Improving Charging Time of Li-Ion Batteries Using Non-Linear Controller

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Supervisor: Dr. Mohsin Kamal

Co-Supervisor : Dr. Kamran Zeb and Dr. Sadiq Amin

School of Electrical Engineering and Computer Science

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Islamabad, Pakistan

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DEDICATION

I dedicate this thesis to the pursuit of sustainable energy solutions and the endless possibilities they hold for a cleaner, more efficient future. This work is dedicated to my family for their unfailing support, patience, and encouragement along the way. To my mentors and professors, whose guidance and insights have been invaluable, shaping my understanding and passion for control systems. Finally, this dedication extends to the global community of researchers and innovators, collectively working towards a world where energy storage technologies, exemplified by the pursuit of improving Li-Ion battery charging times through non-linear control strategies, play a pivotal role in shaping a more sustainable and resilient planet.

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

AI - Artificial Intelligence
C1 - Initial complexity
C2 - Final complexity
CC - Constant Charging
CCCV - Constant Current Constant Voltage
CCV - Conventional Constant Voltage
CRF - Complexity Reduction Factor
CS - Control Systems
EVs - Electric Vehicles
FCU - Fuzzy Control Unit
Fi - Final number of variables for the input
FLC - Fuzzy Logic Control
HIL - Hardware-In-the-Loop
HV - High Voltage
Ib - Battery Current
Ini - Initial number of variables for the input
Li-ion - Lithium-ion
PWM - Pulse Width Modulation
SOC - State of Charge
SOH - State of Health
T - Temperature
VB - Lowest Single-Cell Voltage
Vd - Maximum Voltage Difference
Exp(s) - Exponential Voltage
C2000™ LAUNCHXL-F28379D LaunchPad - A microcontroller development board

Abstract

Among lead acid, nickel-cadmium and other technologies, lithium-ion Batteries are the most popular type because of their superior performance evidenced by very high energy and power density, a long lifecycle, low discharge rates, high reliability, no toxicity and exceptional efficiency. Nevertheless, time spent on refilling lithium-ion batteries while the charge lasts is the single biggest obstacles to the adoption of electric vehicles (EVs). This thesis presents a new fast-charging implementation called fuzzy logic fast charging, for lithium-ion batteries which is capable of monitoring and controlling the charging currents while the batteries are being charged, in real-time and so quickly. Similarly, it also contains a blocking cut-off section and a unit which will control the temperature to avoid any other side effects when using rapid charging. The method suggested also includes measures like overvoltage protection and temperature regulation signals. Extended testing confirmed a 23.33 % shorter charging duration compared with the current technology. The consequent implementation of this approach that’s supported by Arduino and MATLAB Simulink at real-time renewable energy for charging mobile phones and laptops amongst other uses, looks quite empowering in the large-scale deployment of EVs. The thesis discusses the challenge of the prolonged charge timing and presents the developed quick charging technique that increases the charging rate of lithium-ion batteries but is not related to a reduction in efficiency or capacity thus, has exceeded the limits of the conventional charging method.

Keywords: Lithium-ion batteries, fast-charging methodology, fuzzy logic, temperature control, overvoltage protection, real-time implementation, charging efficiency, electric vehicles, rapid charging, Matlab Simulink, Arduino.

Chapter 1

Introduction

The mass diffusion of electric vehicles (EVs) as a sustainable transport solution has literally been greatly facilitated by the use of Lithium-ion (Li-ion) battery integration in the process [1]. Through their famous characteristics: the high energy density, low self-discharge rate and the extended life-cycle, Lithium-ion batteries have been the main source of power for the modern EVs [2]. However, despite numerous pros, the long charging time still limits the practical use of EVs and their smooth implementation in modern life. Being aware that the rechargeable battery lasts depending on what time it is charged for and how well the charging and the overcharging control measures perform, this thesis aims at finding a solution to this problematic prolonging of charging times for lithium batteries.

The existing techniques in charging Li-ion batteries include constant charging under the Constant Current (CC) and Constant Current-Constant Voltage (CCCV) modes by multi-stage and five stages Li-ion battery charging methodologies [3]. However, the Conventional Constant Voltage (CCV) method still comes with some limitations which are the charging time elongation and the likelihood of the speeds of batteries wearing out and a decreased cycle life as well. That's it, that means there is a need to investigate solutions that speed up charging time but also balance between efficient use and Li-ion battery's life cycle.

The intrinsic characteristics of Li-ion batteries introduce an additional question in designing an appropriate charging algorithm, i.e., nonlinear behavior. Landing the core working principles which allow the battery to be charged is our top priority and this will help to minimize the extensive charging time of the traditional batteries and it will lead to the enhancement of the overall battery life.

The importance of non-linear controllers in the field of control systems has grown as one of the promising alternatives to overcome the complications of nonlinearity and dynamics in modern engineering domains. This work specifically deals with the gap area by exhibiting a radical redesign plan, which revolves around the non-linear feedback control as an intelligent answer to the issues observed with the previous fuzzy logic approach in order to improve the battery time through improvement in the FLC. Briefly, we will be comparing the performance of the proposed controller designed with specific variables with an altered version of the controller using independent variables.

It is this thesis titled, "Improving Charging Time of Lithium-ion Battery using a Non-linear Controller," the discussion of which lies in developing such techniques that are aimed at turning the Li-ion battery charging into something new. The main purpose of the conducted evaluation is to find a sensible compromise between fast charging and the long-term life of batteries with the use of non-linear controllers. As a result, EV penetration will be quicker and in the absence of any other obstacles, Li-ion will find many applications. This thesis seeks to introduce novel achievements in the Li-ion battery charging field through a thorough mathematical model analysis, charging protocol application, and next-generation of control strategies integration. That way we could reach a point where improved sustainability and cost-effectiveness of electric mobility are achievable features rather than just dreams.

1.1 Motivation

The immense penetration of Lithium-ion (Li-ion) batteries into the myriad of sectors from consumer gadgets to EVs, clearly shows that they are now a significant player in powering technological innovations [4] [5]. But aside from their popularity, the lithium-ion battery charging system is still a failing and challenging process, which is a big factor against merging them into everyday devices. Long charging durations, which are inherent to traditional charging methodologies, are major snares that prevent the devices depending on Li-ion batteries from becoming fully ready in time and providing a pleasing user experience. In the new digital era, which is defined by the rising consumption of electronic devices with state-of-art lithium-ion batteries for portable powering, electric mobile transportation, and energy storage solutions, our shrewdness on the performance boost in charging Li-ion batteries is much needed. As hardly any of the traditional control methods can handle the issues when employing large power, non-linear control strategies should be the main direction of research for complex engineering systems pertaining to fast charging.

The possibility of li-ion battery charging using non-linear control theory is truly an interesting and intriguing topic which is intellectually stimulating. I find this research to be an intensive and very appealing topic. Through the study of this realm, scientists, therefore, can unleash the capability for great innovations in energy storage technology which, in turn, inspires a trajectory geared towards a future that is characterized by fast, efficient and sustainable storage technology. On the other hand, the positive impact that advances in Li-ion battery charging would lead to is not disposed only inside the range of consumer electronics [6] [7]. In the scope of electric vehicles, the capability to pace up with charging times possesses extensive aspects in improving the prospects of EVs, which decreases range concern and makes the transition to greener transport techniques achievable. Likewise, improved charging efficiency is coping grid-scale energy storage well with overall power system stability and reliability, ensuring harmonious integration of variable renewable energy into the existing power infrastructures.

This is an astonishing thought, that I might somehow be included in a pursuit which will discover newer and exciting ways to solve some of the biggest problems facing humanity today. Just visualize yourself on a journey to overhaul charging techniques, speeding and boosting efficiency by employing non-linear controllers. Learning about the details of the battery charging process through experimental, simulations and detailed data analysis is my opportunity. Once the Li-ion battery charging becomes more transparent to us, we are gifted with various discoveries that can influence the development of other charging technologies in the future. Such a piece of information is not just for the texts, it can also have a tremendous impact on how we generate power on a daily basis. Imagine yourself in a world where charging your gadgets or electric vehicles is enhanced in an instant and as well eco-friendly and energy efficient.

However, this research goes beyond academics and serves the purpose of providing a real contribution to humankind. By improving the discharge of Li-ion battery technology, we gain the opportunity to make contribution to a new generation of energy-storing solutions that care about efficiency, sustainability and availability for everyone. Being someone who has an ambition of bringing about change and holding a place in history, this mission provides you with a worthwhile and exciting journey.

