

Design of Battery Emulator for different battery chemistries

M.Tech. Thesis

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**CENTER FOR ELECTRIC VEHICLE
AND INTELLIGENT TRANSPORT SYSTEM
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Design of Battery Emulator for different Battery chemistries

A THESIS

*Submitted in partial fulfillment of the
requirements for the award of the degree
of*
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by

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**CENTER FOR ELECTRIC VEHICLE
AND INTELLIGENT TRANSPORT SYSTEM
INDIAN INSTITUTE OF TECHNOLOGY INDORE**

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INDIAN INSTITUTE OF TECHNOLOGY INDORE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **DESIGN OF BATTERY EMULATOR FOR DIFFERENT BATTERY CHEMISTRIES** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **CENTER OF ELECTRIC VEHICLE AND INTELLIGENT TRANSPORT SYSTEMS, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2025 to May 2026 under the supervision of Prof. Amod C. Umarikar, Professor, CEVITS, IIT Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Saurav Kumar Raushan

20/05/2026

**Signature of the student with date
(SAURAV KUMAR RAUSHAN)**

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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20/05/2026

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DEDICATION

I dedicate this thesis to my beloved parents, whose unwavering love, prayers, and sacrifices have laid the foundation for all my achievements. Their steadfast belief in my abilities has been my greatest source of strength throughout this journey.

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Abstract

Nowadays **lithium** battery are commonly uses in various application like electric vehicles, battery energy storage system, portable electronic devices like laptop, mobile, digital camera, digital glucometers and pulse Oximeters etc. After recognizing the importance of Li-ion and their relatively high cost so this paper focuses on the development of Lithium-ion battery emulator. **Battery Emulator (BE)** is a specialized tool which work exactly like a real battery in real-time. It can mimic the electrical behavior of battery like power, voltage, current, capacity, and transient dynamics.

The focus of this work is to choose a suitable battery models as well as power converters topologies and their control technique then implement it. This paper first discusses, the motivation behind to chosen of Li-ion battery, following with details technical background of battery technology. After then a literature review of diverse battery modeling approach. The proposed battery emulator based on single phase active rectifier and bi-directional dc-dc converter along with 2-RC ECM battery model, that will capable of delivering both static and dynamic responses.

A **MATLAB /Simulation** of a Lithium-ion BE is proposed that can both give and take power. It acts like a real battery during charging (sink) and discharging (source) cycles." These types of devices play an important role to enhance the test of many applications like electric vehicles (EV), battery management systems (BMS), and battery energy storage system (BESS). Instead of the testing with real batteries, testing with this device allows reduces the cost, time, complexity and increase testing efficiency. It provides safety and repeatable platform for testing purpose. It can replace a real lithium - ion battery in both research and industry related applications.

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Acronym

1. Li – Lithium
2. NiMH – Nickel Metal Hydride
3. BESS – Battery Energy Storage System
4. GESS – Grid Energy Storage System
5. Pb – Lead
6. NaS – Sodium Sulphur
7. NiCd – Nickel Cadmium
8. LCO – Lithium Cobalt Oxide
9. LNO – Lithium Nickel Oxide
10. NCA – Nickel Cobalt Aluminum Oxide
11. LFP – Lithium Iron Phosphate
12. NMC – Nickel Manganese Cobalt
13. LMO – Lithium Manganese Oxide
14. LTO – Lithium Titanate Oxide
15. LiS – Lithium Sulphur
16. LIB – Lithium Ion Battery
17. SOC – State of Charge
18. SOH – State of Health
19. OCV – Open Circuit Voltage
20. ECM – Equivalent Circuit Model

1 Chapter: Introduction

1.1 Introduction

Lithium-ion batteries have revolutionized the energy storage landscape, scaling up from portable consumer electronics to heavy-duty applications like electric vehicles (EVs) and Battery Energy Storage Systems (BESS). Their widespread adoption is driven by a powerful combination of high energy density and robust operational voltage. Today, Li-ion BESS technology is playing a critical role in modernizing modern electrical infrastructure. These storage solutions are important for the stability of renewable energy source grids and it acts as a buffer against fluctuations in generation. Because renewable energy sources are unpredictable, they can make the power grid unstable. Lithium-ion based BESS act like a giant 'Shock Absorber.' It uses technology to instantly steady the grid's voltage and frequency, ensuring that transition to green energy doesn't lead to flickering lights or power crashes.

The design and testing of Battery Energy Storage Systems (BESS) are resource-intensive processes. Because these systems combine complex ICT interfaces with high-power converters and chemical storage, relying on physical hardware for every test is inefficient. Real battery testing is expensive and time-consuming so it limits the scope of testing due to the potential for hardware damage. Adopting a battery emulator addresses these challenges by providing a safe, repeatable, and cost-effective environment. By accurately mimicking battery dynamics, emulators facilitate faster prototyping and more rigorous stress-testing of BMS and power conditioners without the risks associated with real battery packs.

An emulator serves as a physical proxy that mimics the functionalities of an actual device within a hardware setup, distinguishing it from software-only simulation tools. For effective battery emulation, the system must replicate the real-time electrical behavior of the cell—specifically its power delivery, current, voltage profiles, and capacity dynamics. This allows researchers to manipulate battery parameters arbitrarily without the limitations of chemical storage. Li-ion battery emulator consists of an accurate mathematical representation of the battery and a robust two-stage power electronic interface. The power converter features a single-phase active rectifier stage followed by a bidirectional DC-DC converter. This configuration allows the active rectifier to control active and reactive power independently. Battery emulator when supplies power acts as a source and when drain power acts as sink. Instead of using linear amplifiers and heavy resistors to dissipate sink power like low-power emulators, high-power battery emulators utilize switching amplifiers to feed that power back into the grid. Leveraging this switching topology, the proposed IGBT-based battery emulator features a modular design that effectively replicates

the dynamics of various battery chemistries, delivering up to 1.21 kW at 111V [1] . This paper presents a design for a non-dissipative battery emulator—a low-cost alternative to chemical batteries that constructed by combining real-time dynamic modeling with advanced control systems. It highlights a framework that bridges power electronics and parameter identification to recreate the electrical characteristics of diverse battery chemistries without the safety risks of using real cells. An 11.6 Ah, 111 V battery pack of PANASONIC UR Li-ion polymer cells has been selected as the case study, for which a suitable battery model has been chosen and parameter identification has been performed. A simulation work of the emulator has been done so that it is able to source and sink power.

1.2 Aims and Objectives of Thesis

The primary objectives of the thesis are given below:

- i. Understand the primary features and specifications of LIB and other cells also.
- ii. Reviews different battery modeling techniques, prioritize equivalent based circuit model.
- iii. To design a versatile MATLAB/Simulink equivalent circuit model based on real LIB data sheet that is capable of simulating different battery chemistries under varying operational states.
- iv. To develop an integrated power converter system consisting of front-end active rectifier and dc-dc converter (bi-directional) to simulate seamless discharging and charging transitions[2].
- v. To evaluate a battery emulator's accuracy by comparing simulation results with experimental data across various realistic operational scenarios.

1.3 Chapters Overview

The overview of the thesis:

- ❖ Chapter 2 discuss the motivation to choose Lithium -ion Battery for various application. Lithium-ion batteries excel in both systems by providing high energy density and rapid response times, though BESS typically prioritizes modularity and cycle life for localized needs, while GESS focuses on large-scale grid stability, frequency regulation, and peak shaving capabilities. It underscores the constraints

of traditional storage technologies and identifies the specific performance advantages that establish LIBs as the leading solution for modern energy needs.

- ❖ Chapter 3 presents electrochemistry and Operational Principles of LIBs. This section covers the introduction and operating principles of Lithium-ion batteries, alongside a detailed classification of their types and the emergence of advanced battery chemistries.
- ❖ Chapter 4 discusses key battery phenomena such as charging and discharging characteristics, c-rates effects, self-discharging, ageing and thermal behavior. It also introduces basic principles of battery management, setting the stage for accurate battery emulation and control.
- ❖ Chapter 5 reviews the existing literature on battery modeling approaches, focusing on equivalent circuit models and shepherd model. It analyzes the accuracy and limitations of various modeling strategies for emulation purposes. It also presents the topology and circuit design of the battery emulator in this work. It includes Active rectifier and the bidirectional DC-DC converter, their control logic, and key design considerations for enabling both charging and discharging profiles.
- ❖ Chapter 6 presents the simulations and their results of various battery modeling for example equivalent circuit modeling and shepherd modeling and power converter circuits and their control strategies like active rectifier and dc-dc converter.
- ❖ Chapter 7 concludes the thesis by reviewing its key contributions. It also addresses the emulator's current boundaries and outlines future research pathways to sharpen its accuracy and broaden what the system can do.

2 Chapter: Motivation to choose Li-ion Battery

2.1 Comparison of Li-ion battery with GESS

Lithium-ion batteries (LIBs) have emerged as the premier choice among modern Grid Energy Storage Systems (GESSs) due to their unparalleled versatility. Their ability to deliver high power and sustain high energy over durations ranging from milliseconds to hours allows them to serve multiple grid functions simultaneously. One of the major reasons that place LIB on the front in terms of technology as compares to others GESSs can be shown in 2-1[3]

Unlike large-scale mechanical systems like Pumped Storage Hydro (PSH) or Compressed Air Energy Storage (CAES), which require specific terrain and massive capital investment, LIBs are modular and geographically independent. Furthermore, while devices like supercapacitors (EDLC – Electric double layer capacitor) and flywheels (FW) offer quicker bursts of power, their high self-discharge rates make them unsuitable for energy-heavy tasks. Consequently, the distributed nature and technical balance of LIBs provide a superior, all-in-one solution for modern grid stability.

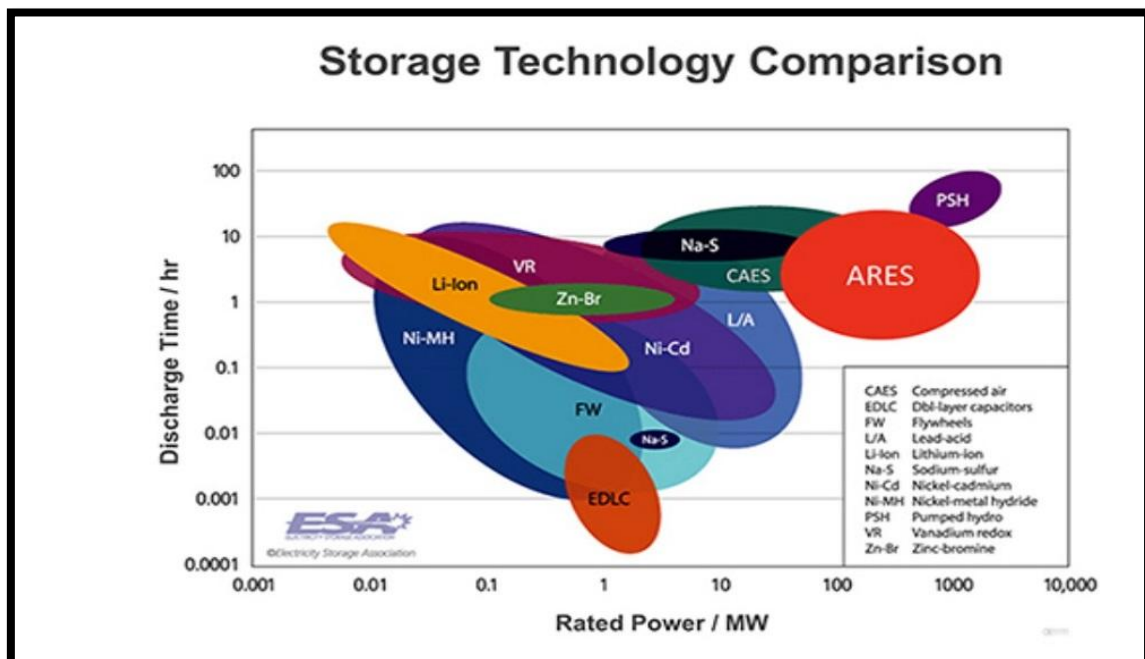


Figure 2-1 Compare different energy storage: Discharge time vs rated power

2.2 Comparison of Li-ion battery with BESS

Although LIBs comprise a diverse range of chemical compositions (as explored in Next chapter 3), their technical dominance over alternative BESS solutions is well-established, rooted in the specific performance metrics outlined below."

- Long cycle life
- High power density[4]
- Low self- discharge[4]
- High energy density[4]
- Relatively

Figure 2-4 presents a Ragone plot of specific energy vs specific power, demonstrating the competitive edge of LIBs for automotive cell applications. It is important to emphasize that since the core cell technology is often identical across industries, the crossover between EV requirements and grid storage solutions is a recurring theme in this analysis. Further evidence of LIB superiority is categorized below.

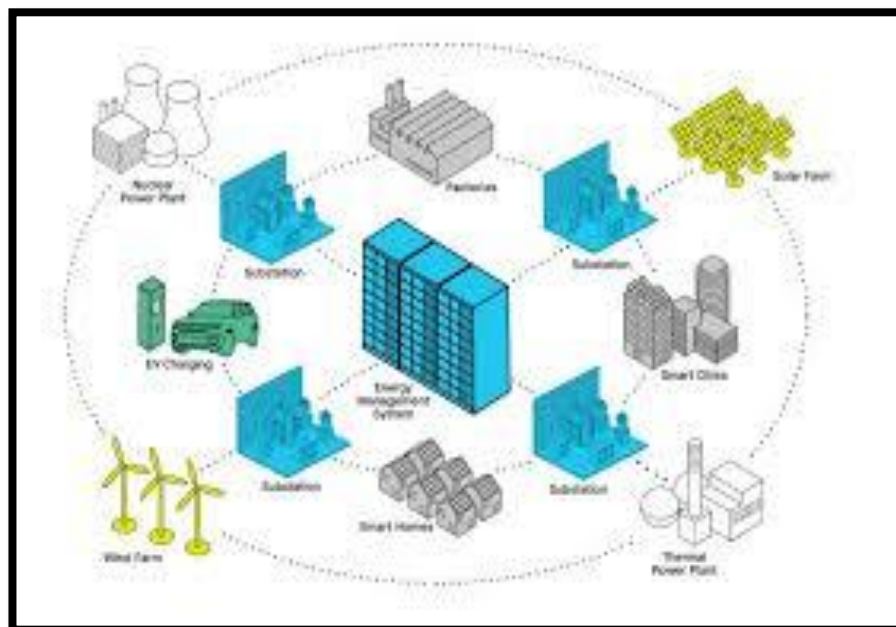


Figure 2-2 Distributed GESS various applications

2.3 Overview of other batteries energy storage system

2.31 Lead acid

A primary limitation of lead-acid battery technology is its relatively low specific energy (30-50Wh/kg) compared to modern lithium-ion chemistries and moderate to high specific power (100-400 W/kg), making them ideal for high-current starter applications but poor for long-range electric vehicles. They are heavy due to lead (Pb) plates but offer reliable, cost-effective power, relying on a 2.1V nominal cell voltage.

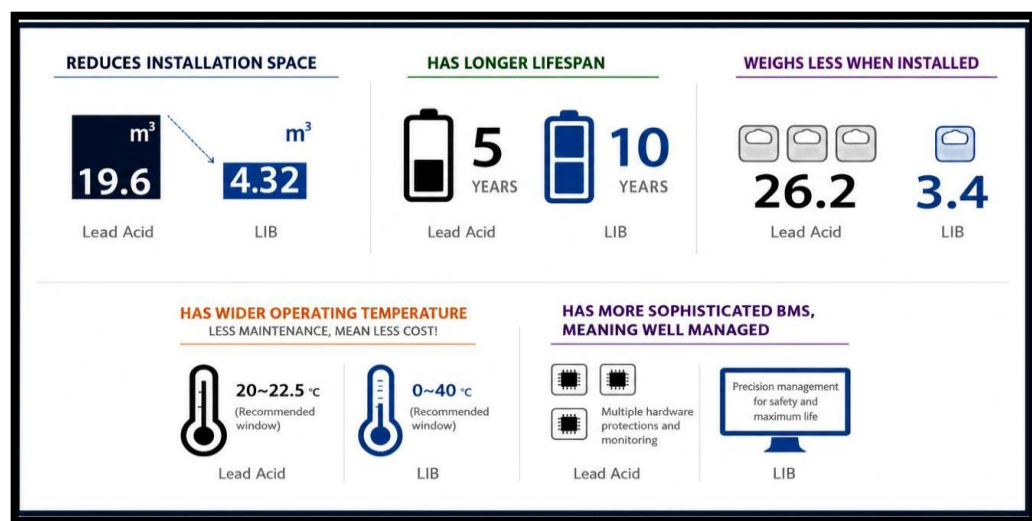


Figure 2-3 Comparing the key performance metrics of lithium-ion and lead-acid batteries.

2.32 Nickel Metal Hydride (NiMH)

Ni-MH and Li-ion batteries offer two different approaches to energy storage. While Li-ion dominates the current market, Ni-MH remains a specialized choice for specific safety and environmental needs. Ni-MH excels in safety and durability. It uses a water-based, non-flammable electrolyte, virtually eliminating the fire risks associated with Li-ion's thermal runaway. It also handles extreme temperatures better and is far easier to recycle. While it is

heavier and less efficient, its physical robustness makes it ideal for stationary systems in high-risk or harsh environments.

2.33 Sodium- Sulphur (Na-S)

Sodium-Sulphur (Na-S) battery [5] is a high-capacity "heavy lifter" designed specifically for large-scale grid storage. It operates at high temperatures (300°C) to (350°C), which keeps its sodium and sulphur electrodes in a molten, liquid state for fast chemical reactions.

A solid ceramic electrolyte separates these liquids, allowing for high efficiency and a long life of 15+ years. Because it uses abundant, low-cost materials and can discharge energy for 6 to 8 hours, it is perfect for stabilizing power grids and storing renewable energy. Na-S batteries are ideal for long-duration storage because they use cheap, abundant materials and can discharge power for many hours at a time. While the heat requirement makes it unsuitable for small devices, it is a safe and sustainable solution for massive, stationary energy plants.

2.34 NiCd

Nickel-Cadmium (NiCd) batteries are the "rugged veterans" of grid storage, valued for their extreme durability compared to the high-performance Lithium-ion (Li-ion). While Li-ion is sensitive to heat, NiCd thrives in harsh temperatures and can last over 20 years with minimal maintenance. However, NiCd falls behind in efficiency and size; Li-ion stores much more energy in a smaller footprint and loses less power during use. Furthermore, NiCd contains toxic cadmium, making it a significant environmental risk compared to modern Li-ion. Ultimately, Li-ion is the standard for efficiency, while NiCd is reserved for remote, extreme environments where reliability is the only priority.

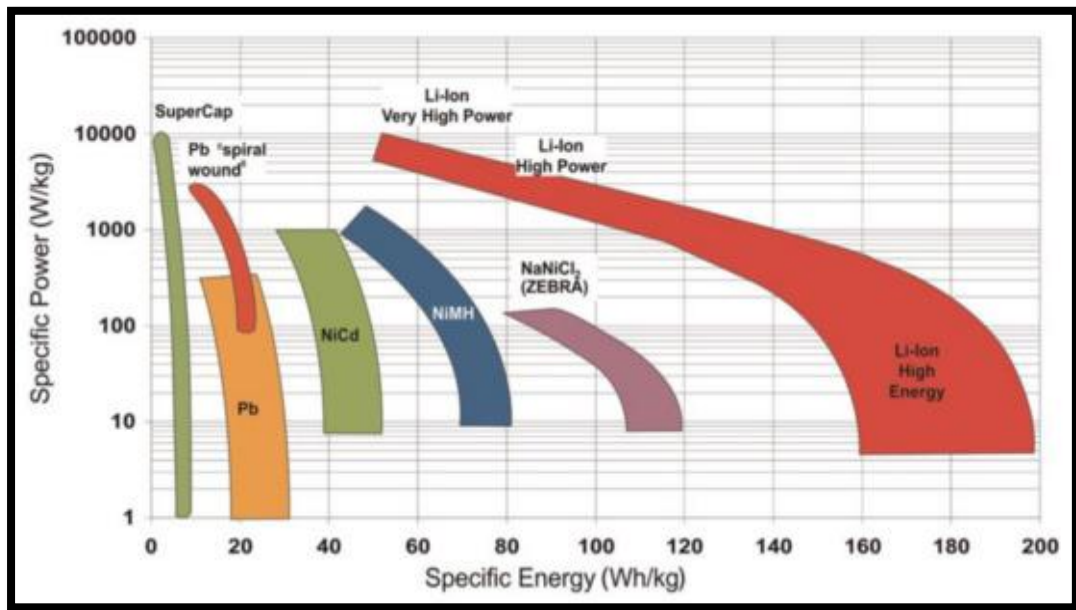


Figure 2-4 Comparison of different energy storage battery systems [13]

	1st	2nd	3rd	4th	5th
ENERGY DENSITY (Wh / kg)	LIB 150-250	NaS 125-150	Flow 60-80	Ni-Cd 40-60	Lead-Acid 30-50
ROUND TRIP EFFICIENCY (%)	LIB 95	NaS 75-85	Flow 70-75	Ni-Cd 60-80	Lead-Acid 60-70
LIFE TIME (yrs)	LIB 10-15	NaS 10-15	Ni-Cd 10-15	Flow 5-10	Lead-Acid 3-6
ECO-FRIENDLY ASPECT	LIB ○	NaS ×	Ni-Cd ×	Flow ×	Lead-Acid ×

Figure 2-5 General comparison of BESS

2.4 Cost view of Li-ion Battery

Economic Evolution of Li-ion Batteries: From Niche to Necessity [6]

The journey of Lithium-Ion Batteries (LIBs) from specialized components in consumer electronics to the backbone of global transportation and energy systems is a definitive case study in industrial scaling. Historically, LIB adoption was severely restricted by high material costs, specifically the limited availability of lithium and the lack of large-scale manufacturing infrastructure. However, the last decade has witnessed a transformative shift, as LIBs have moved centre stage in the automobile and GESS sectors.

Dramatic Price Collapse

The most significant catalyst for this expansion has been the aggressive reduction in unit costs. In 2015, the cost of lithium-ion storage stood at approximately **Rs. 32,500/kWh**. By 2020, this figure had plummeted to roughly **Rs. 13,000/kWh**, representing a price reduction of over 60% in just five years. This trend has only accelerated; by **2026**, prices in the Indian market have continued their downward trajectory, with some EV battery packs now ranging between **Rs. 15,000 to Rs. 25,000/kWh** depending on the specific chemistry, and high-volume LFP (Lithium Iron Phosphate) cells occasionally dipping even lower. Forward-thinking manufacturers played a crucial role in setting these benchmarks. Companies like **A123 Systems** historically aimed for aggressive targets as low as **Rs. 8,500/kWh**, sign to the market that the "price parity" with internal combustion engines was achievable. This rapid decline is not merely a result of cheaper raw materials but is primarily driven by the **economies of scale** generated by the electric vehicle (EV) industry.

Today, the synergy between the automotive and energy storage industries is stronger than ever. The lessons learned from mass-producing EV batteries are directly benefiting grid energy storage systems (GESS), allowing for more resilient and sustainable power networks. As technological advancements continue to optimize cell chemistries, the transition toward a lithium-dependent energy economy appears not only inevitable but economically superior.

