



**Democratic and Popular Republic of Algeria Ministry
of Higher Education and Scientific Research
Echahid Hamma Lakhdar University of El Oued**



Faculty of Technologie

DEPARTMENT OF ELECTRICAL ENGINEERING

Final study memory

Academic Master

Field: Sciences and Technology

Major: Electrical Engineering

Specialization: Electrical Control

Title :

Modeling and Simulation of Battery Pack

DC Fast Charging

Presented by:

**Nefti Ziad
Kanech Said**

Under supervision:

Pr. Zakaria Lammouchi

University year: 2025/2026

Dedication

I dedicate this work to:

- The soul of my beloved father, Ammar, may Allah grant him His mercy.
- My dear mother, whose unconditional support, guidance, and prayers have been a constant source of strength throughout my career.
- My family, My relatives , and My frinds .
- for their support and motivation.

Dedication

I dedicate this work to:

My beloved parents, in recognition of their endless love, sacrifices, encouragement, and unwavering support throughout my academic journey.

My family, whose confidence, motivation, and constant support have always inspired me to move forward.

My respected teachers and professors, whose knowledge, guidance, and valuable advice have greatly contributed to my academic and personal development.

My relatives and close friends, for their encouragement, support, and sincere companionship.

And to all those who have supported me and contributed, directly or indirectly, to the completion of this work.

I dedicate this humble achievement with gratitude and appreciation, hoping that it marks the beginning of greater accomplishments in the future.

Acknowledgements

This dissertation is a truly enlightening journey in our scientific research. It would have never been achieved without the invaluable guidance and the enthusiastic encouragement of our supervisor **pr. Lammouchi Zakaria** , Today, we would like to express our great gratitude to him for his motivational support, constructive suggestions, advantageous comments, gainful recommendations, and particularly for his hard work and his remarkable patience at various stages of the research development.

We also owe all our teachers, for their beneficial lectures, useful documents and advice. Our deepest gratitude goes to the members of the board of examiners for accepting to evaluate this humble dissertation.

Nevertheless, in all of the above efforts to accomplish this research, any errors, mistakes and omissions are solely our own.

Abstract

The rapid growth of electric vehicles (EVs) has increased the demand for efficient and reliable battery charging systems. Among the available charging technologies, DC fast charging has emerged as a promising solution to significantly reduce charging time and improve user convenience. However, fast charging introduces several challenges related to battery performance, thermal behavior, safety, and lifespan.

This work focuses on the modeling and simulation of a battery pack during DC fast charging. A mathematical model of the battery pack is developed to analyze its electrical behavior under different charging conditions. The charging system is simulated using appropriate software tools to evaluate key parameters such as voltage, current, state of charge (SOC), and charging efficiency.

The simulation results demonstrate the effectiveness of DC fast charging in reducing charging duration while maintaining acceptable battery operating conditions. The study also highlights the importance of proper charging control strategies to ensure battery safety and extend battery life. The developed model provides a useful framework for understanding battery pack behavior and optimizing fast-charging systems for future electric vehicle applications.

Keywords: Electric Vehicles, Battery Pack, DC Fast Charging, Modeling, Simulation, State of Charge, Charging Efficiency.

أدى النمو السريع للمركبات الكهربائية إلى زيادة الحاجة إلى أنظمة شحن فعالة وموثوقة. ومن بين تقنيات الشحن المتاحة، يُعد حلاً واعداً لتقليل زمن الشحن بشكل كبير وتحسين راحة المستخدم. (DC Fast Charging) الشحن السريع بالتيار المستمر. ومع ذلك، يطرح الشحن السريع عدة تحديات تتعلق بأداء البطارية وسلوكها الحراري وسلامتها وعمرها الافتراضي.

يركز هذا العمل على نمذجة ومحاكاة حزمة بطاريات أثناء عملية الشحن السريع بالتيار المستمر. تم تطوير نموذج رياضي لحزمة البطاريات لتحليل سلوكها الكهربائي تحت ظروف شحن مختلفة. كما تم إجراء المحاكاة باستخدام برامج متخصصة لتقييم، وكفاءة الشحن (SOC) المعلومات الأساسية مثل الجهد الكهربائي، والتيار، وحالة الشحن. أظهرت نتائج المحاكاة فعالية

الشحن السريع بالتيار المستمر في تقليل مدة الشحن مع الحفاظ على ظروف تشغيل مناسبة للبطارية. كما أبرزت الدراسة أهمية استراتيجيات التحكم المناسبة لضمان سلامة البطارية وإطالة عمرها التشغيلي. ويوفر النموذج المطور إطاراً مفيداً لفهم سلوك حزم البطاريات وتحسين أنظمة الشحن السريع لتطبيقات المركبات الكهربائية المستقبلية.

الكلمات المفتاحية: المركبات الكهربائية، حزمة البطاريات، الشحن السريع بالتيار المستمر، النمذجة، المحاكاة، حالة الشحن، كفاءة الشحن.

Contents

Dedication.....	i
Dedication.....	ii
Acknowledgements	iii
Abstract	iv
List Of Figures	viii
List Of Tables	xii
List Of Symbols And Abbreviations	xiii
General Introduction	1

Chapter1: Terminology and Definitions of Lithium-ion Batteries

1.1 Introduction	4
1.2 Battery Structure	4
1.3 Operating Principles	5
1.4 Terminology and Definitions of Lithium-ion Batteries	6
1.4.1 State of Charge (SOC)	6
1.4.2 Charge/Discharge Rate (C-rate)	7
1.5 Battery Health and Lifetime	8
1.5.1 State of Health (SOH)	8
1.5.2 Life Cycle	9
1.6 Battery Module	9

1.7 Battery Applications	10
1.7.1 Electric Vehicles	10
1.7.2 Portable Electronics	11
1.7.3 Backup Power	11
1.8 Generation Characterization	12
1.9 Conclusion	14

Chapter I: Battery modeling and simulation

2-1 Introduction	16
2-2 Principle and structure of battery charging / discharging characteristics	16
2-3 Existing electrical equivalent battery models	17
2-3-1 Simple battery model Rint model	18
2-3-2 Resistive Thevenin battery model	18
2-3-3 An accurate electrical battery model	19
2.3.4 Models of electrical equivalent batteries.....	19
2-4 Experimental test data on lithium-ion batteries INR 18650	20
2-4-1 Lithium-ion battery specifications used for battery model: LIR18650 mAh	20
2-4-2 Data and Test Description	21
2-5 Resultant Simulation	22
2-5-1 Equivalent circuit modeling (ECM)	22
2-5-2 Pack battery	25
2-5-3 Battery Charger	28
2-6 Conclusion	29

Chapter III: DC Fast Charging

3.1 Introduction	31
3.2 DC Charging Levels	31
3.3 EV Charging Ports and Sockets	32
3.4 DC Fast Charger Power Conversion Systems	34
3.5 Status of the DC Fast-Charging Station with an Isolated DC/DC	35
3.6 Filter	36
3.7 Three-Phase Inverter	36
3.8 Voltage Oriented Control (VOC)	37
3.9 VOC with Active Filtering Function	38
3.10 Voltage Oriented Control (VOC)	38
3.11 Study of the AC-Side Current Loop	40
3.12 DC Bus Voltage Regulation Loop	42
3.13 DC/DC Converter Stage	43
3.14 Electric Vehicle Battery	44
3.15 Simulation Result	45
3.16 Conclusion	50

LIST OF FIGURES

Figures of Chapter 1

<i>Figure (1-1):</i> The Basic Structure of a Lithium Battery	5
<i>Figure (1-2):</i> Battery Discharge	6
<i>Figure (1-3):</i> Battery Charging	6
<i>Figure (1-4):</i> Battery State of Charge in a Percentage Reading	7
<i>Figure (1-5):</i> Curves of Measured Voltage and Capacity under Different Discharging Rates	8
<i>Figure (1-6):</i> Curves of Measured Voltage and Capacity under Different Temperatures.....	8
<i>Figure (1-7):</i> Cell Module Exploded View	10
<i>Figure (1-8):</i> Combination of Multiple Modules Form a Pack	10
<i>Figure (1-9):</i> Electric Car Battery	11
<i>Figure (1-10):</i> Portable Smartphone Battery	11
<i>Figure (1-11):</i> Laptop Battery	11
<i>Figure (1-12):</i> Emergency Power Supply Using Batteries	12
<i>Figure (1-13):</i> Home Battery Storage	12
<i>Figure (1-14):</i> Temperature Effect on Lithium-ion Battery	13
<i>Figure (1-15):</i> The Temperature Profile of Battery	13
<i>Figure (1-16):</i> SOC of Battery	13
<i>Figure (1-17):</i> Voltage of Battery	14
<i>Figure (1-18):</i> Current of Battery	14

LIST OF FIGURES

Figures of Chapter 2

Figure (2-1): MATLAB Model	16
Figure (2-2): Battery Model: used to track battery characteristics	17
Figure (2-3): Resistive Thevenin battery model	18
Figure (2-4): Thevenin battery model with 2RC branches	19
Figure (2-5): Accurate electrical battery model	19
Figure (2-6): INR 18650-20R Battery.....	20
Figure (2-7): Battery charging and Discharging with Experimental DATA.....	22
Figure (2-8): Battery Modeling under Variable Resistive Load using Simulink.....	23
Figure (2-13): Pack battery modeling	26
Figure (2-14): Voltage of battery.....	26
Figure (2-15): Profile of current	27
Figure (2-16): One cell characteristic	27
Figure (2-17): Pack battery characteristic.....	27
Figure (2-18): Battery charging using constant current and constant voltage	28
Figure (2-19): SOC of battery.....	28
Figure (2-20): Profile of current.....	29
Figure (2-21): Battery charging control with CC/CV.....	29

Figures of Chapter 3

Figure (3-1) Off-board and On-board EV Charging Infrastructure, as well as Power Levels....	32
Figure (3-2) EV Charging Ports	33

LIST OF FIGURES

Figure (3-3) EV Charging Sockets	34
Figure (3-4) Simplified Block Diagram of Conventional DC Fast Charger Power Conversion Systems	35
Figure (3-5) Block Diagram of DC Fast-Charger Power Conversion Stages with an Isolated DC/DC	35
Figure (3-6) LCL Filter	36
Figure (3-7) MATLAB/Simulink Block Three-Phase Inverter	37
Figure (3-8) Three-Phase Inverter Configuration (AC/DC Converter)	37
Figure (3-9) Vector Graph of VOC	38
Figure (3-10) Voltage Oriented Control Structure	39
Figure (3-11) Voltage Oriented Control Diagram	40
Figure (3-12) Dynamic Model of the DC Bus Circuit	42
Figure (3-13) DC Bus Voltage Regulation Loop	43
Figure (3-14) PSFB Topology of Isolated DC/DC Converter	43
Figure (3-15) Matlab Simulink Model for DC Fast Charger	47
Figure (3-16) Input Voltage and Current Waveforms	47
Figure (3-17) Direct Current (I_d) Response	47
Figure (3-18) Reactive Current (I_q) Response	48
Figure (3-19) V_d Response	48
Figure (3-20) V_q Response	48
Figure (3-21) DC Bus Voltage (V_{dc})	49
Figure (3-22) DC Current (I_{dc})	49

LIST OF FIGURES

Figure (3-23) Battery Charging Voltage (V_{bat})	49
Figure (3-24) Battery Current (I_{bat})	50
Figure (3-25) State of Charge (SOC)	50

LIST OF TABLES

Table (2-1) Comparison of Electrical Equivalent Battery Models	20
Table (2-2) Battery Model Specifications LIR18650 mAh	21
Table (3-1) DC Charging Levels According to SAE Standards	31
Table (3-2) Battery Pack Parameters	43
Table (3-3) Simulation Input Parameters for Grid and AC/DC Converter	44
Table (3-4) Simulation Output Parameters of DC/DC Converter	45

LIST OF SYMBOLS AND ABBREVIATIONS

Symbol / Abbreviation	Description
EV	Electric Vehicle
Li-ion	Lithium-ion Battery
SOC	State of Charge
SOH	State of Health
OCV	Open Circuit Voltage
CC	Constant Current
CV	Constant Voltage
CC/CV	Constant Current / Constant Voltage
DC	Direct Current
AC	Alternating Current
VOC	Voltage Oriented Control
ECM	Equivalent Circuit Model
UPS	Uninterruptible Power Supply
PWM	Pulse Width Modulation
HFT	High Frequency Transformer
PSFB	Phase Shifted Full Bridge
LCL	Inductor-Capacitor-Inductor Filter
PI	Proportional-Integral Controller
THD	Total Harmonic Distortion
Ah	Ampere-hour
mAh	milliampere-hour

Symbols

Symbol	Description	Unit
V	Voltage	V
I	Current	A
P	Power	W
Q	Battery Capacity	Ah
R	Resistance	Ω
L	Inductance	H
C	Capacitance	F
R _{int}	Internal Resistance	Ω
R ₀	Ohmic Resistance	Ω

LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	Description	Unit
R1	Polarization Resistance	Ω
VOC	Open Circuit Voltage	V
Vdc	DC Bus Voltage	V
i(t)	Battery Current	A
v(t)	Terminal Voltage	V
z(t)	State of Charge	%
Vc1	Capacitor Voltage	V
idc	DC Current	A
Udc	DC Bus Voltage	V
RL	Load Resistance	Ω
kp	Proportional Gain	—
ki	Integral Gain	—
fsw	Switching Frequency	Hz
iLd	Direct-axis Current Component	A
iLq	Quadrature-axis Current Component	A
ULd	Direct-axis Voltage Component	V
ULq	Quadrature-axis Voltage Component	V
ω	Angular Frequency	rad/s
γ_{UL}	Voltage Vector Angle	rad
α, β	Stationary Reference Frame Components	—
d, q	Rotating Reference Frame Components	—
Vmin,bat	Minimum Battery Voltage	V
Lb	Battery Inductance	H
Ctransient	Transient Capacitance	F
Rseries	Series Resistance	Ω
Rtransient	Transient Resistance	Ω

General Introduction

Continuing concerns on climate change have driven the main energy source of our transport system to move away from oil. Electric transmission systems can help reduce oil consumption, battery-powered vehicles would be plugged into the grid, and clean renewable energy sources could recharge their built-in battery systems. The battery storage must provide the vehicle's energy requirement to move to an electric model. Over the past few years, Li-ion battery technology has made Electric Vehicles (EVs) more cost-effective and convenient [1]

Among the various storage technologies available today, lithium-ion battery packs have emerged as the preferred solution due to their high energy density, long lifespan, and excellent performance characteristics. Consequently, optimizing battery charging processes has become a critical challenge for both researchers and industrial stakeholders.

Despite recent developments in the Electric Vehicles market, these vehicles still represent a small fraction of light commercial vehicles globally . However, the growth of EVs remains restricted due to the limited charging infrastructure .

DC fast charging technology represents a major breakthrough in reducing charging time and improving the practicality of electric vehicles and energy storage applications. However, high charging rates can introduce several technical challenges, including thermal stress, battery degradation, efficiency losses, and safety concerns. Therefore, understanding and accurately modeling the charging behavior of battery packs is essential for developing advanced charging strategies that ensure both performance and longevity.

In this context, modeling and simulation provide powerful tools for analyzing battery dynamics, evaluating charging performance, and predicting system behavior under different operating conditions without the need for costly experimental setups. Through mathematical modeling and simulation techniques, it becomes possible to investigate the influence of charging parameters, optimize control strategies, and enhance the overall efficiency of DC fast charging systems.

This work focuses on the modeling and simulation of battery pack DC fast charging systems, aiming to analyze their electrical behavior, evaluate charging performance, and

contribute to the development of efficient, reliable, and sustainable energy storage solutions that meet the growing demands of modern electrified applications.

This work is organized as follows:

Chapter 1 provides a terminology, definitions and characterization of Lithium-ion Batteries and various fields application.

Chapter 2 presents a battery and battery pack design. This chapter includes a presentation of mathematical formulas, battery modeling and simulation.

In this chapter 3 a detailed description of the design and simulation of a DC fast recharging station for Electric Vehicles is carried out. set up used for battery characterization. The design of the components of the system and the control schemes are explained and a simulation of the system, performed in Matlab/Simulink environment is presented.

Chapter 1:
Terminology and Definitions of Lithium-ion
Batteries

1.1 Introduction

As global fossil-fuel sources continue to deplete at a rapid rate, increased demand for renewable and sustainable alternative energy sources has become the new reality. One such source, lithium-ion (Li-ion) batteries, are emerging as a prominent energy storage device for applications in smart grid and electric vehicles [2]. The source of energy for an electric car is the battery packs, which consist of hundreds, sometimes thousands of individual cells packed together.

Lithium-ion batteries because of their high energy density and high power-to-weight ratio, serve as an ideal candidate for EVs. A lithium-ion battery does not have a memory effect, which means it does not lose its maximum energy capacity because of repeated charging and discharging, which is not the case for batteries like lead acid batteries [3]. Lithium-ion batteries can develop high temperatures during operations which can reduce their performance and decrease safety[4].

The operating characteristics of a lithium-ion battery are affected by many factors such as battery internal resistance, charge and discharge currents, working temperature, the number of charge/discharge cycles, and State of Charge (SOC), all needing to be considered comprehensively.

1.2 Battery structure [5]

Batteries are devices used to store and supply energy using electrochemical reactions. They consist of cells containing electrochemical materials and are used in many areas such as portable electronic devices, electric vehicles, and energy storage systems.

The structure of a battery varies depending on its type and specific application, but most include the following components:

1. Anode: This is the negative electrode of the battery where the chemical oxidation reactions occur during discharge.
2. Cathode: This is the positive electrode of the battery where the chemical reduction reactions occur during discharge.
3. Electrolyte: This is an ion-conducting material that allows charges to move between the anode and cathode.