1.2 Problem Statement

The rising rise of EVs with Lithium-ion batteries as a power source has led to critical issues regarding an efficient charger option. The high energy density, as well as the cycle life of the Li-ion battery, offer the solution for the EVs charging and thus their smooth integration into the daily lifestyle. On the other hand, the charging durations still remain the factor which hampers effective EV utilization. Traditional charging methods, often juxtaposed by CC-CV, include many disadvantages. The major ones are that these techniques prolong charging time and at the same time may affect the lifespan of the battery, a problem that increases with the passage of time. The solution of these problems is a non-linear regulator that may vary charging current dynamically to each particular cell in the Li-ion battery. The undetailed non-linear controller must possess the ability to evaluate the fundamental battery attributes e.g. the voltage, temperature, and current, the cut-off mechanisms, and temperature, to reduce the danger of battery degradation when fast charging is involved. The approach is geared toward promoting a charging model that best balances the charging speed and the battery health, to develop a system suitable for use in sustainable and efficient charging of electric vehicles. The objective of our work is to explore the impacts of modifying the parameters of various charge methods that exist to obtain the best practice and to take the capability of non-linear controllers to respond to inherent non-linearities existing in the behaviour of lithium-ion batteries into account. Through the conduct of the experiments, this work will contribute greatly to the improvement of the charging technologies that will, in turn, pave the way for EV adoption and the increase in the usage of Li-ion batteries in different fields.

1.3 Proposed Solution

To deal with the existing deficiency of a longer charging duration of the Li-ion batteries, we propose a design and application of the nonlinear fuzzy logic controller (FLC). The addition of a new FLC which will act as a smart and intelligent controller will be in charge of the speedy and safe charge regulating alongside the elimination of the higher dangers of overcharging and overheating. As fuzzy logic principles are applied to the FLC, the FLC will give an output current that responds to dynamic changes in battery ratings, paying special attention to thermal variations. Fuzzy logic in the controller for completing charging not only increases its efficiency but will also make it possible to protect the battery from its health damage. Besides having the ability to change the charging rate on the spot, based on real-time battery data, temperature etc., also gives the option for a thorough understanding of the charging process. For the proposed method we are going to use a mathematical examination which employs different values of fuzzy variables modifiers and membership functions. This experiment will identify the best configuration for the FLC that would allow charging the batteries quickly without significant damage to the battery cells and undermining the lifetime of the batteries. Our offered plan shall fit the modern changes in charging technologies which enhances the usage of electric cars and Li-ion batteries (as shown in Figure 1.1)

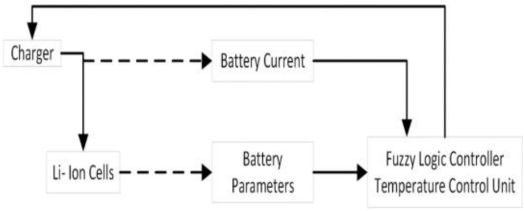


Figure 1.1: Overall System representing Battery, Charger and Control System

1.4 Objectives

Following are some of the objectives of this thesis titled "Improving Charging Time of Li-ion Batteries using Non-Linear Controller".

1. Design and Build a Nonlinear Optimized Technique for Charging Batteries Quickly to Create and implement a nonlinear process in order to have optimal charging of li-ion batteries considering battery system's dynamics and complexity.
2. Simulations and Hardware Testing: Design a precise Simulink model in MATLAB that will correctly model the described non-linear charging method and will permit a full analysis of the simulation by using the model. To prove the given approach via hardware experiments, make sure the theoretical framework corresponds with the actual environment of charging.
3. Observing Fuzzy Logic Controller Behaviour: Watching and analysing the behaviour of the fuzzy logic controller (FLC) by steadily varying the number of fuzzy variables and the membership function parameters is one of the research goals. To learn insights on the influence of the above parameters on the charging process, that will help us understand FLC better to optimise its function of setting the rate.
4. Assess Hardware Reliability and Evaluate Results: To assess the feasibility of the non-linear switching approach by means of hardware experiments and by taking into account the performance in real environments. In order to obtain and compare the experimental results of the old hardware with the charging process to be adopted, and show that the process proposed is better than the old one by its effectiveness.
5. Comparisons to Prior Charging Techniques: A comparison of the proposed non-linear charging system with the past charging method will be done by mainly focusing on improving charging time and efficiency.

Through this research, the aim is to come up with such crucial findings and breakthroughs that will motivate further advancements in li-ion charging technology deepening electric vehicles and other applications as well.

1.5 Literature Review

Fuzzy logic control (FLC) is the fuzzy control that has the most widespread applications due to its power of flexibility. Ismail et al [8] managed to increase the dynamic efficiency of boost dc-dc converter using a fuzzy logic controller and Matlab Simulink tools as feedback for voltage output. As their main goal was to investigate and create a fuzzy logic controller, stepping down the boost DC-DC converter, they have developed a technology which may be used in power electronics. An investigation of various charge levels and ambient temperatures on aged Li-ion batteries was conducted by Zenati et al [9]. Their research end-product that was ready for integration to the FLC system was to monitor the condition of State of Charge (SOC) and State of Health (SOH) of the individual cells, moreover, they gave rise to battery diagnostics. The method the next researchers Zenati et al [10] contributed to extending this by introducing a technique for State of Health (SOH) estimating of lithium-ion batteries based on Fuzzy Logic System (FLS) and computed parameters of the battery.

As suggested by Ali et al [11], this method was the crucial component of a time-efficient, real-time fast-charging approach for lithium-ion batteries that were suitable for the continuous demand of shorter charging times in electronic gadgets and EVs. While Yu et al [12] addressed dimensioning and power management problems, a bi-level multi-objective design and control framework that includes non-dominated sorting genetic algorithm-II and fuzzy logic control was invented. Attia and al. ([13]) focused on developing lithium-ion battery techniques and management throughout material choice, the fabrication process, and the operation stage. The costs of optimisation alternatives were saved by them by using Bayesian optimisation early prediction model.

Sahoo et al.[14] designed a system with a membership function structure of five, in order to operate microgrid frequency control and a multi-input, multi-model fuzzy helping power management system with a number of sources, batteries and load. Chelladurai et al [15] put forward an interval type-two fuzzy logic controlled shunt converter, especially for EV in a way of power charging technology to li-on batteries in an energy storage system. Wu et al [16] explored a Fuzzy logic-based equalisation for li-ion batteries with a new topology that is constituted by a Cuk equaliser circuit and a double-layer selector switch. The carried out research confirmed the potential of balancing actions with superior indicators of time and energy efficiency when the mechanism was implemented under several scenarios. Conclusively, these research findings contribute to the broadening knowledge base of fuzzy logic control usages, battery diagnostics, as well as various storage tactic operations in energy storage systems and electric vehicles. An important exploration path mentioned in the literature involves the so-called creation of fast-charging technologies for the wider use of real-time smart grid applications. These systems try to perform a quick charging of li-ion battery cells and to improve safety and efficiency at the same time. This field of study shadows the use of advanced control algorithms and real-time monitoring systems which dynamically dictate the charging current profile. Also, effective research is connected with the application of multistage constant charging techniques along with fuzzy logic and heat response regimes [3]. Hence the shift to these techniques brings about a more nuanced approach to the charging regiment allowing adjustment to time-to-time battery status parameters for the best results.

With fuzzy logic-based control, the charging process becomes adaptive and with temperature feedback system voltage variation due to battery, ageing is offset, increasing battery longevity. The experimental results that are provided in the literature show that the addition of such enhanced charging methods offers promising outcomes.

Statistic responses assessment showed a 9.76% decline in the charging time if compared to the common CC-CV methods [11]. This is achieved by the process of fast charging without degrading performance or reducing battery life. Besides positive outcomes, the literature contains some of the barriers and areas where optimisation could be improved on. The bottleneck, which stands out among the others, is the long duration of the charging process, which legitimises the call for further optimisation to increase the efficiency of charging processes. Beyond that, the addresses of sophistication and computational costs are so challenging, which is especially true in the applications that need to be real-time.

Finally, the field of fast charging in Li-ion batteries is making amazing discoveries and improvements according to the scientific literature. however, more opportunities and facilities should be explored. Added to the list are factors such as response time, system complexity, and processing overhead. Thus, they have to be taken into account while developing these systems in real applications.

1.6 Novelty: Optimizing the Model

As for battery charging optimization, the utilization of FLCs has gained lots of support for its ability to manage the nonlinearities and uncertainties that are typical of battery systems. The execution of our research, which is concerned with minimizing the charging time of Li-Ion batteries using a FLC, involves several new approaches that help to improve the capability and accuracy of the charging process. undefined

1. **Designing the System, including Battery Parameter Modeling:**
    - This stage primarily focused on the design of the overall system architecture that included the Li-Ion Battery and its components. The novelty is the accurate modelling of battery parameters that includes complete analysis and characterization of the battery behaviour under different operation conditions.
2. **Optimising the Design with Member Function Changes in the Fuzzy Logic Controller:**
    - We meet FLCs with dynamically changed membership functions to improve the control system.
    - The controller shows changes in State of Charge (SoC), temperature, as well as other significant data in real-time by means of the FLC membership function modifications.