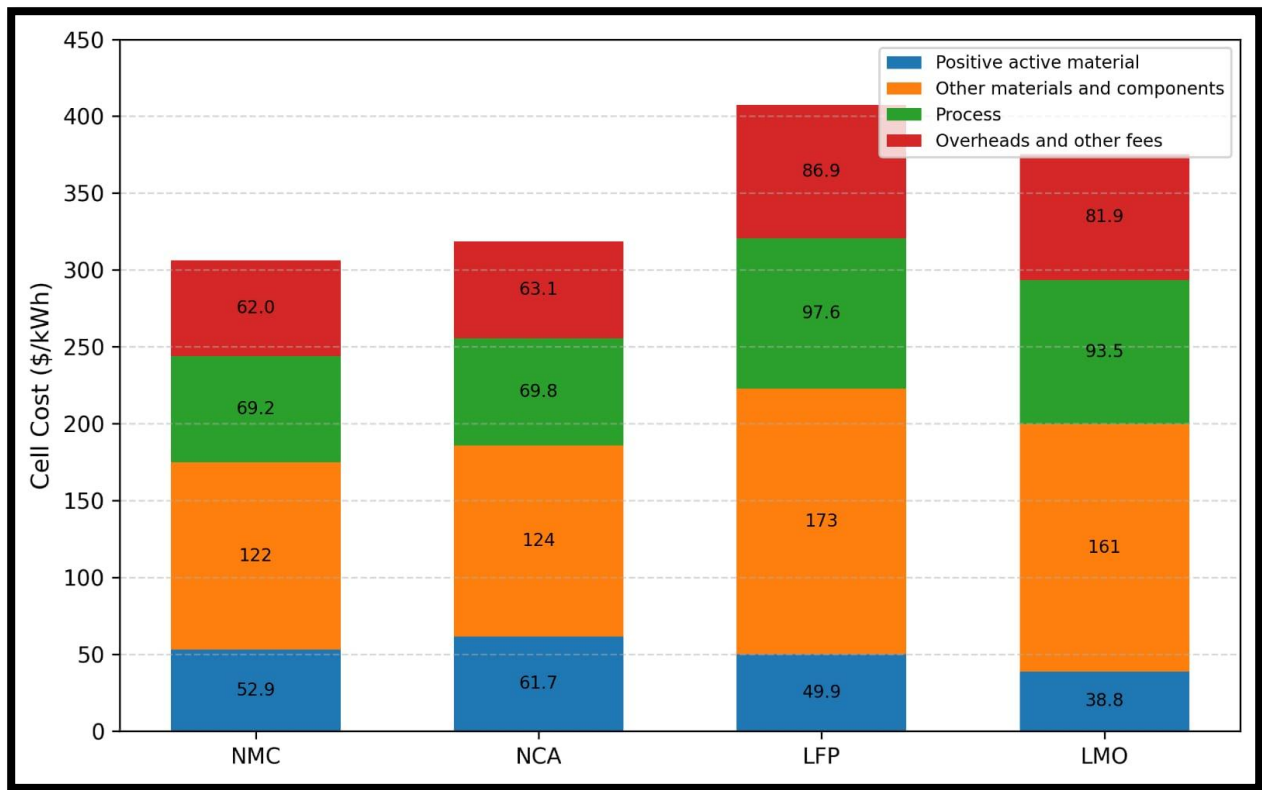


Figure 2-6 Cost comparison of different – different battery

3 Chapter: Electrochemistry and Operational Principles of LIBs

Lithium-based batteries have solidified their position at the pinnacle of modern energy storage, fundamentally changing how we power the world. Their dominance is rooted in superior electrochemical characteristics that allow for higher voltage and energy density. Within the "lithium" family, there is a crucial technical distinction between lithium-metal and lithium-ion batteries, defined primarily by the architecture of the anode. The primary difference between these two technologies lies in the material used for the negative electrode as anode. Lithium-metal battery[7] is utilizing pure metallic lithium as anode, which theoretically offers the highest energy density. Lithium-Ion Batteries (LIBs) utilize a carbon-based anode, most commonly graphite. In the below section Lithium -ion introduced first then Lithium metal. At the end of the chapter, we will know more about some other LIBs chemistries [3].

3.1 Lithium -ion battery and their types

Lithium-ion batteries do not contain metallic lithium. At the place, they use a lithium compound that allows ions to move back and forth between the electrodes. It has excellent balance of safety, high power, and cycle life. It uses mainly in device like mobile, tablet, ups, GESS, EV etc.

- **Anode Material:** A carbon-based host, typically Graphite.
- **Mechanism (Intercalation):** Instead of the electrode physically dissolving or growing, lithium ions "intercalate"—meaning they slide into the molecular layers of the graphite (anode) or the metal oxide (cathode).
- **Rechargeability:** Fully rechargeable (secondary). Because the lithium stays in ionic form (Li^+) rather than becoming a metal, it is much safer and survives thousands of charge/discharge cycles.
- **Types:** LCO, LNO, NCA, LMO, NMC, LFP

3.11 Lithium Cobalt Oxide: LCO (LiCoO_2)

It was a landmark in the history of electrochemical energy storage. Commercialized in the early 1990s, it was the first cathode material to make lithium-ion batteries a viable consumer product. At the atomic

level, LCO belongs to the layered oxide family, characterized by an $\alpha\text{-NaFeO}_2$ type hexagonal structure. The battery operates on the principle of intercalation. During charging, an external voltage pulls lithium ions out of the cathode lattice, moving them through electrolyte which would be stored in the graphite anode. During discharge, the process reverses, and the ions slide back into the LiCoO_2 structure. LCO is primarily prized for its volumetric energy density. Because it is a dense material, it exhibits a high volumetric energy density, allowing it to store a significant amount of energy within a compact footprint., which is the most critical requirement for thin smartphones and wearable tech. It provides a nominal voltage of 3.7V and a very flat discharge curve, ensuring that electronic devices receive consistent power until the battery is nearly depleted.



Figure 3-1 LCO Prismatic cell

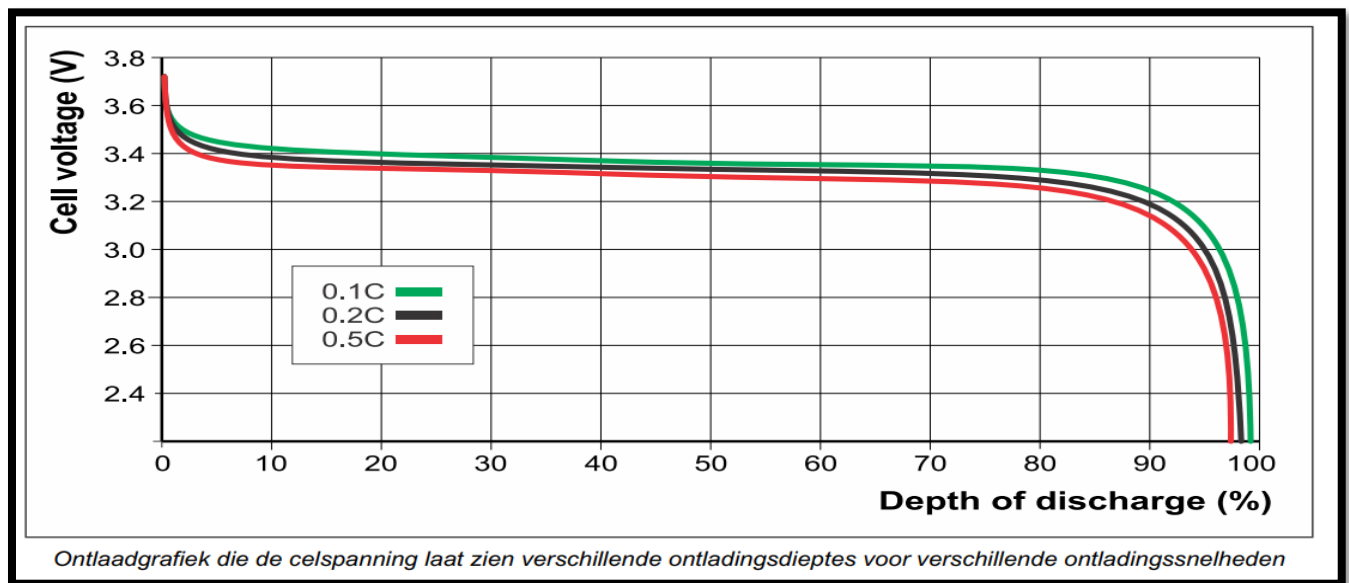


Figure 3-2 Effect on battery capacity due to different c-rates

3.12 Lithium Nickel Oxide: LNO (LiNiO_2)

Lithium Nickel Oxide (LiNiO_2), commonly known as LNO, is a high-energy cathode material that represents the "purest" form of the nickel-rich layered oxide family. LNO is a layered transition metal oxide where nickel (Ni) replaces cobalt as the primary active element in the crystal lattice. It operates with a high discharge voltage of around 3.7V to 3.8V. Its standout feature is its high specific capacity.

While it is theoretically superior to the more common Lithium Cobalt Oxide (LCO) in terms of energy capacity and cost. In your research on Electric Vehicles (EVs), you will recognize LNO as the fundamental "end-member" chemistry that inspired the development of modern NMC and NCA batteries. LNO provides more energy per gram than almost any other commercialized layered oxide, which is critical for reducing the weight of EV battery packs.

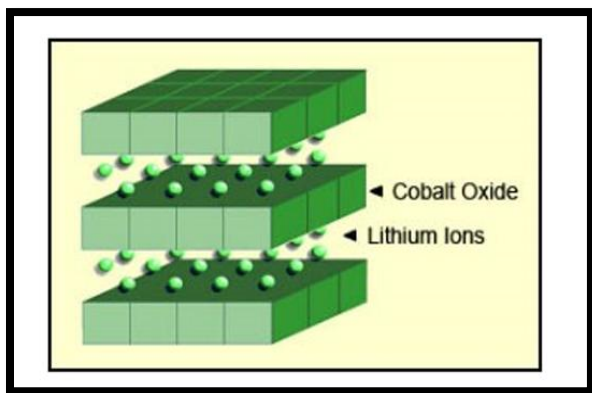


Figure 3-4 Cathode structure of LNO and LCO

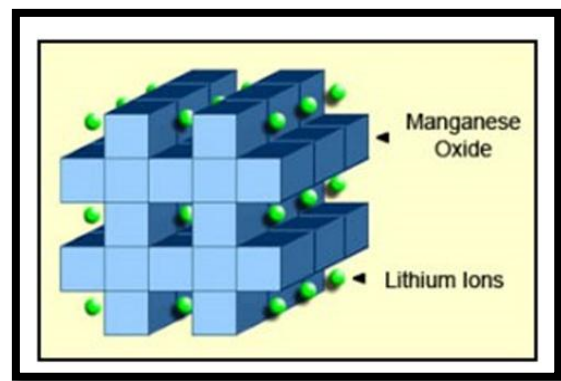


Figure 3-3 Cathode structure of LMO



Figure 3-6 Panasonic NCR 18650b 3.7V cell



Figure 3-5 Keppower P1634TC 16349 3V 100mAh

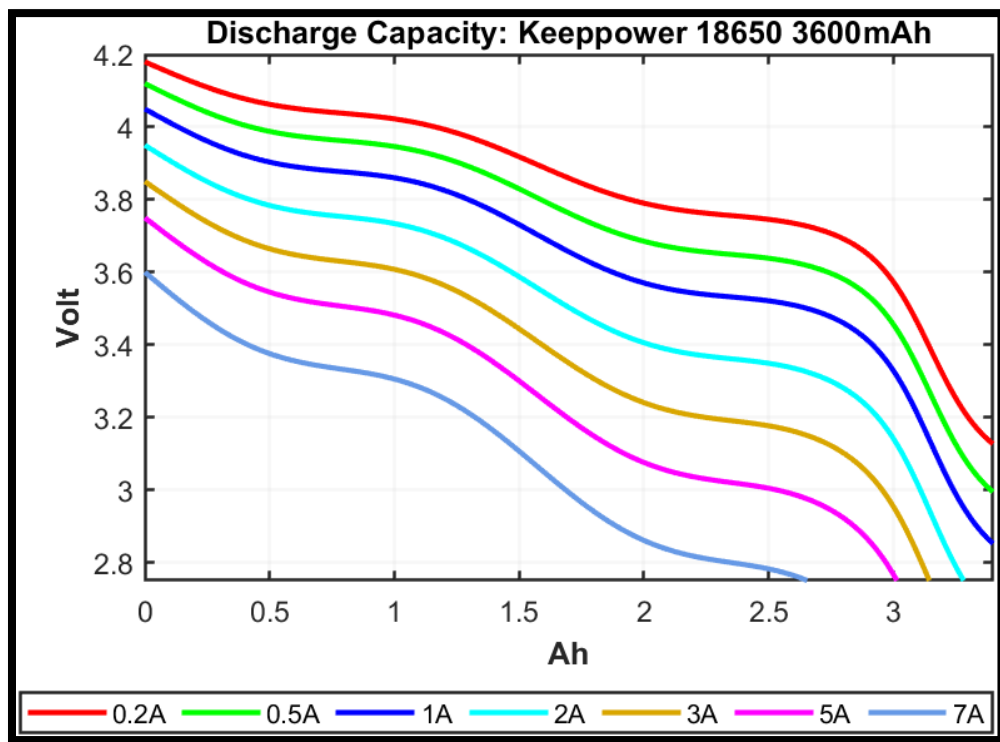
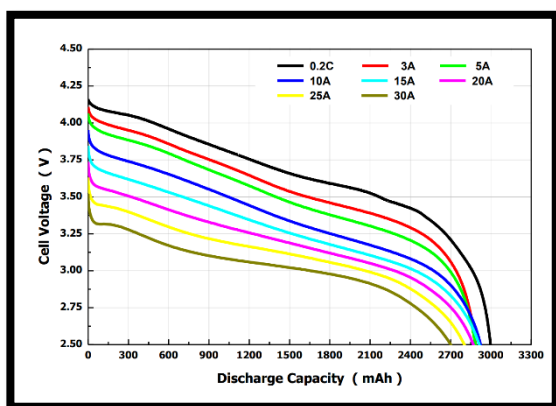


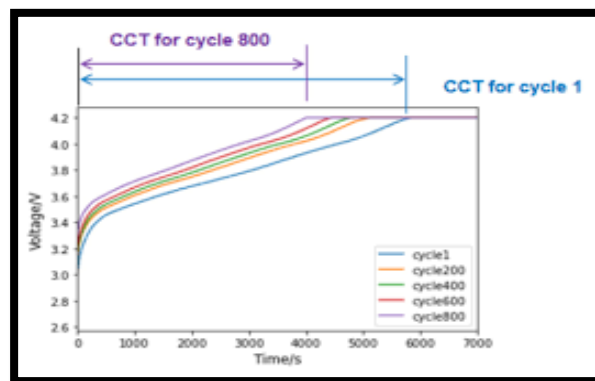
Figure 3-7 Keppower 3600mAh battery discharge capacity

3.13 Lithium Nickel Cobalt Aluminium Oxide: NCA (LiNiCoAlO_2)

NCA is a high-performance cathode material. It belongs to the family of nickel-rich layered oxides. The defining characteristic of NCA, however, is the substitution of a small fraction of the metal content with Aluminum. While aluminum is electrochemically inactive, its presence is vital for structural reinforcement. During the charging phase, lithium ions are deintercalated from these stabilized oxide layers, migrating through the electrolyte to intercalate into the graphite anode. The presence of aluminum raises the "thermal runaway" temperature, providing a critical safety buffer that pure nickel or cobalt oxides cannot achieve on their own. Because of its exceptional energy-to-weight ratio, NCA is utilized in applications where space is limited but power requirements are extreme. It is widely recognized as the technology that powered the early "long-range" electric vehicle revolution.



(a) Discharge characteristics of NMC cell



(b) Charge characteristics of NMC cell

Figure 3-7.1 NMC battery discharge and charge characteristics at different C-rates

3.14 Lithium Nickel Manganese Cobalt Oxide: NMC (LiNiMnCO_2)

Today, NMC is the most versatile and widely used Lithium-ion chemistry on the market. Its success lies in its "tri-metal" cathode, which blends the best properties of Nickel, Manganese, and Cobalt to overcome the limitations of earlier "single-metal" designs—such as the high cost and instability of LCO, or the low energy density of LMO. Operationally, the NMC cell relies on the "intercalation" principle, frequently described as the rocking-chair (or shuttle-chair) mechanism. During charging, lithium ions deintercalate from the NMC cathode, migrate through the liquid electrolyte, and insert themselves between the graphite layers of the anode.



Figure 3-8 Samsung SDI - Battery technology roadmap

3.15 Lithium Iron Phosphate: LFP (LiFePO_4)

Lithium Iron Phosphate (LFP) represents the safest and most durable chemistry within the Lithium-ion battery family. The rise of LFP technology represents a pivot in the energy industry toward pragmatism and safety. While the early years of the lithium-ion revolution were focused on squeezing every possible watt into the smallest space (using chemistries like LCO or NCA), the current era is defined by the need for massive scale and environmental responsibility. This is where LFP excels.

Cathode is made of Lithium Iron Phosphate (LiFePO_4). In this structure, the phosphorus and oxygen atoms are joined by strong covalent bonds, forming a stable framework that does not easily break down, even under high heat or physical stress. When charging, lithium ions pull away from the LFP cathode lattice, traveling through the electrolyte and across a microporous polymer separator to settle within the graphite anode. During discharge, the reverse occurs as the ions migrate out of the anode and back to the cathode host. This internal ionic journey forces electrons to stream through the external circuit, providing the electric power necessary to drive the vehicle's motor or energize connected systems.

LFP is known for its exceptionally flat discharge curve. It maintains a very steady nominal voltage of **3.2V** for nearly 90% of its discharge cycle, which is highly beneficial for power electronics as it provides a consistent power supply. Because of its weight (lower energy density than NMC), LFP was historically used in stationary systems, but it has recently seen a massive surge in the automotive sector. Many standard-range EVs (like the

Tesla Model 3 RWD) and electric buses use LFP. It is perfect for city driving where safety and longevity are more important than extreme long-range. LFP is the "gold standard" for home and industrial solar batteries (e.g., Tesla Powerwall alternatives). Its long life ensures the battery lasts as long as the solar panels. Furthermore, LFP addresses the "cost vs. performance" dilemma. By using iron (Fe) as the primary cathode metal, it avoids the price volatility of nickel and cobalt. This has allowed electric vehicle manufacturers to lower the entry price of cars, making green transportation accessible to a broader market.

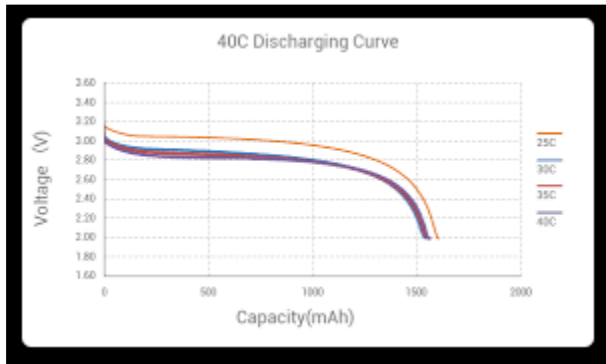


Figure 3-9 Discharge characteristics of LFP battery at different c-rates



Fig. 3-9.1FBTECH LFP cell 3.7V 6Ah

3.16 Lithium Manganese Oxide: LMO (LiMn_2O_2)

LiMn_2O_2 is a prominent member of the lithium-ion family distinguished by its unique structural architecture and high-rate capability. While chemistries like LCO and NMC rely on layered structures, LMO is defined by its three-dimensional spinel structure. This fundamental difference in molecular design makes it the "sprinter" of the battery world, capable of delivering rapid bursts of energy with a high degree of thermal safety and cost-efficiency. LMO functions through the same fundamental intercalation process as other lithium-ion cells, but its voltage and energy profile are distinct. It operates at a nominal voltage of approximately 3.7V to 3.8V. However, the trade-off for its high power and safety is its specific energy. Because the manganese spinel structure is relatively heavy and takes up more space for the amount of lithium it can host, LMO provides a lower energy density (roughly 100-150Wh/kg) compared to nickel-rich alternatives.

3.2 Lithium -Metal battery and their types

Lithium-metal battery energy storage devices that utilize [8] pure metallic lithium as anode to achieve the highest theoretical energy density of any lithium-based chemistry. While they offer exceptional storage capacity and a long shelf life for specialized applications like medical implants and military sensors, they are traditionally non-rechargeable due to the risk of internal short circuits. Lithium-metal batteries are classified primarily by their rechargeability and their cathode chemistry. In contrast to conventional Lithium-ion batteries[7] that utilize a graphite anode, Lithium-metal batteries employ pure metallic lithium as the negative electrode, enabling a significantly higher energy density. These are the most common type. They are designed for single-use applications where long shelf life and high energy density are critical. Current research focuses on solid-state electrolytes to overcome these safety challenges, aiming to make rechargeable lithium-metal technology a reality for next-generation electric vehicles. The classification of Li-metal batteries is

3.21 Lithium Titanate Oxide – LTO ($\text{Li}_4\text{Ti}_5\text{O}_{15}$)

LTO battery replace the traditional graphite anode with a lithium-titanate nanocrystal structure, providing a high-surface area that facilitates exceptionally fast charging and discharging. This chemistry is renowned for its extreme safety and thermal stability, as it is virtually immune to the dendrite formation and "thermal runaway" that can affect other lithium-ion types. Furthermore, Lithium Titanate Oxide (LTO) cells exhibit an exceptional cycle life that frequently exceeds 20,000 cycles, rendering them highly suitable for heavy-duty applications such as electric vehicles (EVs) and grid energy storage systems (GESS). However, their primary limitations include a lower nominal voltage of 2.4 V and a reduced energy density relative to conventional nickel-based chemistries [9] [10].

3.22 Lithium Sulphur (Li-S)

Lithium-Sulphur (Li-S) batteries utilize Sulphur-based cathode coupled with a lithium-metal anode, offering a theoretical energy density that significantly surpasses conventional Lithium-ion technologies. They are prized for their low cost and environmental sustainability due to the abundance of sulphur, making them a promising candidate for weight-sensitive applications like aviation and long-range transport. However,

widespread commercialization is currently limited by the "shuttle effect," where sulphur species dissolve into the electrolyte, leading to rapid capacity fade and shorter cycle lives [11].

3.3 [3]Comparison of various Lithium battery

A comparison of key features of lithium battery can be seen in table below

Types[12]	Specific capacity (mAh/kg)	Nominal Voltage	Specific Energy (Wh/kg)	Cycle-life	Safety	Lifetime	Cost
LCO [3]	140	3.7	110 - 190	500-1000	Poor	Average	High
LMO [3]	146	3.8	100 - 120	1000	Average	Poor	Average
NCA [3]	180	3.6	100 - 150	2000 - 3000	Low	High	High
NMC [3]	145	3.6	100 - 170	2000 – 3000	Low	Good	High
LFP [3]	170	3.3	90 – 115	>3000	High	Average	Average
LTO [3]	170	2.2	60 – 75	>5000	High	High	High

1 Specification of Panasonic Single cell ECM based battery model [3].

Conclusions: The choice of a specific lithium-ion battery chemistry inherently involves a multi-variable trade-off. The optimal configuration depends entirely on the target application's operational requirements—whether it prioritizes the high energy density and long-range endurance of NMC, the robust thermal safety and cycle life of LFP, or the ultra-fast charging capabilities of LTO. The evolution of lithium-based energy storage has moved away from a "one-size-fits-all" solution toward a highly specialized ecosystem of chemistries. By manipulating the transition metals in the cathode and the structural architecture of the anode, researchers have created a spectrum of batteries that each address specific trade-offs between energy density, safety, lifespan, and cost, c-rates, thermal stability. As the global push for electrification intensifies, the choice of battery chemistry has become the most critical design decision in the development of modern EVs and GESS.

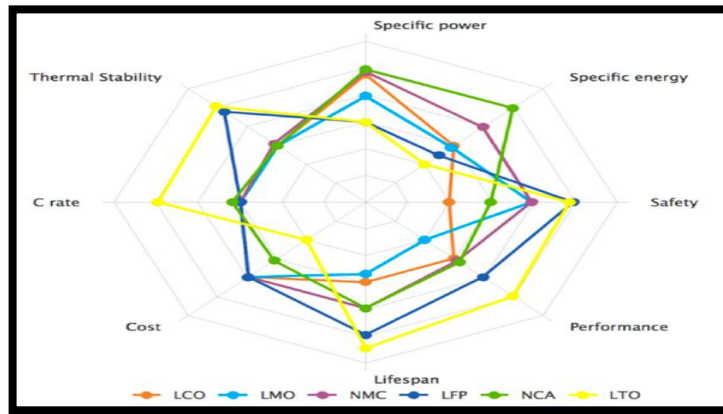


Figure 3-10 Spectrum: Comparison of various Li-ion chemistries [14].