4. Separator: This is a porous membrane that separates the anode from the cathode while allowing ions to pass through.

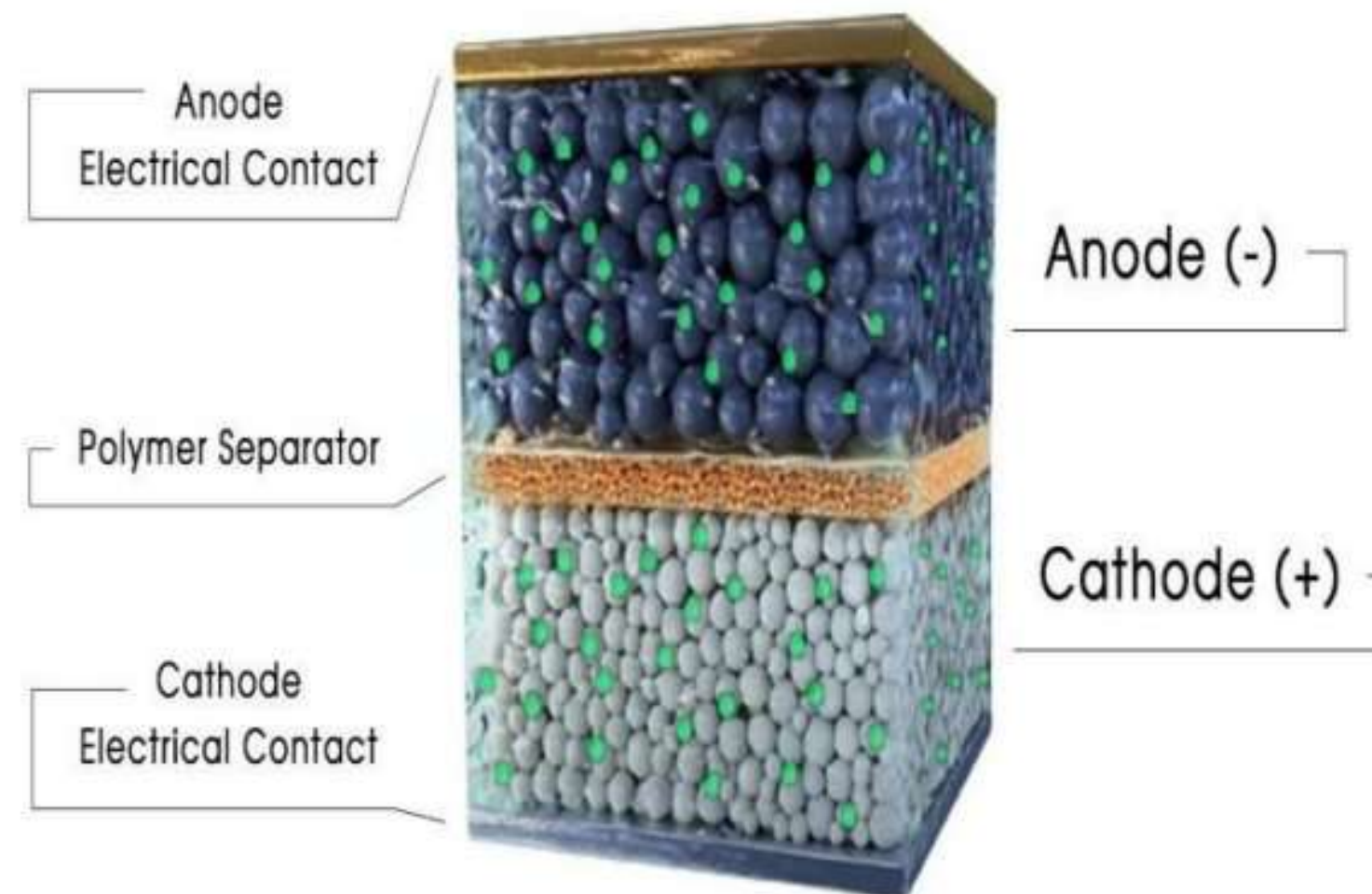


Figure (1-1): The basic structure of a lithium battery

1.3 Operating principles [6]

Batteries use the principle of electrochemistry to convert chemical energy into electrical energy. This principle is based on oxidation and reduction reactions that occur between the electrochemical materials of the anode and cathode.

When a battery is charged (Figure 1-3), an oxidation reaction occurs at the anode, resulting in the release of electrons. The electrons are then captured by the cathode, where a reduction reaction occurs. During this process, ions move through the electrolyte to balance the charges between the anode and cathode.

When the battery is discharged (Figure 1-2), the chemical reactions are reversed. Electrons are forced to return from the cathode to the anode through an external circuit, generating an electric current that can be used to power devices or systems. Ions also flow through the electrolyte to maintain charge balance .

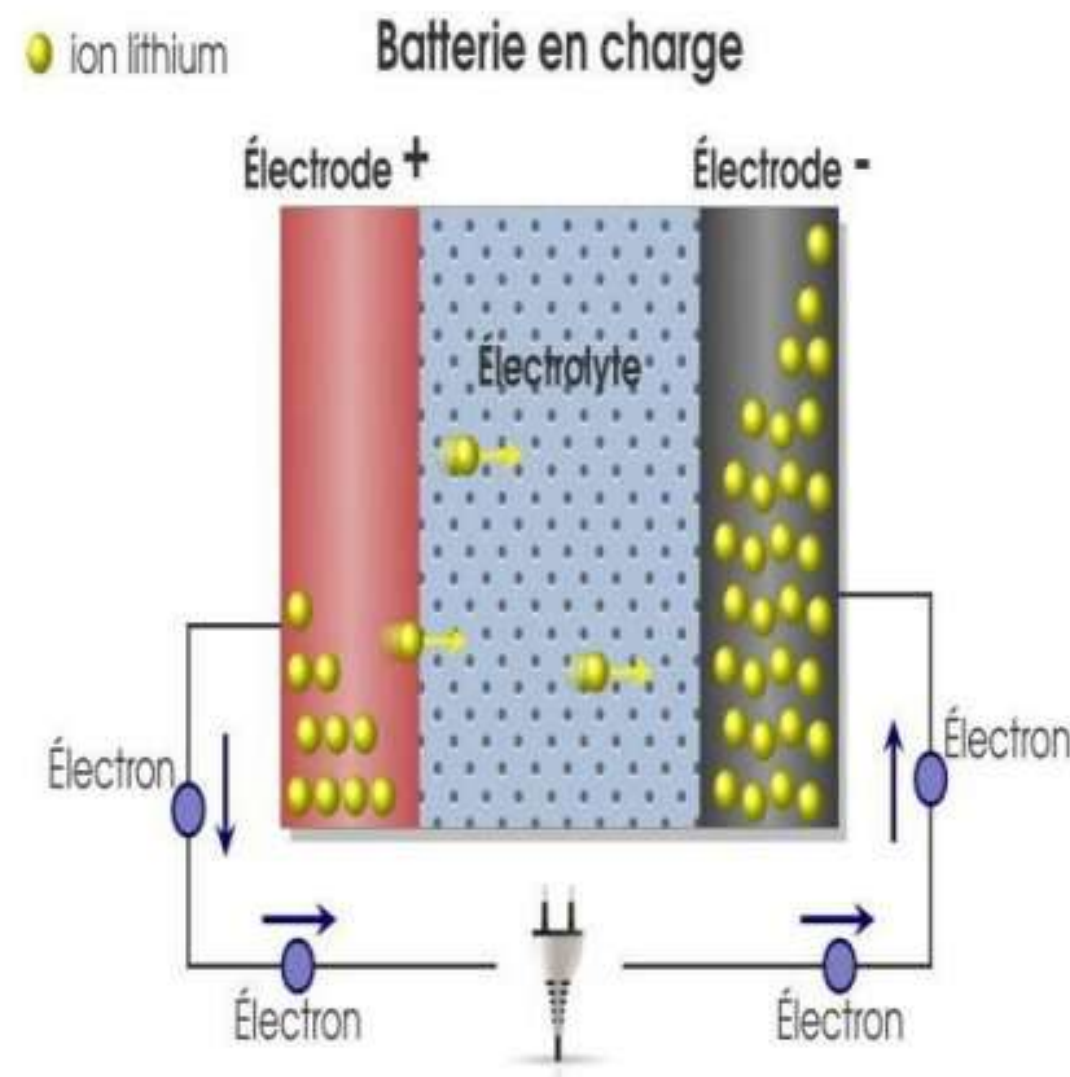


Figure (1- 2): Battery discharge

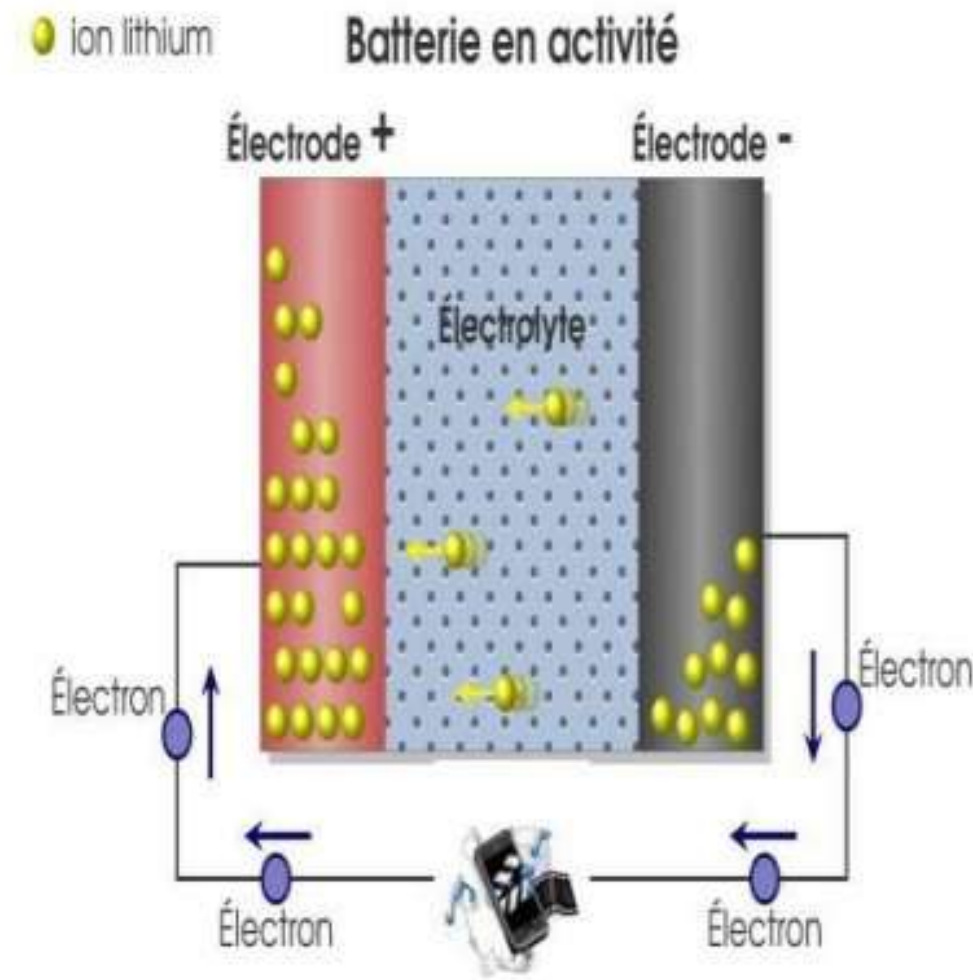
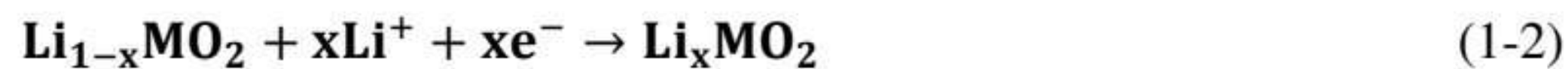


Figure (1-3): Battery charging

The positive electrode, which is the cathode during discharge and anode during charge, is normally coated with a lithium metal oxide ($Li_{1-x}MO_2$). The negative electrode, which is the anode during discharge and is the cathode during charge, is composed of graphite. During discharge, the lithium ions deintercalate from the negative electrode giving off electrons as shown in the equation below :



The ions from the negative electrode then move across the separator and intercalate into the metal oxide active material of the positive electrode:



1.4 Terminology and Definitions of Lithium-ion Batteries [4]

The research on lithium-ion batteries mainly focuses on their technical indicators to describe the "pros and cons" of the performance.

1.4.1 State of Charge (SOC)

The State of Charge (SOC) is defined as the state of available electrical energy in a battery, usually expressed as a percentage as shown in Figure (1-4). It represents the ratio of the remaining

capacity of a battery after discharging to its fully charged capacity.

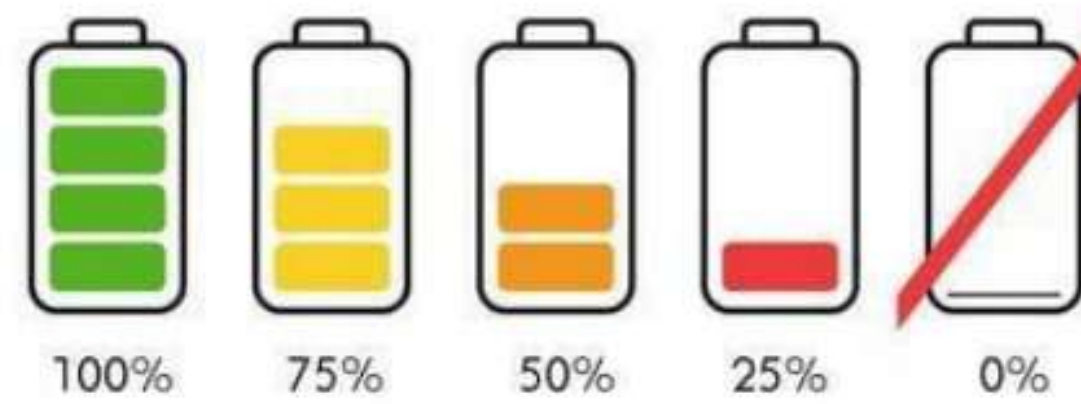


Figure (1-4): Battery state of Charge in a percentage reading.

Its value range is 0~100%. When SOC = 0%, it means the battery is completely discharged, and when SOC = 100%, it means the battery is fully charged. Because the available electrical energy varies with the charging/discharging current, temperature, and aging, the definition of charge state is also categorized into two kinds: absolute charge state and relative charge state. The absolute State of Charge is a reference value calculated according to the designed fixed capacity value when the battery is manufactured. The absolute State of Charge of a new fully charged battery is 100%. Even if an aged battery is fully charged, it will not reach 100% under different charge and discharge conditions.

1.4.2 Charge/ Discharge Rate (C-rate)

The charge/discharge rate refers to the current value required to charge/discharge the battery with respect to its rated capacity. For example, one C-rate is the current that would fully charge or discharge the battery within one hour, and is numerically equal to the battery's rated capacity. For example, for a battery cell with a capacity of 24 Ah: with 48 A discharge, the discharge rate is 2C, and the discharge is completed in 0.5 hours; and, when charging occurs at 12 A, the charge rate is 0.5C, and the charging is completed in 2 hours. Figures 1.5 and 1-6 show the relationship between the measured voltage and capacity of a battery under different discharging rates and temperatures. When the discharging rates are high, the battery capacity decreases. When the temperature decreases, the battery capacity also decreases accordingly.

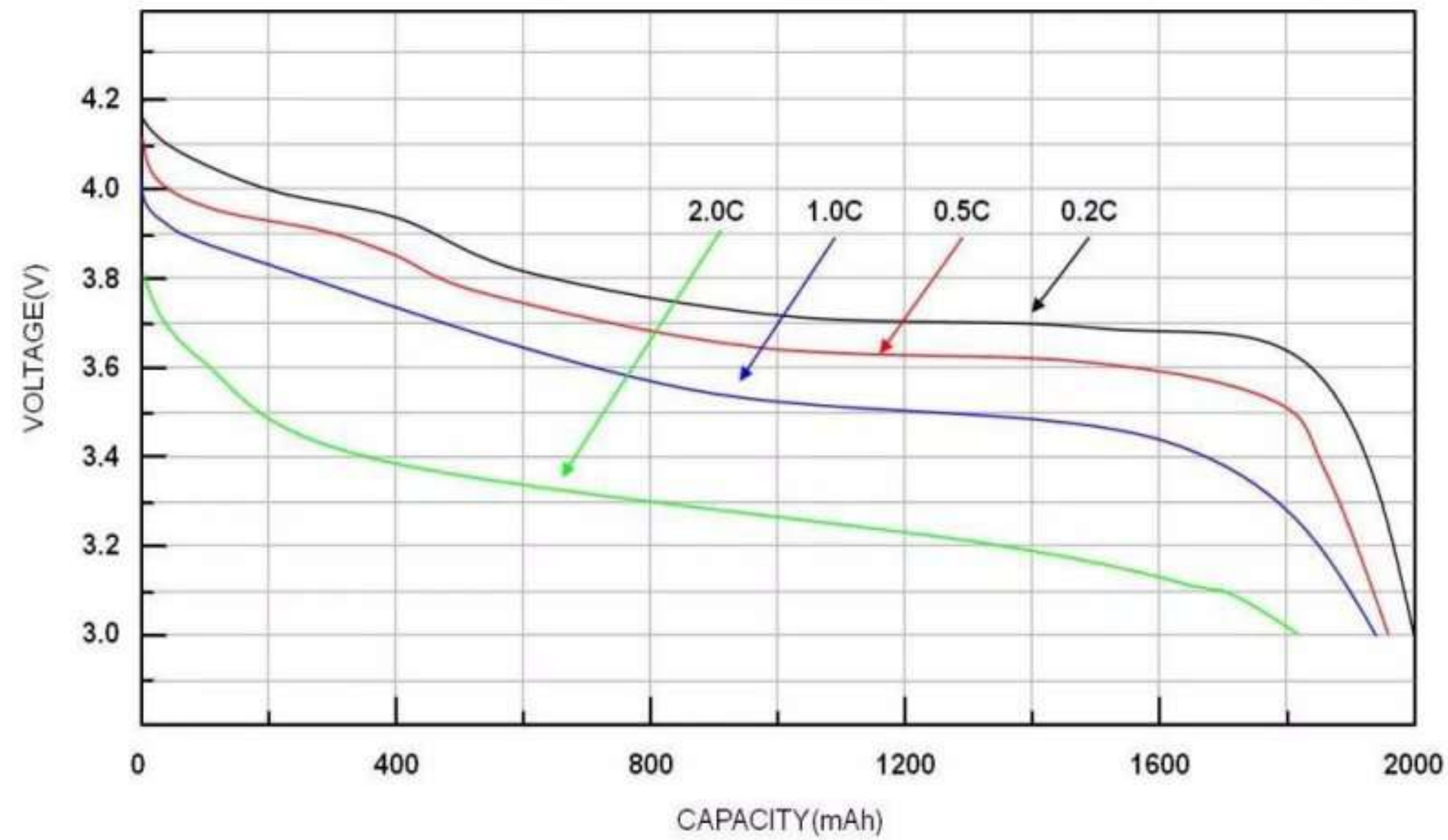


Figure (1-5): Curves of measured voltage and capacity under different discharging rates.