- This dynamic optimisation method increases the ability of the controller to be able to handle the charging process. The outcome of this is a more efficient controller and shorter charging time.

3. **Building the Control Unit and Cut-off Block to regulate battery health, excessive voltage, and cut-off condition:**
    - Constructing a tailor-made control unit and a cut-off module is our third step.
    - The control unit checks and regulates battery health as well as overvoltage protection and disconnection management.
    - Ensure the safety and longevity of the Li-Ion battery through the implementation of robust control mechanisms while at the same time improving the charger's efficiency.

4. **Achieving up to a 23.3% Improvement in Charging Time:**
    - Probably the most positive side of our study is that we have implemented fast charging.
    - Powerful systems derived by merging those novelties have displayed an uptake of charging time efficiency by 23.3% in comparison to the previously implemented FLC [11].
    - The simulation of the disproportionate enhancement of this technique not only confirms the usefulness of our approach but also has substantial implications in the various sectors where these batteries are employed.

Chapter 2

Fuzzy Logic Controller and Fundamental Block

The Li-ion battery, known for being its complex nonlinear behaviour, is a challenge for a precise mathematical model recommendation. A controller that does not need a specified battery model is required to acknowledge and solve the problem.

2.1 Selection of a Non-Linear Controller

Choosing just the right non-linear regulator is a significant step towards time control of the charging of Li-ion batteries. The charge control policy must be complex and adaptable that can handle the battery charging processes aimed at maximizing efficiency and reliability. Numerous features decide the selection of the non-linear controller which are designed to deal with technical problems of Li-ion battery charging.

Performance Requirements: A selected non-linear regulator has to be exactly with the highest efficiency indexes of the charging process and battery health. This includes response times to be quick, precise tracking of set points, and robustness to operation condition changes. Furthermore, the controller should present robustness and resistance to interferences in order to assure the safety of the charge and prevent overcharging and undercharging.

Complexity and Computational Requirements: Taking into account the limited memory and the complexity of the control algorithm, it is necessary to achieve performance and computational efficiency. Controllers with a huge number of complexity in variation may have higher requirements for computational power, which in turn can hinder their deployment in real-time charging systems. Consequently, the intermediate level of controllers including easy operation but efficient characteristics have been applied to industrial controllers.

Adaptability and Tunability: Ideally, a universal non-linear controller for Li-ion battery charging should be able to work with different battery chemicals, capacities and conditions in the surroundings. It should allow quick manual tuning to achieve efficient charging under different working regimes. Moreover, the controller will have dynamic adjustment characteristics to make a change in its behaviour depending on the altering battery conditions and external factors.

Stability and Safety: Assurance of the safety and stability of the charging process is one of the key attributes of a non-linear controller. Such property of the control board must be embedded to prevent charging-related oscillations or instability. Moreover, it needs to have inbuilt safety data to control parameters like voltage, current, temperature, and state of charge (SOC) to prevent overvoltages, overcurrents, overheating, and over-discharge.

Real-time Implementation: Since the battery charger systems are in real-time, the implemented non-linear controller should be able to be implemented in real-time using the available hardware platforms such as microcontrollers or digital signal processors (DSPs). The system should be designed with low latency and quick response times to facilitate timely feedback during the charging process. In addition to this, the device should be compatible with a wide range of development platforms and simulation tools for straightforward integration and troubleshooting.

Compatibility with System Architecture: Composed the linear controller, which should be in synchronous with the entire system architecture and control scheme in the Li-ion battery charging system. It should be able to synchronously communicate with the other control units, sensors, actuators, and communication interfaces in order to provide integrated and coordinated operation and communication within the system. Compatibility with already existing hardware and software components is vital for the possible interoperability and big-scale implementation of the charging system.

In other words, the non-linear controller is the key to creating the shortest charging time for Li-ion batteries. Through pondering performance specifications, complexity, adaptability, stability, real-time ability and compatibility with the system architecture, researchers and engineers can choose the most appropriate controller to maximize the efficiency and stability of the charging process with no impact on the functionality of the system. However, In this comprehensive report, the role of the FLC along with some basic blocks in the process of nonlinear mapping is of paramount importance. This improves the efficacy of charging of Li-Ion batteries.

2.2 A Fuzzy Logic Controller

The Fuzzy Logic Controller is the main part of the non-linear controller system that is suggested to reduce the Li-Ion battery charge time. FLC is a robust type of control system that shows the best ability in decision-making and process control in problematic areas where traditional control theory is not so functional. In terms of charging Li-ion batteries, it finds a fuzzy logic controller which determines the charging current using fuzzy logic principles dynamically.

The FLC system is made up of four important parts: the stage of fuzzification which is followed by the fuzzy rule base, the fuzzy inference engine, and defuzzification. Fuzzification is the transformation of actual input bits to fuzzy linguistic variables by the help of membership functions, and the fuzzy rule base provides the operational control to the system storing the parameters. The inference engine puts linguistic fuzzy inputs into an output, following the preset rules and the defuzzification process translates the fuzzy linguistic output to a true value (as shown in Figure 2.1 and 2.2).

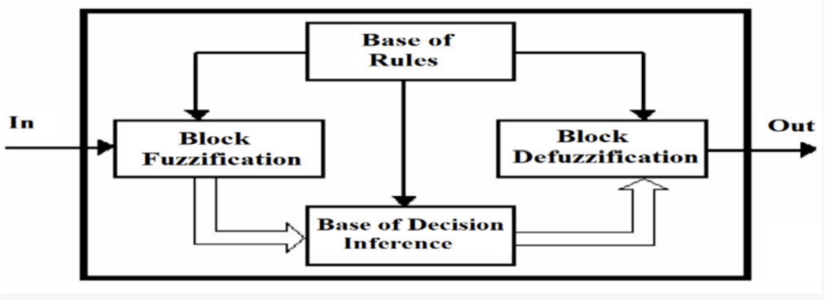


Figure 2.1: The block diagram of Fuzzy Logic System

A Fuzzy Logic-based Arduino controller is used to presented for the FLC architecture, which incorporates two critical inputs: acceptable, minimum voltage among a string of cells (VB), the limits should be the lowest in the battery string and the maximum relative voltage between any two cells in the string (Vd). In order to convert input data into linguistic fuzzy sets, the fuzzifier is used. With the use of a rule base and fuzzy data, the inference engine obtains the optimal activation value for the charging current. Finally, the defuzzifier is the tool that turns fuzzy linguistic sets into the numerical charging current value (Icharge). The set of rules [11] offers symbols of the size of VL, L, M, S and VS which correspond to very large, large, medium, small and very small, respectively.

The discussed fuzzy logic controller incorporates membership functions for Vb, Vd, and icharge denoted as µB, µA, and µi as depicted in figure 2.2. The center of gravity idea and max-min approach are employed in the fuzzified and inference engine for the rules engendering from battery charging by fuzzy control. Figures 3.1 and 3.2 represent the flattening of a three-dimensional graphical plot of the fast-charging fuzzy logic controller that acts upon the dynamic variations of Vd and VB to modulate the current. The new temperature control device would be able to ensure that the extra high charging current is not too harmful to the life of the battery. These innovative

FLC design, which is based on rules and has adaptability, are the core of the movement to increase the charging efficiency of Li-ion batteries.

Fuzzy logic and technological variables, used in defining fuzzy sets and setting up a set of rules, are employed to simulate the complicated and non-linear functioning of Li-Ion batteries. The FLC acquire data from the VB and Vd, and the fuzzy logic technique will be employed in estimating the charging current making use of specialized membership functions and fuzzy rules. This real-time computation agrees with the battery, which constantly changes. Therefore, charging follows the parameter, guaranteeing an efficient use of resources and maintenance of the battery.

The most important thing in this item of application is FLC technique by cases charging when usually control measures fail. In the cases where either input values exactness is impossible or the very complex system behaviour exists, FLC is surely more resistant and adaptable.

The FLC- incorporated into the nonlinear control system covers the lack of conventional charging strategies and, so, more flexible and productive charging schedules are achieved. It improves the time of charging as well as the rule-based command of keeping the battery in proper health by sensing the language variables. Developing this new usage of FLC technology is indeed a great marvel in the industry, as it can effectively increase charging efficiency for Li-Ion in a number of products ranging from electric vehicles to smaller electronic gadgets.

