium-ion batteries based on back propagation neural network and fuzzy logic control. *International Journal of Energy Research*, *44*(6), 4812–4826. https://doi.org/10.1002/er.5274

Wang, X., Cheng, K. W. E., & Fong, Y. C. (2018). Non-equal voltage cell balancing for battery and super-capacitor source package management system using tapped inductor techniques. *Energies*, *11*(5), 1–12. https://doi.org/10.3390/en11051037

Wu, T., Qi, Y., Liao, L., Ji, F., & Chen, H. (2021). Research on equalization strategy of lithium-ion batteries based on fuzzy logic control. *Journal of Energy Storage*, *40*(March), 102722. https://doi.org/10.1016/j.est.2021.102722

Xie, J., Wei, X., Bo, X., Zhang, P., Chen, P., Hao, W., & Yuan, M. (2023). State of charge estimation of lithium-ion battery based on extended Kalman filter algorithm. *Frontiers in Energy Research*, *11*(May), 1–15. https://doi.org/10.3389/fenrg.2023.1180881

Xiong, R., Tian, J., Mu, H., & Wang, C. (2017). A systematic model-based degradation behavior recognition and health monitoring method for lithium-ion batteries. *Applied Energy*, *207*, 372–383. https://doi.org/10.1016/j.apenergy.2017.05.124

Xu, X. (2017). Research on Fuzzy PID Charging Control of Battery Pack. *World Journal of Engineering and Technology*, *05*(03), 421–427. https://doi.org/10.4236/wjet.2017.53036

Yang, R., Gao, L., & Wu, T. (2020). Comparative study on Equalization Technology of Lithium Battery packs for Electric vehicle. *IOP Conference Series: Earth and Environmental Science*, *461*(1). https://doi.org/10.1088/1755-1315/461/1/012030

Ye, Y., Cheng, K. W. E., Member, S., Fong, Y. C., Xue, X., Member, S., & Lin, J. (2016). *Topology , Modeling and Design of Switched-Capacitor-Based Cell Balancing Systems and*

Their Balancing Exploration. *1*(1). https://doi.org/10.1109/TPEL.2016.2584925

Zhai, C., Luo, F., & Liu, Y. (2020). A Novel Predictive Energy Management Strategy for Electric Vehicles Based on Velocity Prediction. *IEEE Transactions on Vehicular Technology*, *69*(11), 12559–12569. https://doi.org/10.1109/TVT.2020.3025686

Zhang, L., Peng, H., Ning, Z., Mu, Z., & Sun, C. (2017). Comparative research on RC equivalent circuit models for lithium-ion batteries of electric vehicles. *Applied Sciences (Switzerland)*, *7*(10). https://doi.org/10.3390/app7101002

Zhang, S., Ma, X., & Qiu, D. (2020). Battery equalization strategy for LiMn2O4 battery based on fuzzy control. *IOP Conference Series: Materials Science and Engineering*, *790*(1). https://doi.org/10.1088/1757-899X/790/1/012068

Zheng, Y., Ouyang, M., Lu, L., Li, J., Han, X., & Xu, L. (2014). On-line equalization for lithium-ion battery packs based on charging cell voltages: Part 1. Equalization based on remaining charging capacity estimation. *Journal of Power Sources*, *247*, 676–686. https://doi.org/10.1016/j.jpowsour.2013.09.030

Appendix

I. [Fuzzy-PID controller code]

```
 Name='fuzzy-pid controller'
 Type='mamdani'
 Version=2.0
 NumInputs=2
 NumOutputs=1
NumRules=15
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'
[Input1]
 Name='Average_SOC'
 Range= [0 100]
NumMFs=3
MF1='S':'trimf',[-10000 0 30]
MF2='M':'trimf',[0 30 70]
MF3='L':'trimf',[30 70 100000]
[Input2]
Name='Change_SOC'
Range= [0 10]
NumMFs=5
MF1='VS':'trimf',[-100000 0 2]
MF2='S':'trimf',[0 2 4]
MF3='M':'trimf',[2 4 6]
MF4='L':'trimf',[4 6 8]
MF5='VL':'trimf',[6 8 1000000]
[Output1]
Name='Current'
```

Range= [0 5]

NumMFs=5

MF1='VS':'trimf',[-10000 0 1]

MF2='S':'trimf',[0 1 2]

MF3='M':'trimf',[1 2 3]

MF4='L':'trimf',[2 3 4]

MF5='VL':'trimf',[3 4 10000]