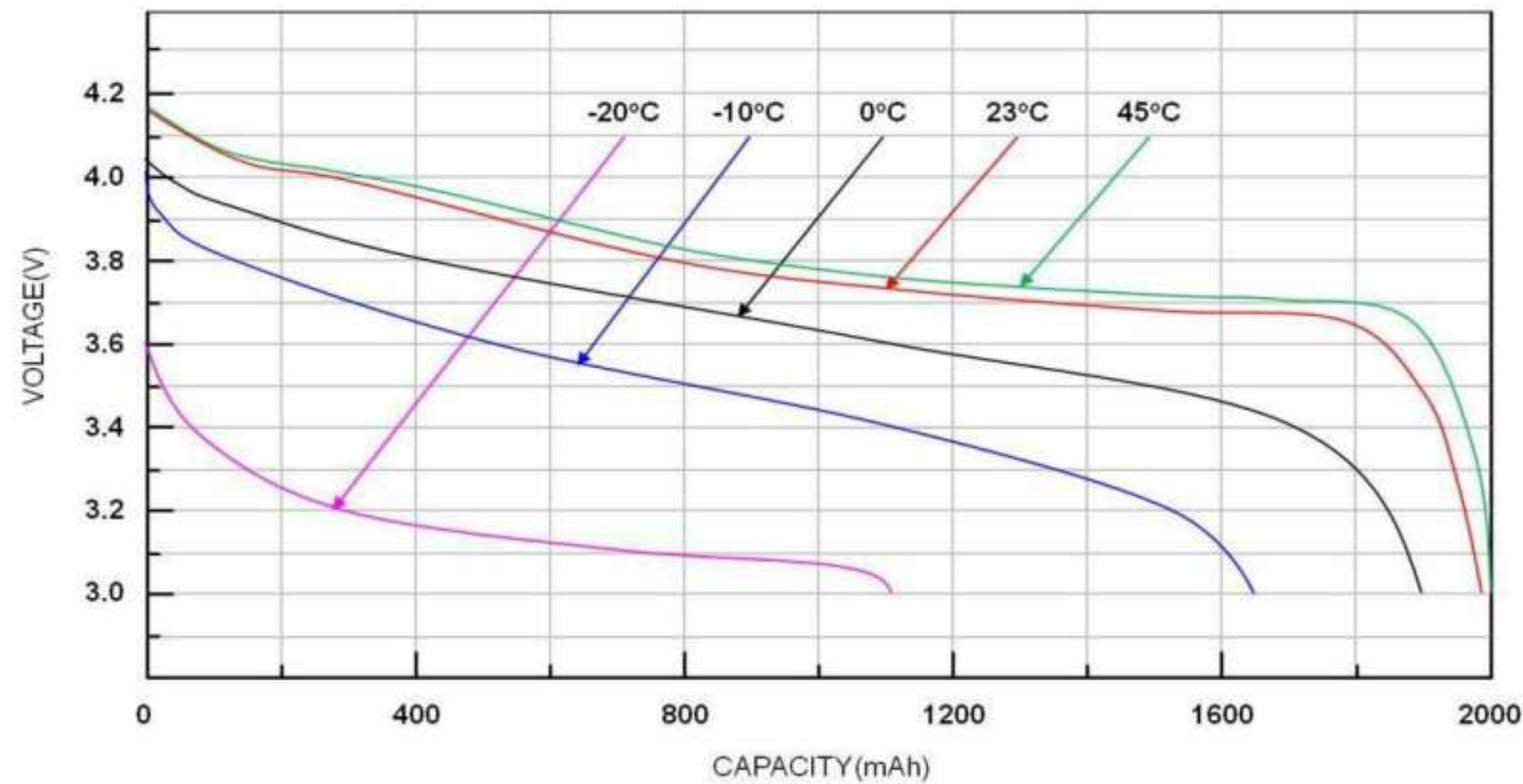


Figure (1-6): Curves of measured voltage and capacity under different temperatures

1.5.1 State of Health (SOH)

The State of Health (SOH) characterizes the battery's ability to store electrical energy relative to a new battery. It represents the state of a battery from the beginning to the end of its life as a percentage and is used to quantify the battery's performance state. There are many performance indicators of batteries. SOH has many definitions referring to the battery's capacity, discharge rate. The most common definition for SOH uses the decay of battery capacity for defining the SOH, as follows:

$$SOH = \frac{Capacity_{aged}}{Capacity_{rated}} \times 100\% \quad (1-3)$$

Where $Capacity_{aged}$ is the current capacity of the battery and $Capacity_{rated}$ is the rated capacity of the battery.

1.5.2 Life Cycle

The life cycle is the number of times a battery has undergone complete charging and discharging until it reaches its end of life. The battery life is defined by two parameters: cycle life and calendar life. Cycle life refers to the number of times the battery can be charged and discharged in cycles before it reaches end of life defined as the time when the battery capacity decays to 80%

1.6 Battery Module [3]

A module is a collection of cells interconnected in series, parallel, or a combination of both to achieve desired voltage and capacity. When multiple modules are interconnected, the produced structure is a battery pack. This is a standardized method before manufacturing the pack[7][8]. Producing modules for a pack gives many advantages, increased overall strength, increased heat dissipation, and easy maintenance.

The Fraunhofer innovation platform has defined the intended design of the module made out of cylindrical cells as shown in fig4. It has 3 main elements, One being the cell, the cell holders, and conductor templates. The cell holders are designed in such a way that they can be further attached to other modules to form a complete pack as shown in fig 5. Creating a module like this will eliminate the adhesive dispensing process, unlike a Tesla Model Y battery pack where the cells have an adhesive bonding between them. Recycling, repairing, and re-manufacturing these kinds (Tesla model Y type) of packs becomes very difficult. The module type that's given by the Fraunhofer innovation platform provides the flexibility to produce any variety of battery packs that can serve various functions. For the production of the prismatic cell module, since the exact specifications of the prismatic cells are not provided by the Fraunhofer innovation platform, the structure and specs of prismatic cells are assumed.

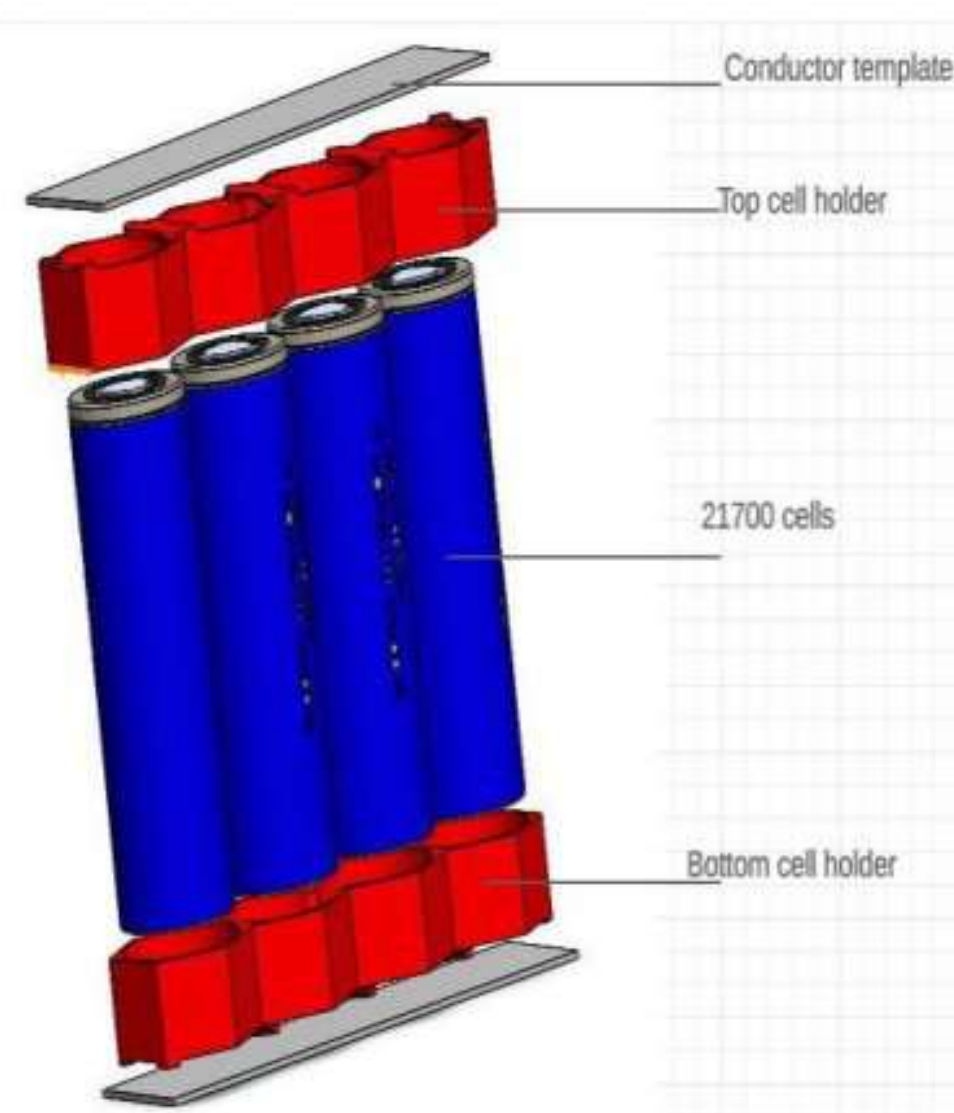


Figure (1-7): Cell module exploded view modules

form a pack



Figure (1-8): Combination of multiple modules

1.7 Battery applications [5]

Batteries have many practical applications in various fields. Here are a few examples of battery applications :Renewable energy storage: Batteries play an essential role in storing energy produced from renewable sources such as solar and wind power. They allow excess energy to be stored and released when demand is high. This contributes to the effective integration of renewable energies into the power grid. [9]

1.7.1 Electric vehicles

Batteries are used as the main power source in electric vehicles, such as cars, buses, and electric bicycles. They store the electrical energy that powers the vehicle's electric motor. [10]



Figure (1-9) Electric car battery

1.7.2 Portable electronics

Batteries power a wide range of portable electronic devices such as smartphones, tablets, laptops, , etc. They enable mobile and wireless use of these devices.

**Figure (1-10):** Portable smartphone battery**Figure (1-11):** Laptop battery

1.7.3 Backup power

Batteries are used to provide backup power during power outages. They are used in uninterruptible power supply (UPS) systems to maintain power to critical equipment such as computers, servers, communication systems, etc. [11]



Figure (1-12): Emergency power supply using batteries

Residential energy storage: Batteries are used in residential energy storage systems, such as solar energy storage systems, to enable homeowners to use stored energy during peak periods or in the event of a power outage. [12]

**Figure (1-13):** Home battery storage

1.8 Generation Characterization

The temperature of the chamber was changed to 50°C. The cell was rested for an additional three hours in order to provide the battery enough time to reach the ambient temperature. The chamber was then increased by 10°C every three hours,

To test the next SOC point, the chamber temperature is changed back to 25°C and the cell is discharged for 10% SOC at 1C rate; The above procedure is then repeated

The diagram below shows the temperature profile that was applied at each SOC. A 1C discharge was carried out at the end of the temperature profile to bring the cell to a new SOC value.