3.4 The rise of advanced Lithium-ion chemistries

3.4.1 Lithium-Air Battery

Lithium-air battery has high energy density (nearly 3500 Wh/kg) by using a lithium metal anode and an air cathode. Despite this potential, challenges like low efficiency, poor cycle life, and sensitive packaging keep them in early research stages.

3.5 Summary and Relevance to Grid Energy Storage

The development of lithium-based energy storage has resulted in a diverse technological landscape where specific chemistries are tailored to meet distinct operational demands. No single battery type dominates every sector; instead, a strategic selection process determines which material is best suited for a given application.

Lithium Iron Phosphate (LFP) has solidified its position as the premier choice for **stationary grid storage**. While its specific energy density is relatively modest compared to alternative chemistries, its robust crystal framework and inherent resistance to thermal runaway ensure an exceptional safety profile for utility-scale installations. When combined with its ability to endure thousands of cycles and its lower manufacturing cost, LFP provides the most reliable return on investment for balancing renewable energy loads.

In contrast, the Electric Vehicle (EV) market continues to prioritize range and weight, making high-energy density batteries chemistries NCA and NCM the industry Favorites [13]. For specialized use cases—such as transit buses or industrial equipment that require near-instantaneous recharging—**Lithium Titanate (LTO)**

offers an unmatched lifespan and safety profile, provided the higher initial cost can be justified by the operational intensity.

The horizon of energy storage lies in high-capacity frontiers like **lithium-air** and **lithium-sulphur**. These "beyond-lithium-ion" technologies promise to drastically increase energy storage limits, potentially enabling the electrification of heavy transport and aviation. However, their mainstream success depends entirely on solving current degradation and stability issues through continued breakthroughs in material science and engineering.

4 Chapter: Characterization of Lithium-ion Battery Dynamics

The fundamental nature of lithium-ion batteries (LIBs). Although a battery may appear to be a simple device designed to store and release electrical energy, its internal structure reveals a complex electrochemical system. In this section it is intended to elaborate on some of the main characteristics of LIBs [3] [6].

4.1 Charge and discharge characteristics

The charge-discharge characteristics of a battery define its operational efficiency, typically illustrated by a curve plotting terminal voltage against state-of-charge (SoC). It is primarily governed by the Constant Current-Constant Voltage (CC-CV) protocol to ensure safety and longevity. During the CC (Constant Current) phase, the charger delivers a steady current, causing the battery voltage to rise rapidly until it reaches its maximum threshold. Once this upper voltage limit is hit, the system switches to CV (Constant Voltage) mode, where the voltage is held steady while the current gradually tapers down as the battery reaches full saturation. On the discharge side, the voltage typically remains on a stable plateau before dropping sharply near the end-of-discharge, with higher C-rates leading to increased voltage sag due to internal resistance. Efficiently managing these modes is critical for your work in battery emulators to accurately replicate real-world charging profiles and prevent cell degradation.

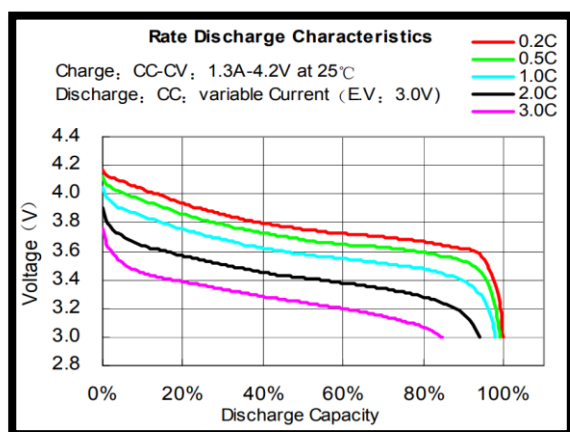


Figure 4-1 Discharge curve for different c-rate

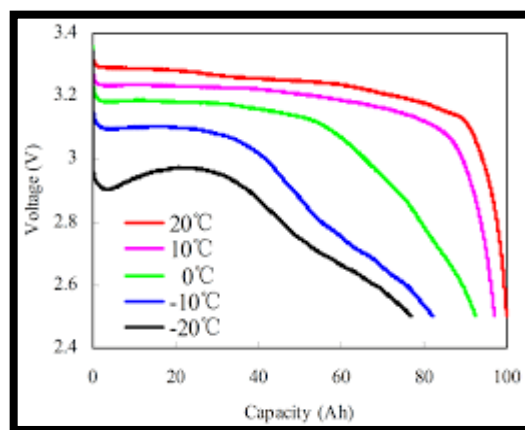


Figure 4-2 Discharge curves at different temperatures

4.2 Battery Phenomenon

4.21 C-rate effect

The C-rate effect captures the inverse relationship between operating current and available capacity, where high charge or discharge rates lead to a noticeable drop in the battery's usable energy. This occurs because, at high currents, ion diffusion in the electrolyte lags behind the electrochemical reactions, leading to incomplete utilization of active materials. Charging or discharging at lower rates allows more complete reactions, recovering capacity.

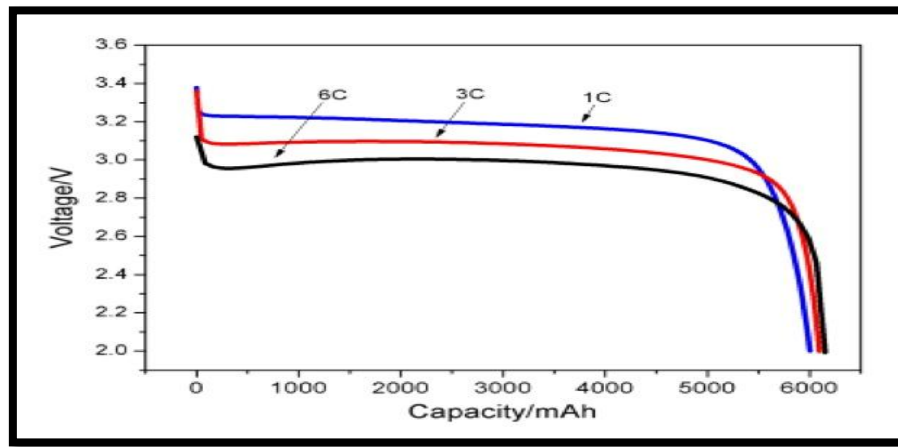


Figure 4-3 Effect of c-rate on battery

4.22 Self- discharge

Self-discharge denotes the spontaneous loss of charge in a battery without any external load. Although all battery chemistries experience self-discharge, lithium-ion batteries exhibit relatively low self-discharge rates, as summarized in Table 4.1. It is also temperature and SOC dependent; higher temperatures and higher SOC's tend to accelerate self-discharge.

Battery type[3]	Alkaline	Lead-acid	Ni-Cd	Li-ion	Ni-MH
Self-discharge	2-3%	<5%	10-15%	<5%	20-30%

2 Self-discharge for various battery types [3]

4.23 Temperature Effect

The thermal behavior of lithium-ion systems is a critical determinant of both their operational efficiency and long-term degradation. While these batteries achieve peak performance in a controlled “Goldilocks zone” of **23°C to 25°C**, deviations from this range trigger immediate physical and chemical shifts. Cold environments impede ion mobility and heighten internal resistance, leading to sluggish power delivery and reduced usable capacity. In contrast, elevated temperatures lower resistance and can briefly boost capacity, but this comes at

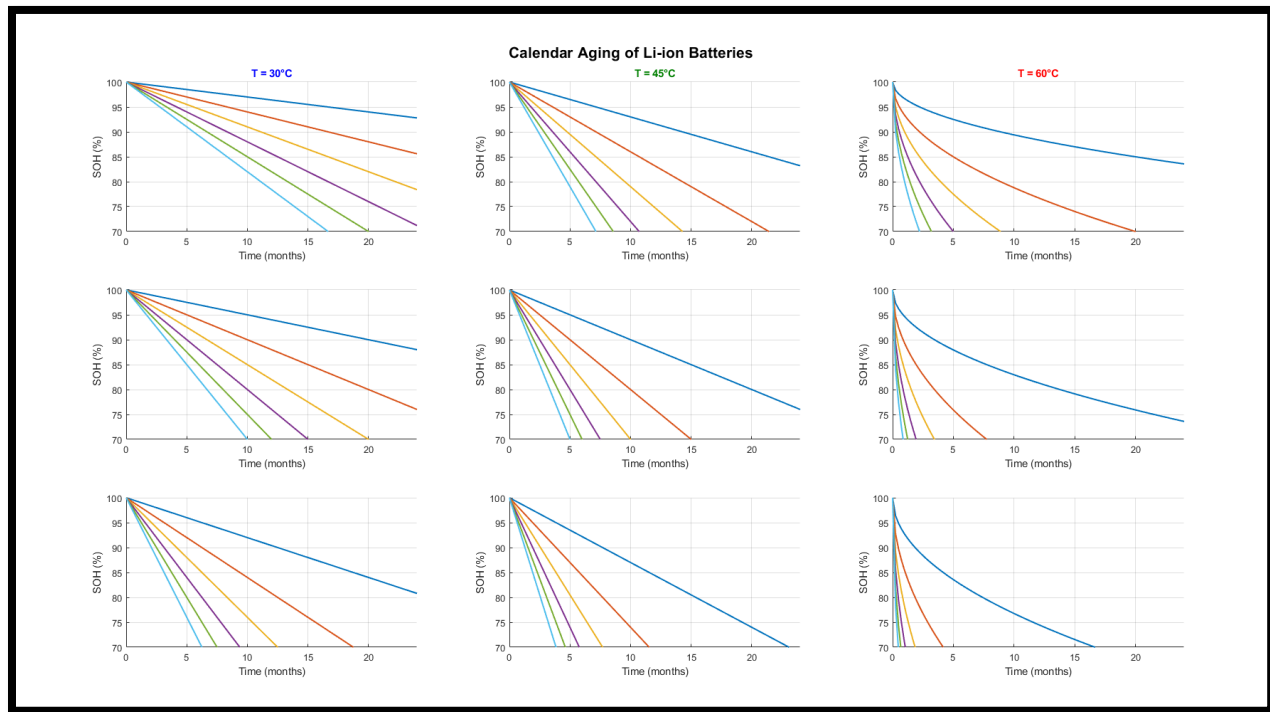


Figure 4-4 Calendar aging measured on 6 Li

The cost of accelerated aging; the intensified chemical activity speeds up self-discharge and permanently degrades the cell’s internal structure. For battery emulators, accurately modeling these temperature-dependent resistance changes the vital for predicting real-world behaviour under varying thermal loads.

4.24 Ageing Effect

The degradation of lithium-ion batteries is a multifaceted process driven by coupled chemical and mechanical phenomena. Chief among these is the growth of the Solid Electrolyte Interphase (SEI) layer, which irreversibly consumes cyclable lithium ions. This degradation manifests as "capacity fade" and is typically accompanied

by "power fade," where internal resistance rises due to microstructural electrode cracking and electrolyte decomposition. These aging mechanisms are significantly accelerated by harsh operating conditions, including elevated temperatures, extreme states of charge (SOC), and high C-rates. For high-fidelity battery emulators, capturing these aging dynamics is crucial for predicting long-term system health and reliability. Consequently, tracking the State of Health (SOH) is vital to enable timely intervention before the system hits its conventional end-of-life (EOL) threshold—typically defined as a drop to 80% of the nominal capacity.

4.3 Battery SOC and SOH

4.3.1 Battery SOC

The State of Charge (SoC) is a fundamental metric that quantifies a battery's instantaneous available energy relative to its maximum capacity, operating analogously to a conventional vehicle's fuel gauge. Expressed as a percentage, a value of 100% denotes a fully charged cell, while 0% signifies complete depletion. Within a Battery Management System (BMS), high-accuracy SoC estimation is critical; it serves as the primary safeguard against hazardous operational extremes such as overcharging and deep discharging, both of which can induce irreversible degradation and permanently impair battery health. Since SoC cannot be measured directly with a physical sensor, it is typically estimated through methods like "Coulomb Counting," which tracks current flow over time, or by measuring the Open Circuit Voltage (OCV). In high-fidelity battery emulators, modeling the nonlinear relationship between OCV and SoC is essential for replicating realistic voltage behaviour during various load cycles. Environmental factors, such as temperature fluctuations and aging, can cause "SoC drift," requiring advanced algorithms like Extended Kalman Filters (EKF) for real-time correction. Maintaining the battery within a specific "SoC window"—often between **20% and 80%**—is a common strategy to maximize the cycle life and safety of electric vehicle battery packs. Ultimately, precise SoC monitoring ensures the reliability of the power electronics interface and provides the user with an accurate estimate of remaining driving range [3].

Classification	Methodology
Direct measurement	OCV, Terminal Voltage, Impedance method
Book-keeping Estimation	Coulomb Counting, Modified Coulomb Counting
Adaptive Systems	Kalman Filters (EKF, UKF), Neural Networks, Fuzzy neural network, BP neural network
Hybrid Methods	Coulomb Counting + Kalman Filter Coulomb Counting and EMF Per -unit system and EKF

3 Soc classification and methodology

4.32 Battery SOH

State of Health (SOH) reflects the physical condition and performance capability of a battery. It is typically quantified as a percentage, where **100%** represents a fresh cell and a drop to **80%** usually signals the battery's "end-of-life" for automotive applications. Unlike the daily fluctuations of SoC, SOH represents long-term, irreversible degradation caused by factors like SEI layer growth, lithium plating, and electrode fracturing. It is determined by tracking two primary indicators: capacity fade, which reduces total energy storage, and power fade, which increases internal resistance. Because SOH cannot be measured directly, it requires sophisticated estimation techniques in the BMS, such as analyzing incremental capacity. Accurate SOH monitoring is essential for safety, as it helps predict potential cell failures and ensures the battery can still deliver the required current for peak acceleration.

4.4 LIB Pack Concept

A typical lithium-ion battery pack comprises numerous individual cells arranged in series-parallel configurations to form modules. Several modules combine to form a tray, each managed by a dedicated Battery Management System (BMS) to ensure safe operation and uniform charging/discharging. Fig. 4.3 shows an example of a battery tray from Panasonic containing 312 18650-type cells.[3]

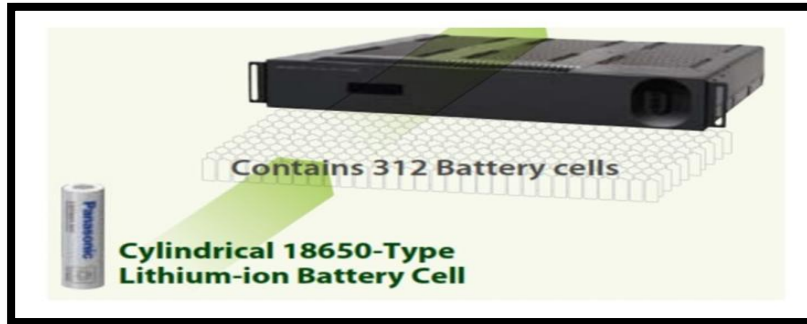


Figure 4-5 LIB tray - Panasonic

Multiple trays form a battery rack, which typically delivers voltages between 500 1000 V. A main BMS oversees the entire rack, communicates with the Power Conditioning System (PCS), and reports key parameters like terminal voltage, SOC, SOH. Fig. 4.4 illustrates a battery pack from LG Chem, showing the full assembly from individual prismatic cells to container-scale storage solutions.

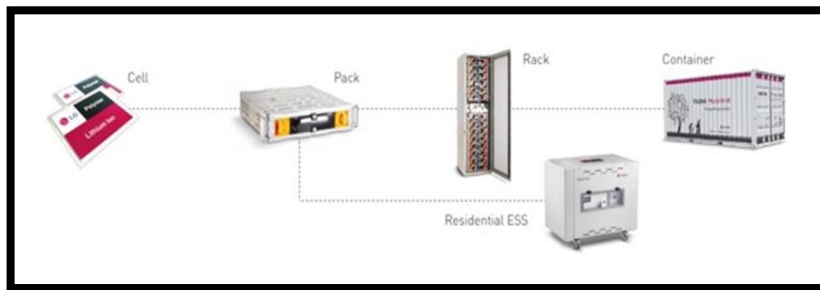


Figure 4-6 LIB Assembly for a GESS by LG chem

5 Chapter: Battery modeling and Power Converters: Literature review

The surge in demand for high-performance energy storage (GESS) and portable consumer electronics like smartphones and laptops—has transitioned into a new era dominated by the electrification of transport and the stabilization of power grids. This shift toward large-scale applications such as electric vehicles (EVs) and renewable energy integration has necessitated a deeper understanding of battery dynamics. As a result, the academic and engineering communities have produced an extensive array of sophisticated battery models, ranging from simple mathematical representations to high-fidelity electrochemical simulations, to accurately predict performance across these diverse sectors.

Battery model with different levels of abstraction are discussed in the literature, and these can be divided mainly into three categories: **Analytical**, **Electrochemical**, and **Electrical equivalent circuit models** [14]. All other models are typically a combination of the above three. Analytical models use mathematical models to replicate the behavior of the batteries. It is also known as empirical model. Examples of this model Shepherd model, Nerst model, Unnewehr. Electrochemical models using physics which goes inside the battery. It is also known as physics base model. EECMs represent battery behavior using electrical components such as resistors, capacitors to mimic the battery's external electrical characteristics. They are based on the reaction processes taking place inside the battery [15].

5.1 Equivalent Circuit Model

In this chapter, we investigate the simpler approach to modeling cell operation, which uses electrical-circuit analogs to define a behavioral or phenomenological approximation to how a cell's voltage responds to different input-current stimuli [16]. That is, we invoke knowledge of common electronic elements to define a circuit that has behavior that closely matches the observed behavior of the battery cell [16]. The equations that describe the circuit therefore also closely describe the observed operation of the cell. Such models are called equivalent-circuit models [16]. We make a circuit in this model, the circuit acts as description of cell behavior, and their various circuit elements acts as analogs to some of internal process of battery [16]. The simplest electric model consists of an ideal voltage source in series with an internal resistance. This model, however, does not take into account the battery SOC. There is another model based on an open circuit voltage in series with a resistance and parallel RC circuits with the so-called Warburg impedance. Equivalent-circuit cell models don't have all of the features of physics-based models but are adequate form any applications [14].

Compared to the other two models, electrical models have comparatively low complexity and can be easily linked to an electronic circuit where cells are typically modeled using parallel pair of dynamic, nonlinear resistors and capacitors [14]. Based on complexity, a wide variety of equivalent circuit models have been implemented where a suitable order of parallel RC networks can be used as an equivalent circuit [14]. For instance, uses the first-order RC (1RC model) equivalent circuit to different model parameters such as open-circuit voltage and cell behavior [14]. Second-order RC equivalent circuits model (2RC ECM model) has also been presented to improve accuracy, particularly in modeling the dynamic characteristics [14]. Further, analyses computational complexity of an n th order RC equivalent circuit. Based on the trade-off, between accuracy and complexity, 2RC model is now most commonly used for modelling of Li-ion cells[14].

2RC BATTERY MODEL

Fig. 5-2 shows the most commonly used 2RC model, where R_s , R_1 , R_2 , C_1 , and C_2 are non-linear impedances dependent on the state of charge of the cell. R_1 , R_2 , C_1 , and C_2 are used to model the transient response of the voltage across the cell, and R_s models the sudden drop and rise in output voltage due to loading and unloading of the cell [17]. The terminal voltage and the open-circuit voltage is given by V_t and OCV , respectively [17]. The current flowing through the cell is I_B , and conventionally it is taken as positive for discharging and negative for charging [17].

For the analysis, we focus our discussion on the V-I modeling and the dynamic performance of Li-ion cells, which affect the operating current-voltage characteristics of battery cells with multiple dimensions and chemistries [17]. The equivalent model, shown in Fig. 5-2 shows a two parallel RC pair, Fig. 5-1 shows a single parallel RC pair.

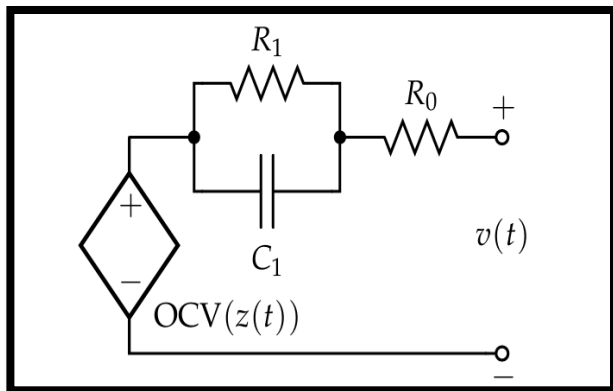


Figure 5-1 1RC model for Li-ion cell

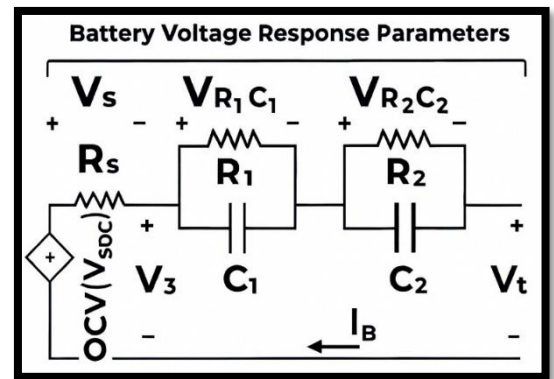


Figure 5-2 2RC model for Li-ion cell

Various important parameters of the cell model

A. State of Charge (SOC)

The State of Charge (SoC) and in turn, Depth of Discharge (DoD) can be found through (1) and (2)[14]

$$\diamond \text{ DOD} = 100 - \text{SOC} \quad (1)$$

$$\diamond \text{ SOC} = \text{SOC}_{\text{initial}} - \int IB * \frac{100}{Cu*3600} \quad (2)$$

SoC_{initial} represents the initial state of charge on the battery. A fully charged cell (100% SoC_{initial}) is taken and (a fully charged cell is drawing 0.001C or less current during charging). IB, in amperes, is the constant discharging current flowing through the cell. Cu is the useable capacity of the cell in ampere-hours and is mapped from the discharge current's magnitude [17].

B. Open Circuit Voltage (OCV)

Open-circuit voltage (OCV) is the equilibrium terminal voltage under zero-current conditions, matching the cell's electromotive force and indicating its stored energy. Because \$SoC\$ depends non-linearly on OCV, their precise relationship is mapped using experimental characterization data. To mathematically formulate the final SoC-OCV profile, a combination of polynomial and exponential functions is generally used for interpolation. This relationship is governed by equation (3), where a-f represent positive fitting coefficients extracted individually for each cell.[17] [14].

$$\diamond \text{ OCV}(\text{soc}) = -ae^{-b(\text{soc})} + c + d(\text{soc}) - e(\text{soc})^2 + f(\text{soc})^3 \quad (3)$$

C. DC Resistance (Rs)

In normal cell operation, the instantaneous voltage drops at the start of discharge and the immediate rise upon current interruption represent ohmic transient responses. These effects are modeled by the series resistance Rs Fig. 5.1(a)], which can be calculated for both charging and discharging conditions using equations (4) and (5)

$$\diamond R_s = V_s / I_B = \text{OCV} - V_3 / I_B \quad (4)$$

$$\diamond V_3 = V_{R1C1} + V_{R2C2} + V_t \quad (5)$$

The value of V_s can also be found experimentally by measuring the voltage of the cell, as shown in Fig. 5-2. It should also be noted that the value of R_s also depends upon whether the cell is being charged or discharged [14].