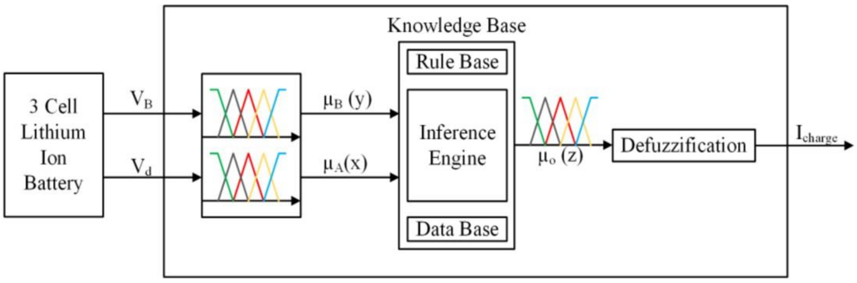


Figure 2.2: Fuzzy Logic System Block Diagram

2.3 Key building blocks of the model

This explicit accelerating process of Li-ion battery charging is one of the key points. It is designed to ensure that things run properly, safely, and for a long time. The model consists of the FLC block and the Temperature and Cut-off Control block which are the integral components.

2.3.1 Fuzzy Logic Controller (FLC) Block:

FLC block is the control center that makes the charging process possible. At this level of control, it uses fuzzy logic to make decisions and control the system especially when input is difficult to measure accurately or when the system has complicated behavior. Here, charging currents are calculated automatically based on certain parameters, hence, assuring the correct charging current for the specific battery.

2.3.2 Temperature and Cut-off Control Block

This rectification block acts like the temperature and safety controller in the battery. It monitors temperature and avoids overvoltage conditions for the effective performance of the battery and to preserve its long life. The temperature control starting at the battery is responsible for monitoring its temperature and adjusting the charging current to ensure that the battery is in optimal charging conditions during the whole process.

If the temperature increases substantially, the system will reduce the charging current to avoid overheating. The retaining block acts as a dam. When the voltage value exceeds ordinary levels, the charging process is turned off and the battery is kept from being spoiled.

These fundamentals when put together achieve a cohesive charging system that not only handles the difficult non-linearity of Li-Ion batteries but also ensures safety and efficiency. The introduced model intends to innovate the charging mechanism by merging the FLC, Temperature, and Cut-off Control modules, and it ensures the fast charging processes without compromising the life and health of the Li-Ion battery.

2.3.3 Voltage Difference and Minimum Voltage Block:

The block which covers gaining signal information that is crucial in an FLC design to optimize the charging time of the Li-Ion battery charger is the FLC. From this block, the two parameters which are of our concern will be computed; they are VB and Vd (as shown in Figure 2.3)

1. Lowest Single-Cell Voltage (VB): Such a value that is defined as VB is the lowest in voltage among the whole series of the cells. It is a mandatory feature showing a flag in case any individual cell of the battery underperforms or gets hot. VB information allows the system to use the battery voltage as the main indicator of battery health.

2. Maximum Voltage Difference (Vd): Vd is the biggest voltage discontinuance across the two cells in the battery combination. It is this value that allows making any differences in charging status of the individual cells visible. Vd that is higher increases the prospect of a proper fast charging process with cells that are experiencing the differences in charging requirement more significantly.

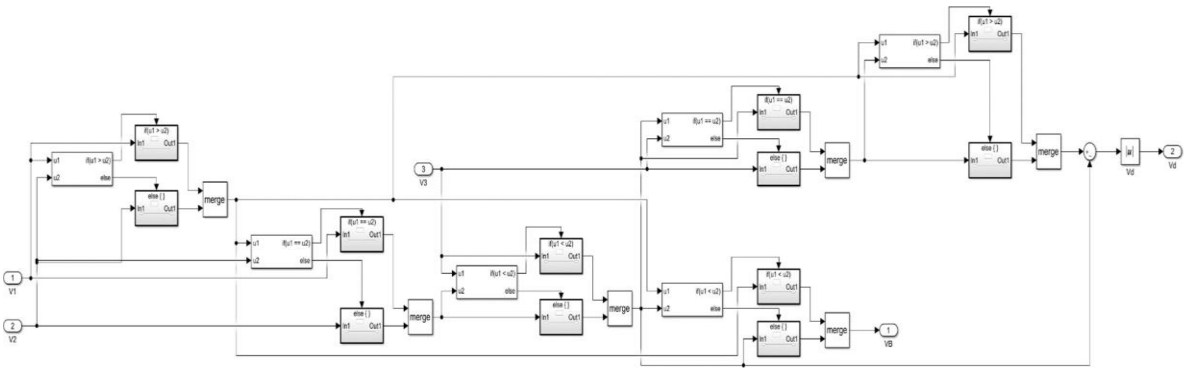


Figure 2.3: Vb and Vd block of system

Chapter 3

Design and Implementation

3.1 Fuzzy Logic Variable Elimination for Increased System Performance

The total number of input variables and the value of variables attract notable attention and therefore the efficiency of FLCs that are designed and implemented for optimising battery [17] charging becomes the main objective. This does in turn implies that in order to enhance the overall system efficiency the the amount of input variables should be minimized without losing the relevant information. A vast amount of fuzzy logic variables scale was reduced with several solutions used.

In the first step, input factors that manifested themselves in charging stages and influenced battery performance were carefully selected. The main inputs of FLC are considered Vb, Vd and charging current as they have proven to be the most significant in determining battery health including the efficiency of the charging process.

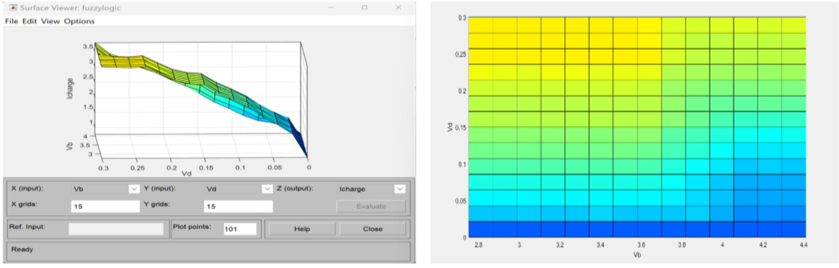
In consequence, feature extraction was used to notice any exactly or highly correlated input data that are being duplicated. The processing involved in taking out the main elements from the data led to the omission of inessential information therefore, the FLC model got polished and became an integrated part of this streamlined process. A number of linguistic phrases per variable input was selected for the ground of achieving a compromise between increasing model complexity and accuracy. The application of linguistic term reduction methods, which can involve clustering or partitioning algorithms, helped to reduce the number of the fuzzy set groups in place while ensuring the representation of the whole input space was adequately achieved.

It was also efficient because the rule base was cleaned to remove rules that were redundant or overlapping due to which computation expenses were reduced and response time was faster. Pruning and Merging rules were considered to address the speed and to achieve accurate control performance. Fuzzy inference techniques base their work on these features of simplicity and accuracy of the selection of gain parameters. The efficiency of fuzzy logic-based system variable reduction techniques is verified through simulations and testing processes. A factor analysis of the factors which contribute to the accuracy of control, the reaction time and the computing overhead of the system was conducted to see how these factors changed after the data reduction had been conducted.

In an outcome-based system, the FLC model is systematically improved by making iterative changes and fine-tuning in order to enhance the efficiency of its functioning. The necessary balance of computational complexity and control performance was realized by us changing input values, rule words and rule base parameters.

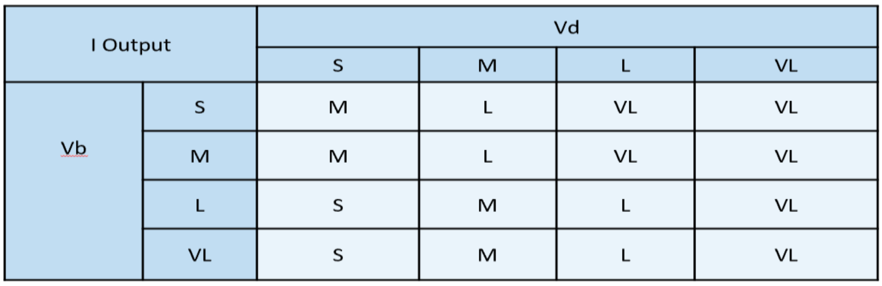
In this section, the logic of fuzzy logic variables reduced strategies in the fuzzy logic controller for the battery charging optimization that goes from five (as shown in Figure 3.1) to four (as shown in Figure 3.2) and thereby makes a great improvement in computing performance. The purpose of the reduction in variables is not only to make the control system simpler but also to increase system performance and efficiency.