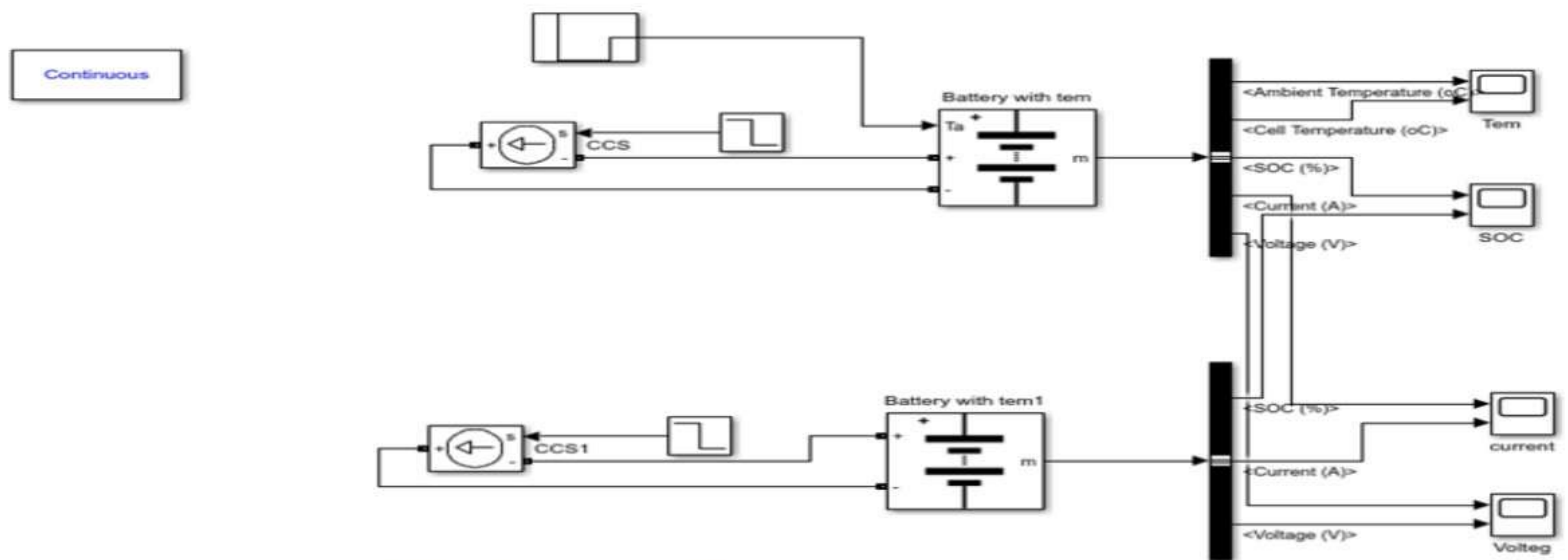


Figure (1-14) : Temperature Effect on Lithium-ion Battery

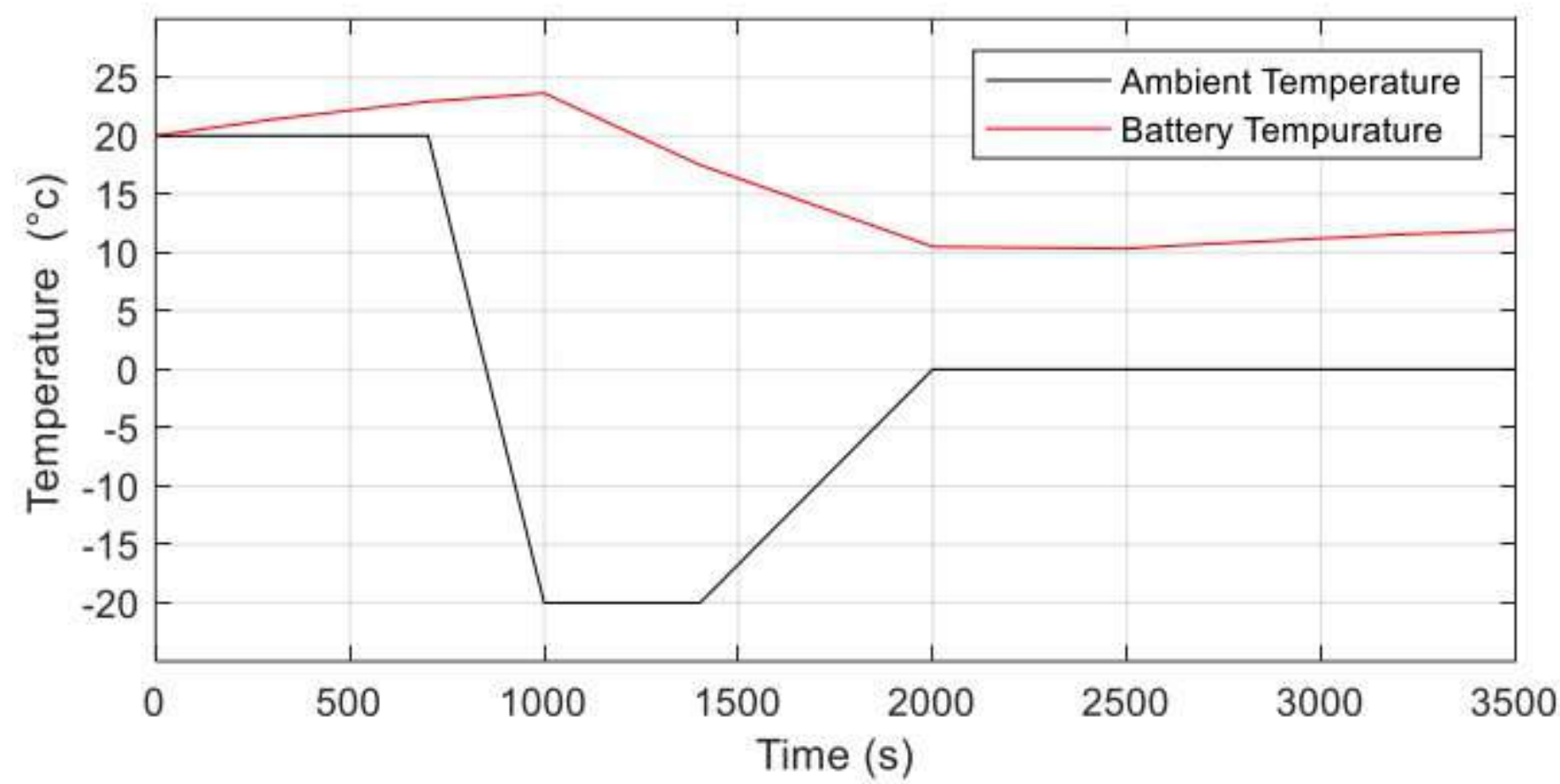


Figure (1-15): The temperature profile of battery

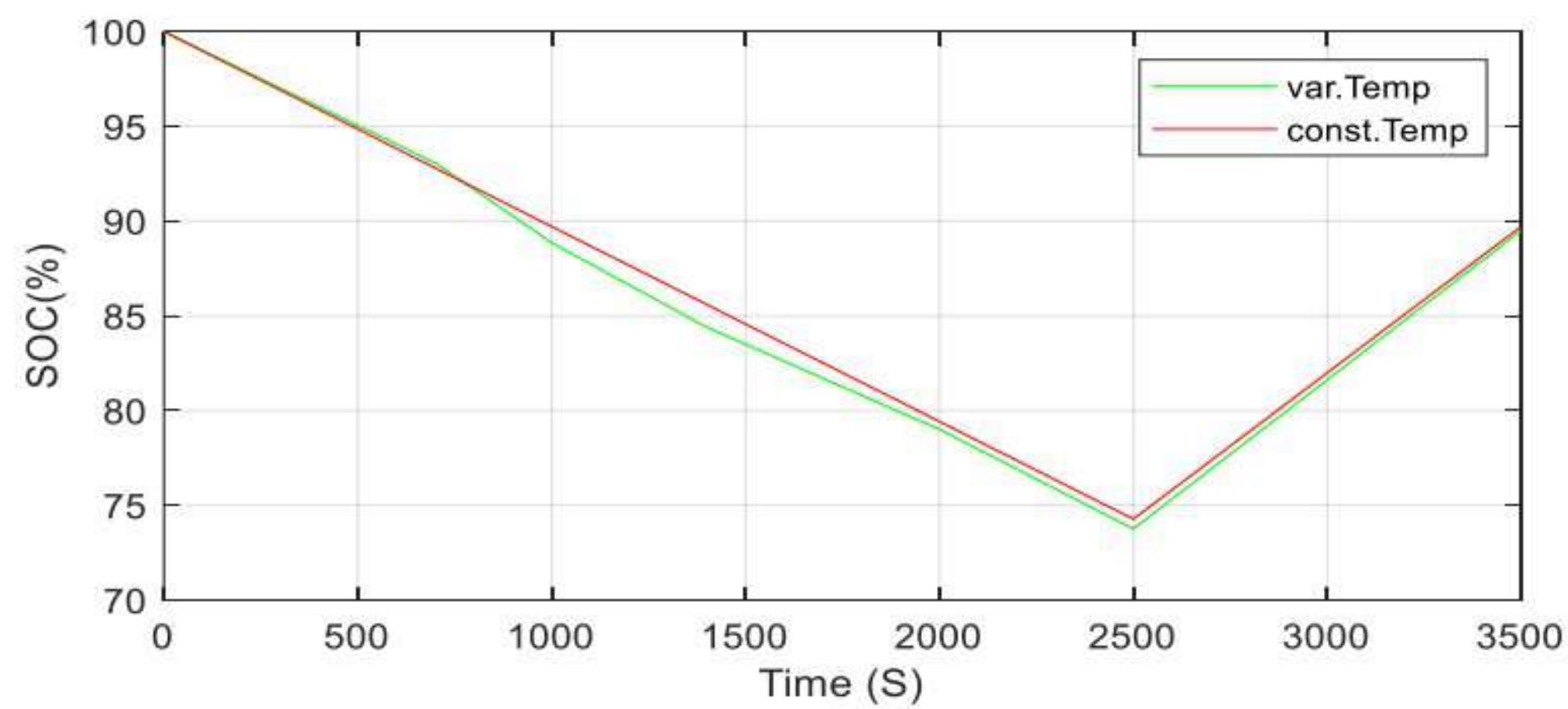


Figure (1-16) : Soc of battery

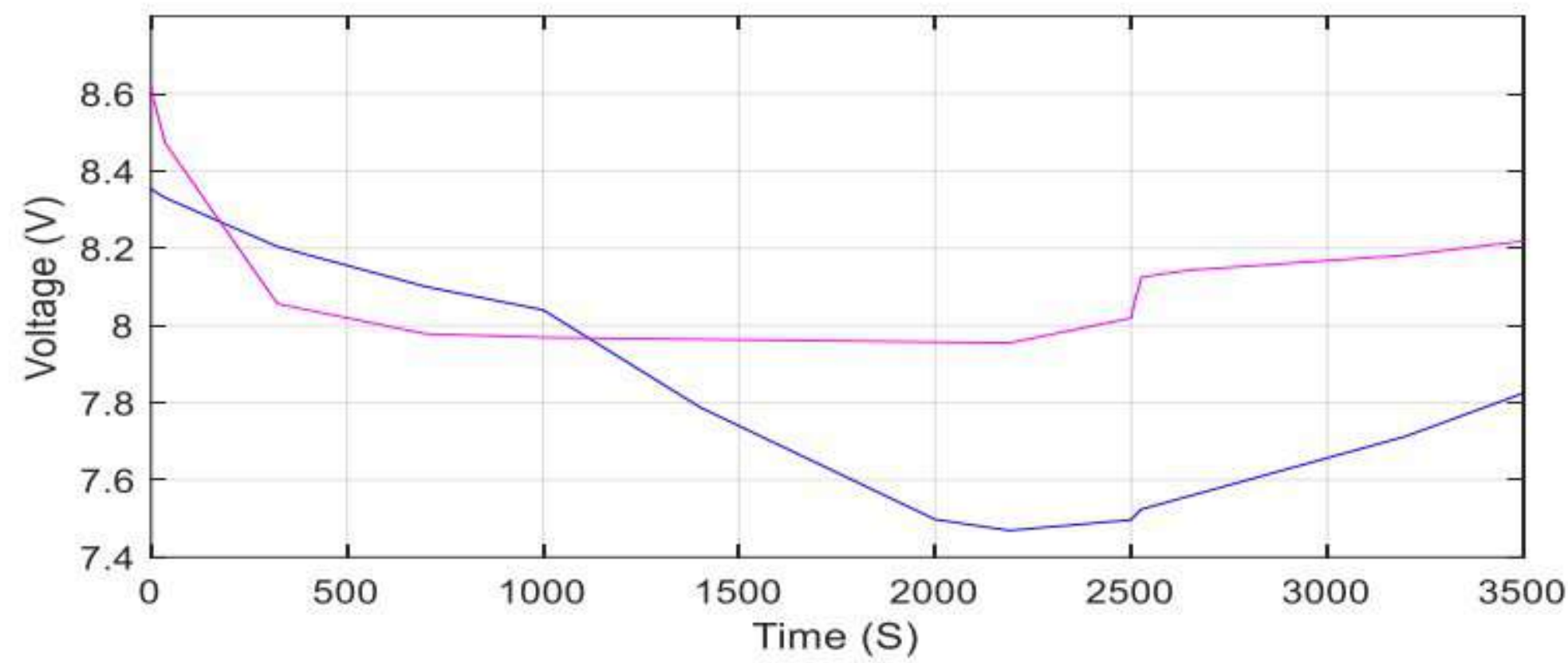


Figure (1-17) : Voltage of battery

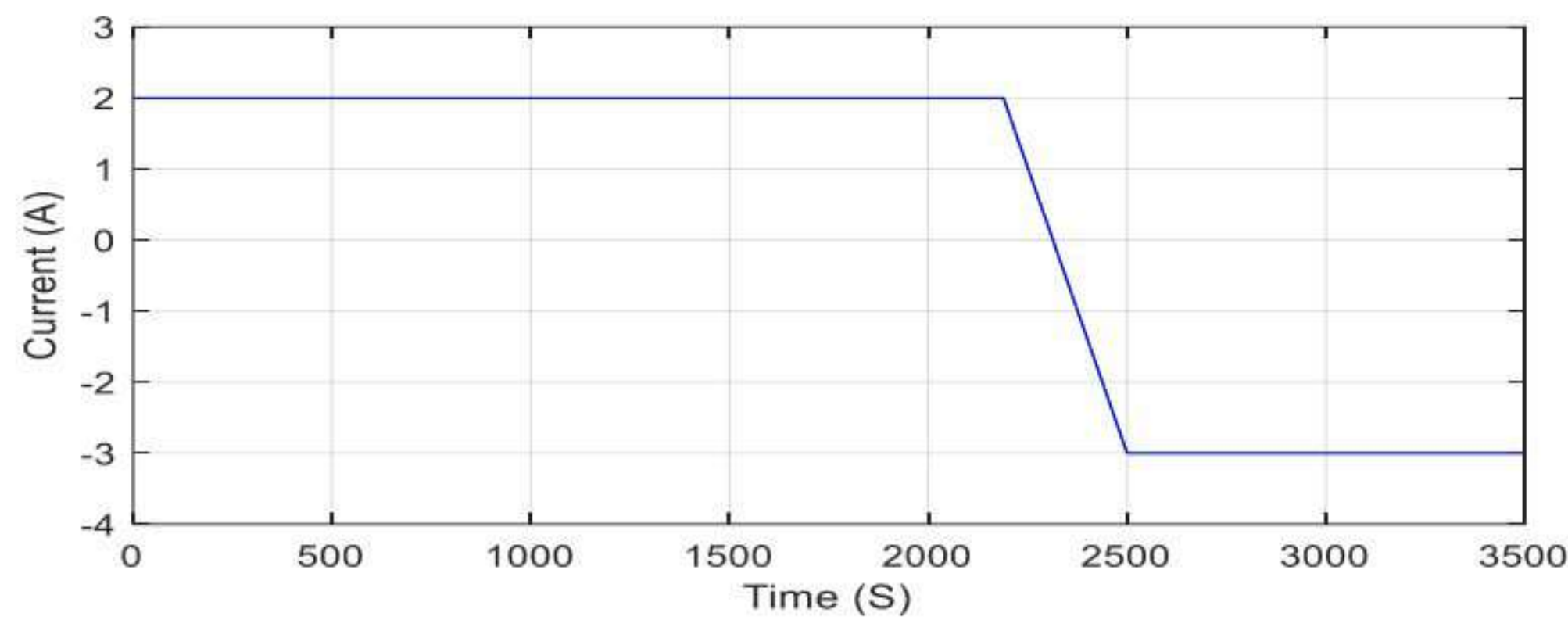


Figure (1-18) :Current of battery

1.9 Conclusion

This chapter introduced the fundamental concepts, terminology, and definitions related to lithium-ion batteries. The chapter also highlighted the main components, characteristics, and electrochemical behavior of lithium-ion batteries, as well as their advantages such as high energy density and charging capability. Furthermore, various applications of lithium-ion batteries were presented, including electric vehicles, renewable energy storage systems and industrial applications.

Understanding these basic concepts provides a comprehensive overview of battery modeling, management systems, control, and DC fast charging technologies in subsequent chapters.

Chapter 2:
Battery modeling and simulation

2.1 Introduction

For long distances, Battery EVs are one of the largest disadvantages to be limited range. Especially with low temperature, low battery capacity and strength of the auxiliary devices, the requirements of the additional energy requirements decrease in the reasons. On the other hand, the battery is required for the power, security and economy of an EV. The best design of the battery management system will significantly contribute to the life of the battery.

The battery model is used to define working dynamics. This model is indispensable for estimating SOC status and simulation of battery management system. It is also difficult to model and simulate this process. The equivalent circuit model comprises resistance, capacitors, fixed voltage source and other circuit elements to simulate the battery dynamics (Qin et al., 2019). When the widely used equivalent circuit models are examined, Rint, RC, PNGV, Thevenen models (Johnson, 2002). This chapter includes a presentation of mathematical formulas, battery modeling and simulation, and charging and discharging processes using Simulink/Matlab.

2.2 Principle and structure of battery charging / discharging characteristics:

The initial stage in the development process would be to build and parameterize an analogous circuit that would properly replicate the behavior of the battery. This is estimated with the help of MATLAB and estimation techniques and measured data on lithium-ion batteries (because of its many benefits, including high specific energy densities, high energy densities, and extended cycle lives). Parameterization is achieved by discharging and charging current pulses. With the help of MATLAB, it is possible to construct mathematical models of predicting and optimizing the performance of the complex system. Various processes are depicted in accordance with the block diagram of the MATLAB-based rechargeable battery model. [13]

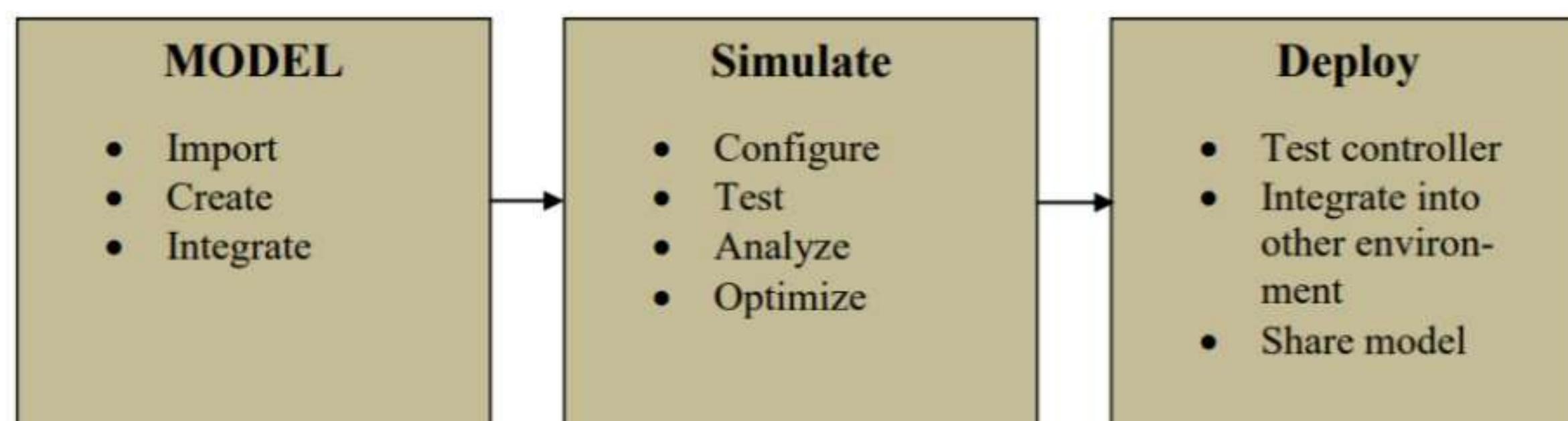


Figure (2-1): MATLAB Model

The mathematical model between battery input and output parameters, as well as the simulator, can only be obtained through battery modelling and simulation. In addition to being important for estimating battery performance and design, simulations and modelling are required to determine the electrical system's capacity and best part selection. Every facet of the parameters extraction of manufacturers' discharge characteristics is described in relation to battery modelling . [13]

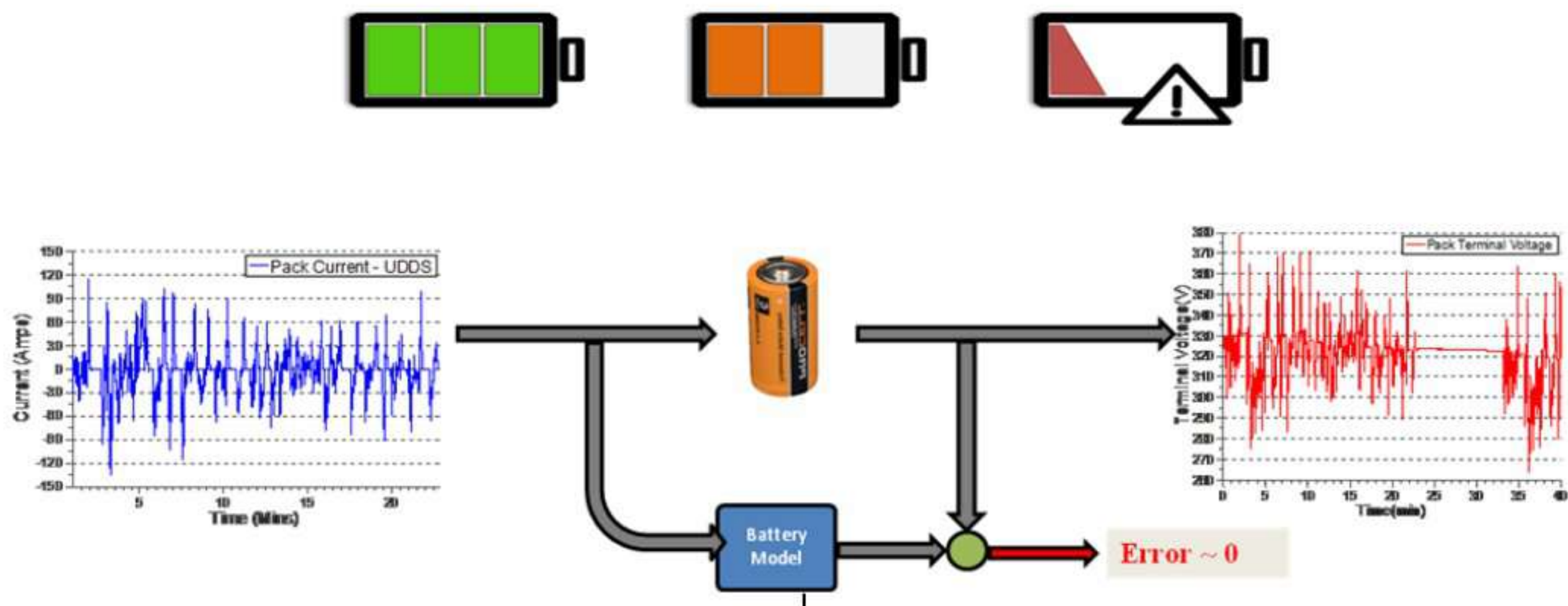


Figure (2-2): Battery Model: used to track battery characteristics

2.3 Existing electrical equivalent battery models [14]

The mathematical relationship between the elements of Lithium-ion batteries and their V-I characteristics, state of charge (SOC), internal resistance, operating cycles, and self-discharge is depicted in a Lithium-ion battery model. The equivalent circuit model of a Lithium-ion battery is a performance model that uses one or more parallel combinations of resistance, capacitance, and other circuit components to construct an electric circuit to replicate the dynamic properties of Lithium-ion batteries. Time domain analysis is used to produce the most often utilised electrical equivalent models. The simplest model equation for battery model can be represented by Open Circuit Voltage (OCV)

$$v(t) = OCV \quad (2-1)$$

SOOC of a cell is 100% when cell is fully charged and SOC is 0% when cell is fully discharged. The amount of charge removed from 100–0% is the total capacity measured in Ah or mAh. Following are the models used for Lithium-ion battery to determine the performance on the system [15].

2.3.1 Simple battery model R_{int} model [12]

Figure 1 illustrates the most widely used battery model. It consists of an ideal battery with open circuit voltage (OCV) V_0 , a constant equivalent internal resistance R_{int} , and $v(t)$ as the terminal voltage. When completely charged, the terminal voltage $v(t)$ may be determined by measuring the open circuit voltage, and R_{int} can be determined by connecting a load and detecting both the terminal voltage and current.

SOC is represented as $z(t)$ of a cell is 100% when cell is fully charged and SOC is 0% when cell is fully discharged. The amount of charge removed from 100–0% is the total capacity (Q) measured in Ah or mAh.

$$v(t) = OCV(z(t)) - i(t)R_{int} \quad (2-2)$$

$$\frac{dz}{dt} = \frac{-i(t)}{Q} \quad (2-3)$$

$$z(t) = z(t_0) - Q \int_{t_0}^t i(T) dT \quad (2-4)$$

At the point when a battery is completely charged, its Open Circuit Voltage is higher than when it is discharged. The R_{int} model appears to be relatively simple, however it ignores the variable nature of the internal resistance related to temperature, state of charge, and electrolytic concentration.