[Rules]

If (Average_SOC is S) and (Change_SOC is VS) then (current is VS)

If (Average_SOC is S) and (Change_SOC is S) then (current is VS)

If (Average_SOC is S) and (Change_SOC is M) then (current is M)

If (Average_SOC is S) and (Change_SOC is L) then (current is L)

If (Average_SOC is S) and (Change_SOC is VL) then (current is VL)

If (Average_SOC is M) and (Change_SOC is VS) then (current is VS)

If (Average_SOC is M) and (Change_SOC is S) then (current is S)

If (Average_SOC is M) and (Change_SOC is M) then (current is M)

If (Average_SOC is M) and (Change_SOC is L) then (current is M)

If (Average_SOC is M) and (Change_SOC is VL) then (current is VL)

If (Average_SOC is L) and (Change_SOC is VS) then (current is S)

If (Average_SOC is L) and (Change_SOC is S) then (current is S)

If (Average_SOC is L) and (Change_SOC is M) then (current is S)

If (Average_SOC is L) and (Change_SOC is L) then (current is M)

If (Average_SOC is L) and (Change_SOC is VL) then (current is M)

II. State of charge controller MATLAB function

```
function [S1,S2,S3,S4,S5,S6,S7,S8] = fcn(SOC1,SOC2,SOC3,SOC4,P1,P2)
High = max ([SOC1 SOC2 SOC3 SOC4]);
Low = min ([SOC1 SOC2 SOC3 SOC4]);
if High==SOC1&&Low==SOC2
   S1=P1;S2=1;S5=P2;
   S3=0;S4=0;S6=0;S7=0;S8=0;
elseif High==SOC1&&Low==SOC3
```

```
    S1=P1;S2=P1;S4=P2;S7=P2;
    S3=0;S5=0;S6=0;S8=0;
elseif High==SOC1&&Low==SOC4
    S1=P1;S2=P1;S6=P2;
    S3=0;S4=0;S5=0;S7=0;S8=0;
elseif High==SOC2&&Low==SOC1
    S3=1;S4=P1;
    S1=0;S2=0;S5=0;S6=0;S7=0;S8=0;
elseif High==SOC2&&Low==SOC3
    S3=P1;S4=1;S7=P2;
    S1=0;S2=0;S5=0;S6=0;S8=0;
elseif High==SOC2&&Low==SOC4
    S3=P1;S4=P1;S6=P2;
    S1=0;S2=0;S5=0;S7=0;S8=0;
elseif High==SOC3&&Low==SOC1
    S3=P2;S5=P1;S6=P1;
    S1=0;S2=0;S4=0;S7=0;S8=0;
elseif High==SOC3&&Low==SOC2
    S2=P2;S5=1;S6=P1;
    S1=0;S3=0;S4=0;S7=0;S8=0;
elseif High==SOC3&&Low==SOC4
    S5=P1;S6=1;
    S1=0;S2=0;S3=0;S4=0;S7=0;S8=0;
elseif High==SOC4&&Low==SOC1
    S3=P2;S7=P1;S8=P1;
    S1=0;S2=0;S4=0;S5=0;S6=0;
elseif High==SOC4&&Low==SOC2
    S2=P2;S5=P2;S7=P1;S8=P1;
    S1=0;S3=0;S4=0;S6=0;
elseif High==SOC4&&Low==SOC3
    S4=P2;S8=P1;S7=1;
```

```
S1=0;S2=0;S3=0;S5=0;S6=0;
else
   S1=0;S2=0;S3=0;S4=0;S5=0;S6=0;S7=0;S8=0;
end
end
```

III. Controller selection MATLAB code

```
Threshold for controller selection
Larger error threshold = 1;
Error = SOCmax-SOCmin;
% Controller selection based on error magnitude
if error > largererrorthreshold
controller = fuzzycontroller;
else controller = pidcontroller;
end
```

IV. data reader from excel file code

```
data = read matrix('battery_Exp'); %%data reading
SOC= data(:,1);
RO=data(:,2);
R1=data(:,3);
C1=data(:,4);
R2=data(:,5);
C2=data(:,6);
OCV=data(:,7);
 i=2.3;
%% input data
cn=(2.3*3600);
t=3600;
Qe=2.72;
T1=R1.*C1;
T2=R2.*C2;
UT=OCV-i.*RO-i.*R1.*Qe.^(-t/T1)-i.*R2.*Qe.^(-t/T2);
```