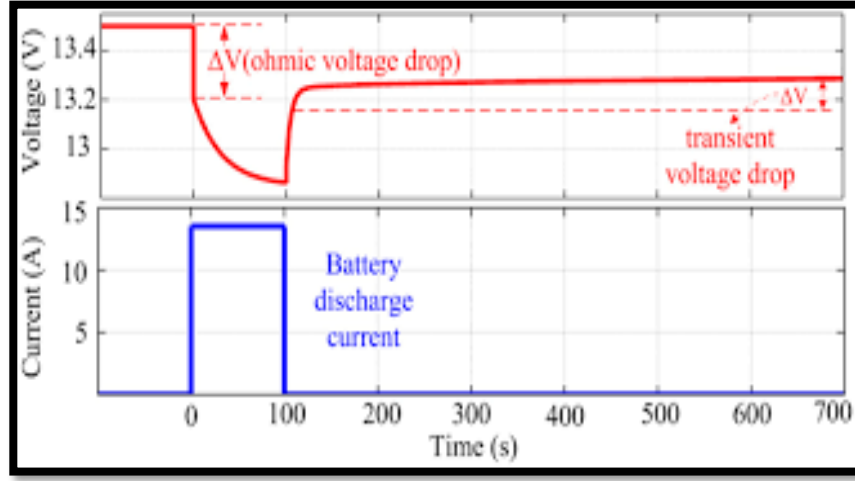


Figure 5-3 Voltage parameter during relaxation interval in Internal Impedance Parameter Extraction

D. Internal Impedance (Resistors and Capacitors)

The parallel RC pairs are responsible for the transients in the model's terminal voltage curve and can be used to model the transient behavior of the cell. The RC pairs use two different time constants, one shorter compared to the other to model the transient response. The internal impedance values, at a particular SoC, can be found during charging, discharging, or the relaxation interval. In this paper, the relaxation interval is used to determine these values. The internal impedances were calculated using (6) – (10)[14].

$$\diamond \quad V_{\text{transient}} = V_{\text{sh}} \left(1 - e^{-\frac{t}{\tau_{\text{sh}}}}\right) + V_{\text{lo}} \left(1 - e^{-\frac{t}{\tau_{\text{lo}}}}\right) \quad (6)$$

$$\diamond \quad V_{\text{sh}} = R_1 * I_B \quad (7)$$

$$\diamond \quad V_{\text{lo}} = R_2 * I_B \quad (8)$$

$$\diamond \quad \tau_{\text{sh}} = R_1 * C_1 \quad (9)$$

$$\diamond \quad \tau_{\text{lo}} = R_2 * C_2 \quad (10)$$

Model Implementation in MATLAB/ Simulink

Fig. 5-3 shows the MATLAB/Simulink implementation of 2RC model (shown earlier in Fig. 5-2). The value of R_S , at different SoCs, is found experimentally and incorporated in the Simulink model in the form of a look-up table. OCV is incorporated through (3), which is a function of SoC (as discussed in Section IIB). For the evaluation of $VR1C1$ and $VR2C2$, it is important to analyze Fig. 5-2 where “A” represents the node through which current is entering the parallel RC pair. The voltage drops across a parallel RC pair network can be found by applying nodal analysis at node “A” as given by (11)[14].

$$\diamond I = C \frac{dV}{dt} + \frac{V}{R} \quad (11)$$

Applying Laplace transform on (11) and rearranging for V gives (12), which is then used to quantify $VR1C1$ and $VR2C2$ as provided by (13) and (14), respectively.

$$\diamond V = \left(\frac{1}{s}\right) * \left(\frac{1}{C} - \frac{V}{RC}\right) \quad (12)$$

$$\diamond V_{R1C1} = \left(\frac{1}{s}\right) * \left(\frac{IB}{C1} - \frac{VR1C1}{R1 * C1}\right) \quad (13)$$

$$\diamond V_{R2C2} = \left(\frac{1}{s}\right) * \left(\frac{IB}{C2} - \frac{VR2C2}{R2 * C2}\right) \quad (14)$$

The parameter extraction for the conventional 2RC equivalent circuit model is typically performed using relaxation intervals of four hours and thirty minutes, respectively. While standard 2RC models—such as those designed with a one-hour relaxation interval—are generally constrained and evaluated using a single cell chemistry (such as NMC), our proposed modeling strategy enables high-fidelity performance predictions across multiple Lithium-ion chemistries (NMC and $LiFePO_4$) and varying cell capacities.

To characterize the cells, a pulsed-discharge experimental profile was implemented. Beginning from a fully charged state (100% SoC) at equilibrium, the cell was discharged at a 1C rate for six minutes, followed by a six-minute open-circuit relaxation period to allow the terminal voltage to approach its true equilibrium state. The voltage captured at the absolute end of this relaxation interval was recorded as the Open Circuit Voltage (OCV), as illustrated in Figure 5-2. This characterization sequence was executed at 10% SoC decrements across the entire operating range. This methodology, initially applied to the NMC cell, was replicated for the $LiFePO_4$ cells. The model's accuracy was subsequently validated by comparing the experimental and simulation transient voltage curves, the results of which are detailed in the following section.[14]

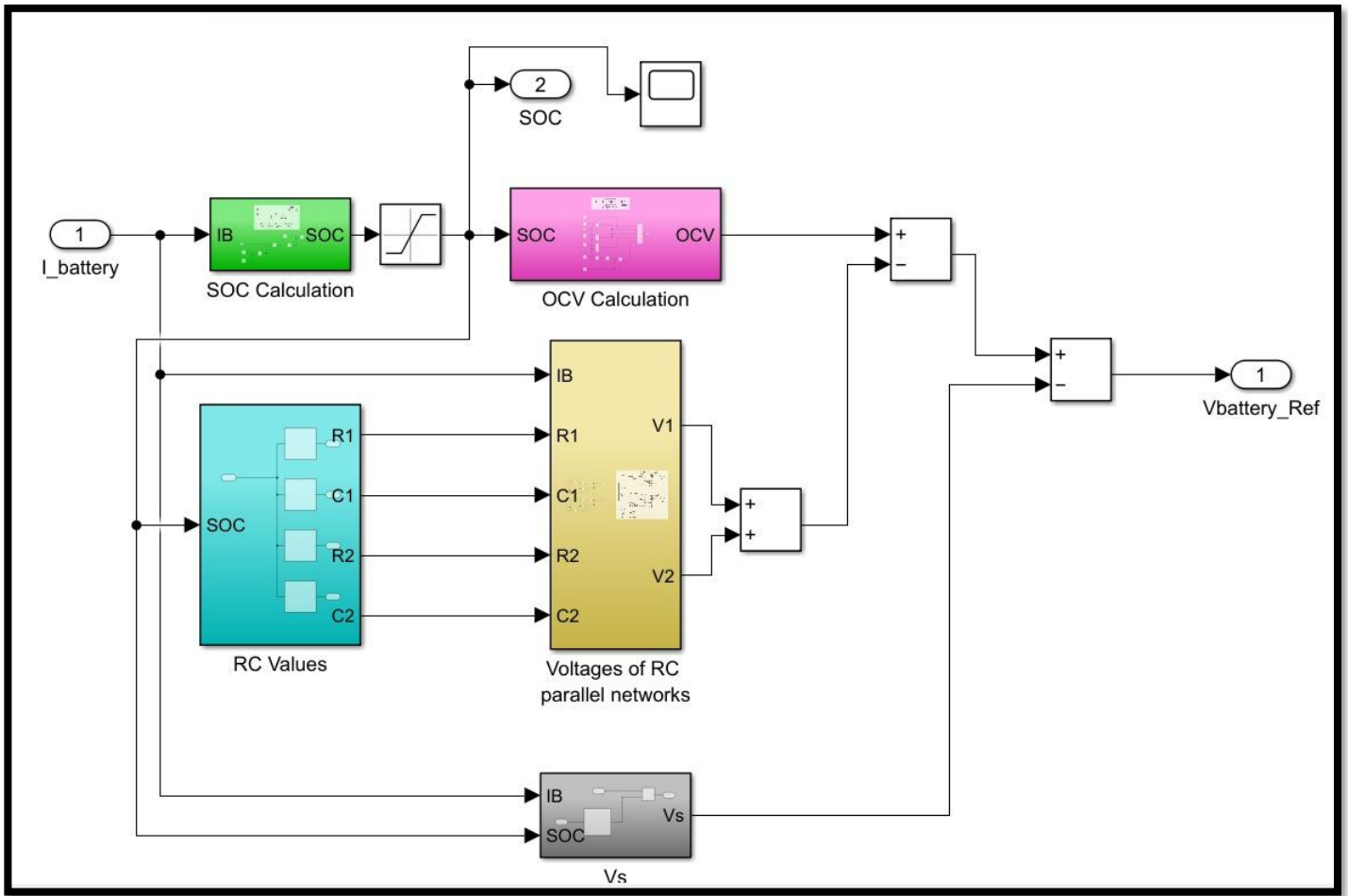


Figure 5-4 2RC Simulink implementation of the model [14]

Parameter	Value
Rated capacity(mAh)	2500
Cell size	18650
Rated Voltage	3.7
Safety Limits	4.1 - 3

4 NMC Cell uses for testing[14]

Coefficient	a	b	c	d	e	f
Value	2.1	35	3.46	0.34	0.17	0.5

5 Values of coefficient for NMC cell [14]

SOC (%)	R_s (m Ω)	R_1 (m Ω)	C_1 (*10 ³ F)	R_2 (m Ω)	C_2 (*10 ³ F)
90	44	7.52	0.986	12.7	4.259
80	46	7.14	0.858	17.2	3.633
70	46	9.48	1.054	15.5	6.303
60	46	11.91	1.863	14.2	26.003
50	46	6.00	3.423	12.0	6.621
40	46	6.00	2.185	12.0	6.431
30	46	4.00	3.750	16.0	2.689
20	46	7.27	1.195	21.7	3.812
10	46	11.61	1.228	13.6	8.715

6 Extracted Impedance Parameter for NMC cell for modeling [17]

5.2 Shepherd Model

This section presents an enhanced, computationally efficient battery dynamic model. A key advantage of this formulation lies in the straightforward nature of its parameter extraction process. The framework is derived from the classic Shepherd equation, which describes the electrochemical behavior of a battery directly as a function of terminal voltage, open-circuit voltage, internal resistance, discharge current, and state of charge (SoC)—applicable to both charging and discharging regimes. In this work, a modified version of the Shepherd model is adopted. Specifically, the formulation replaces the traditional polarization resistance with a polarization voltage term, effectively eliminating the algebraic loop errors frequently encountered during electrical system simulations in MATLAB/Simulink. Furthermore, this model relies solely on the battery SoC as a state variable to dictate transient voltage behavior. While this assumption remains highly accurate under steady-state conditions (constant current profiles), it introduces modeling inaccuracies when subjected to highly dynamic or rapidly varying current profiles. [18] [6].

The charge and the discharge dynamics of the battery model are validated experimentally with four batteries types eg. Lead -acid, Li-ion, NiMH and NiCd. It will show the results of an experimental validation for four types of batteries.[18] The Shepherd battery voltage is given by:

$$V_{ocv} = E_o - K \left(\frac{Q}{Q-it} \right) + A. \exp (- B. it)$$

5.21 The discharge model

The Fig. 5-5 shows a typical discharge characteristic, for a Nickel-Metal Hydride cell. The proposed discharge model is similar to the Shepherd model but can represent accurately the voltage dynamics when the current varies and takes into account the open circuit voltage (OCV) as a function of SOC. A term concerning the polarization voltage is added to better represent the OCV behavior and the term concerning the polarization resistance is slightly modified.

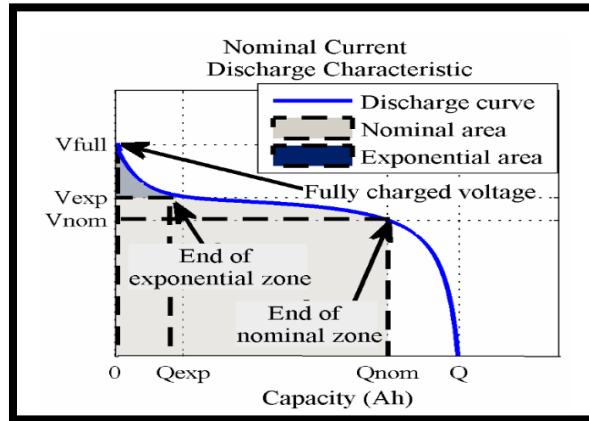


Figure 5-5 Typical discharge curve of NiMH cell

The modified Shepherd battery voltage is obtained by:

❖ **Li-ion**

$$\text{Discharge: } V_{\text{batt}} = E_o - R \cdot i - K \frac{Q}{Q - i \cdot t} (i \cdot t + i^*) + \text{Exp}(t) \quad [19], [20] \quad (1)$$

Where,

V_{batt} = battery voltage (V)

E_o = battery constant voltage (V)

K = Polarisation resistance (V/Ah)

Q = battery capacity (Ah)

$i \cdot t$ = actual battery charge (Ah)

A = exponential zone amplitude (V)

B = exponential zone time constant inverse (Ah)⁻¹

R = internal resistance

i = battery current (A)

i^* = filtered current (A)

This model is characterized by passing a filtered current (i^*) through the polarization resistance to capture the slow transient voltage dynamics observed experimentally during current step responses. This filtering mechanism also serves as a computational workaround to prevent algebraic loop errors within Simulink. In this framework, the non-linear SoC-OCV relationship is represented by the polarization voltage term. While the exponential characteristics in equation (1) are specific to Lithium-ion dynamics, other battery types (including Lead-Acid, NiMH, and NiCd) display a continuous charge-discharge hysteresis across their entire SoC range. This phenomenon can be represented by a non-linear dynamic system

$$\text{Exp}(t) = B \cdot |i(t)| \cdot (-\text{Exp}(t) + A \cdot u(t)) \quad (2)$$

Where,

$\text{Exp}(t) = \text{exponential zone voltage}(V)$

$i(t) = \text{battery current (A)}$

$u(t) = \text{charge or discharge mode}$

The exponential voltage depends on its initial value $\text{Exp}(t_0)$ and the charge ($u(t) = 1$) or discharge ($u(t) = 0$) mode. Fig. 5.6 shows the complete discharge model system.

❖ Lead-acid

$$V_{\text{batt}} = E_o - R \cdot i - K \frac{Q}{Q - it} (it + i^*) + \text{Exp}(t) \quad [15]$$

❖ NiMH and NiCd

$$V_{\text{batt}} = E_o - R \cdot i - K \frac{Q}{Q - it} (i \cdot t + i^*) + \text{Exp}(t) \quad [15]$$

5.22 The Charge model

The charge behavior, particularly the end of the charge (EOC) characteristic, is different and depends on the battery type. The Lead-Acid and Li-Ion batteries have the same EOC characteristics, because the voltage increases rapidly when the battery reaches the full charge. This phenomenon is modelled by the polarization resistance term. In the charge mode, the polarization resistance increases until the battery is almost fully charged ($it = 0$). Above this point, the polarization resistance increases abruptly. Instead of the polarization resistance of the discharge model equation (1), the polarization resistance is now given by:

$$\text{Pol. Resistance} = K \frac{Q}{it} \quad (3)$$

Theoretically, when $it=0$ (fully charged), the polarization resistance is infinite. This is not exactly the case in practice. Indeed, experimental results have shown that the contribution of the polarization resistance is shifted by about 10% of the capacity of the battery. Equation (3) can be re-written to:

$$\text{Pol. Resistance} = K \frac{Q}{it - 0.1Q} \quad (4)$$

Similar to the discharge model, the exponential voltage for the Li-Ion battery is the $A \cdot \exp(-B \cdot it)$ term and for the Lead-Acid, the voltage is given by equation (2).

For NiMH and NiCd battery, polarization resistance will be

$$\text{Pol. Resistance} = K \frac{Q}{|it| - 0.1Q} \quad (5)$$

❖ Li-ion

$$V_{\text{batt}} = E_o - R \cdot i - K \frac{Q}{it - 0.1Q} \cdot i^* - K \frac{Q}{Q - it} \cdot it + A \cdot \exp(-B \cdot it)$$

❖ Lead-acid [15]

$$V_{\text{batt}} = E_o - R \cdot i - K \frac{Q}{it - 0.1Q} \cdot i^* - K \frac{Q}{Q - it} \cdot it + \text{Exp}(t)$$

❖ NiMH and NiCd

$$V_{\text{batt}} = E_o - R \cdot i - K \frac{Q}{|it| - 0.1Q} \cdot i^* - K \frac{Q}{Q - it} \cdot it + \text{Exp}(t)$$

The above proposed model based on specific assumption and has limitations:[15]

Model assumptions:

- The internal resistance is treated as a constant parameter across all operating regimes, independent of charge/discharge states or current amplitude.
- Model parameter extraction is based solely on discharge profile data, with the resulting values applied symmetrically to the charging phase.
- The battery capacity is treated as independent of discharge rates, thereby excluding Peukert's law from the model formulation.
- Temperature effects are decoupled from the system dynamics, assuming the battery operates under ideal, constant-temperature conditions.
- Long-term self-discharge mechanisms are excluded from the simulation framework.
- The cell is assumed to have no memory effect, ensuring reproducible capacity tracking across cycles [15].

Model Limitations

- The model restricts the no-load battery voltage to a range between 0V (fully depleted) and a maximum mathematical ceiling of E_0 .
- The available capacity is strictly bounded by a lower limit of 0 Ah and an upper limit representing the nominal capacity (Q).
- Due to these boundary conditions, the calculated SoC is strictly capped at 100% meaning the variable will not exceed its maximum scale even if the battery undergoes overcharging[15].

Type	Lead-Acid	NiCd	Li-ion	NiMH
Parameters	12.7V 7.2Ah	1.2V 2.3Ah	3.3V 2.3Ah	1.2V 6.5Ah
E_0 (V)	12.4659	1.2705	3.366	1.2816
$R \Omega$	0.04	0.003	0.01	0.002
$K(V/Ah)$	0.047	0.0037	0.0076	0.0014
A (V)	0.83	0.127	0.26422	0.111
$B (Ah)^{-1}$	125	4.98	26.5487	2.3077

7 Parameters of various Battery types[15]

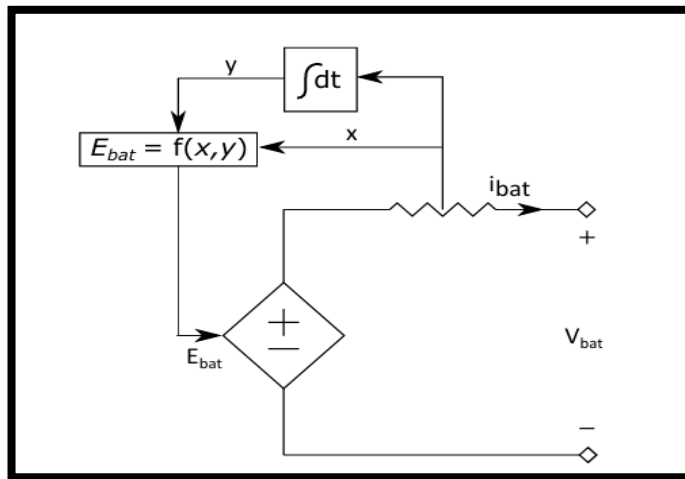


Figure 5-6 Simple Battery model representation

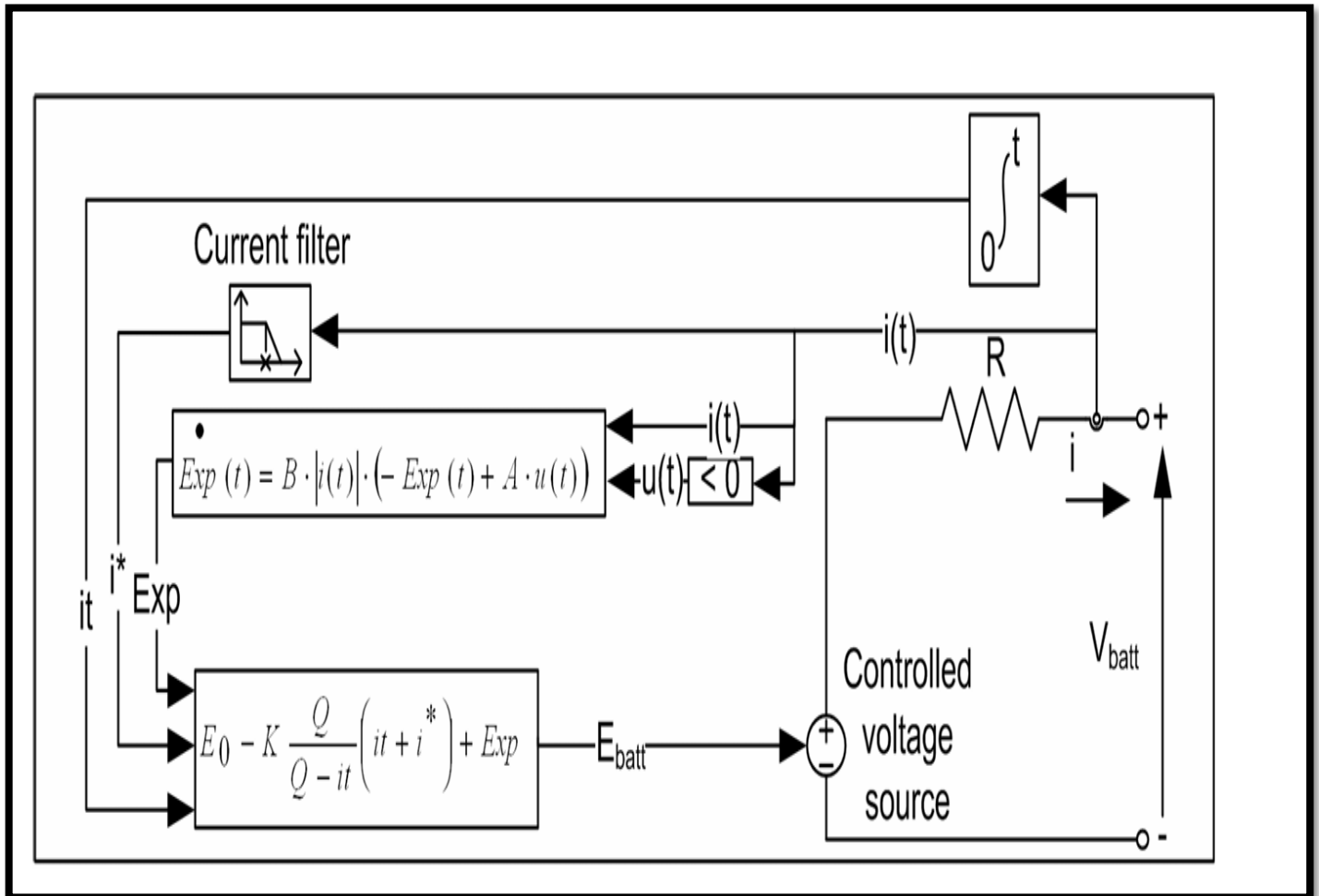


Figure 5-6.1 Modified Shepherd discharge battery model

Cell to Module arrangement

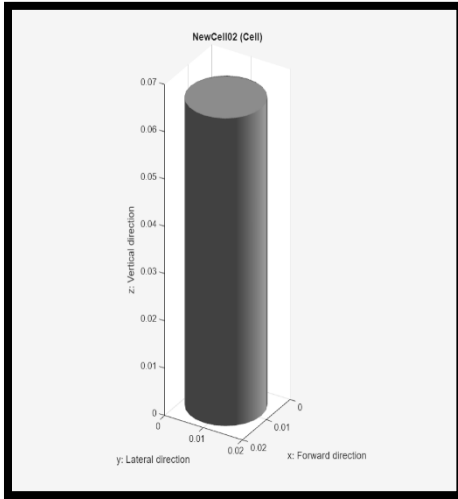


Figure 5-9 Single cell

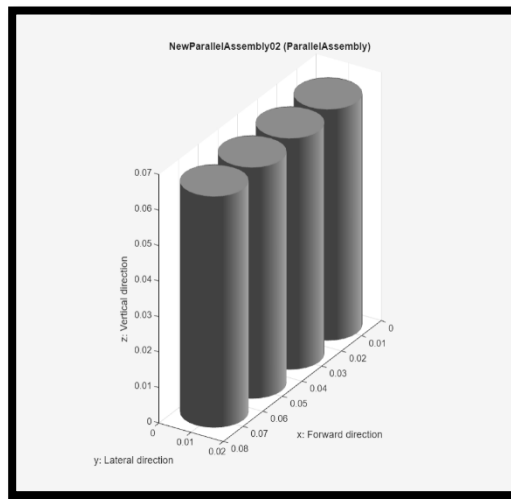


Figure 5-7 Parallel arrangement

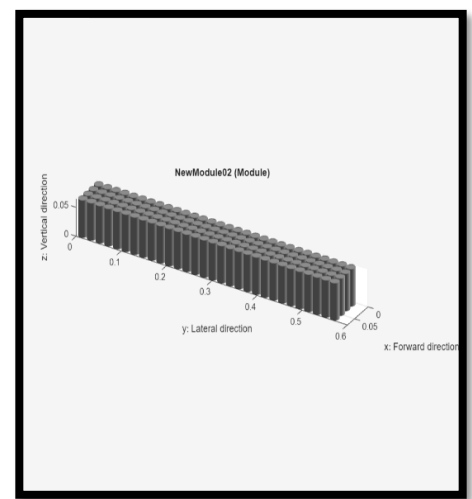


Figure 5-8 Module representation

Parameters	Single cell	Pack(30s4p)
Nominal Voltage	3.7 V	111 V
Nominal Capacity	2.9Ah	11.6 Ah
Charge limit	4.3 V	129 V
Discharge limit	2.7 V	81 V
Weight	0.049 Kg	5.88 Kg
Diameter	9.12 mm	
Height	65.1 mm	
Volume	$2.165 \cdot 10^{-5} \text{ m}^3$	$284.93 \cdot 10^{-5} \text{ m}^3$

8 Specification of Panasonic UR Li-ion battery [21]

5.3 Active Rectifier

An **active rectifier**, also known as a Pulse Width Modulation (PWM) rectifier, is a power electronics converter that converts Alternating Current (AC) to Direct Current (DC) [22] using active switching devices like **IGBTs** or **MOSFETs** instead of passive diodes. While a standard diode bridge is uncontrolled and allows current to flow only in one direction, an active rectifier provides bidirectional power flow and precise control over the output voltage and input current.