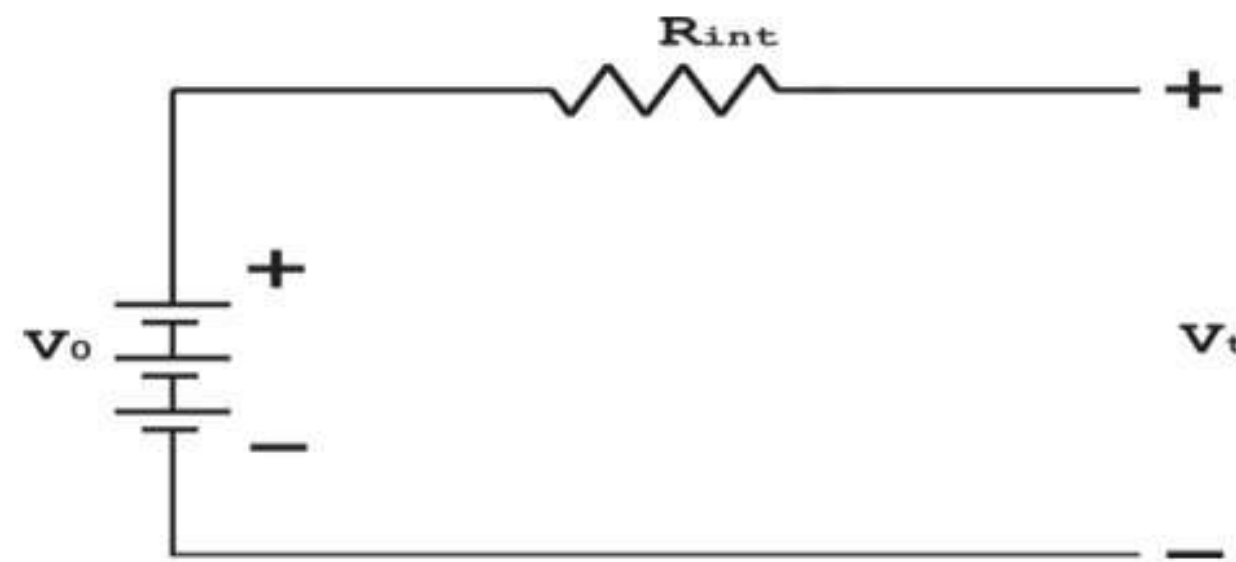


Figure (2-3): Resistive Thevenin battery model.

2.3.2 Resistive Thevenin battery model [14]

Figure (2-3) shows the circuit schematic for the resistive Thevenin battery model. This model has two types of internal resistances, R_0 and R_1 , which are connected to the charging and discharging properties of the battery, respectively. Electrical and non-electrical losses are modelled by the internal resistances R_0 and R_1 . Diffusion Voltages also can be closely found using 1 or more RC parallel branches. The model gives better results than R_{int} model, however transient conditions like the capaci-

tance effect are not considered. As a result, this model is non-dynamic and unsuitable for applications involving electric vehicles and electric hybrids [16].

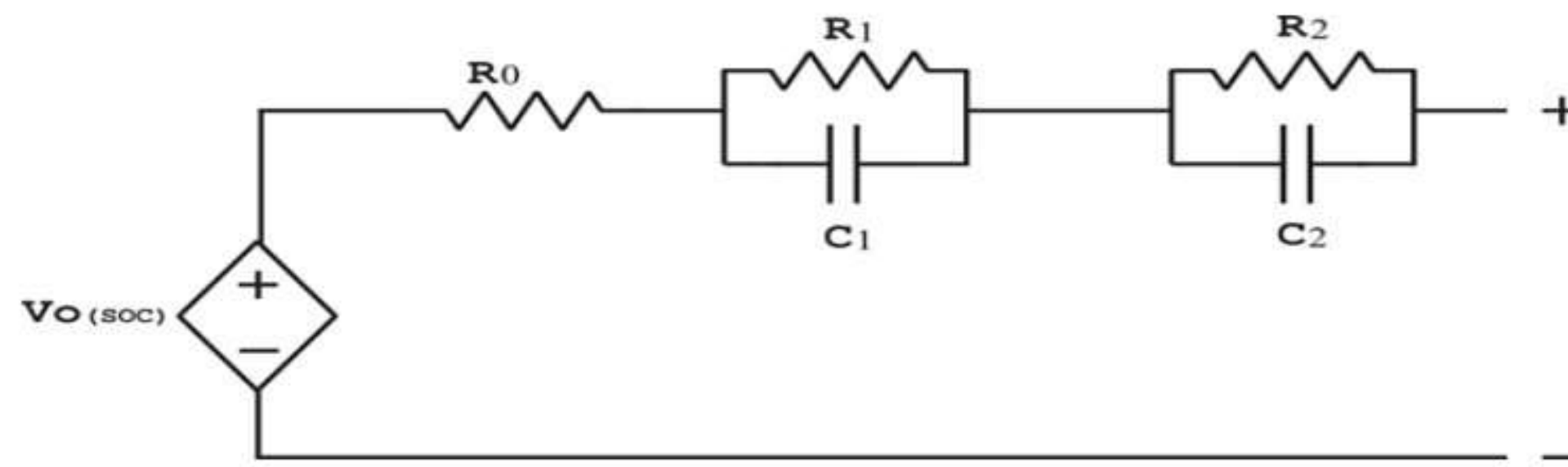


Figure (2-4) Thevenin battery model with 2 RC branches.

In relaxation mode, voltage gradually reduces to zero, this is termed as diffusion voltage which can be closely approximated using parallel RC branches (**Figure 2-4**).

$$v(t) = OCV(z(t)) - i(t)R_{int} - V_c1(t) \quad (2-5)$$

2.3.3 An accurate electrical battery model [14]

An Accurate Electrical Battery Model, models the battery capacity, charging state, and run time using a capacitor and a current controlled source. The circuit takes into account the battery life time as well as the slow and fast transient response. A voltage controlled voltage source that is a function of state of charge is used to overcome the barrier between SOC and OCV (**Figure 4**) [17].

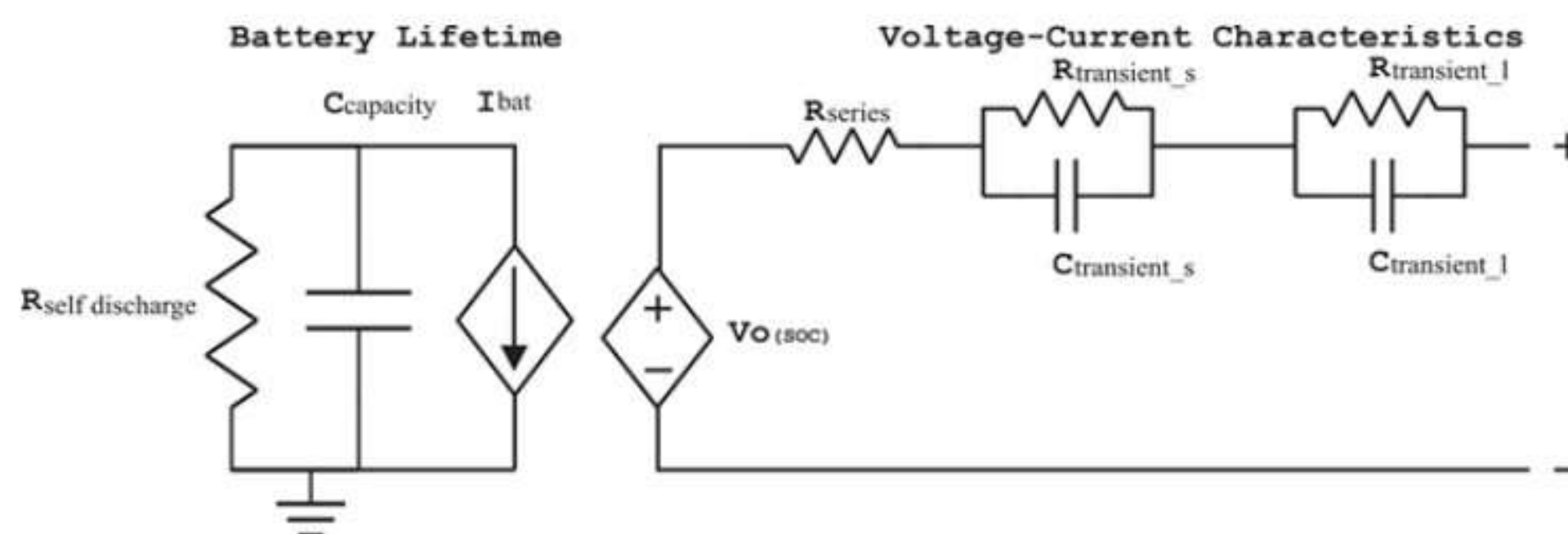


Figure (2-5) Accurate electrical battery model.

2.3.4 Models of electrical equivalent batteries

Table 1 gives the different Electrical equivalent circuit models along with its important features so that it will be useful to predict the performance of the battery and for which application the battery can be used for.

S.No.	Battery model	Features
1	<i>Rint</i> model	Model is static.
2	Thevenin electric model	Does not consider the dependency of state of charge.
3	Second order RC Thevenin model	Model does not consider the parameters like temperature and capacity.
4	Accurate electrical equivalent model	Model considers the battery life time.

Table (2-1) Comparison of electrical equivalent battery models .

2.4 Experimental test data on lithium-ion batteries INR 18650 [18]

CALCE provided open access to our experimental test data on lithium-ion batteries, including continuous full and partial charge and discharge cycles, storage, dynamic driving modes, open-circuit voltage measurements, and impedance measurements. This test data can be used to estimate battery condition, predict remaining life, model accelerated battery degradation, and analyze reliability. A description of the INR 18650 battery and each of its tests is provided below.



Figure (2-6): INR 18650-20R Battery

2.4.1 Lithium-ion battery specifications used for battery model: LIR18650 mAh are given in the following Table 2 [19].

Capacity	Nominal capacity: 2600mAh (0.52A discharge, 2.75V)
Nominal voltage	3.7V
Internal impedance	$\leq 70\text{m}\Omega$
Discharge cutoff voltage	3.0 V
Maximum charge voltage	4.200.05V
Standard charge discharge current	0.52A
Rapid charge discharge current	1.3A
Maximum pulse discharge current	2.6 A

Table(2-2) Battery model specifications LIR18650m AH.

2.4.2 Data and Test Description (as an example):

The data is mainly for the following steps:

- o "3. Now Discharge until the voltage drops to 2.5V
- o 4. Fully Charge at constant rate to 4.2V"
- The spike at the beginning (step-index 1-4) was a charging process (step-index 1 for resting, step-index 2-3 for charging) to ensure the battery is fully charged before data collection from the low current discharge test.
- Step-index 4 (also step-index 9) is a resistance measurement step, so there is a negative current for just one data point.
- In addition, steps with 0A are usually from a resting period. The resting period is particularly necessary, but the data may be ignored depending on the focus.

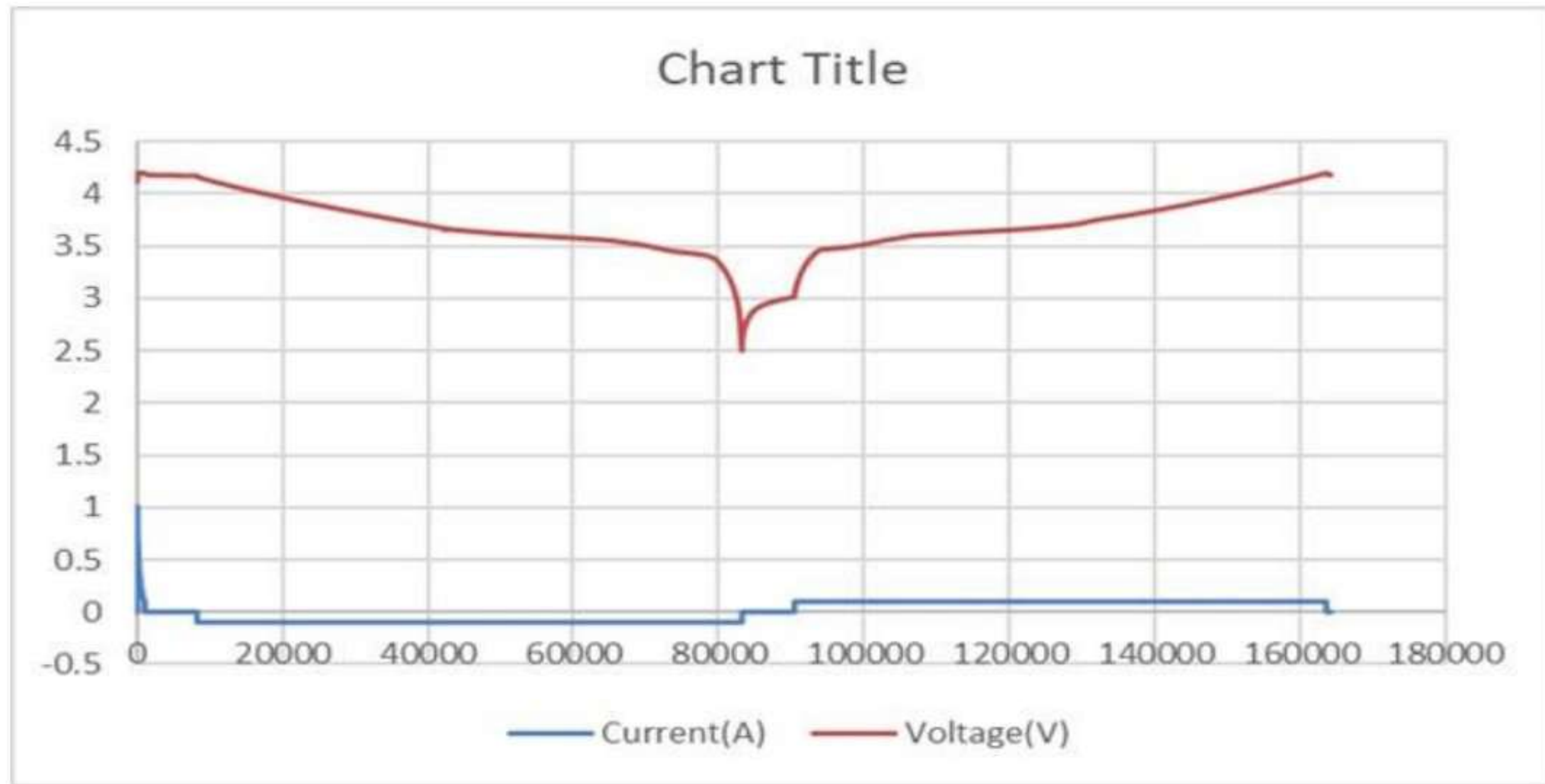


Figure (2-7): Battery charging and Discharging with Experimental DATA

2.5 Resultant Simulation

2.5.1 Equivalent circuit modeling

Equivalent circuit modeling (ECM) is the most common approach for battery numerical analysis. For lithium cells, a one or two RC block model with no parasitic branch is a common choice [1-3]. It has the advantage of being computationally simple. Fig.1 shows the ECM presented for batteries, For lithium cells a one RC block model.

Recall that charge is found by integrating electric current, so you can use an Integrator block (Simulink → Continuous library). Assume that the initial battery charge is 33 ampere-hours. This will be the initial condition of the integrator.

Hint Time in Simulink is measured in seconds. One ampere-second is equivalent to 1/3600 ampere-hours. **Figure (2-(9-10-11-12)).**

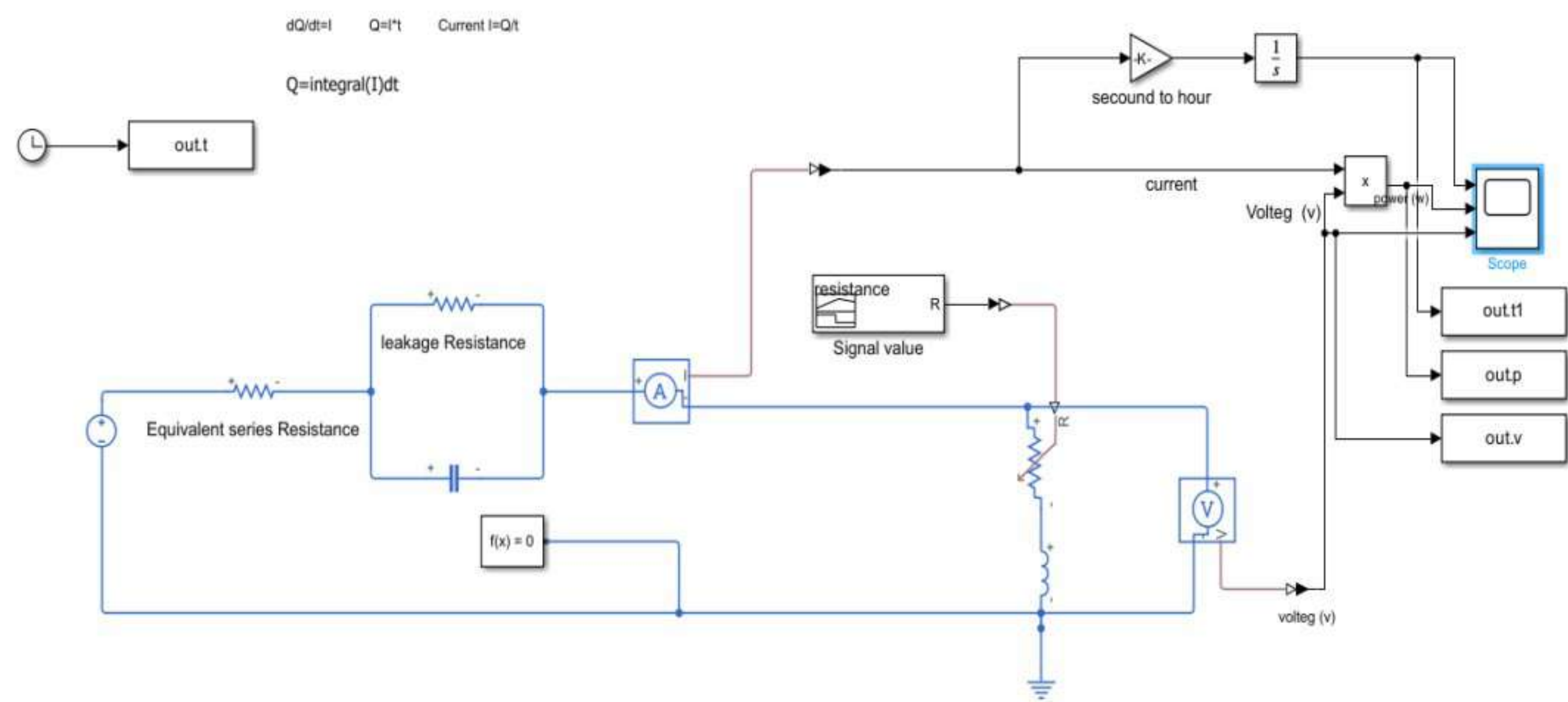


Figure (2-8): Battery Modeling under Variable Resistive Load using Simulink.