I Output		Vd				
		VS	S	M	L	VL
Vb	Vs	VS	M	L	VL	VL
	S	VS	M	L	VL	VL
	M	VS	M	L	VL	VL
	L	VS	S	M	L	VL
	VL	VS	S	M	L	VL

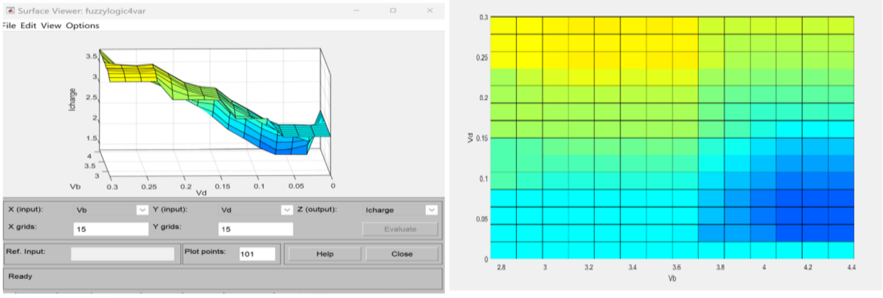


X (input): Vb
Y (input): Vd
Z (output): Icharge
X grids: 15
Y grids: 15
Ref. Input:
Plot points: 101

Figure 3.1: The Fuzzy Logic with 5 Variables



I Output		Vd			
		S	M	L	VL
Vb	S	M	L	VL	VL
	M	M	L	VL	VL
	L	S	M	L	VL
	VL	S	M	L	VL



Surface Viewer: fuzzylogic4var

X (input): Vb

Y (input): Vd

Z (output): Icharge

X grids: 15

Y grids: 15

Ref. Input:

Plot points: 101

Ready

Figure 3.2: The Fuzzy Logic with 4 Variables

3.2 Estimating Complexity of Fuzzy Logic System

The use of fuzzy logic system is crucial in providing an effective charging time of Li-Ion batteries. It goes without saying that the complexity of these systems is a very important factor for analysis of their performance and potential for further enhancement. The number of fuzzy linguistic variables and the total number of rules can estimate a fuzzy-logic system complexity [18]. To represent this complexity, we denote:

$Ini1$ and $Ini2$ as the initial number of variables for the first and second inputs, respectively. $Fi1$ and $Fi2$ as the final number of variables for the first and second inputs, respectively.

The initial complexity $C1$ of the FLS is formulated as:

$$C1 = Ini1 \times Ini2$$

For instance, if $Ini1 = 5$ and $Ini2 = 5$, the initial complexity ($C1$) would equate to $5 \times 5 = 25$.

Upon refining the system by reducing linguistic variables and total rules, the final complexity $C2$ can be computed as:

$$C2 = Fi2 \times Fi2$$

Assuming $Fi2 = 4$, the final complexity ($C2$) would amount to $4 \times 4 = 16$.

Consequently, we ascertain the Complexity Reduction Factor (CRF) as the ratio of the difference in complexities to the initial complexity:

$$CRF = \frac{C1 - C2}{C1}$$

Substituting the given values, the CRF yields a reduction of complexity by 36%. This reduction signifies the efficiency gained through the reduction of linguistic variables and rules, thereby potentially enhancing the efficiency of the fuzzy logic system in optimizing the charging time of Li-Ion batteries.

3.3 Battery Modeling in Simulink MATLAB

In our study aimed at improving the charging time of Li-Ion batteries using a nonlinear controller, we employed a built-in battery model within Simulink MATLAB. This battery model serves as a generic dynamic representation capable of encapsulating the behavior of various rechargeable battery types. The battery model incorporates an equivalent circuit that allows for the modification of parameters to mimic specific battery types and their corresponding discharge characteristics.

The model adjusts accordingly for battery recharging when the current is negative, adhering to specific charge characteristics derived from the discharge curves. The exponential voltage phenomenon, represented by the Exp(s) transfer function, captures hysteresis effects during charge and discharge cycles.

Parameter	Value
Rated Capacity	2.6 Ah
Internal Resistance	0.0138 Ω
Nominal Voltage	3.6 V
Maximum Capacity	2.6 Ah
Fully Charged Voltage	4.190 V
Nominal Discharge Current	1.13 A
Capacity @ Nominal Voltage	2.35 Ah
Exponential Voltage	3.8894 V
Exponential Capacity	0.12774 Ah

Table 3.1. Detailed parameters extracted from the Li-Ion battery datasheet.

3.3.1 Parameterization

To instantiate the battery model, parameters are extracted from battery data sheets, including rated capacity, internal resistance, and voltage characteristics. These parameters are critical for accurate representation and are derived from both specification tables and discharge characteristic plots. Battery parameters can be extracted from data sheets. For instance, parameters extracted from the Li-ion battery data sheet are shown in Table 3.1. These parameters, including rated capacity and internal resistance, are crucial for model accuracy.

3.3.2 Li-Ion Battery Equations

The battery model utilises these equations for Li-ion batteries [19].

Discharge Model:

$$f_1(it, i^*, i) = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot \exp(-B \cdot it)$$

Charge Model:

$$f_2(it, i^*, i) = E_0 - K \cdot \frac{Q}{it + 0.1 \cdot Q} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot \exp(-B \cdot it)$$

Parameters:

E_0 : Nonlinear voltage (V)
K : Polarization constant (V/Ah) or resistance (Ω)
Q : Maximum battery capacity (Ah)
A : Exponential voltage (V)
B : Exponential capacity (Ah^{-1})
it : Extracted capacity (Ah)
i^* : Low-frequency current dynamics (A)
i : Battery current (A)

3.3.3 Temperature Effects

The following equations show how temperature affects the model parameters for Li-ion batteries [20]:

Discharge Model (i* > 0)

$$f_1(it, i^*, i, T, T_a) = E_0(T) - K(T) \cdot \frac{Q(T_a)}{Q(T_a) - it} \cdot (i^* + it) + A \cdot \exp(-B \cdot it) - C \cdot it$$

$$V_{\text{batt}}(T) = f_1(it, i^*, i, T, T_a) - R(T) \cdot i$$

Charge Model (i* < 0)

$$f_1(it, i^*, i, T, T_a) = E_0(T) - K(T) \cdot \frac{Q(T_a)}{it + 0.1 \cdot Q(T_a)} \cdot i^* - K(T) \cdot \frac{Q(T_a)}{Q(T_a) - it} \cdot it + A \cdot \exp(-B \cdot it) - C \cdot it$$

$$V_{\text{batt}}(T) = f_1(it, i^*, i, T, T_a) - R(T) \cdot i$$

Parameters:

$E_0(T)$: Nonlinear voltage (V)
$K(T)$: Polarization constant($V/$Ah) or resistance(Ω)
$Q(T_a)$: Maximum battery capacity (Ah)
$R(T)$: Thermal resistance, cell to ambient (°C/W)
T_{ref} : Nominal ambient temperature (K)
T : Cell or internal temperature (K)
T_a : Ambient temperature (K)
$\frac{\Delta Q}{\Delta T}$: Max temperature coefficient capacity (Ah/K)
C : Nominal discharge slope curve($V/$Ah)

The cell or internal temperature, T, at any given time, t, is represented as:

$$T(t) = L^{-1} \quad P_{\text{loss}}R_{\text{th}} + T_a \frac{1}{1 + s \cdot t_c}$$

where:

$$P_{\text{loss}} = (E_0(T) - V_{\text{batt}}(T)) \cdot i + \frac{\partial E}{\partial T} \cdot i \cdot T$$

L^{-1} denotes the inverse Laplace transform.

Incorporating these equations and parameters into our Simulink MATLAB model enables accurate representation and analysis of battery behavior, facilitating the development of efficient charging strategies for Li-Ion batteries.

3.4 Temperature Control Unit

The Temperature Control Unit algorithm is meticulously crafted to regulate the charging process, incorporating real-time monitoring of battery current (Ib) and temperature (T). The primary goals are keeping the battery temperature within a safe range and dynamically altering the charging current in response to temperature circumstances.

Continuous Sensing: The Temperature Control Unit periodically measures the battery current (Ib) and temperature (T).

$$Ib = f(t)$$

$$T = g(t)$$

Temperature-Based Charging Adjustment: If the battery temperature (T) falls below 40°C, the Temperature Control Unit sends the fuzzy logic-calculated output current to the battery. Consequently, we can have a slower charging rate if the air around is not yet warm enough. If the temperature goes abound the set value of 40°C, the unit conducts an investigation of Ib within the limits of 3.6 to 4.0 A for deciding on the charging current ICharge.

$$I_{charge} = \begin{array}{ll} 3.5\text{ A} & \text{if } 3.6 \leq Ib \leq 4.1 \\ 3.0\text{ A} & \text{if } 3.1 \leq Ib < 3.6 \\ 2.6\text{ A} & \text{otherwise} \end{array}$$

The algorithm samples the battery temperature at an interval less than 2sec to determine if it's increasing or stabilizing. This process of double check assures the conditions of charging, especially concerning the response to temperature, immediate reaction to changes in temperature and avoid potential battery damage.