- **Boost Action:** Most active rectifiers are "boost-type," meaning the output DC voltage is always higher than the peak of the AC input voltage. The input inductor stores energy when the switches are closed and releases it to the DC-link capacitor when they open.
- **PWM Control:** By varying the duty cycle of the switches, the controller shapes the input current into a sinusoid that is perfectly in phase with the supply voltage[23].
- **Four-Quadrant Operation:** Because active switches can be controlled, the converter can handle power flowing from AC to DC (rectification) or from DC back to AC (inversion/regeneration).
- **Power Factor Correction:** Active rectifiers can achieve a unity power factor ($\cos\alpha=1$), meaning the AC source sees the converter as a purely resistive load.

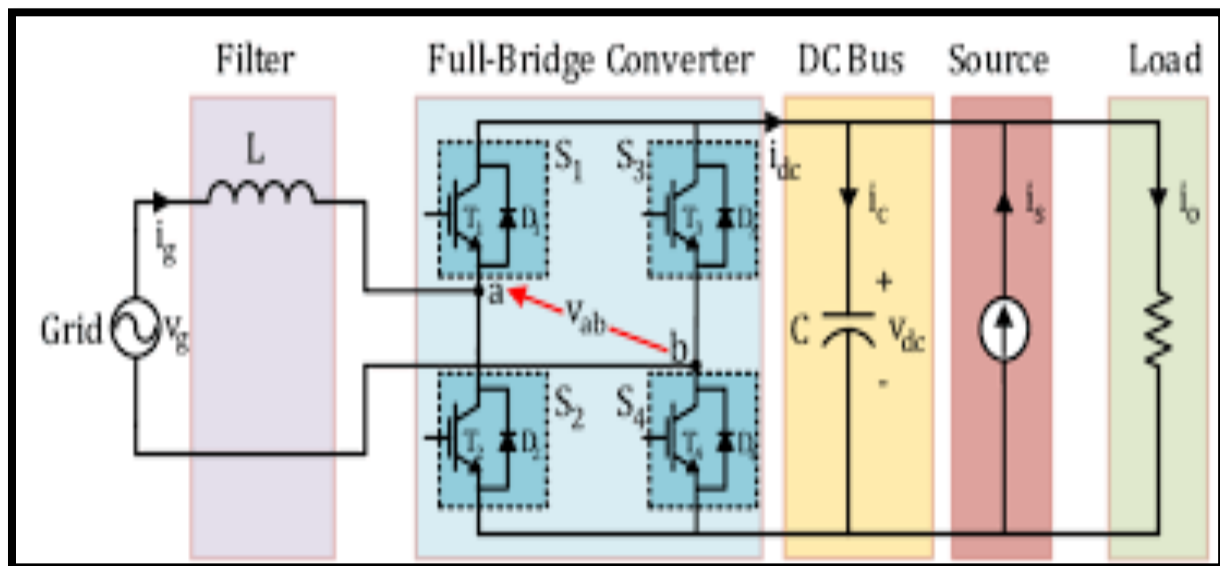


Figure 5-110-1 Circuit diagram of active rectifier

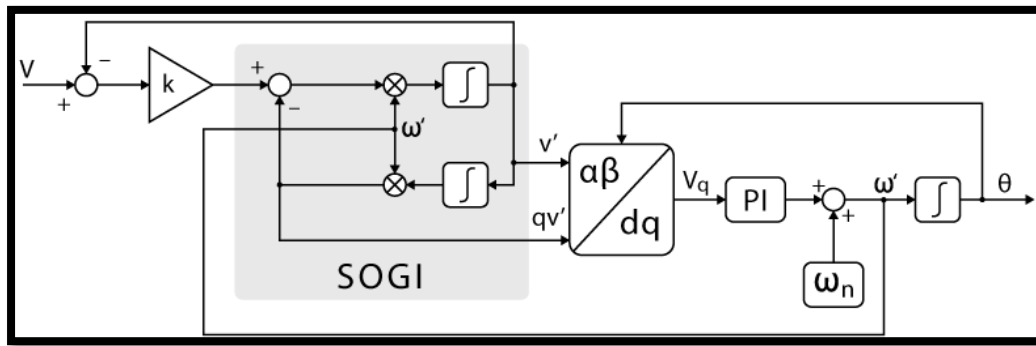


Figure 5-11 Block diagram of SOGI - PLL

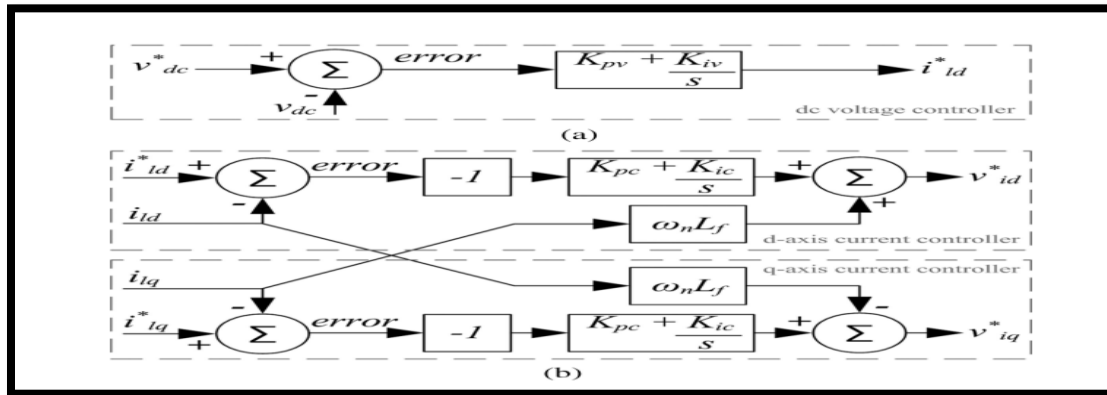


Figure 5-10-2 Block diagram of d-q current controller

Features	Rectification AC TO DC	Inversion DC TO AC
Power Flow	Grid to Load	DC source to Grid
Id current references	Positive	Negative
Phase Angle	Current in phase with voltage	Current 180 degree out of phase
Outer loop goal	Maintain constant DC Voltage	Control Power Discharge
Converter role	Controlled rectifier	Grid –tied inverter

9 Controller Logic of two stage power converter

Design of Active Rectifier

Parameter	Value
Rated Power	2 KW
Input Voltage	230 V RMS
Input Current	8.7 A
DC link Capacitance	3000 μF
DC link Voltage	400 V
Switching Frequency	10 KHz
Grid Frequency	50 Hz
Grid Inductance	4.4 mH

10 Parameters of Active Rectifier

Formula uses:

$$L_{\text{filter}} = \frac{V_{dc}}{4 * f_{sw} * 8 * I_{max}}$$

$$C_{dc} = \frac{P}{2 * \pi * f_g * V_{dc} * \Delta V}$$

Types of regulators	Coefficient	Value
D-axis current component	K _{pc}	8.12
D-axis current component	K _{ic}	20
Q-axis current component	K _{pc}	8.12
Q-axis current component	K _{ic}	20
DC link voltage	K _{pdc}	0.08
DC link voltage	K _{idc}	30

11 Coefficient of PI Regulators of Active Rectifier [21]

5.4 Bi-directional DC-DC Converter

The most common non-isolated bi-directional topology is the **Synchronous Buck-Boost converter**. It consists of two active switches (typically MOSFETs or IGBTs), an inductor, and input/output capacitors.

- **Buck Mode (Forward Direction):** When power flows from a high-voltage source (V_{high}) to a lower-voltage load (V_{low}), the converter acts as a step-down (Buck) converter.
- **Boost Mode (Reverse Direction):** When power flows from the low-voltage side to the high-voltage [24]side (such as during regenerative braking), the converter acts as a step-up (Boost) converter.
- **Bidirectional Control:** These converters require a sophisticated control strategy (such as Complementary PWM) to manage the transitions between buck and boost modes smoothly while maintaining stability.

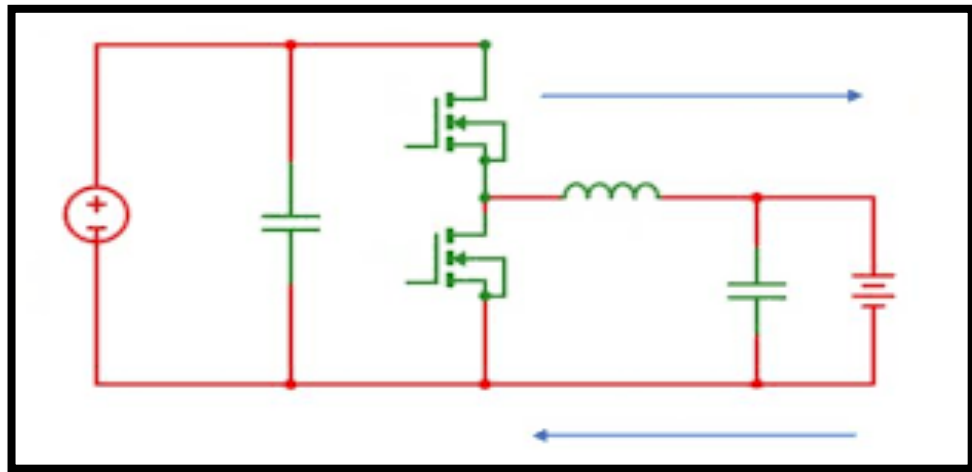


Figure 5-13 Bi-directional dc-dc converter circuit diagram [10]

Formula use:

$$\diamond L = \frac{(V_{in} - V_o)D}{I_{ripple} \cdot f_s}$$

$$\diamond C = \frac{(1-D)V_o}{8LV_c f_s^2}$$

$$\diamond \text{Current ripple} = \frac{V_{in}(1-D)D}{L f_s}$$

$$\diamond \text{Voltage ripple} = \frac{(1-D) \cdot V_o}{8LC f_s^2}$$

Parameter	Value
Power	1.28 KW
Input voltage	200V
Output Voltage	111 V
Current ripple	10%
Voltage ripple	1%
Switching frequency	25Khz

12 Parameter of bi- directional dc-dc converter [24]

Types of regulators	Coefficient	Value
Proportional current component	Kp	2.3
Integral current component	Ki	20
Proportional voltage component	Kp	23
Integral voltage component	Ki	450

13 Coefficient of PI Regulator of bi-directional dc-dc converter

5.5 Battery Emulator diagram

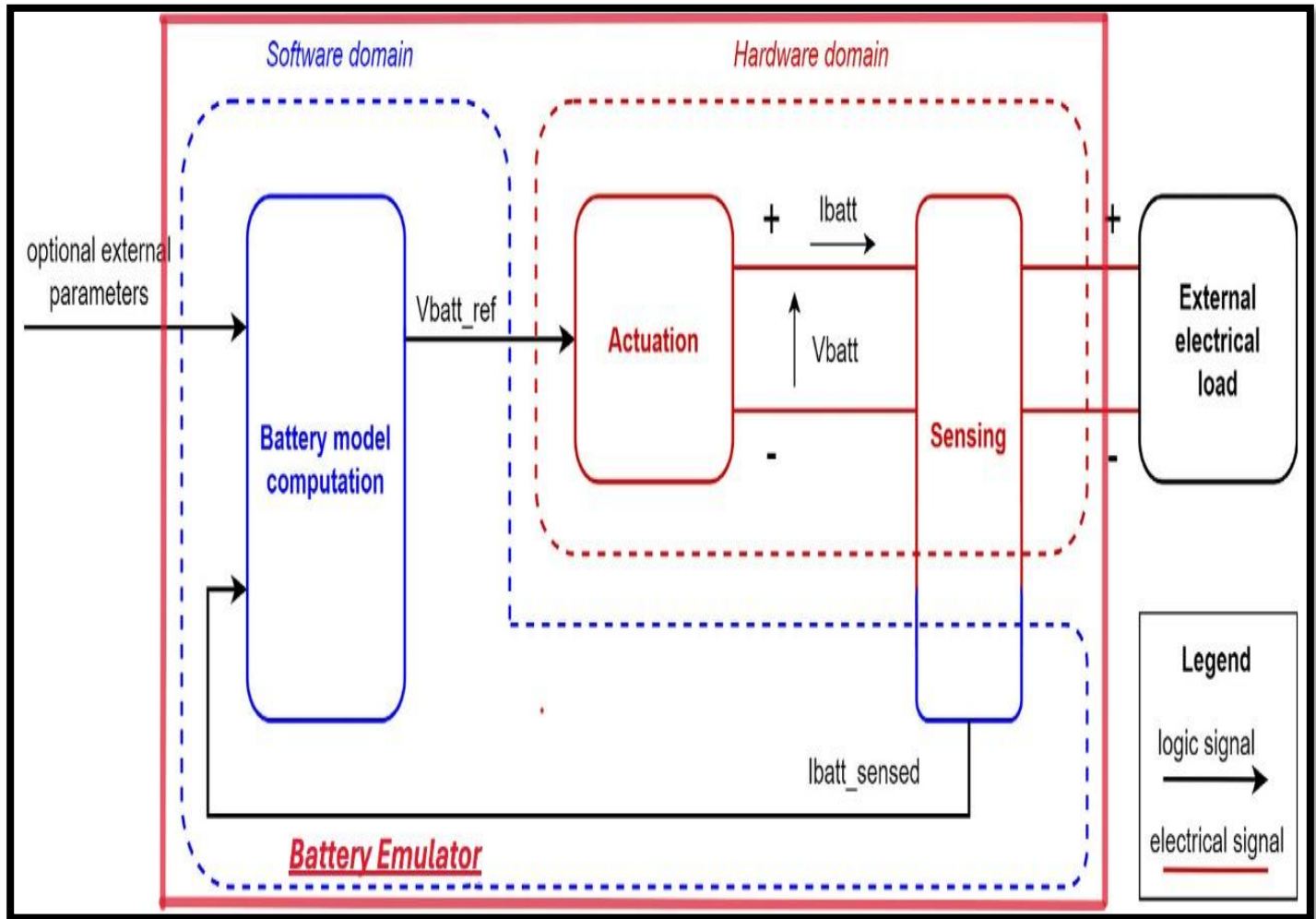


Figure 5-14 Synopsis of the model battery Emulator [7]