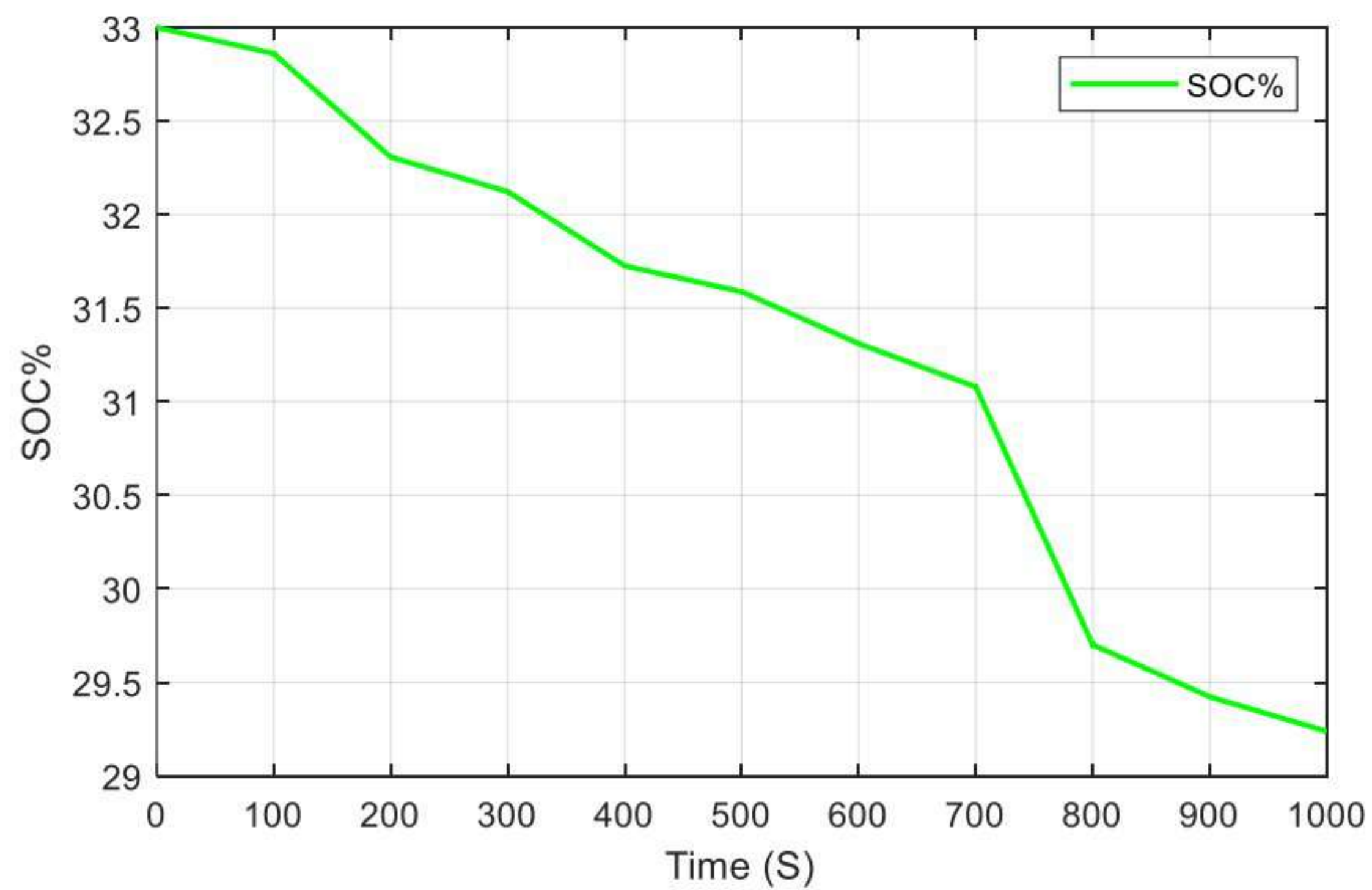


Figure (2-9): battery SOC profile

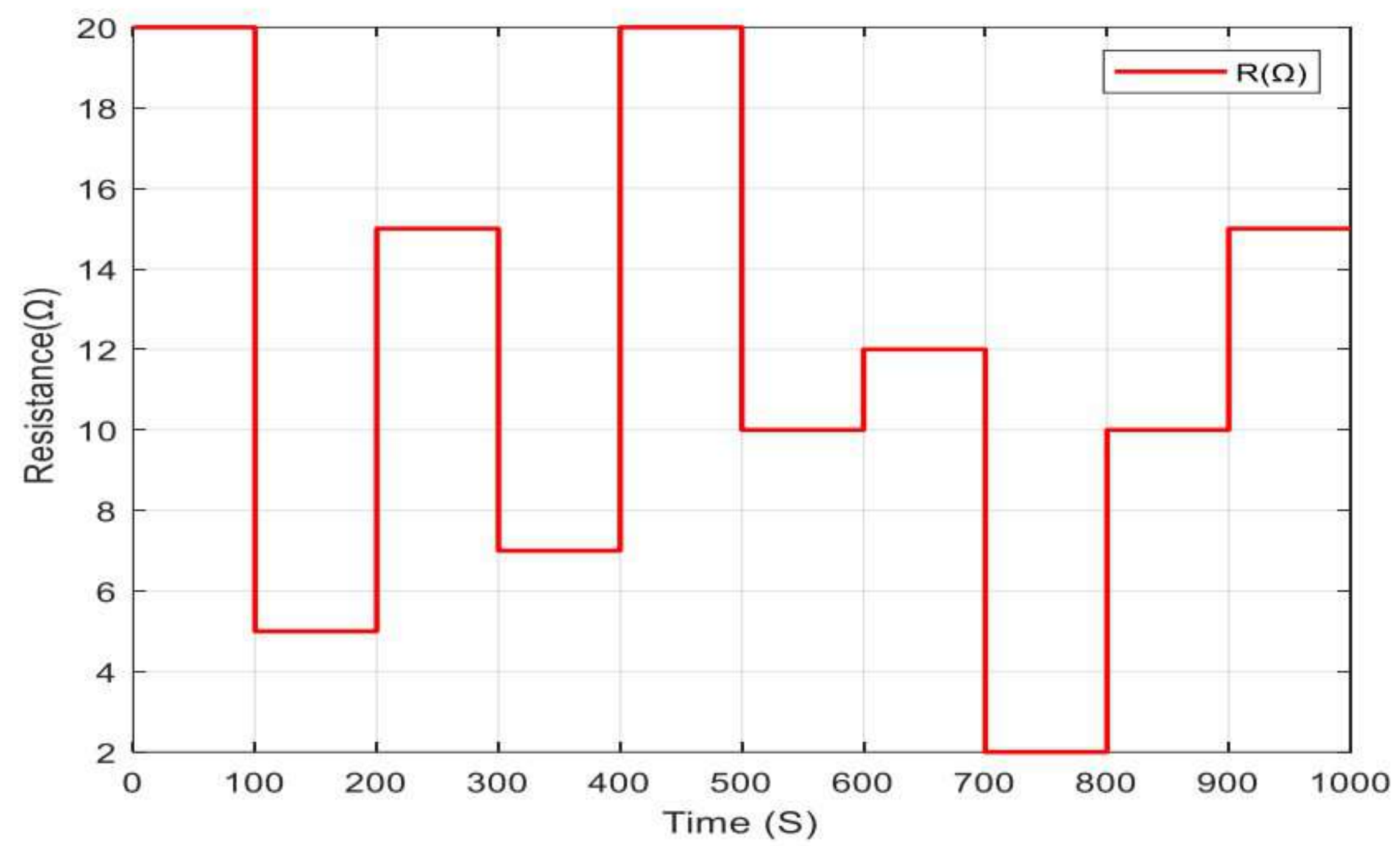


Figure (2-10): Variation of resistance

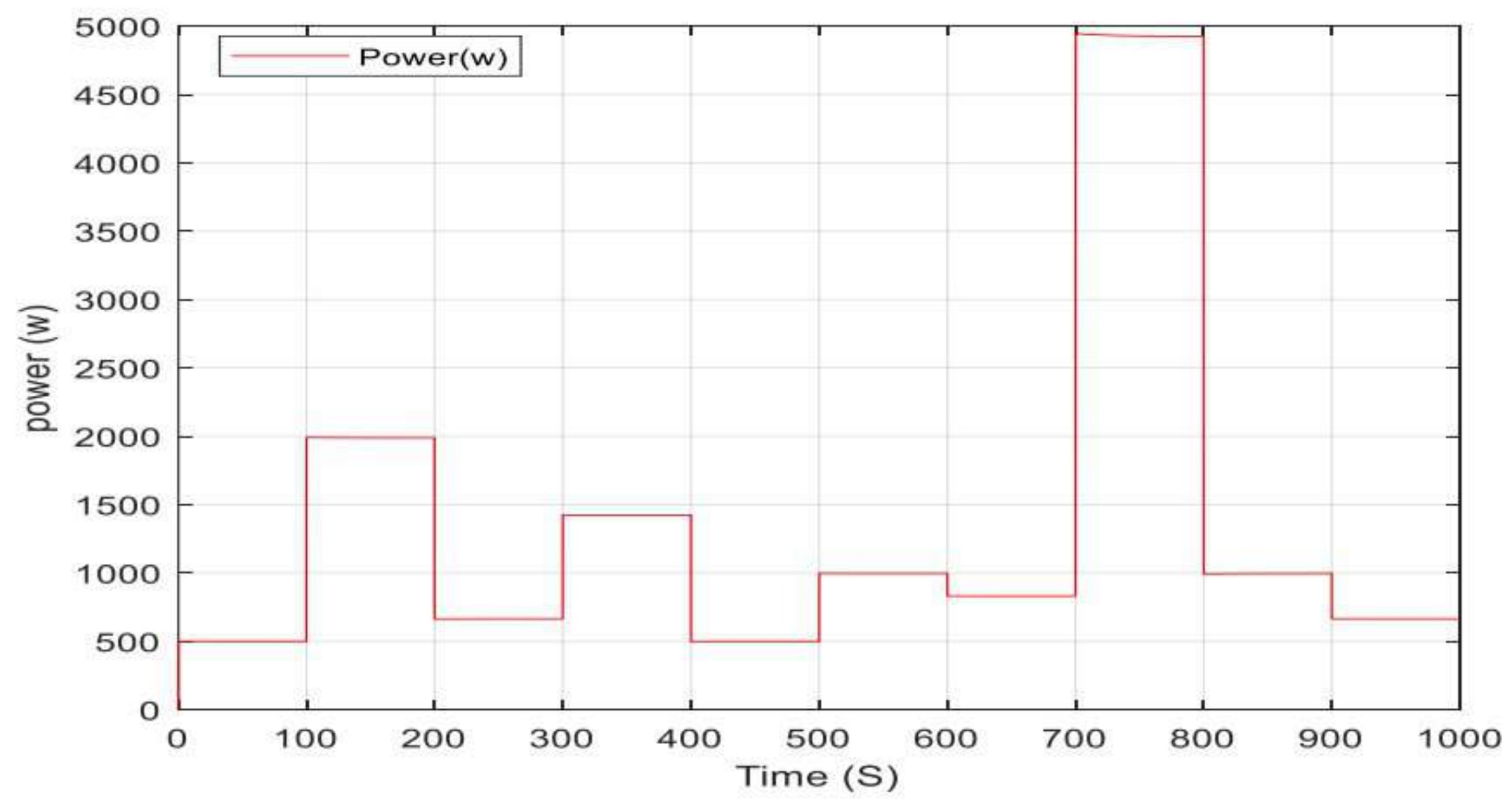


Figure (2-11): Variation of Power

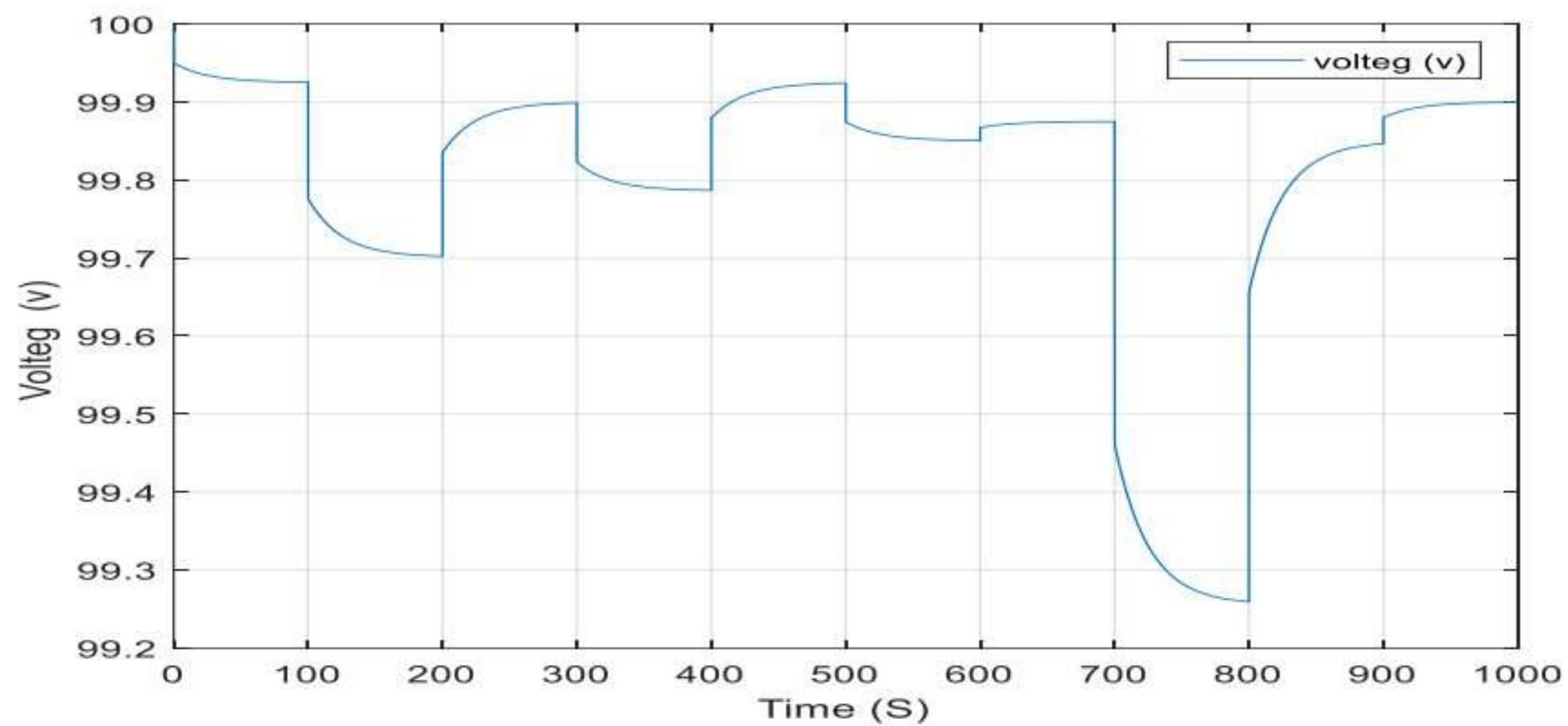
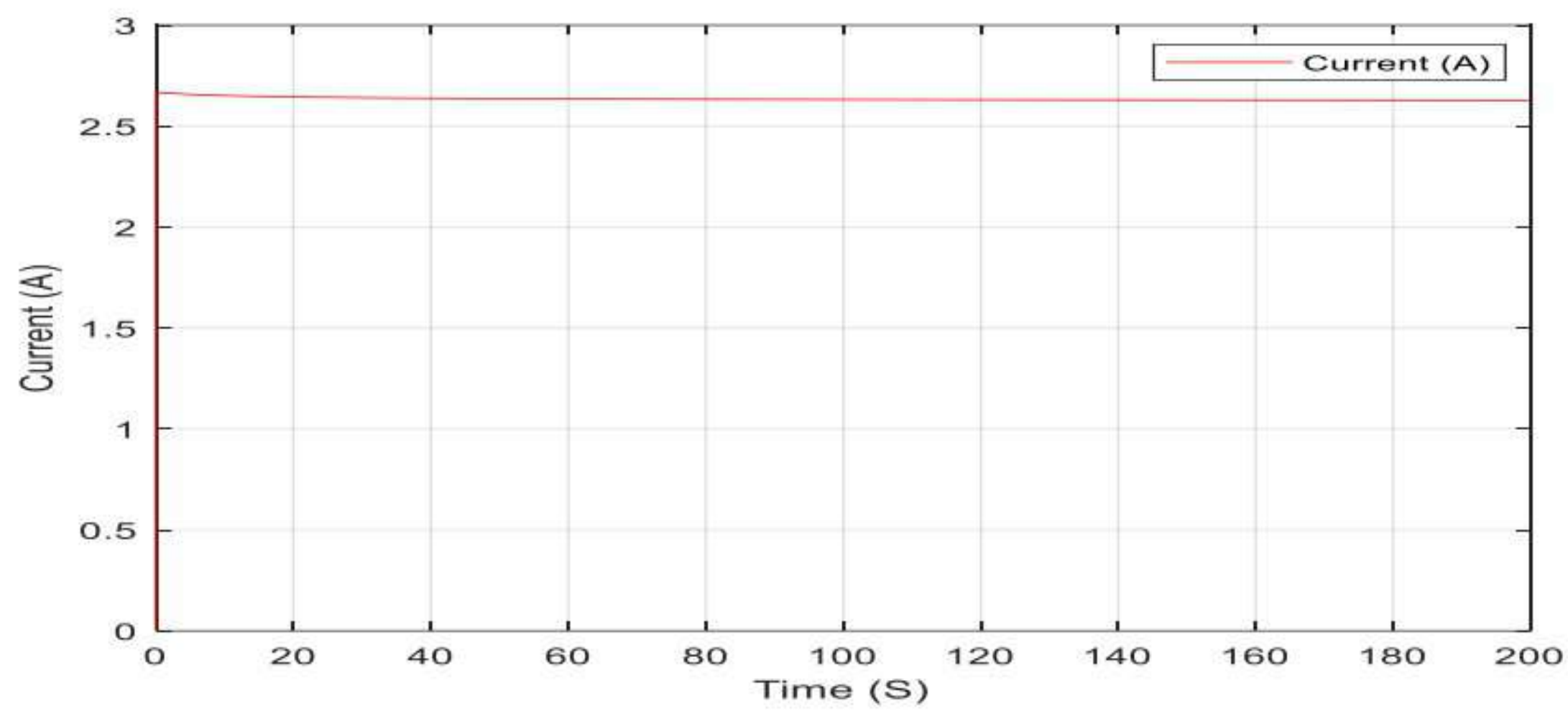
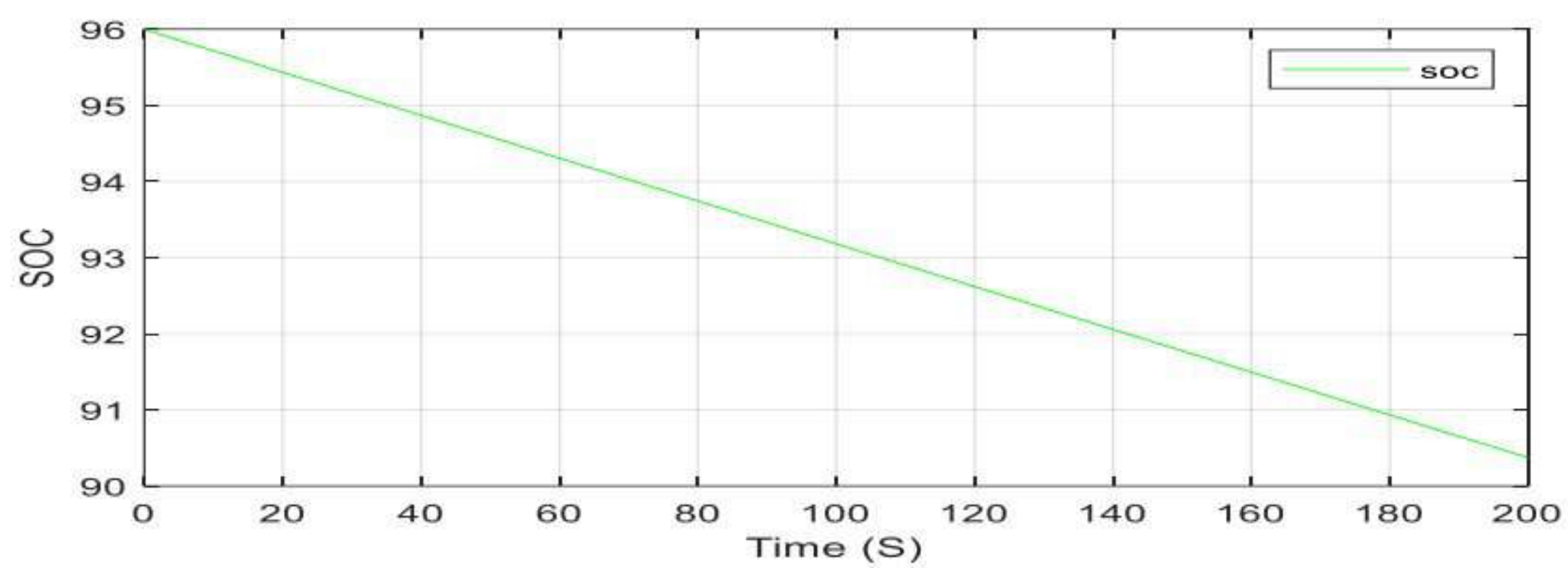
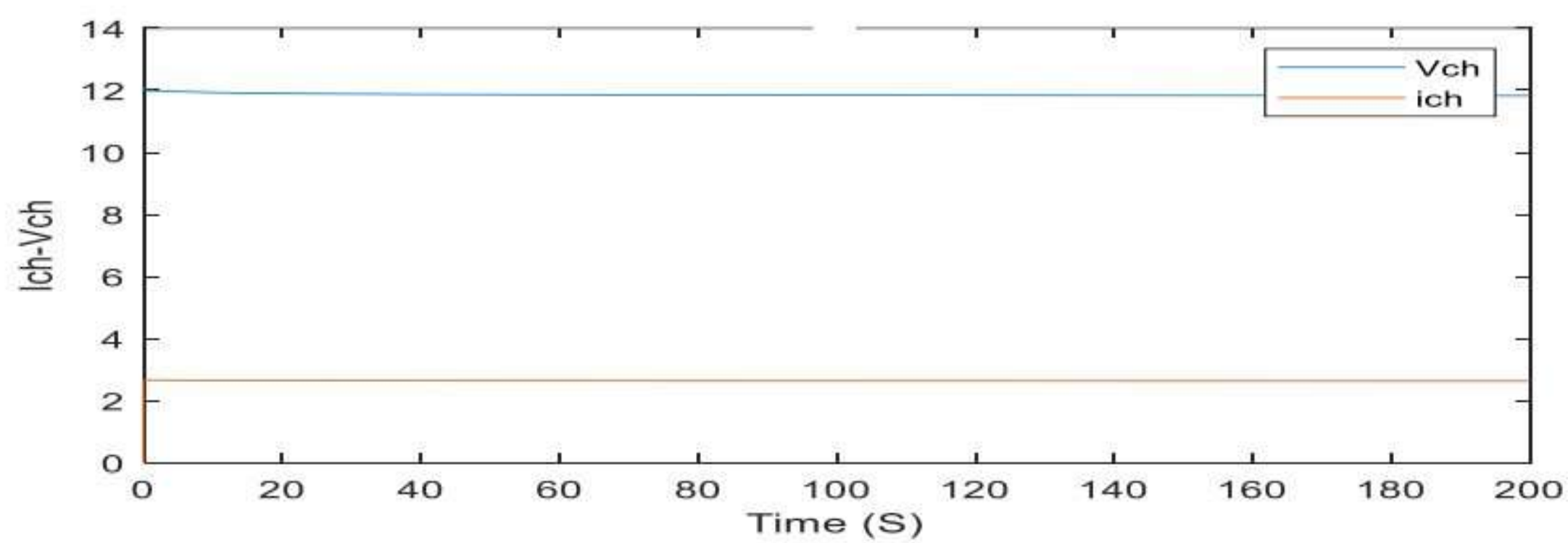