The Temperature Control Unit (TCU) is one of the most important unit that make up of the whole charging strategy of the Li-Ion battery system [21]. The gadget diminishes the hot-up, which is considered a well-known cause of decrease of potential of a battery, as it sticks the charging current changes depending of temperature. This methodical approach not only aims at making the charging process the most expeditious at the speed level but also makes sure that the battery's health is maintained during its usage life.

Chapter 4

Simulation and Results

The proposed nonlinear controller for enhancing the charging time of the Li-ion battery is realized and simulated utilizing Simulink (as shown in Figure 4.1), an advanced simulation tool that is pertinent for modeling and simulating dynamic systems. The Simulink model that was developed is capable of simulating [3] the functioning of the battery charging system and at the same time test how effective the proposed controller is in attaining the target improvements. The stages below define the implementation process:

1. **Model Initialization and Setup:**
    - The Simulink model was comprised of the fundamental blocks and components required to explain the model of Li-Ion battery system: the battery model itself, charging circuits and control algorithms.
    - The real-world conditions were better portrayed by adjusting the parameters such as battery capacity and voltage along with charging current and ambient condition.
2. **Battery Parameter Modeling:**
    - The block and subsystem designs in Simulink were created and modelled from the battery parameter modelling of the previous research phase.
    - This includes modelling the battery voltage, current and state-of-charge (SoC) and other essential parameters needed for the realistic simulation.
3. **Integration of FLC:**
    - The suggested technique was used to create a non-linear controller which was next integrated into Simulink.

- This controller through analysis of the real-time data form the battery system, determines the optimum charging current and voltage, effectively increasing the charging times.

4. **Optimizing with Fuzzy Logic Controller (FLC):**
    - Simulink model involved the FLC with custom inference methods developed and appropriate Simulink blocks.
    - The FCU incorporated the motion of proposed membership function modifications to cater to adaptive control methods for better overall performance.
5. **Control Unit and Cut-off Block Design:**
    - The Simulink model encompassed the control unit along with the HV cut-off block, which regulated the battery health, overlooked over-voltage and controlled HV cut-off status.
    - We have tested the logic gates, comparators, and feedbacks individually in order to guarantee the battery's safety and best performance during charging processes.
6. **Simulation and Validation:**
    - The developed Simulink model went through vigorous simulation testing for functional accuracy and performance quality.
    - Depending on the charging situation and operational settings, the gain in charging time by the controller was investigated to see whether it can compromise the safety and reliability of the battery system.
7. **Results Analysis:**
    - The result was compared to the reference to examine the effectiveness of the new installed non-linear controller and to verify whether it provides the necessary improvements concerning charging time or not.
    - The contribution of the methodology was assessed based on the performance criteria, which included fast charging capability, charging time as well as battery health indicators.
8. **Iterative Refinement:**
    - Hence, based on the results of the simulation [22], minor changes were made to the Simulink model and to parameters of the controller for the better tuning process and to eliminate the revealed defects.

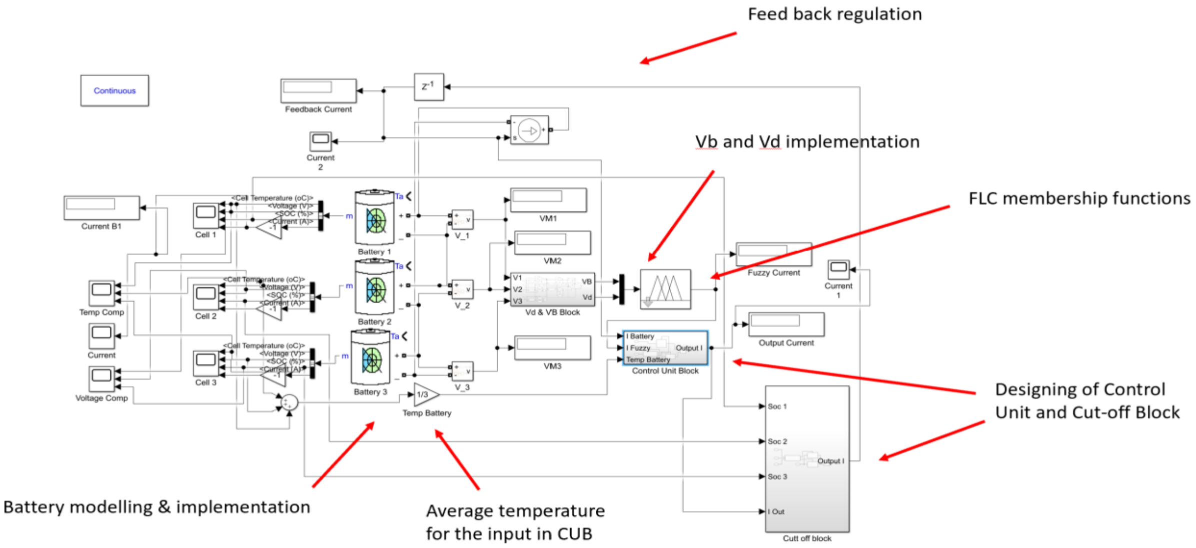


Figure 4.1: Simulink Model for Fast Charging of Li-ion Batteries

This section explains the module-based implementation process via Simulink. The model is developed and integrated after being thoroughly verified in order to shave off time in charging Li-ion batteries.

4.1 Simulink Results

We will show detailed analysis of the experimental data obtained from 3 Li-Ion batteries of various charge levels in the next section. The investigation centered around the exploring of time, voltage, current, SoC, and temperature profiles which allowed the getting of the knowledge about behavior of batteries and the efficiency of the suggested non-linear controller for the progress of the charging procedure. According to the results from the simulation, there is a notable decrease in the time needed for charging when the FLC is used. The average charging time was cut from 7640 seconds to 5860 seconds, denoting a significant 23.3% improvement in efficiency when it comes to charging. This decrease in charging time proves the validity of the control in improving the efficiency of charging and prolonging battery life(see Fig. 4.2). The figure below represents 5 variable FLC simulation results [11] compared with 4 variable FLC simulation results. An observation of the three current cell profiles was exceptionally interesting.

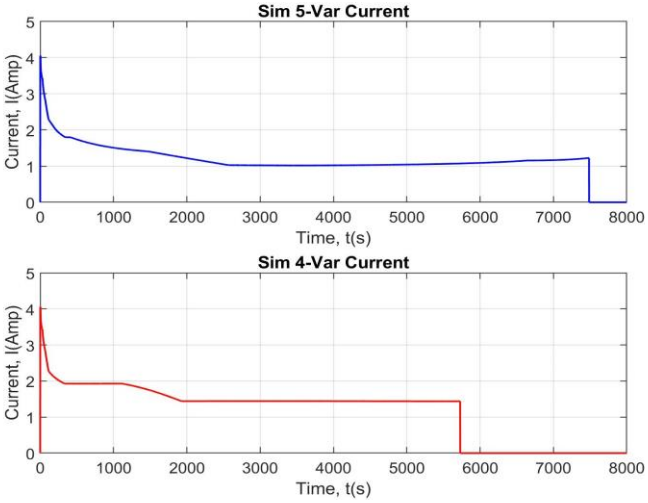


Figure 4.2: Current Profile with 5 & 4 Variables

Initially, a higher current was observed during the early stages of charging as the batteries rapidly absorbed charge. However, as the batteries approached their fully charged state, the charging current gradually decreased. This behavior can be attributed to the controller's dynamic adjustment of the charging rate to prevent overcharging and ensure battery health (see Figure 4.2).

The voltage profiles exhibited an exponential increase during the initial stages of charging, reflecting the application of charging current to the batteries. As the batteries approached full charge, the voltage stabilized, indicating a balance between charge absorption and voltage regulation. The voltage regulation mechanism implemented in the controller effectively maintained the voltage within safe limits throughout the charging process, preventing overvoltage conditions (see Figure 4.3).

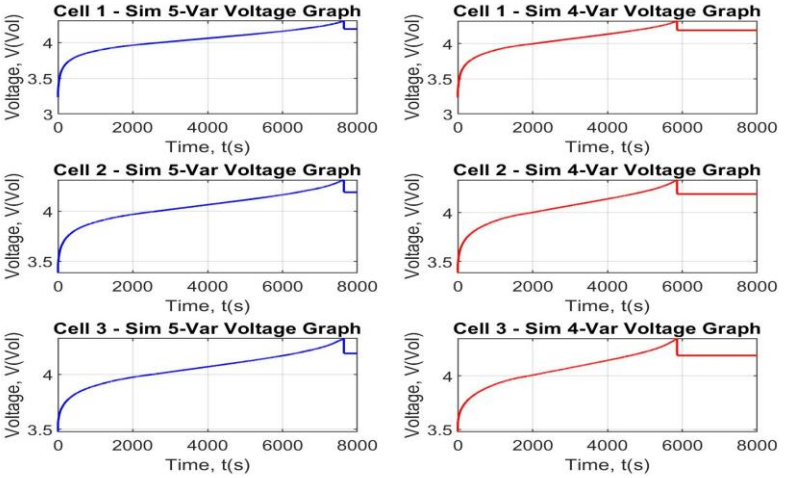


Figure 4.3: Voltage Profile with 5 & 4 Variables

The battery's state of charge has increased linearly during the charging process, consistent with expectations. As more charge was absorbed by the batteries, the SoC gradually approached 100%, indicating near-full charge. The linear increase in SoC reflects the proportional increase in the amount of charge stored in the batteries over time (see Figure 4.4).