6 Chapter: Simulations and Results

6.1 Simulations

6.11 ECM Battery Model Simulation

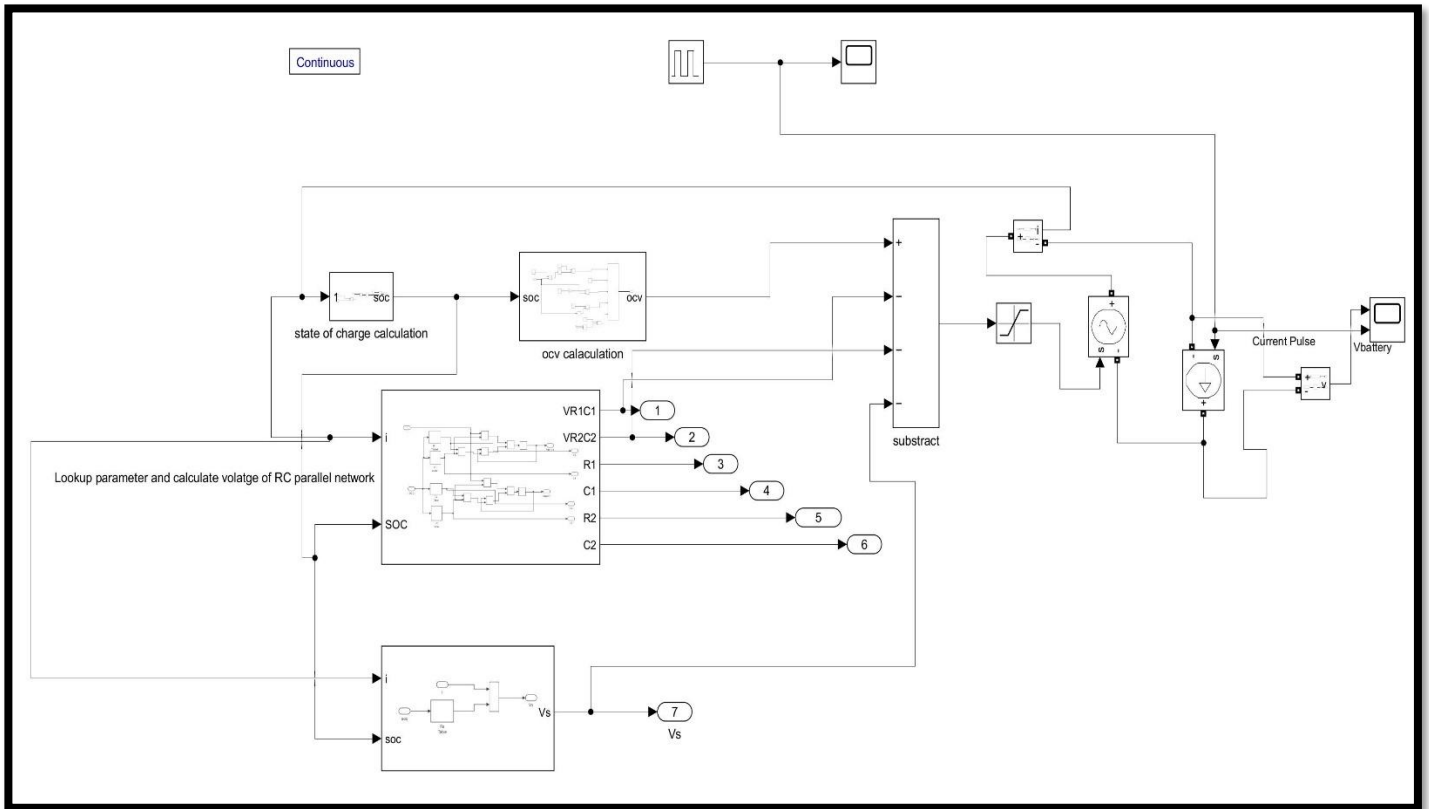


Figure 6-1 2RC ECM model simulation

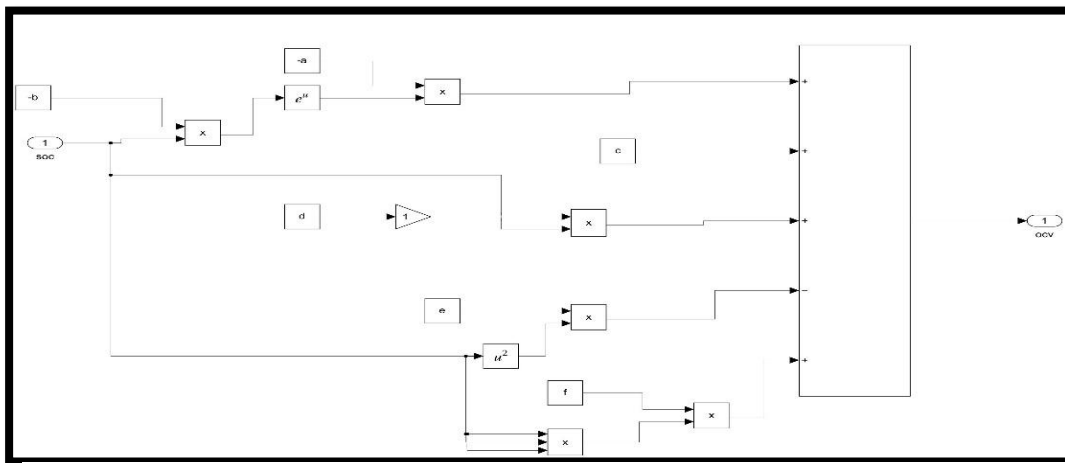


Figure 6-2 Open circuit Voltage calculation

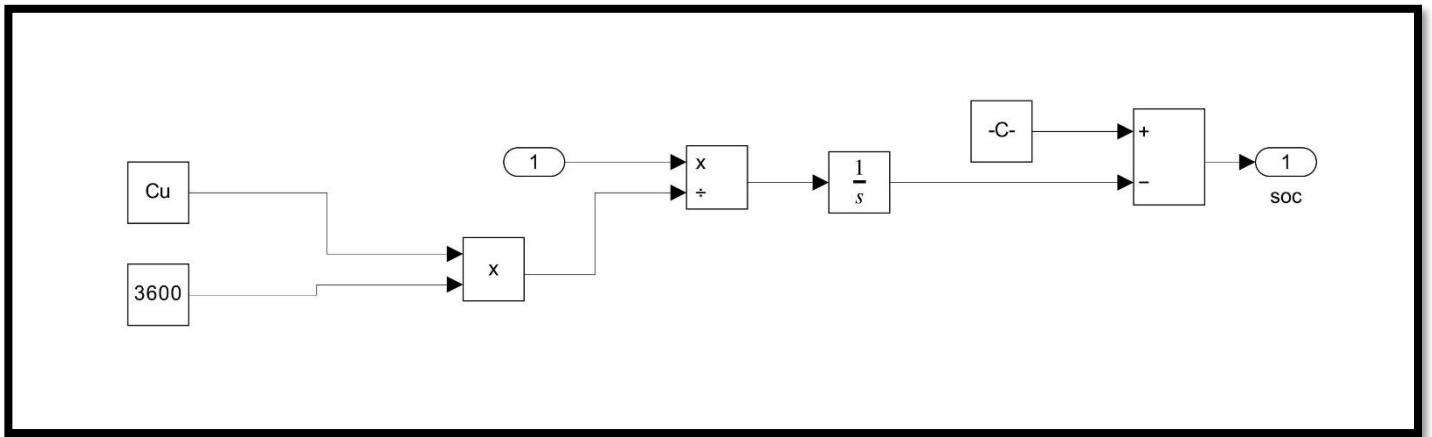


Figure 6-3 SOC Calculation

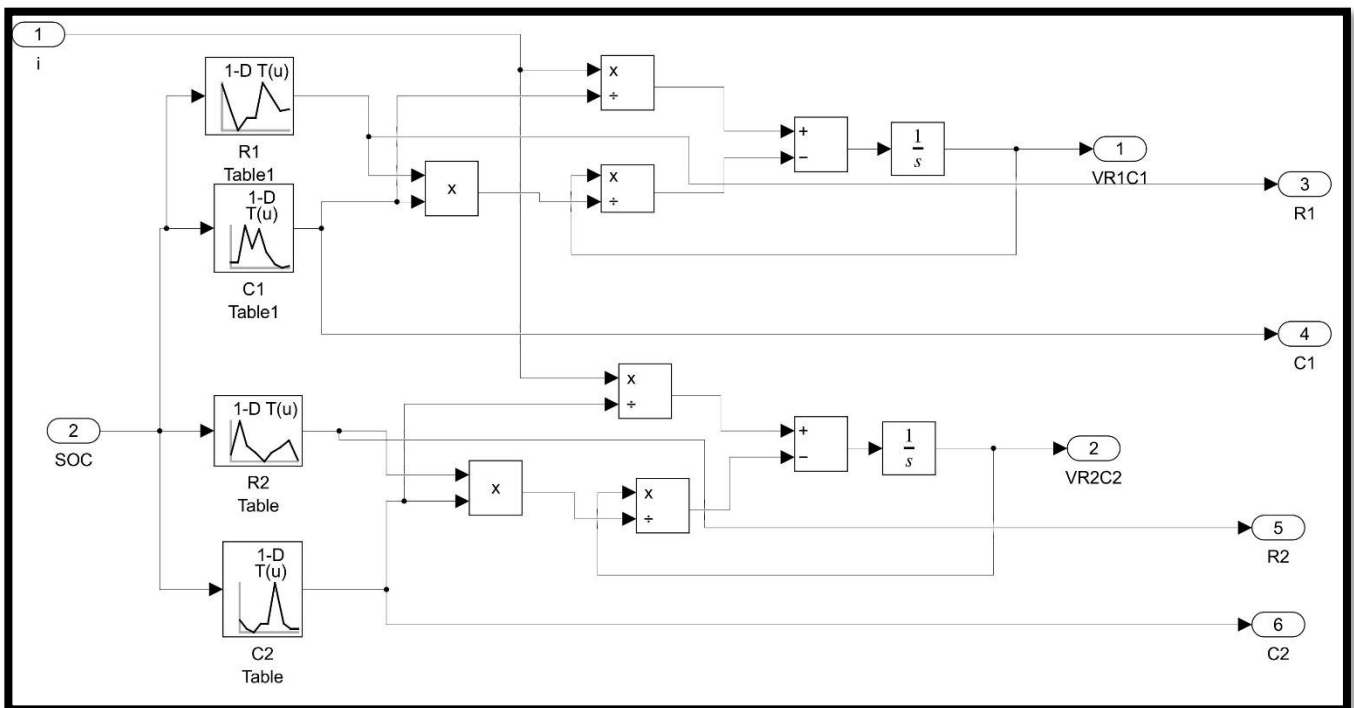


Figure 6-4 RC Values and voltage across parallel network

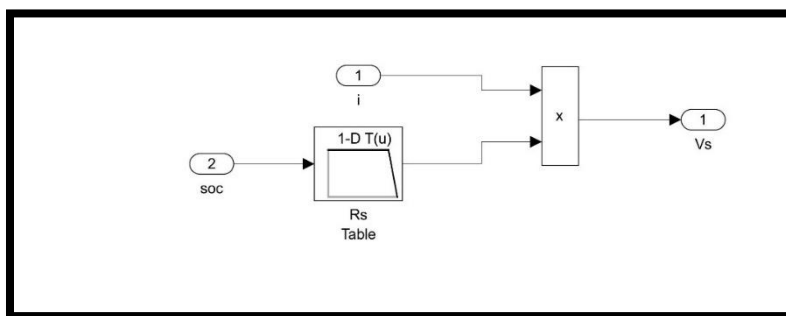


Figure 6-5 Vs Calculation

6.12 Shepherd Battery Model Simulation

Lithium -ion Battery

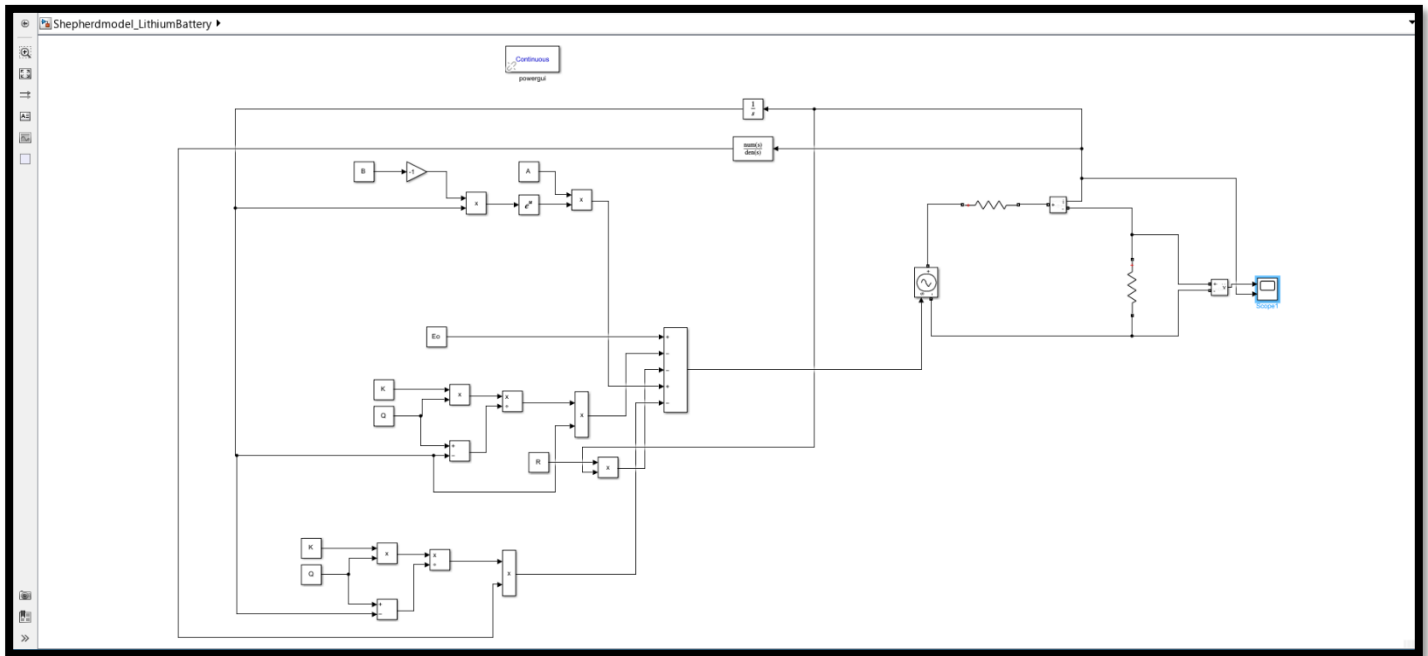


Figure 6-6 Lithium -ion battery model simulation

Lead -Acid Battery

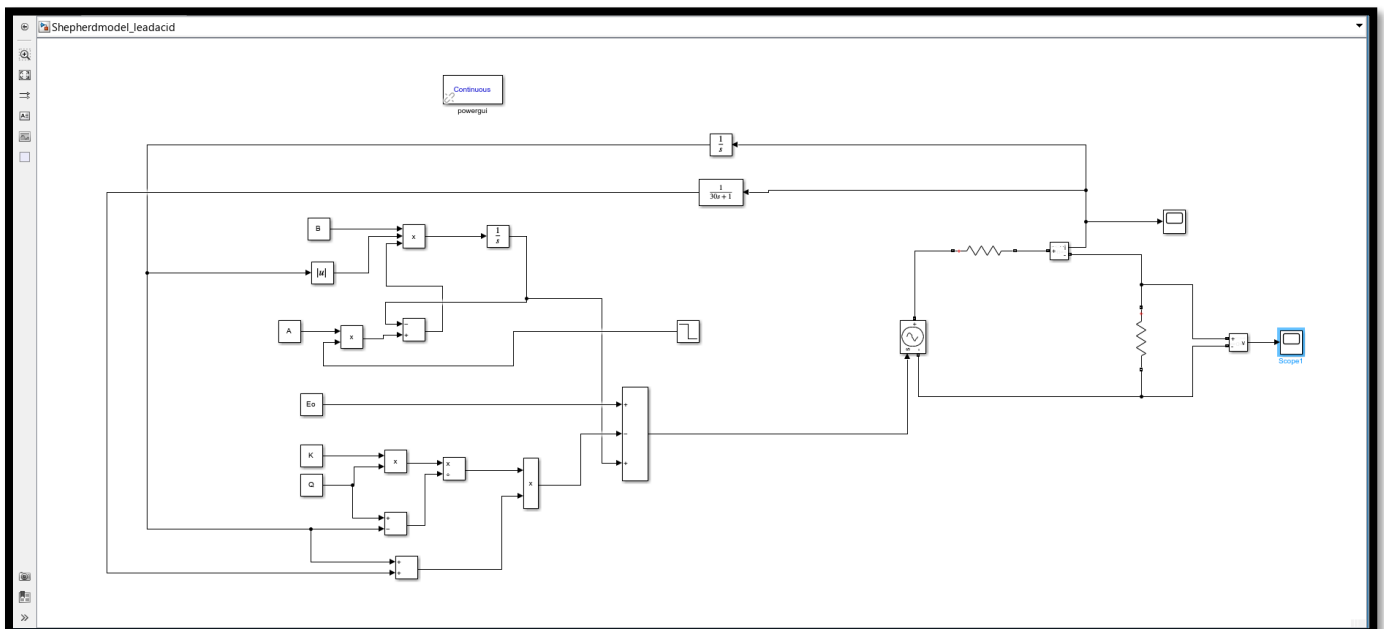


Figure 6-7 Lead-Acid battery model simulation

6.13 Battery model simulation through Battery Builder App

ECM Model

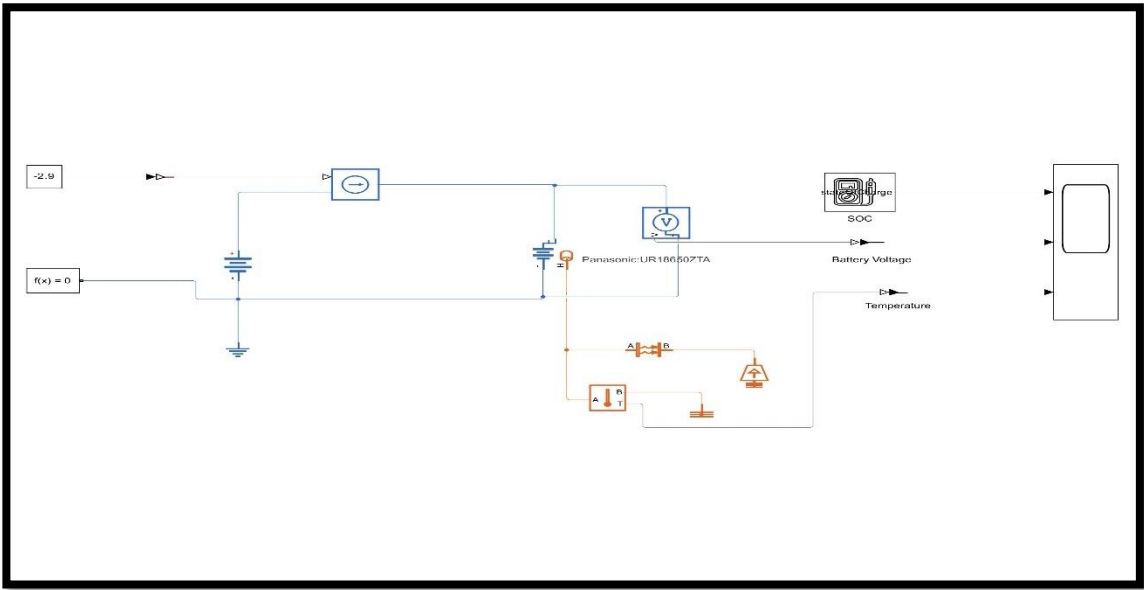


Figure 6-8 Single cell cylindrical shape ECM Model