Figure (2-12): battery voltage profile

2.5.2 Pack battery

The battery pack was configured using a three-cascaded battery architecture (**Figure (2-13)**) to increase the output voltage and energy capacity required for high-power applications. The simulation results in **Figure (2-(14-15-16-17))** demonstrated the effectiveness of the cascaded configuration in ensuring stable voltage distribution, improved power delivery, and better energy management during charging and discharging operations. The analysis also highlighted the influence of pack configuration on the overall system performance, efficiency, and reliability, which makes this approach suitable for integration with DC fast charging systems and electric vehicle applications.

**Figure (2-15): Profil of current****Figure (2-16): one cell characteristic****Figure (2-17): pack battery characteristic**

2.5.3 Battery Charger

Battery chargers are power converters. These systems are an indispensable part of many power systems that require energy transfer from one voltage value to another, as the required voltage value may be different from the voltage value provided. These systems can be used in three different structures: Buck, Boost and Buck-Boost Converters.

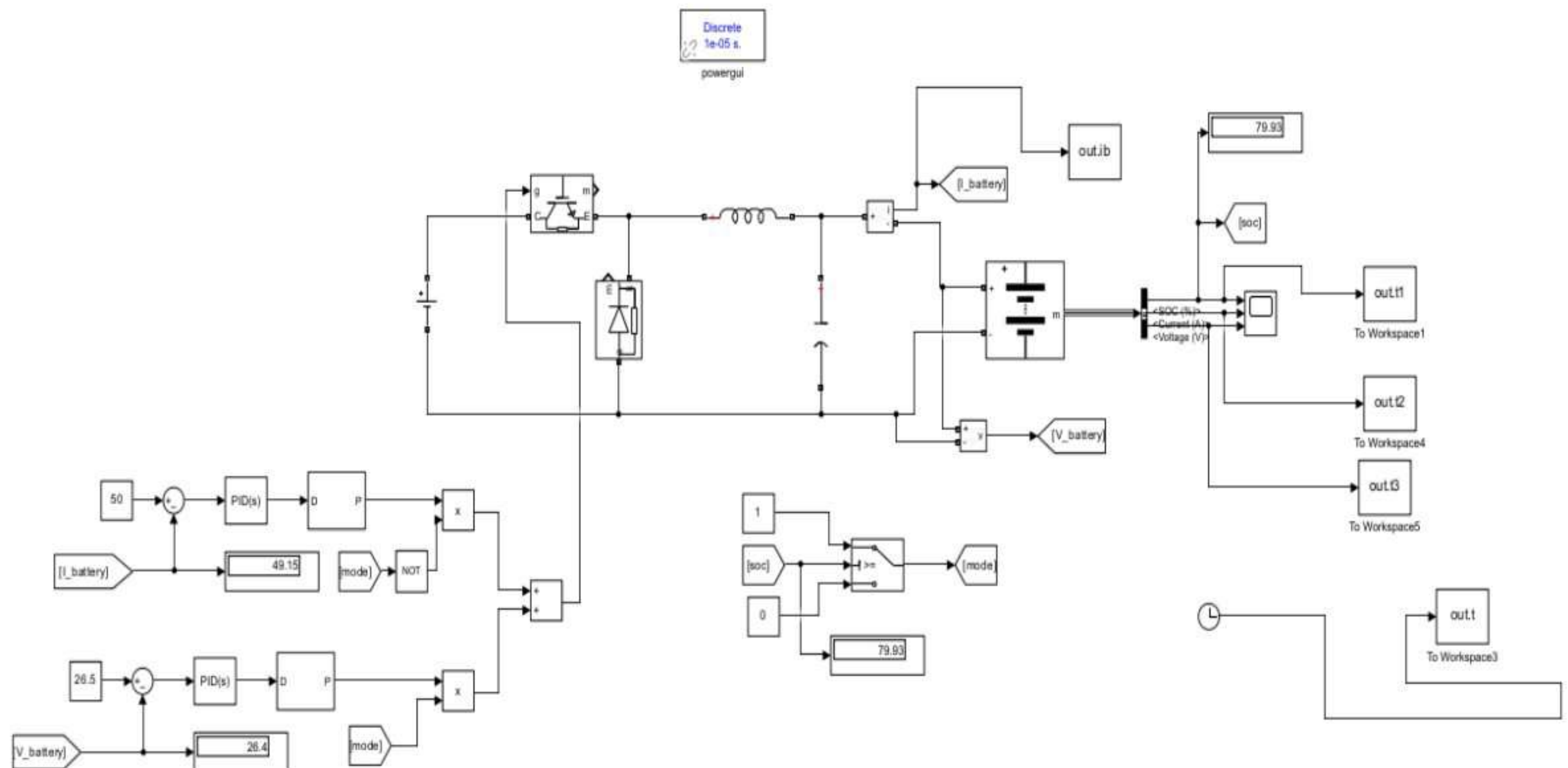


Figure (2-18): Battery charging using constant current and constant voltage

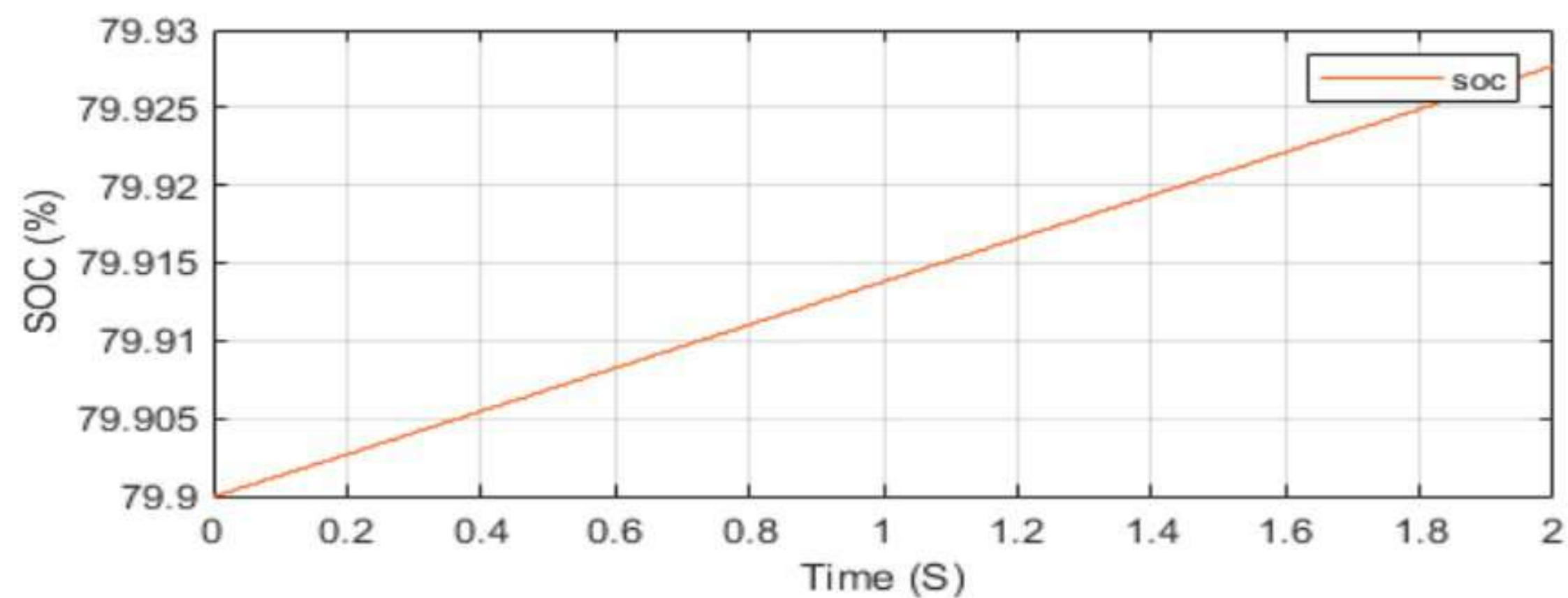


Figure (2-19): Soc of battery

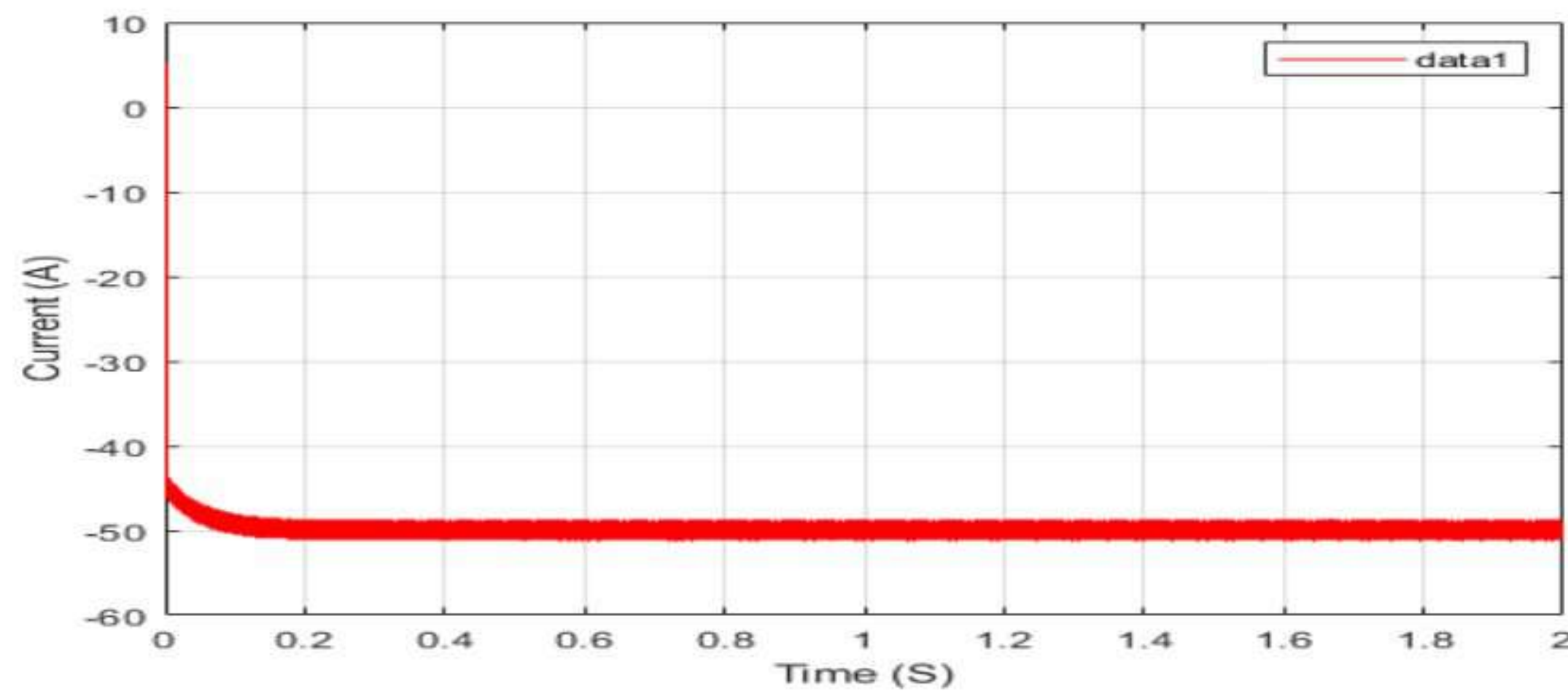


Figure (2-20): Profil of current

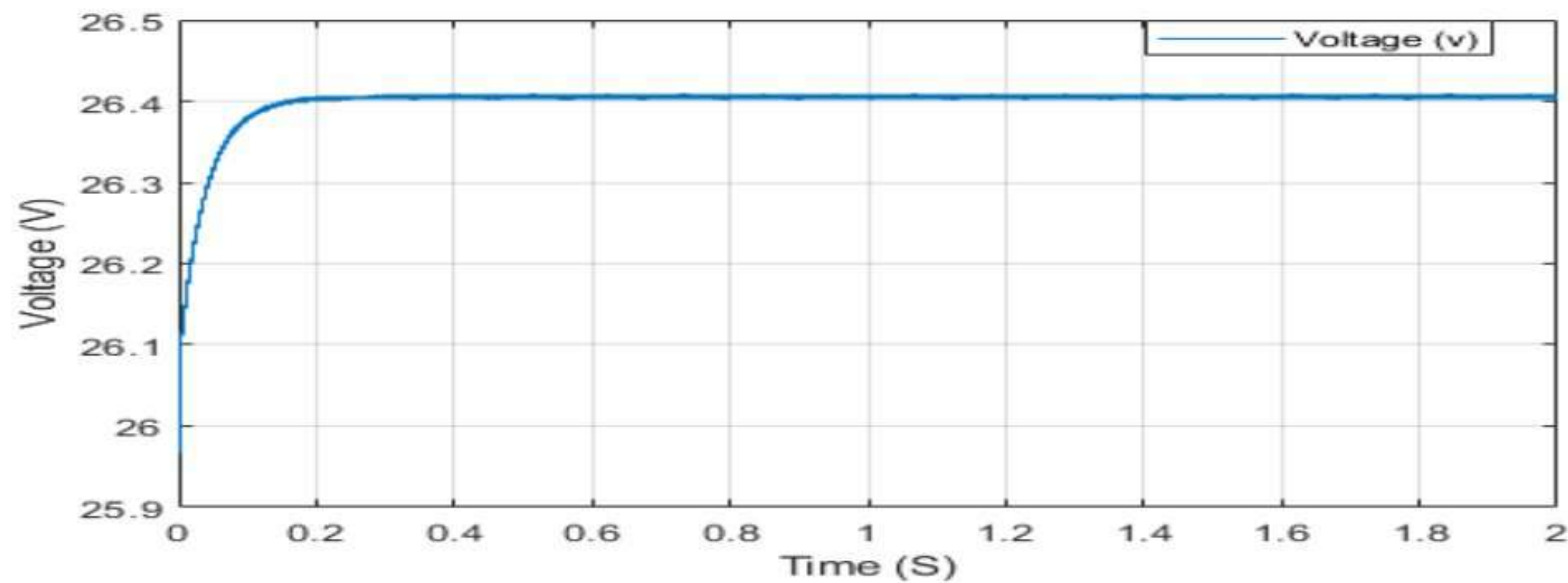


Figure (2-21): Battery charging control with CC/CV

2.6 Conclusion

This chapter presented the modeling and simulation of lithium-ion batteries and battery packs, highlighting their electrical and dynamic behavior under different operating conditions. The developed models provide an effective tool for analyzing important battery parameters such as voltage, current, power, and state of charge. The obtained results establish a strong foundation for the next chapter, which focuses on the design and simulation of the DC fast charging system for electric vehicle applications.