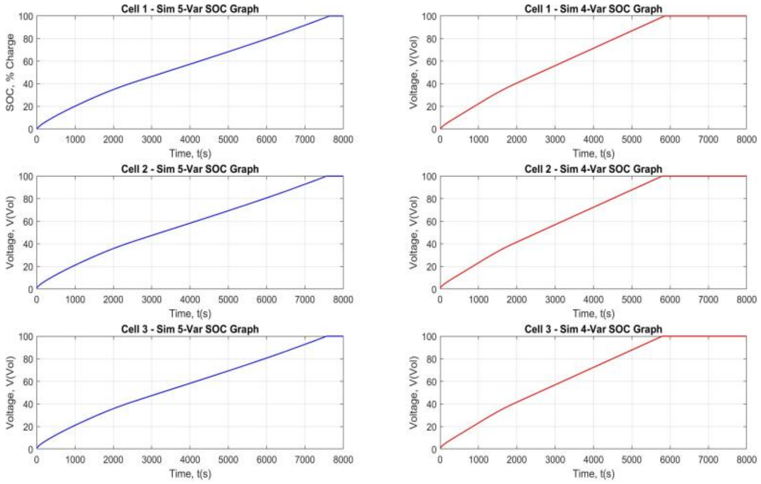


Figure 4.4: State of Charge Profile with 5 & 4 Variables

Temperature measurements during the charging process remained within a narrow range, approximately around room temperature. This stability in temperature indicates effective thermal management and proper operation of the battery charging system. The controller's ability to regulate the charging rate and prevent excessive heat generation contributed to maintaining temperature within acceptable limits (see Figure 4.5).

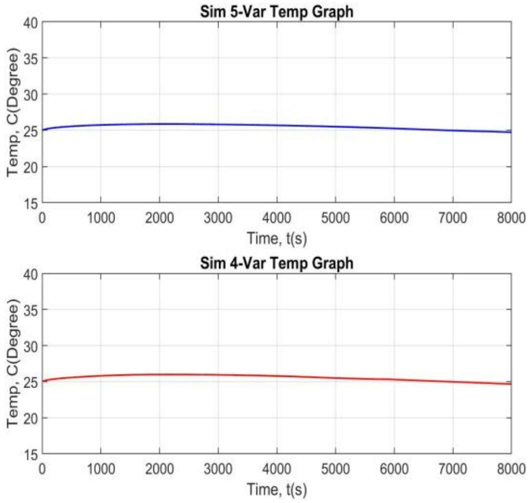


Figure 4.5: Temp Profile with 5 & 4 Variables

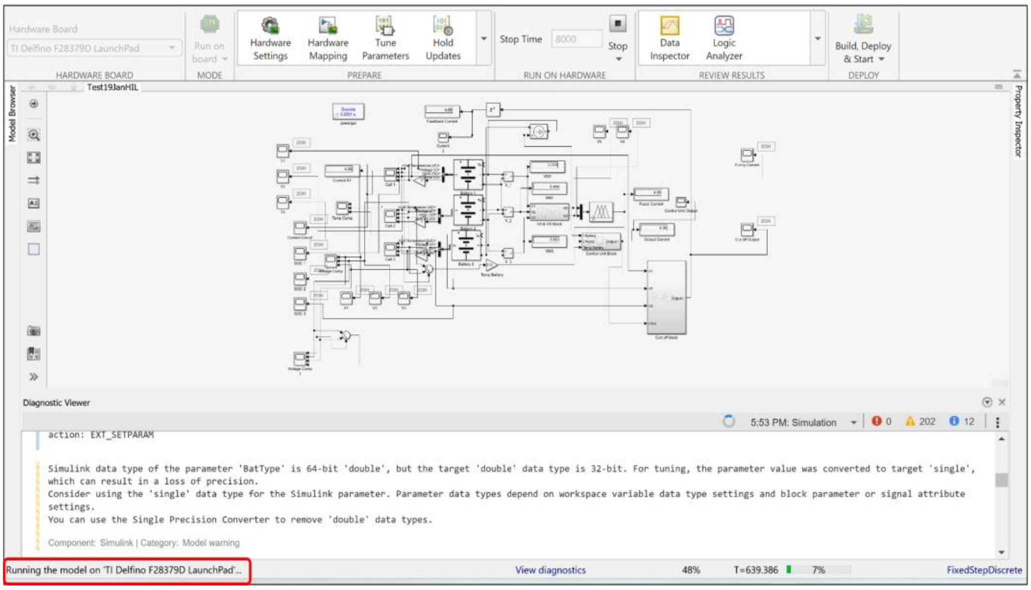
As a whole, the comprehensive analysis of the experimental findings verifies the increasing Li-Ion battery charging efficiency. The observed improvements in charging time, coupled with stable voltage, current, SoC, and temperature profiles, validate the practical viability of the controller in real-world battery charging applications. The summary of Results are mentioned in Table 4.1.

Table 4.1. Summary of Results

Parameter	**Observation**
Charging Time (seconds)	7648s → 5860s (23.3% Improvement)
Initial Current (A)	Higher initial current, gradually decreases with time
Voltage Profiles	Initial rise exponentially stabilizes near full charge
Controller Effectiveness	Dynamically adjusts current for faster charging
Overall Performance	Significant improvement in charging time

4.2 HIL Implementation and Results

In the pursuit of enhancing Li-ion battery charging time, we leveraged the C2000™ LAUNCHXL-F28379D LaunchPad in a systematic approach for hardware demonstration. Our methodology was structured to ensure precision and reliability in experimentation. The initial step involved discretizing the system to an optimal sample size, a crucial aspect for facilitating precise experimentation. This stage launched the base for more in-depth investigations. The use of Matlab as a programming environment for our C2000™ LAUNCHXL-F28379D LaunchPad, provided a platform for real-time simulation, which proved to be the critical component of our study. Such a combination enabled the formation of a whole system of different control mechanisms and led to the selection of the best one. In order to maximize the charging procedure, we had twice the type of fuzzy logic algorithms (4 and 5 variables), each of them. The selection of these measures is motivated by the tough nature of Li-ion battery charging kinetics. Observed results presented dramatic success plus had a deviation of less than 0.1% from simulated results. The strict verification process made sure that our equipment (hardware-in-the-loop) was highly reliable and constantly accurate (see Figure 4.6)



```
action: EXT_SETPARAM

Simulink data type of the parameter 'BatType' is 64-bit 'double', but the target 'double' data type is 32-bit. For tuning, the parameter value was converted to target 'single',
which can result in a loss of precision.
Consider using the 'single' data type for the Simulink parameter. Parameter data types depend on workspace variable data type settings and block parameter or signal attribute
settings.
You can use the Single Precision Converter to remove 'double' data types.

Component: Simulink | Category: Model warning
```

```
Running the model on 'TI Delfino F28379D LaunchPad'...    View diagnostics    48%    T=639.386    7%    FixedStepDiscrete
```

Figure 4.6: Hardware-In-Loop Implementation

This technique plays a vital role because of its capability to improve the levels of reliability and accuracy in determining the lifespan of Li-ion batteries in their daily use. The method opens up the avenue for system development as it connects the previously separated design and field operation stages.

Lastly, the outcomes of the analysis are shown as using the C2000™ LAUNCHXL-F28379D LaunchPad and Matlab, validating that our way to do it is practical and useful. Li-ion battery charging nowadays has been among the most efficient and widely used systems worldwide.

4.3 Hardware Implementation

During the hardware realisation phase, the connection between Arduino and MATLAB is paired up to efficiently provide charge control of Li-ion (Li-ion) batteries. This hardware implementation consists of three 2400 mAh Li-ion battery cells connected in series and a current sensor ACS-712 that measures the current through the batteries. In addition, an LM-315 temperature sensor is comprised to ensure conductive charging conditions by detecting the temperature of the battery cells (see Figure 4.7).