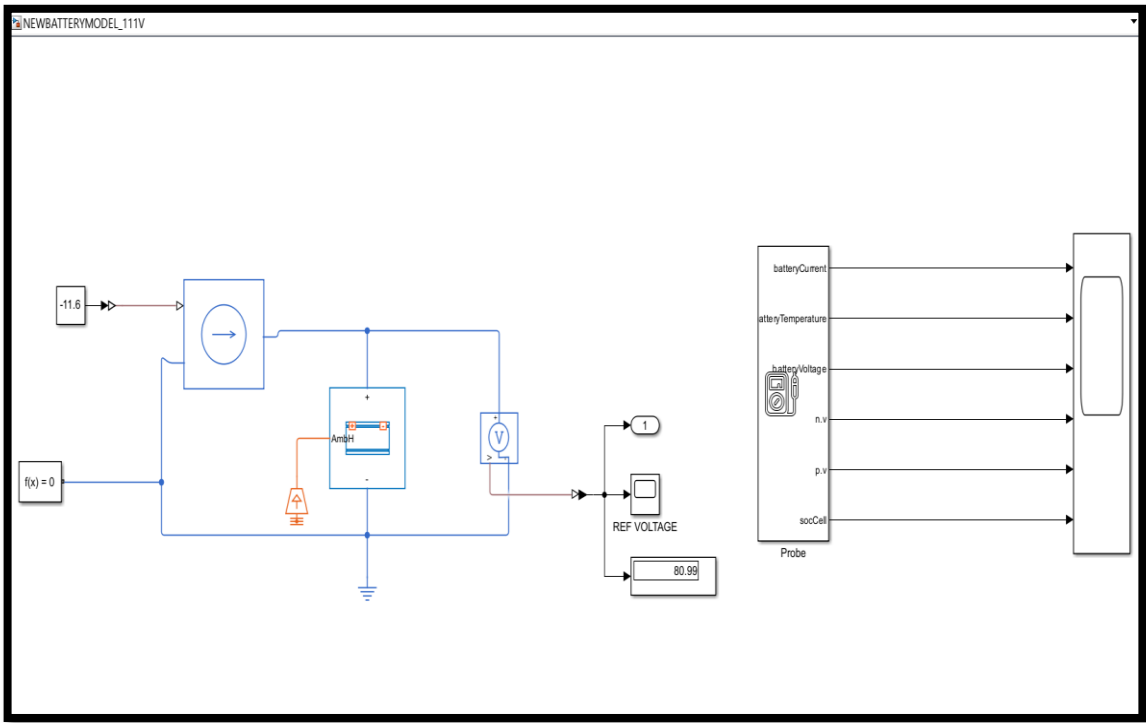


Figure 6-9 ECM based cylindrical shape Battery model

6.14 Single Phase Active Rectifier Circuit

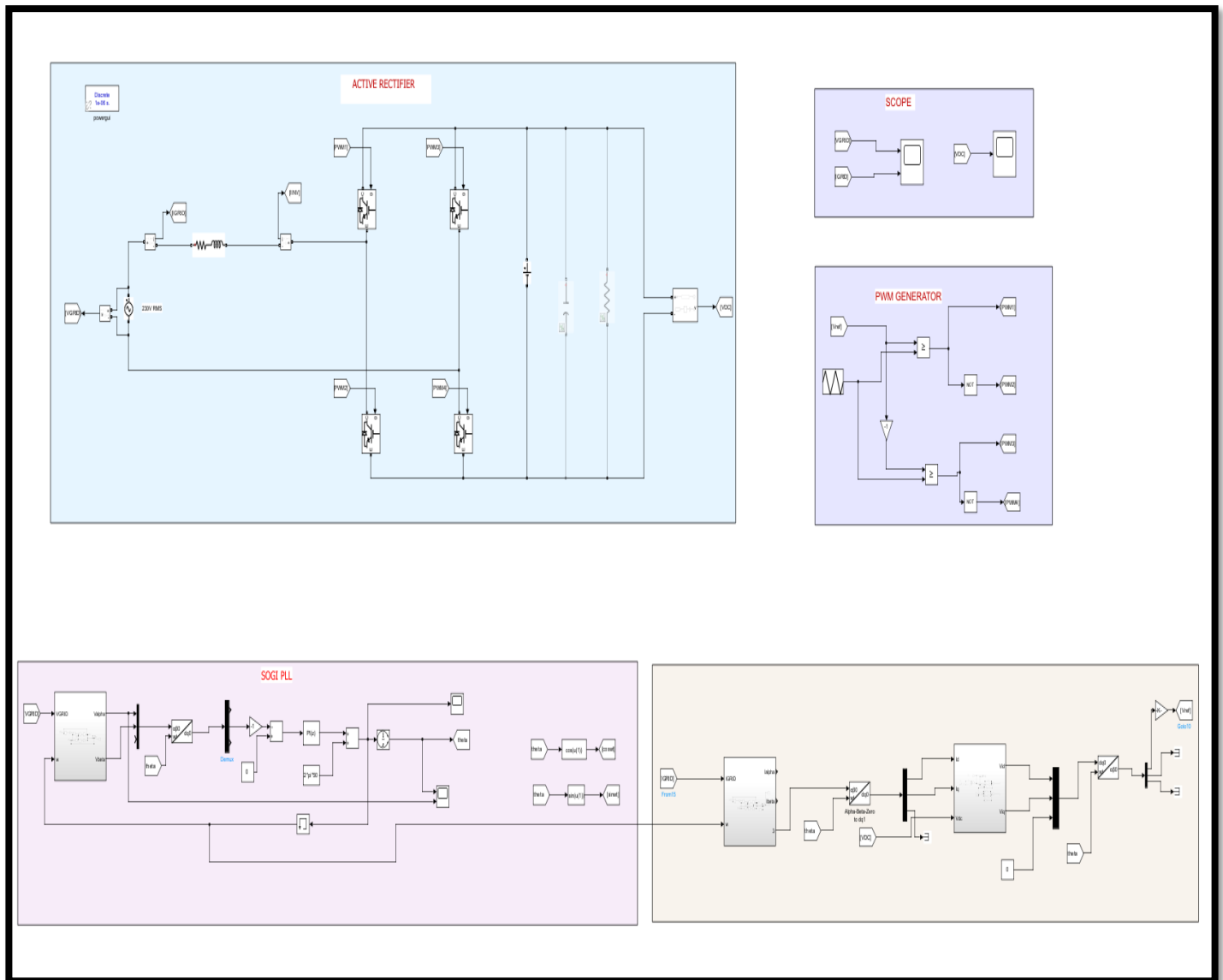


Figure 6-10 Single phase Active Rectifier and SOGI- PLL control

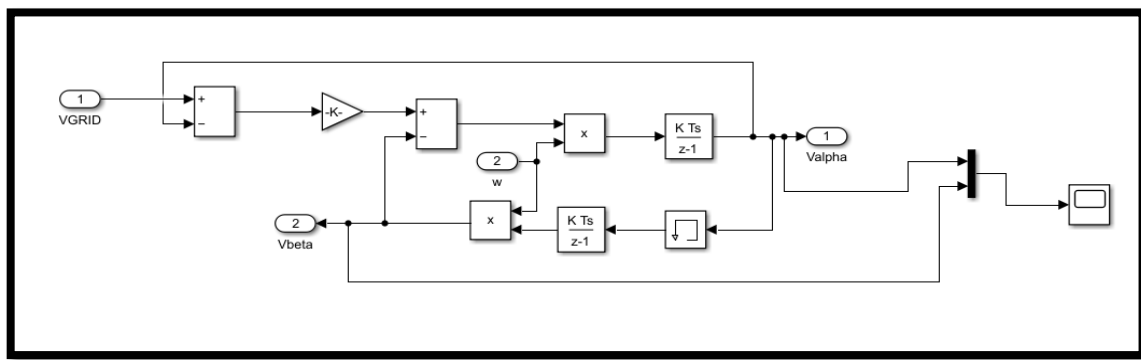


Figure 6-11 SOGI-PLL

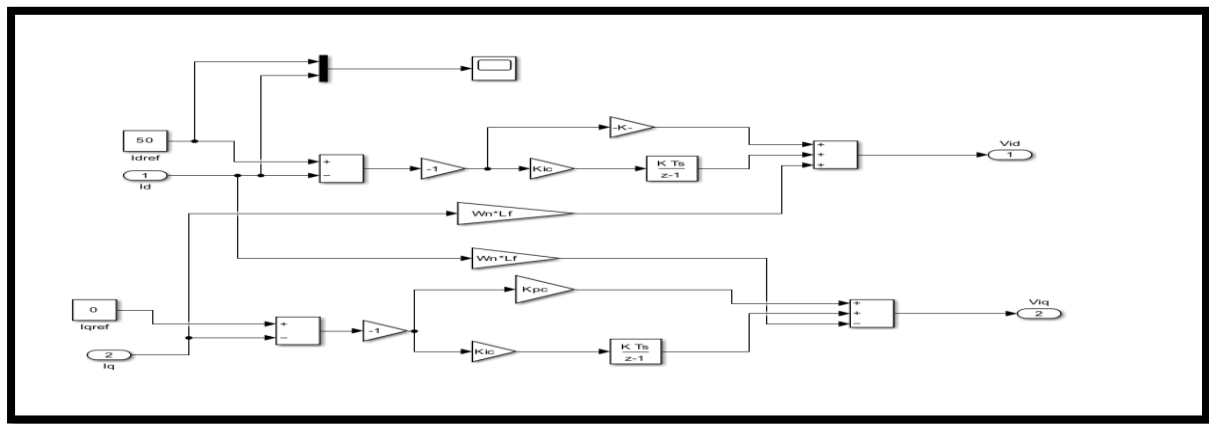


Figure 6-12 d-q current controller

6.15 Two stage power converter circuit

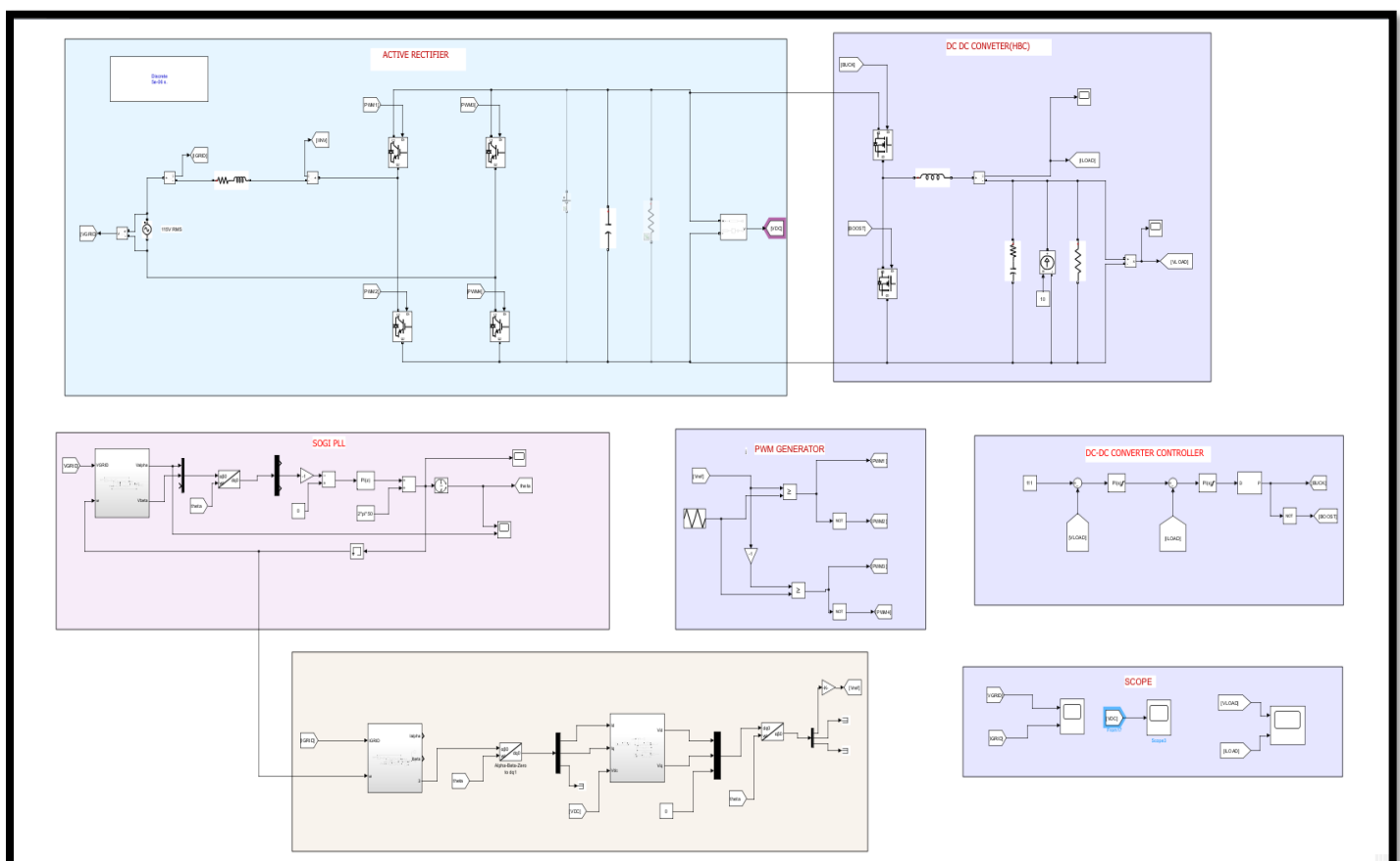


Figure 6-13 Simulation of active rectifier with bidirectional dc-dc converter

6.16 Battery Emulator Simulation

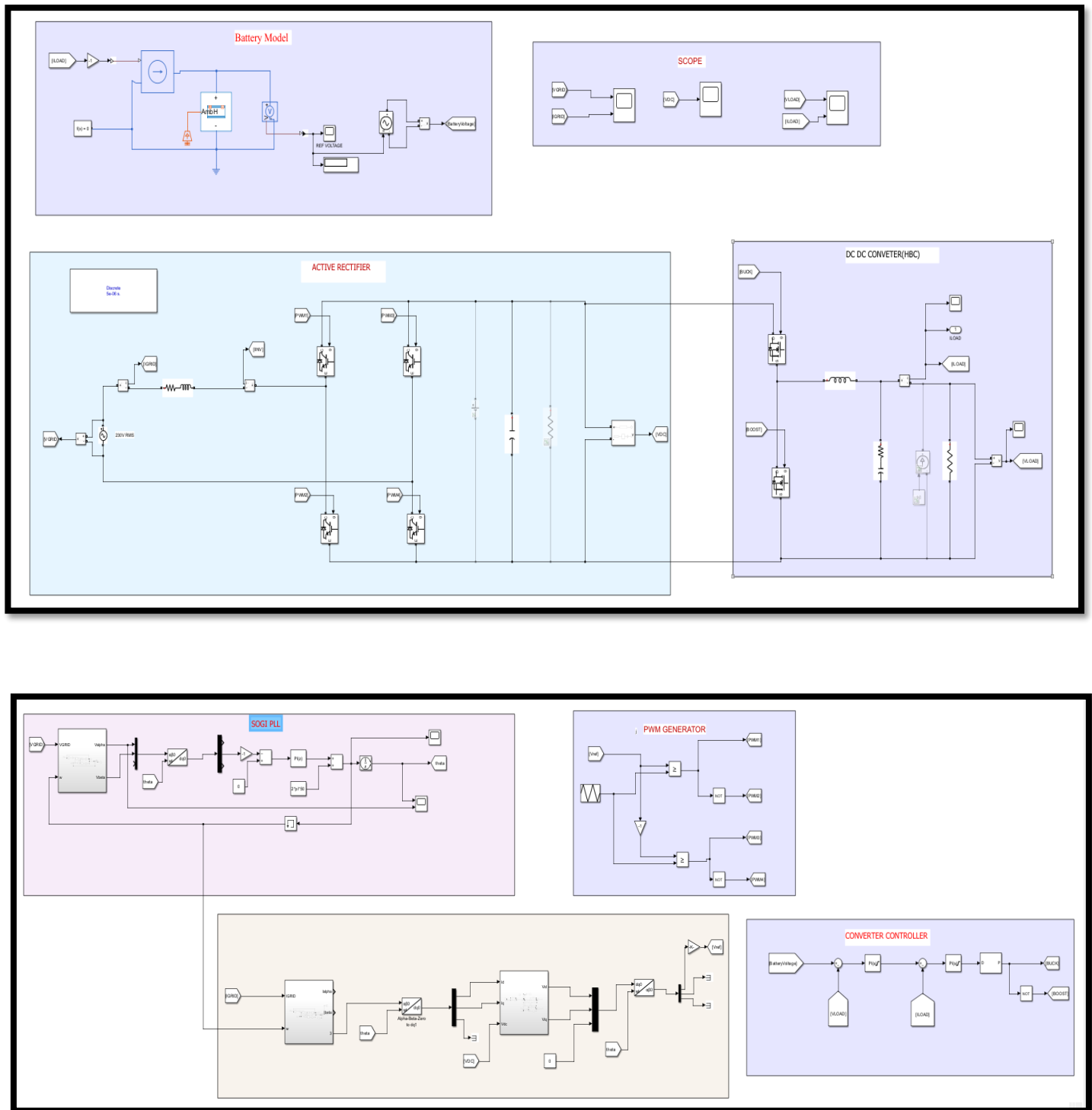


Figure 6-14 Simulation of Battery Emulator

6.2 Simulation Results

6.2.1 ECM Model

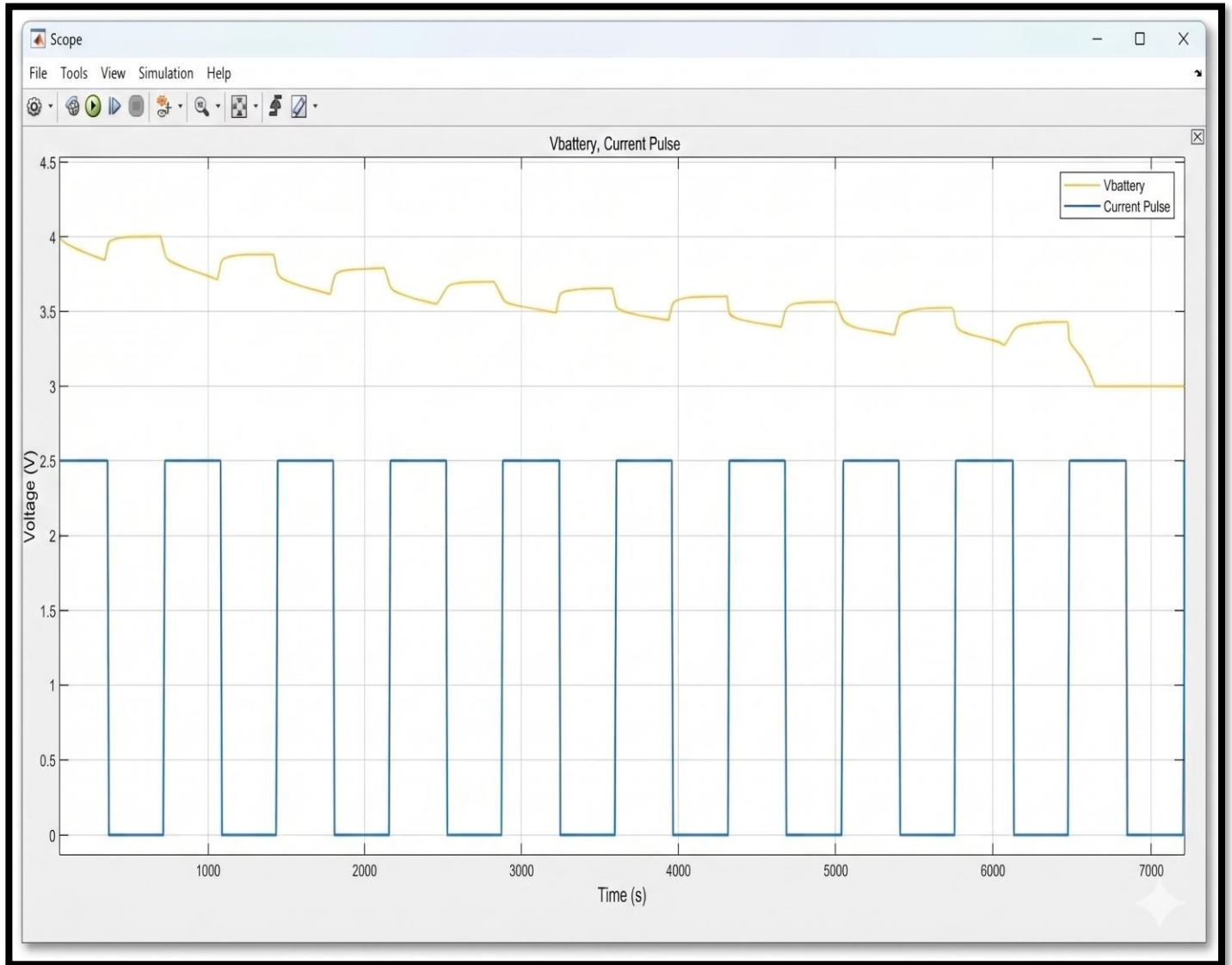


Figure 6-15 ECM Pulse discharge test of NMC cell

6.22 Shepherd Model

Lead-Acid Battery

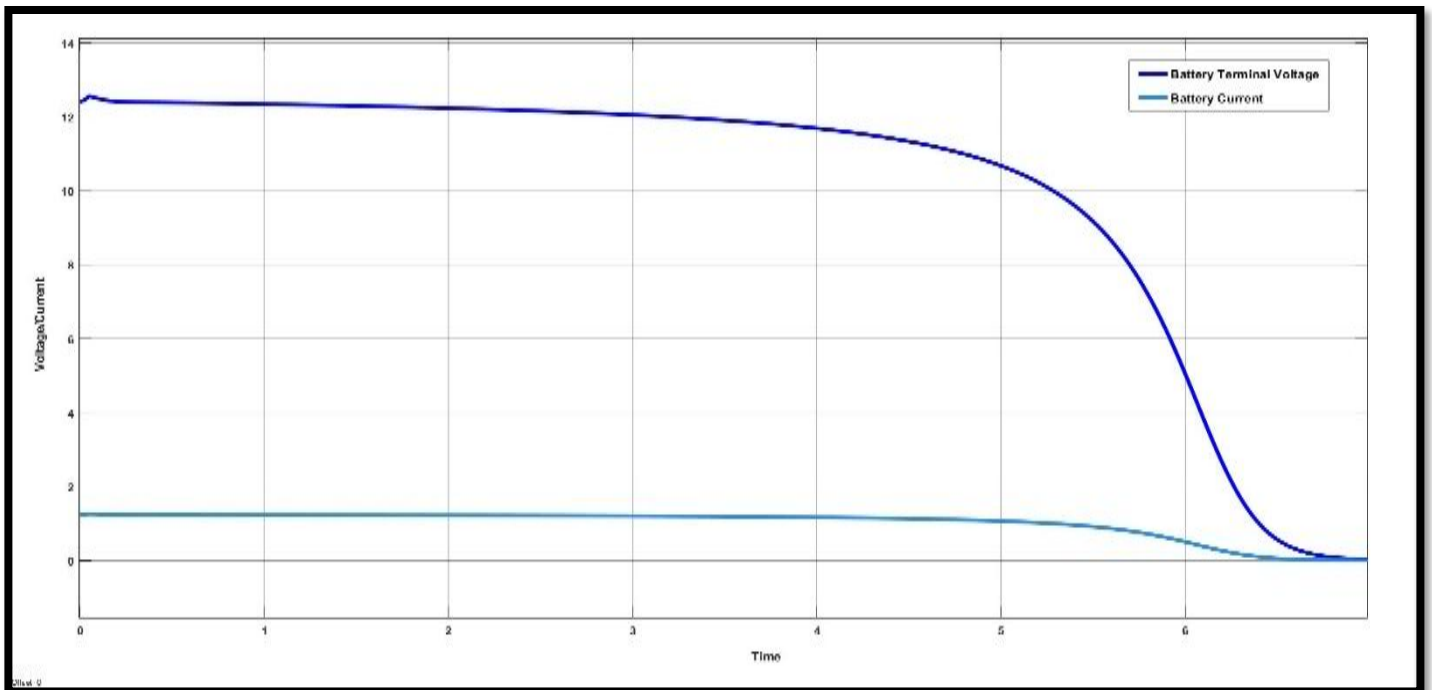
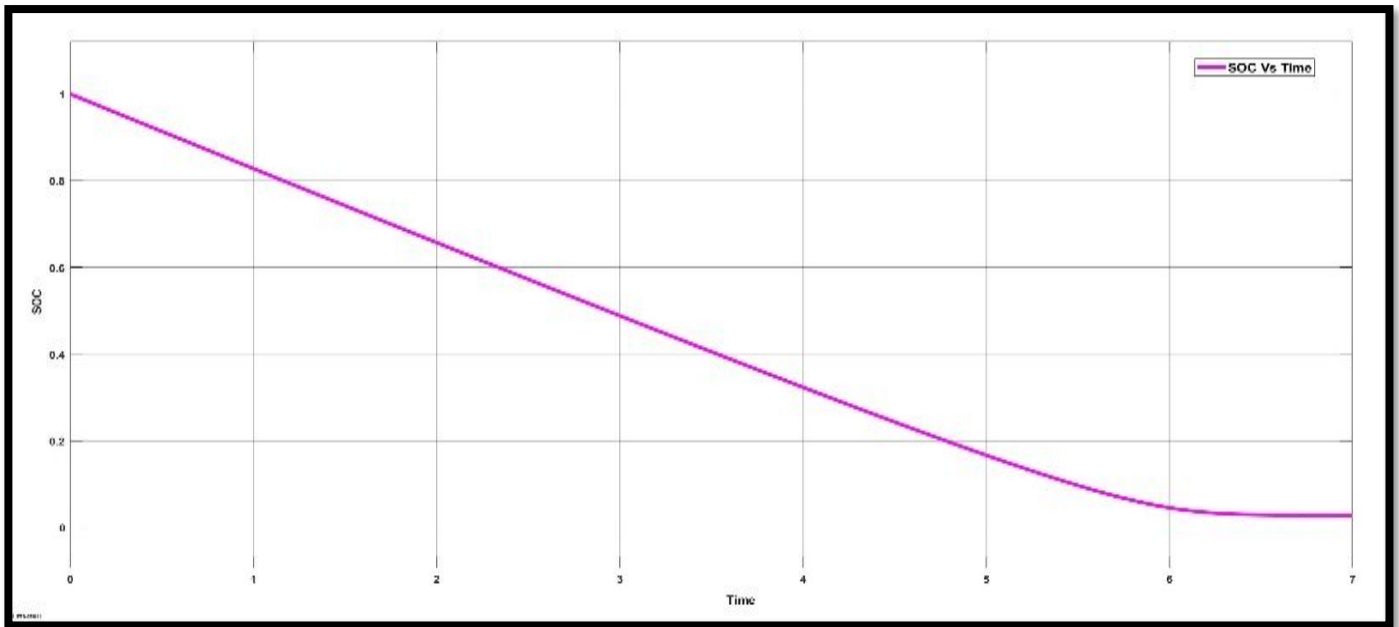


Figure 6-16 Dynamic discharge curve of 7.2Ah, 12V Lead-Acid battery

Lithium-ion Battery

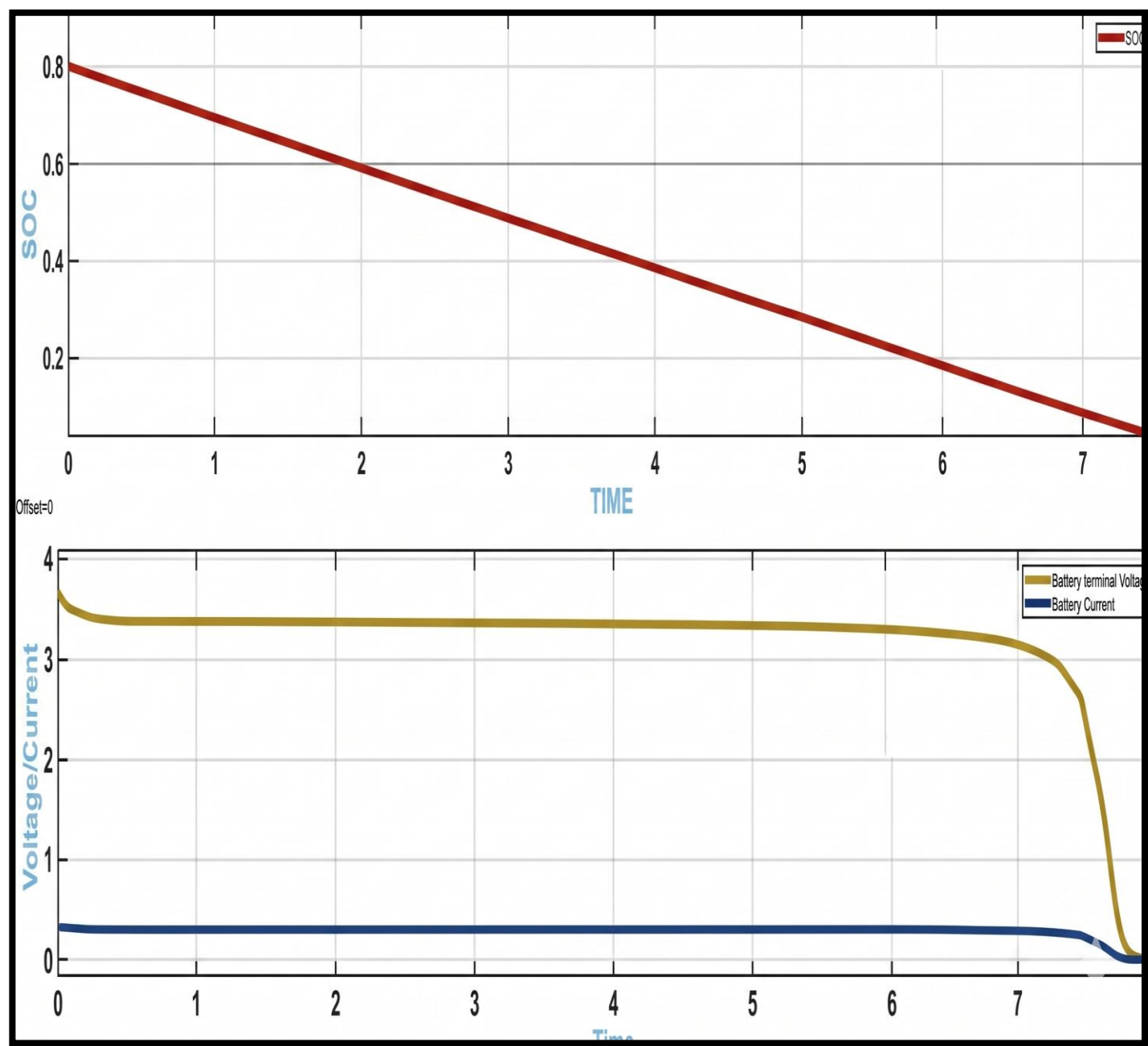


Figure 6-17 Dynamic discharge curve of 2.3Ah, 3.3V Li-ion battery

NiMH Type Battery

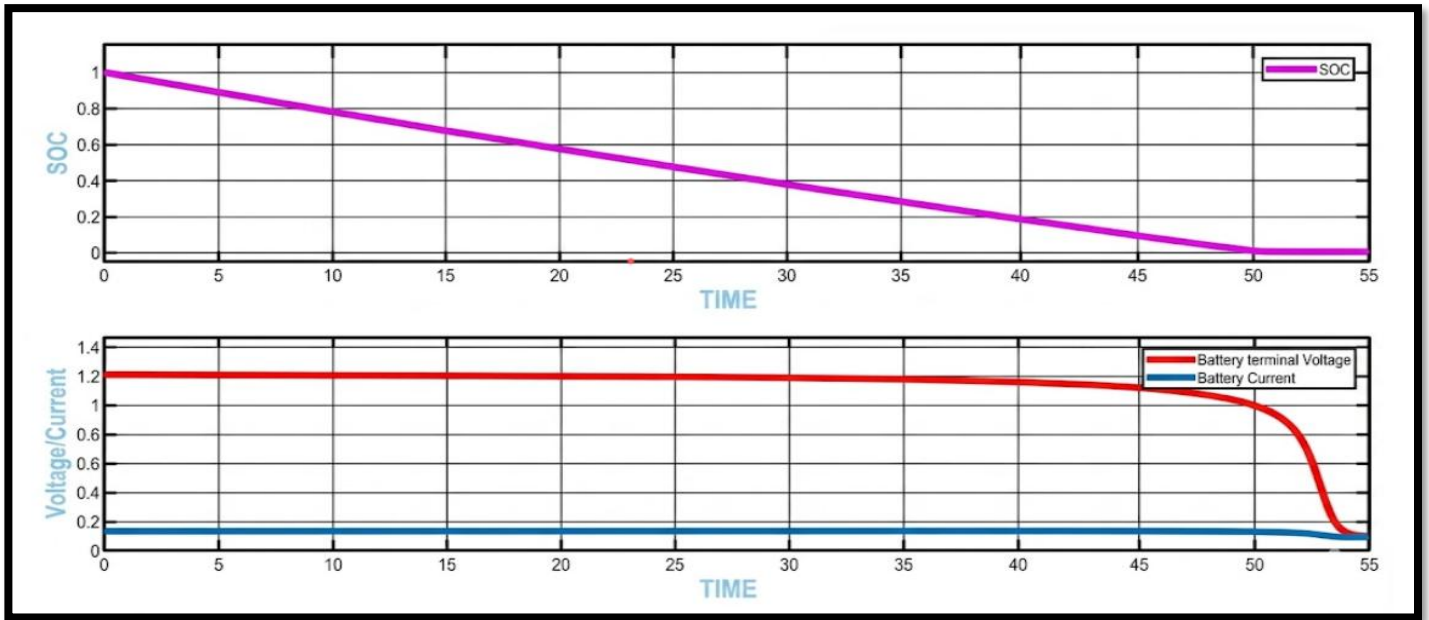


Figure 6-18 Dynamic discharge curve of 6.5Ah, 1.2V NiMH battery

NiCd Type Battery

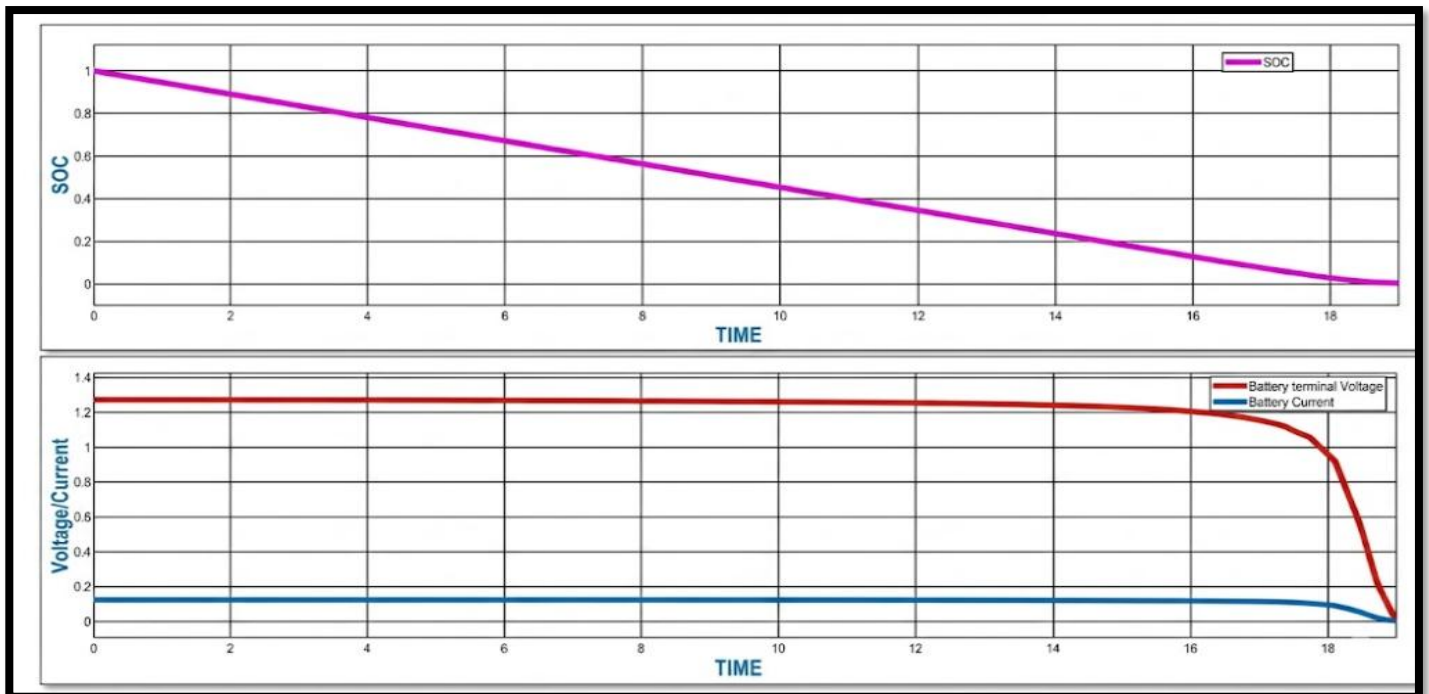


Figure 6-19 Dynamic discharge curve of 2.3Ah, 1.2V NiCd battery

6.23 ECM based cylindrical shape Panasonic Battery model

Li-ion cell

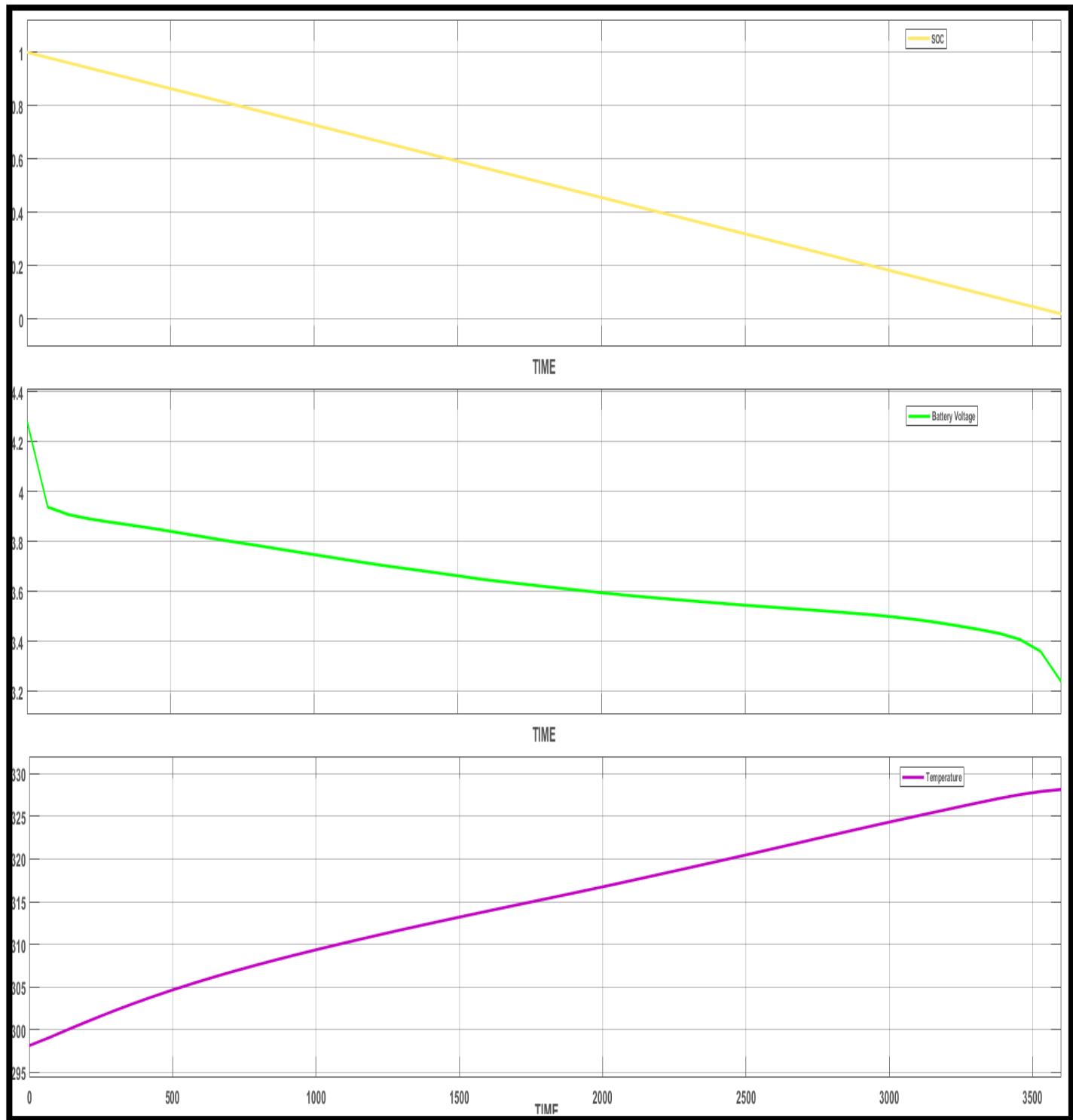


Figure 6-20 Panasonic Single cell dynamic discharge curve of 3.7V Li-ion, 2.9Ah battery

Li-ion Battery: 30s4p combination

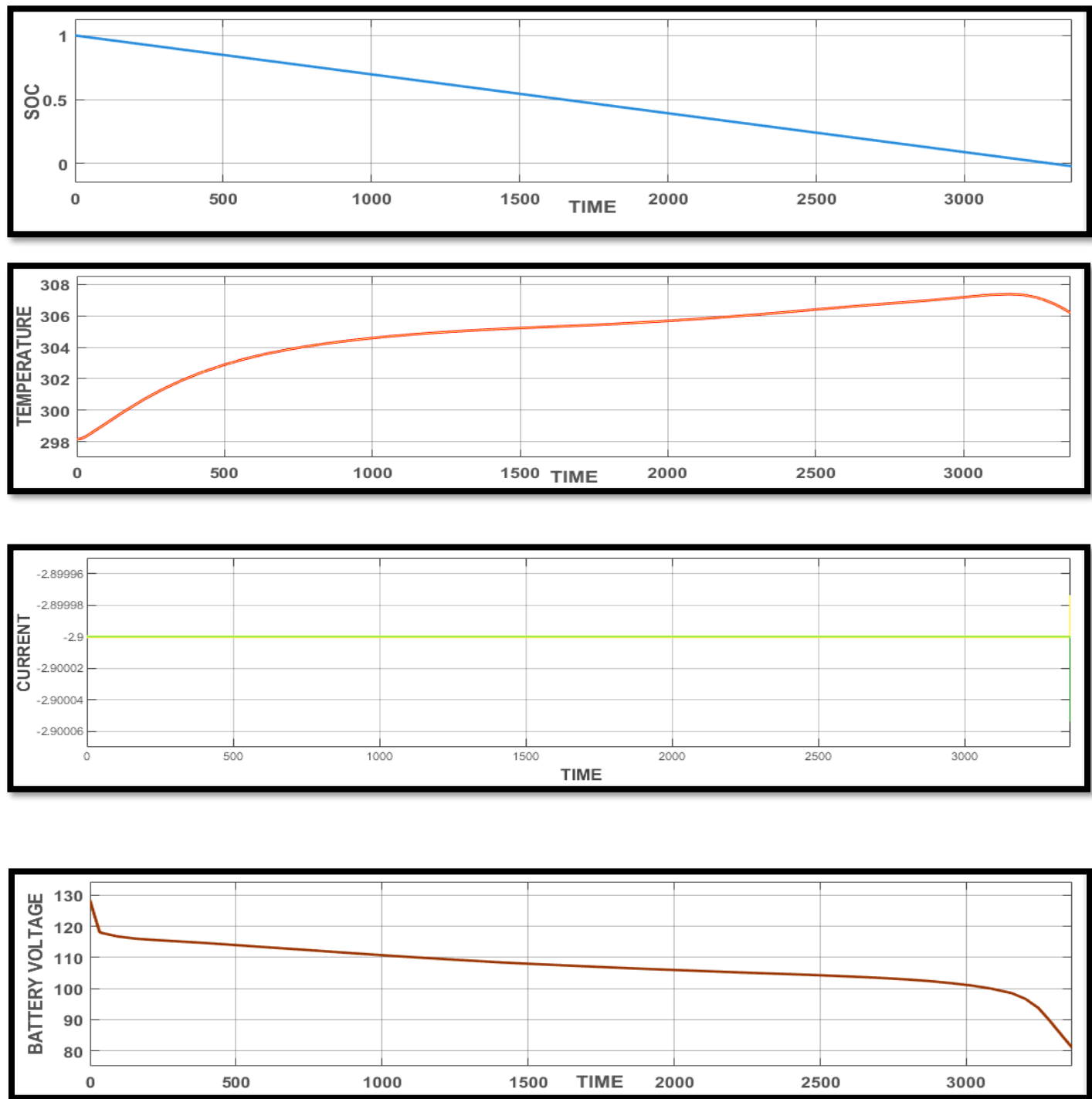


Figure 6-21 Panasonic battery dynamic discharge curve of 111V, 11.6Ah

6.24 Single Phase Active Rectifier

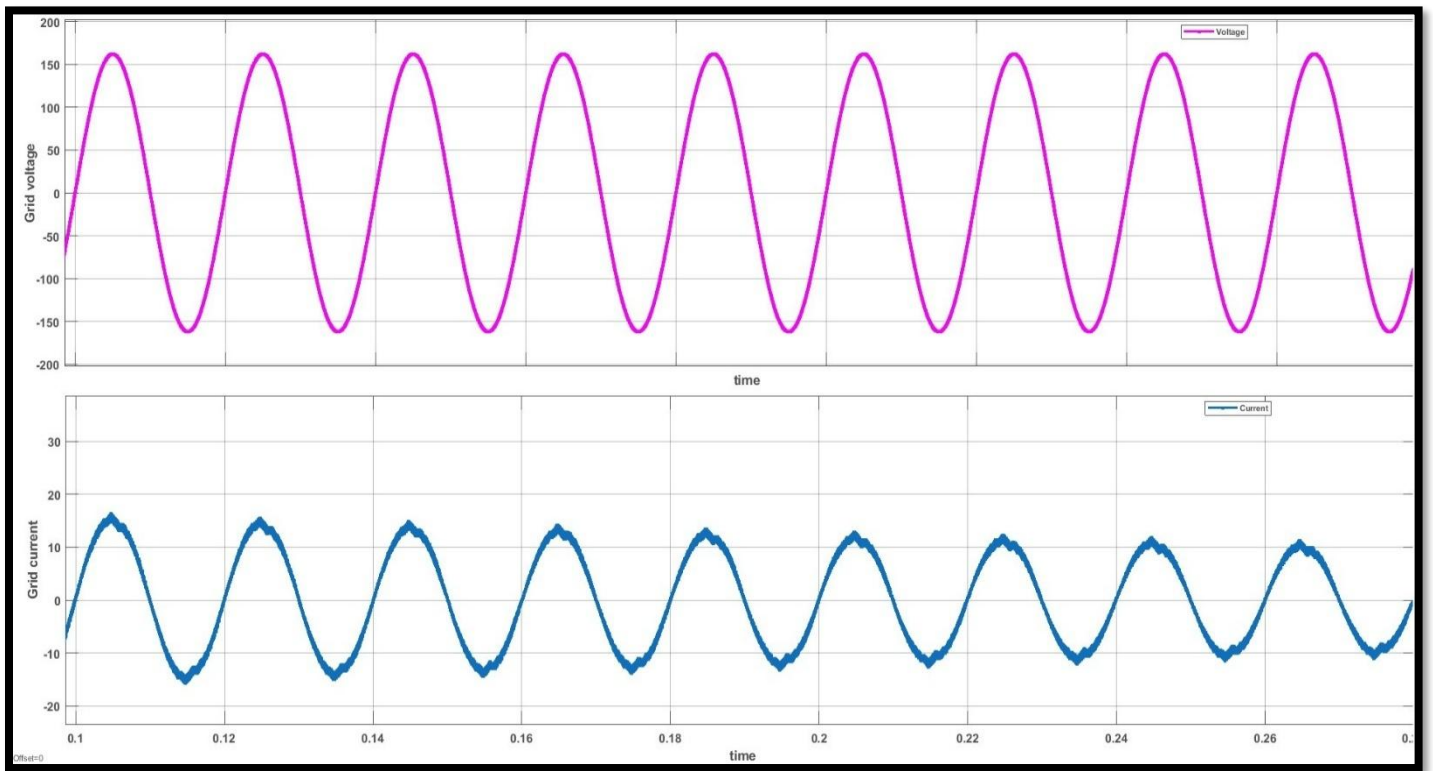


Figure 6-22 Grid voltage and current during discharging mode

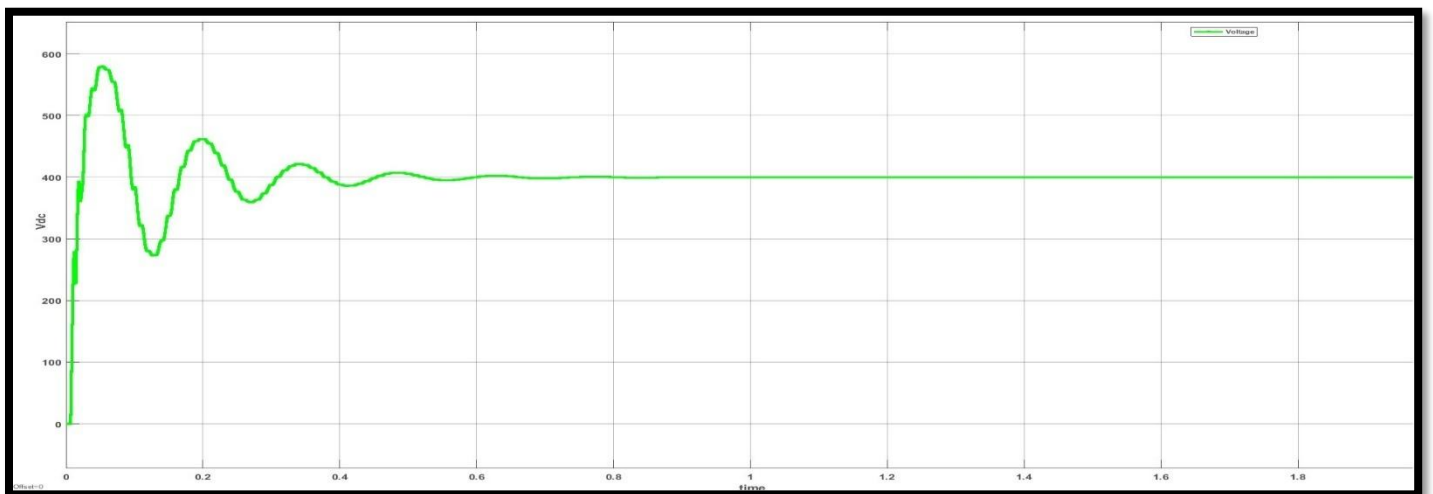


Figure 6-23 DC link voltage during discharging mode

6.25 DC-DC Converters

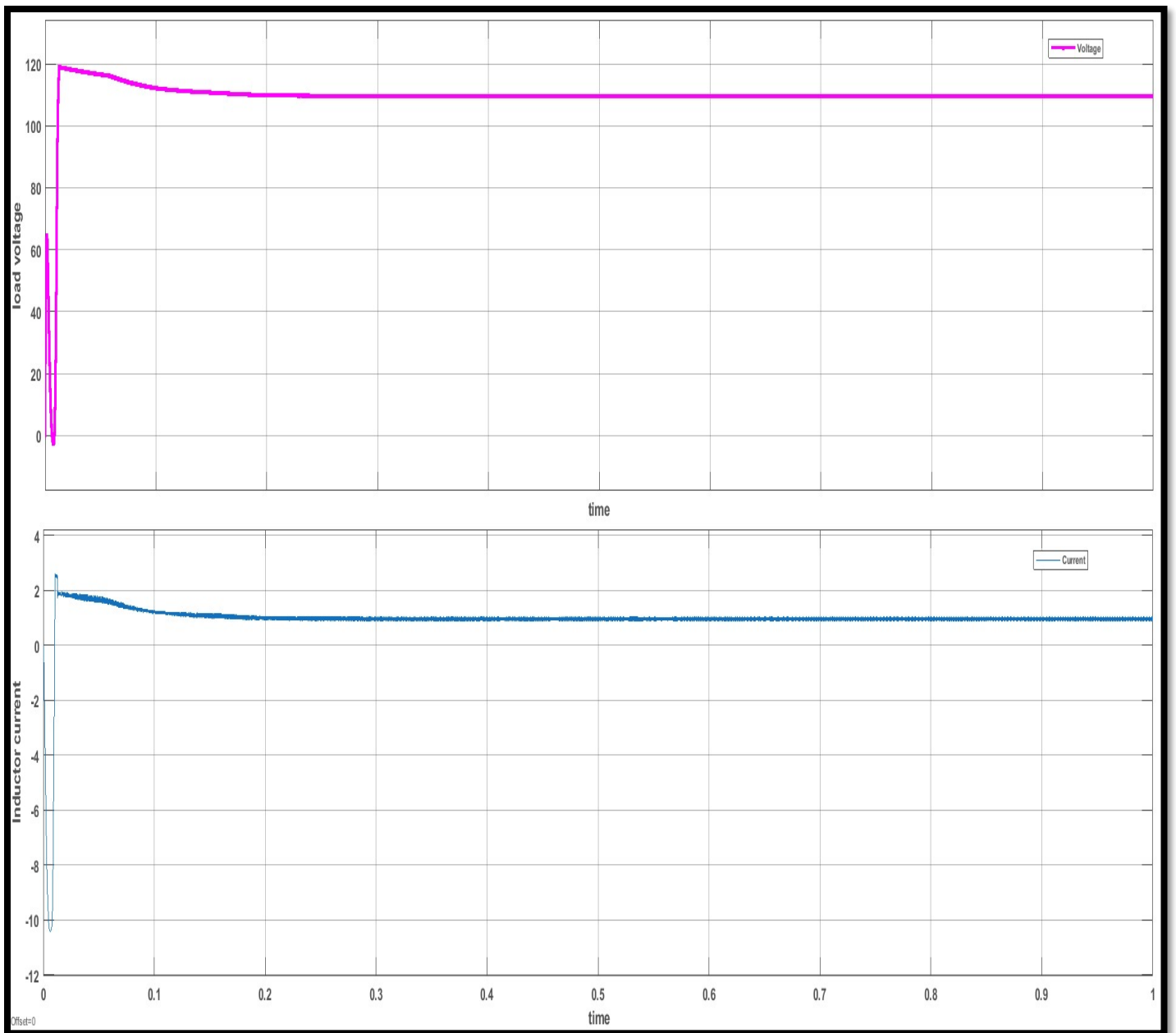


Figure 6-24 Voltage and current waveform during discharging across R-load of dc-dc converter

7 Chapter: Conclusions and Future work

7.1 Conclusions

This thesis has explored the modeling and emulation of Lithium-ion Batteries (LIBs), with a specific focus on empirical and ECMs techniques and real-time implementation. Several key conclusions can be drawn from the work presented in the previous chapters:

The motivation for selecting LIBs as a core energy storage medium was discussed in Chapter 2, emphasizing their high energy density, scalability, and suitability for both high-power and high-energy applications. Although LIBs are currently associated with high costs, projections indicate a significant reduction in cost as manufacturing processes improve and economies of scale take effect. Alternatives such as Sodium-Sulphur (Na-S) and Vanadium Redox (VR) flow batteries were also acknowledged for their potential in stationary storage applications, particularly for long-duration and large-scale energy requirements.

In Chapter 3, a comparative analysis of prevailing LIB chemistries was conducted. Among these, Lithium Iron Phosphate (LFP) emerged as a favorable candidate due to its thermal stability, long lifecycle, and relatively lower cost. However, chemistries like Lithium Nickel Cobalt Aluminum Oxide (NCA), Lithium Nickel Manganese Cobalt Oxide (NMC), and Lithium Titanate Oxide (LTO) also exhibit promising capabilities, though their adoption is currently limited by cost and availability of raw materials. Novel chemistries such as lithium-silicon anodes were briefly reviewed, presenting interesting prospects for future energy-dense solutions.

Prior to the modeling phase, Chapter 4 presented a comprehensive review of battery behavior, including the effects of c-rate, temperature, self-discharge and aging. These parameters significantly influence battery performance and underline the complexity of accurate modeling.

Chapter 5 offered a literature review of existing battery modeling methodologies. ECM and Empirical models, such as the Shepherd model, offer a reasonable balance between computational simplicity and accuracy when operating within specified ranges. It is observed that simulated curve match very well the real curves during 90% of discharge no matter the discharge current amplitude. The dynamic behavior of battery for discharge is obtained close to experimental behavior for Li-ion batteries.

A thermal model was added to the ECM-based battery model created in the MATLAB using Battery Builder app. This allows for the simulation of terminal voltage changes across different temperatures.

However, their dynamic performance is often limited due to oversimplified assumptions and lack of non-linear behaviors and circuit design of the battery emulator were presented, highlighting the roles of the active rectifier and the bidirectional DC-DC converter. The active rectifier ensures regulated DC link voltage and supports bidirectional power flow, while the bi-directional DC-DC converter accurately emulates battery terminal behavior using reference voltages from the battery model.

7. 2 Future Work

To further enhance the modeling fidelity and tracking accuracy of the developed battery emulator, the following recommendations are proposed:

- **Thermal Network Integration:** Couple your electrical 2RC ECM with a lumped-parameter thermal model to simulate how internal battery temperature changes under high C-rates and how it affects terminal voltage.
- **Electro-Chemical & Degradation Modeling:** Integrate long-term degradation mechanisms (such as SEI layer growth and power/capacity fade) into the simulation to emulate aged batteries or cells at various States of Health (SoH).
- **Hardware-in-the-Loop (HIL) Testing:** Implement your developed mathematical models on a real-time simulator (such as dSPACE, OPAL-RT, or Typhoon HIL) to validate model execution speed and real-time response.
- **Prototype Development:** Design and assemble the physical PCB layouts for the low-power control circuitry and power stages (Active Rectifier and Bidirectional DC-DC converter) using wide-bandgap semiconductors like SiC or GaN MOSFETs for higher efficiency.
- **DSP-Based Control:** Transition your simulated control blocks into actual C-code deployed on a digital signal processor (such as a TI C2000 microcontroller) to drive the physical switching signals.

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