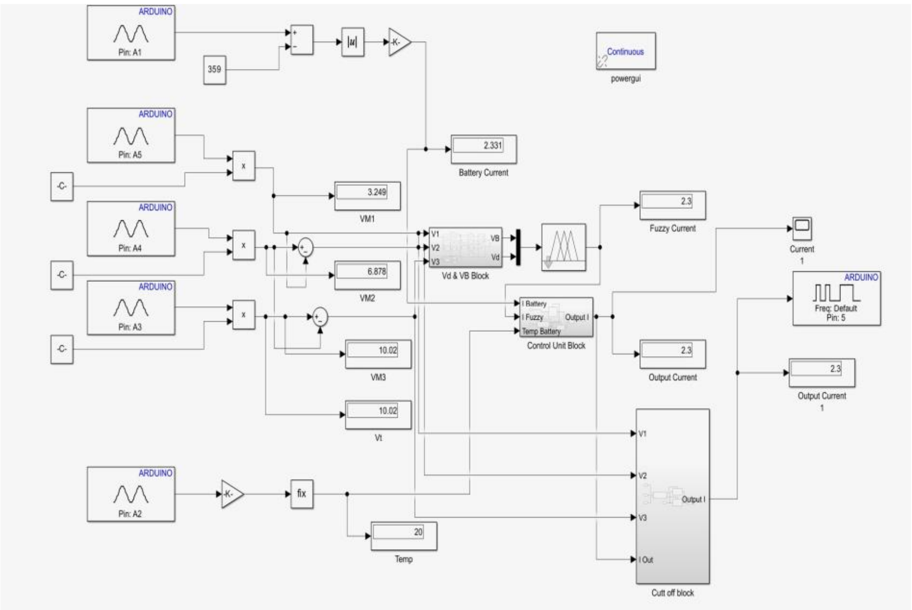


Figure 4.7: Arduino Mega 2560 Real Time Integration

In order to precisely capture the voltage variations among battery cells, the system is endowed with three voltage sensors for sentively sensing each voltage independently. These sensors get real-time data from the sensors and then send them to the control system so that it can carefully monitor and modify charge conditions. Putting MATLAB to use for design functions such as data analysis and control algorithm execution is one of the central processing units for our system. The data from the sensors is analysed inside the computers with MATLAB, where algorithms calculate parameters such as the lowest value of the single cell voltage and the highest voltage between the three cells. These calculations are vital in finding the best charging method that ensures optimum diverging currents of each cell and prevents specific cells from overcharging or undercharging. A FLC is applied in order to create a dynamic adjustment of the charging current established on the basis of the calculated parameters and a determined set of rules for functioning. This regulator changes the charging process in a manner that keeps the battery temperature low at most under the 40°C level, for safety purposes of the battery.

Matlab outputs the control signal, which is then transmitted to Arduino to handle. Arduino outputs the corresponding PWM signals that are in turn the form of regulated electric current for more fine-tuning of the charging control. A current-controlled DC power supply also helps to regulate the current flow to the batteries through a PWM signal. Thus, only the correct charging current is supplied to the batteries at the right time in the right amount. While the regulated current is fed back into the main circuit which joins the batteries in series and completes the closed loop control system. Such a complex software technique serves as a basis for proper and accurate charging of Li-ion batteries which are known for quick charging with the maintenance of top performance and safety. In real time the application of monitoring, data treatment and control algorithms is quite useful therefore it is making the designing process of better charging processes easier and this fact, in turn, leads to improving battery technology in a variety of applications (see Figure 4.8). The results obtained fall in 1% variation with the simulation, which verifies the authenticity of hardware.

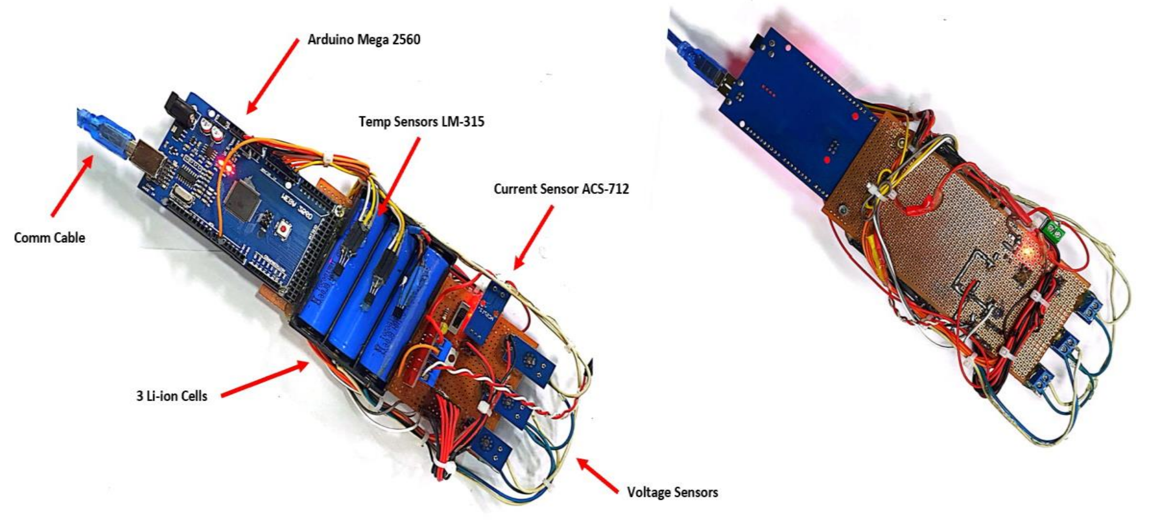


Figure 4.8: Implemented Hardware

Chapter 5

Conclusion

We have built up this thesis work with a non-linear controller, and later it has been confirmed that this controller can shorten the charging time of Li-ion batteries by a considerable amount. Our contributions and findings can be summarized as follows:

- **Development and Implementation of Non-linear Optimized Technique**: A method of the linear optimization and the non-linear generalizing has been developed and applied quickly for the Li-ion batteries charging. It implicates exceptional gains in both efficiency and safety, addressing key challenges in contemporary battery charging technologies.
- **Comprehensive Simulation Model**: The model was fully simulated using the definition of all parameters, careful accurate modeling of the function block, and the running of the individual components through simulation before clustering them together. The entailed cautiousness has helped to maintain a smooth running of the integrated battery system that has become crucial in the acquisition of the knowledge needed for the future progress.
- **Integrating Simulink with Arduino for HIL and hardware implementation**: We have determined the Simulink app connection with Arduino that has enabled implementation without problems in the hardware and software domain, as well as Hardware-in-the-Loop (HIL) simulations. This connection has expedited the development process and increased the robustness of our system.
- **Robust Battery Monitoring and Protection Mechanisms**: The main system we are using is the battery that has perfect battery health monitoring, overvoltage prevention together with cut-off states which all make the battery safe and long lasting. These qualities are critical for ensuring the battery's integrity and protecting against any risks.

- **Comparative Analysis and Performance Evaluation**: We confirmed our approach's efficacy by comparing it to typical charging procedures. The results of this investigation were good, proving the superiority of our non-linear optimised approach for increasing charging efficiency.
- **Charging Time Improvement**: Our research has shown a 23% reduction in the charging time that usually takes place when compared with previous technique [11]. This great leap shows the actual merits and utility of the described approach.

In conclusion, the pathways described in this thesis create workable techniques for speeding up the charging process of Li-ion cells. We have recorded authentic improvements in overcoming basic difficulties on battery technology by means of non-linear control strategies, advanced models of simulation, and perfect cooperation with equipment prototypes. The results that we obtained just pave the way for the research and innovation that would eventually be applied to all areas from consumer electronics to electric cars.

5.1 Future Works

In contemplation of the various practical investigations and implementations that are implied in the improvement of Li-ion battery charging time employing non-linear controllers. There is a need to scale the methodology to accommodate various battery configurations beyond those currently considered. This involves investigating how the non-linear controller can adapt to different chemistries, sizes, and arrangements of Li-ion batteries, taking into account factors such as varying capacities, voltages, and internal resistances. Exploring the integration of the non-linear optimized technique into wireless charging systems is a promising direction. This entails examining how the controller can optimize charging efficiency, stability, and safety in the context of wireless charging protocols. Challenges such as energy transfer efficiency, alignment tolerance, and electromagnetic interference must be addressed to fully realize the potential of wireless charging for Li-ion batteries. Efforts towards standardization and commercialization of the developed charging technique are crucial for its widespread adoption in real-world applications. Collaboration with industry stakeholders will be critical for improving the technique and ensuring interoperability with electric cars, portable gadgets, and grid-scale energy storage technologies. Emphasis should be placed on optimizing cost-effectiveness, reliability, and interoperability to facilitate seamless integration into existing infrastructures. By pursuing these future directions, this research aims to significantly contribute to enhancing the efficiency, reliability, and accessibility of Li-ion battery charging technologies, thus accelerating the transition towards sustainable energy solutions.

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