Chapter 3
DC Fast Charging

3.1 INTRODUCTION

Now a day's Electric vehicle is boosting the market & day by day demand for electric vehicle is goes on increasing due to increasing in cost of fuel. The electric drive train & power train is most effective technology to improve vehicle efficiency but estimating optimum point between efficiency & cost is crucial. As we know that, electric vehicle is majorly consists of Battery, controller, motor & battery management system but out of which Battery is most important device to run the vehicle. As we knows that in electric vehicle the cost of the battery is one of the major factor, so performance & charging of battery will be very important. But as the usage Of electric vehicle will increase, battery charging demand will also increase. We need to increase battery charging infrastructure to fulfill the battery charging demand.

Generally we are using AC Charging system to charge the battery but it takes more time to charge it. So to reduce charging time & to provide fast charging, we are using DC Fast charger. DC Fast charging infrastructure consists of various different charging algorithms to charge the battery.

In this chapter a detailed description of the design and simulation of a DC fast recharging station for Electric Vehicles is carried out. The system consist of a single AC/DC grid connected inverter, a DC-Bus and DC/DC converter to recharge the batteries of the EVs. The design of the components of the system and the control schemes are explained and a simulation of the system, performed in Matlab/Simulink environment is presented.

3.2 DC charging levels.

Figure 1 and Table 1 list the charge level according to various international standards and norms for charging cars . As DC charging systems are primarily designed for use in outdoor stations (Home, office, Public private), they require suitable wiring. They are more efficient, allowing for faster charging. In reality, modern charging stations transform DC voltages to levels more suited for EV battery packs. Overall, fast-charging stations exhibit a higher usage rate compared to public Level 2 charging stations, with Fast DC stations displaying a utilization rate nearly three times higher than AC charging points [20, 21].

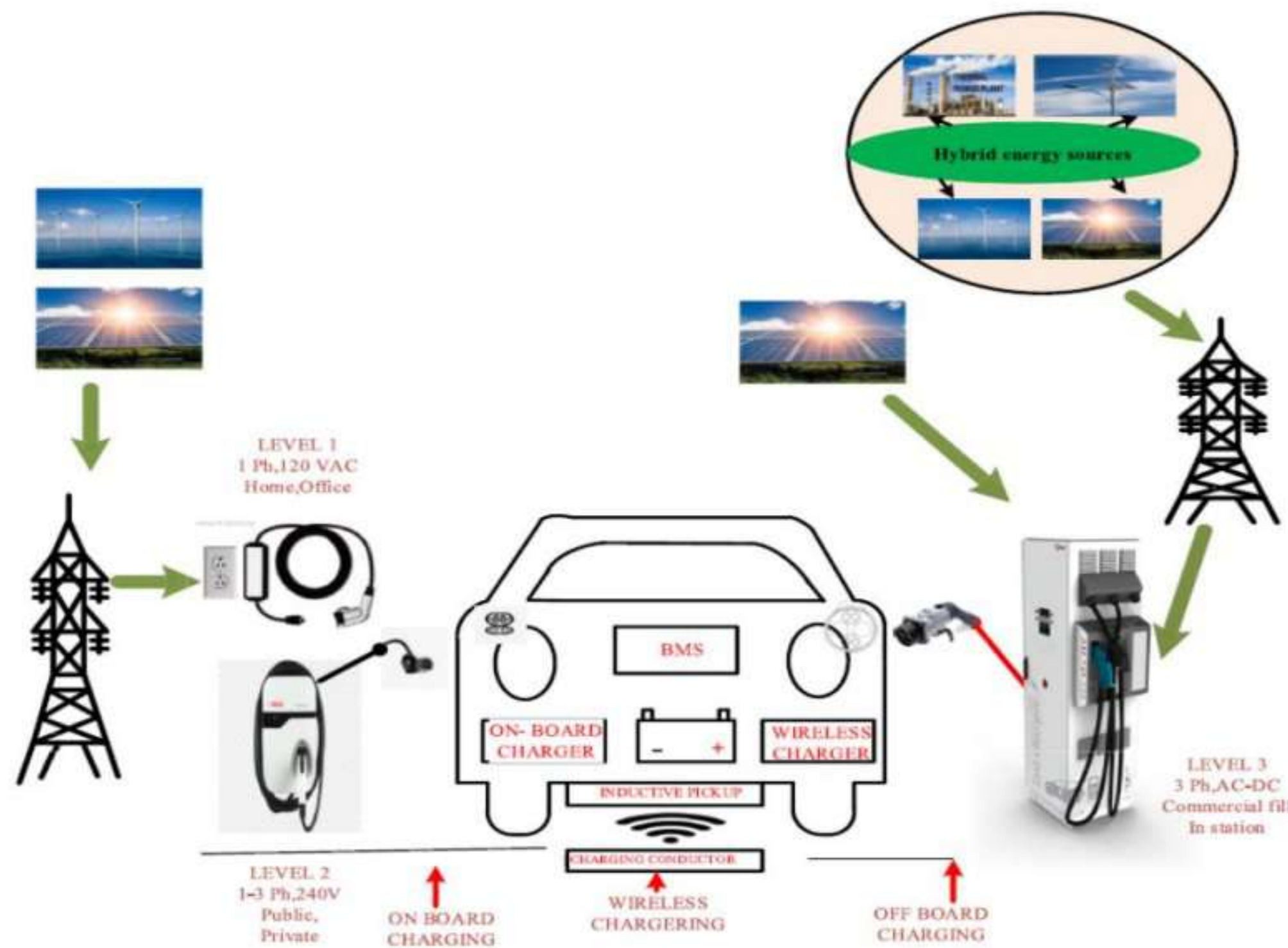


Figure (3-1) Off-board and On-board EV charging infrastructure, as well as power levels.

There are three types of chargers available: Level 1, Level 2, and Level 3. Level 1 chargers provide up to 40 kW of charging power at 250–450 V and 80A. Level 2 chargers are similar to Level 1 chargers, but their rated current is 200 A, and their operating voltage can reach 400 V. Level 3 chargers have a rated voltage of 600 V, a maximum current of 400 A, and a rated power of 240 kW . [22]

TABLE (3-1):DC charging levels.

Level of charging	Power(KW)/current(A)
<i>SAE standards</i>	
Level1: $V_{dc} = 200 - 450V$	40KW/80A
Level2: $V_{dc} = 200 - 400V$	90KW/200A
Level3: $V_{dc} = 200 - 600V$	240KW/400A

3.3 EV Charging ports and Sockets. [23]

One of the most important components for charging these electric-based vehicles is the charging ports, and the other is the charging sockets. In addition to complying with the standards to be charged, EV's electrical infrastructure must also be suitable for charging the charging unit

and fasteners. There are standard and prepared charging levels suitable for each EV. For example, the current parameter for EV or hybrid EV can be charged from low-level-1 chargers or from level-2, level-3 chargers that can offer high-value current. The connection equipment to be used may also vary depending on the type of charging unit, the current presented to the vehicle, the voltage level and the country in which the system is located.

In addition to the fact that EVs can be provided with the conditions required for optimal charging and control systems that keep these conditions within a certain framework, there are international standards for ensuring control. These standards both ensure safety and provide optimal solutions. Below is a list of charging port and socket standards in Figure-2 and Figure-3.

	USA	JAPAN	EU		CHINA
Single Phase/ 3-Phase AC Charging	 SAE J1772 Level 1, Level 2 Single phase	 SAE J1772 Level 1, Level 2 Single phase	 IEC 62196 Level 1 Single Phase	 IEC 62196-2 Level 2,3 Single/Three phase	 IEC 62196 Level 1,2 Single/Three Phase
DC Fast Charging /AC- DC Combo	 Level 1 + DC Level 2 + DC SAE J1772 Combo	 JEVS G105- 1993 CHAdeMO DC Fast Charging	 IEC 62196-3 Hybrid Combo		 GB/T 20234.3- 2011 DC Fast charging

Figure (3-2) EV Charging ports.

	USA	JAPAN	EU	CHINA
Single Phase/ 3-Phase AC Charging	 SAE J1772 Level 1, Level 2 Single phase	 SAE J1772 Level 1, Level 2 Single phase	 IEC 62196-2 Level 1, 2 Single/Three phase	 IEC 62196 Level 1,2 Single/Three Phase
DC Fast Charging /AC- DC Combo	  SAE J1772 Level 2 + DC Combo Tesla Supercharger	 CHAdeMO DC Fast Charging	 IEC 62196-3 Hybrid Combo	 GB/T 20234.3- 2011 DC Fast charging

Figure (3-3) EV Charging Sockets.

3.4 DC fast charger power conversion systems [22]

Various governing bodies have developed standardized protocols for the DC fast charging system to certify compatibility. The block diagram of conventional DC fast charger power conversion systems is shown in Figure 2.

There are two primary options for designing a DC fast charger system. The first option involves incorporating a line frequency transformer before the AC/DC stage to achieve isolation from the grid (refer to Figure 2(a)). The subsequent DC/DC stage, however, is non-isolated in this configuration.

The second option utilizes a high-frequency transformer within an isolated DC/DC converter to provide the necessary isolation (refer to Figure 2(b)).

In scenarios where a single-module charger fails to meet the power requirements of the DC fast charger system, a strategy involves connecting multiple identical modules in parallel to collectively increase the output power. This is illustrated in Figure 2(c) and (d).

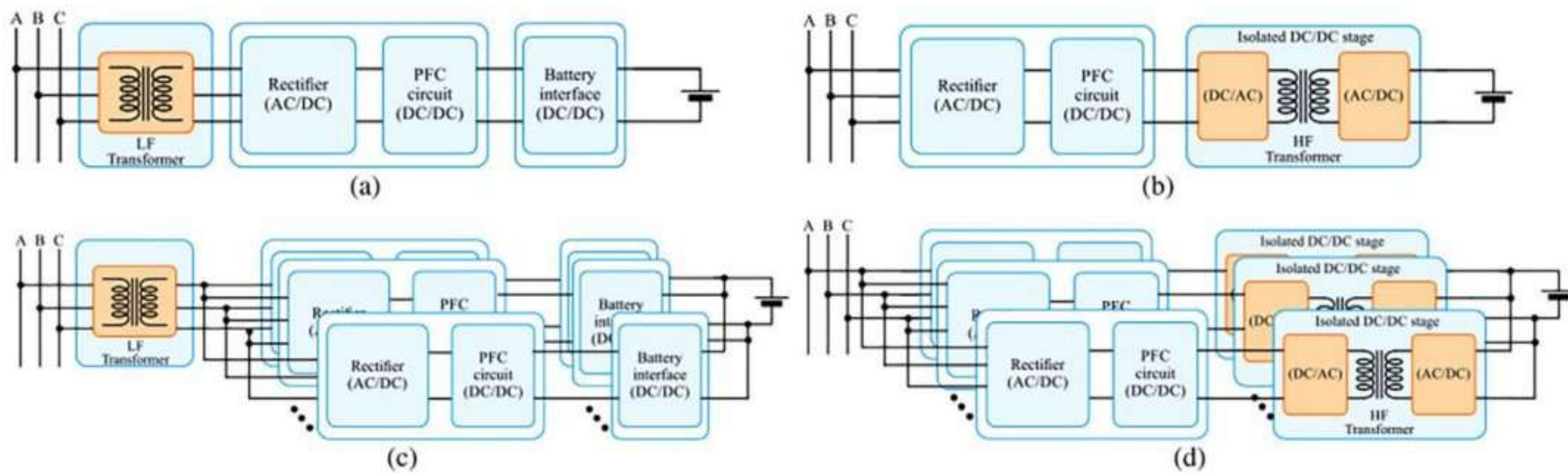


FIGURE (3-4) Simplified block diagram of conventional DC fast charger power conversion systems. (a) Single-module charger with a non-isolated DC/DC converter. (b) Single-module charger with an isolated DC/DC converter. (c) Multiple paralleled version of the type of module shown in (a). (d) Multiple paralleled version of the type of module shown in (b).

3.5 Status of the DC Fast-Charging Station with an isolated DC/DC [23]

Galvanic isolation is required between the grid and the EV battery pack.. In this work the way of galvanic isolation using a high frequency transformer (HFT) in the DC/DC stage. The block diagram of conventional DC fast charger power conversion systems with isolated DC/DC converter stage is shown in Figure 5.

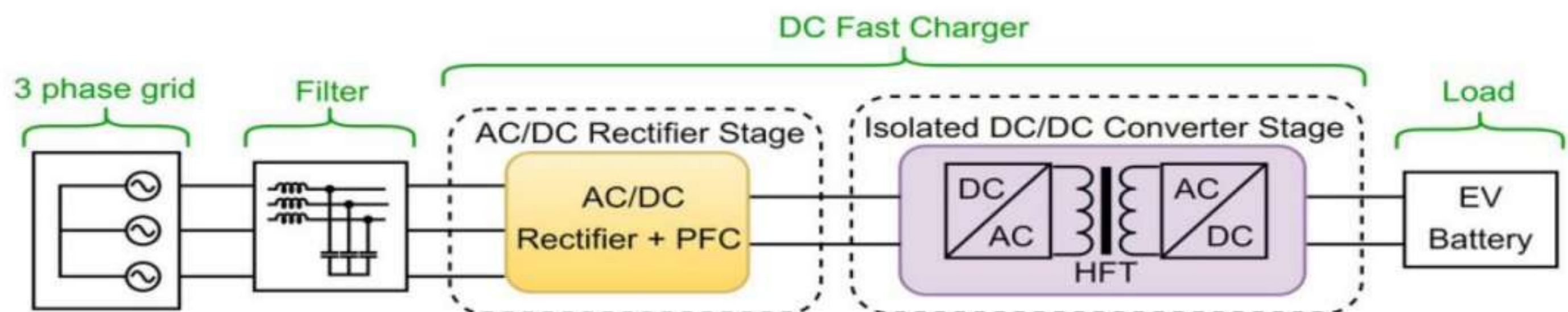


Figure (3- 5) Block diagram of DC fast-charger power conversion stages with an isolated DC/DC

A filter connected at the input stage of the rectifier reduces the harmonic distortion of the current drawn by the rectifier itself. Mostly, LC or LCL filters are preferred due to their better performances, as compared to L filters .

3.6 Filter [24]

Filters are divided into two separate groups in terms of construction elements, active and passive filters. The filter model used in this study belongs to the passive filter group. Passive filters are used as mains converter interface to reduce the harmonic effect in the system and to meet electromagnetic compatibility standards. Many passive filter topologies have been reported in the literature. Inductive filters were first recommended in the literature. These filters are first order filters. For this reason, a high value inductor is required to reduce the harmonic effect, but a high value inductor will lead to a high voltage drop. Therefore, the response of the control time is affected by this situation. Therefore, in order to reduce the size of reactive circuit elements, higher value switching frequencies should be preferred. It should be noted that increased switching frequency increases the losses in the power converter. The characteristic of second order LC filters is that they increase the higher frequencies and the reduction in filter volume. The downside of the LC filter

topology is the presence of a resonant frequency that can amplify high order current harmonic components, and in addition, problems from inrush currents in the output capacitor arise. High-order current harmonic components cause general instability in the installed system. LCL filters, as an alternative solution to LC filters, with developments, It is a third-order passive filter used in many voltage source applications. The LCL filter topology results in a reduction in volume and voltage drop through inductors compared to the simplest L topology.

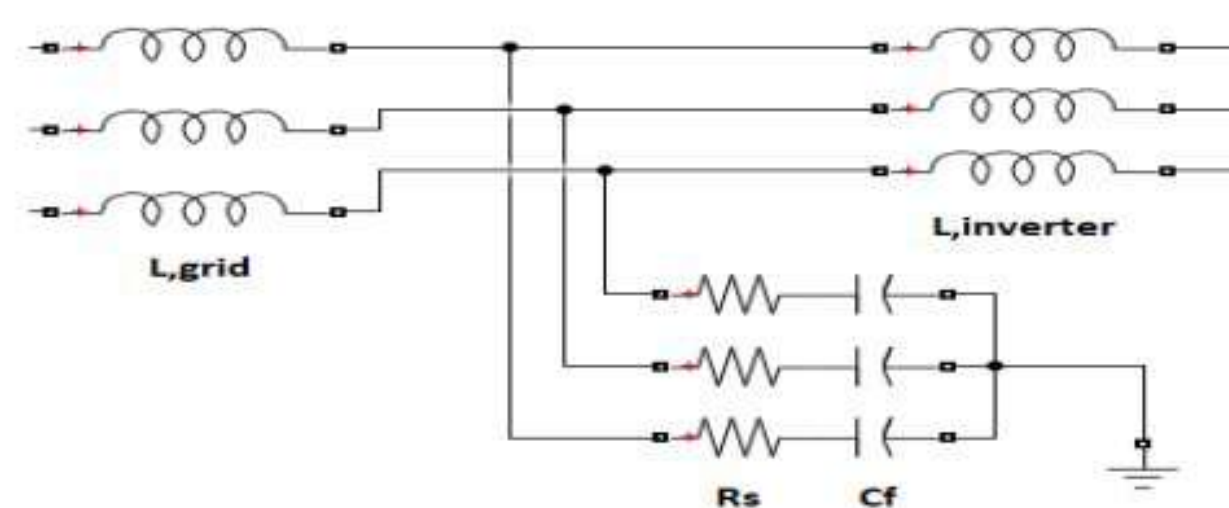


Figure (3.6) LCL Filter

3.7 Three Phase Inverter

The three-phase inverter in the modeled power system is used to turn AC power DC power. The Universal Bridge block used as the inverter in the design is used by the IGBT preferential choice. The universal bridge block allows the use of six power switches connected in a bridge configuration and the use of power transformation. Is a block in the basic structure used to form two-level voltage welded converters .

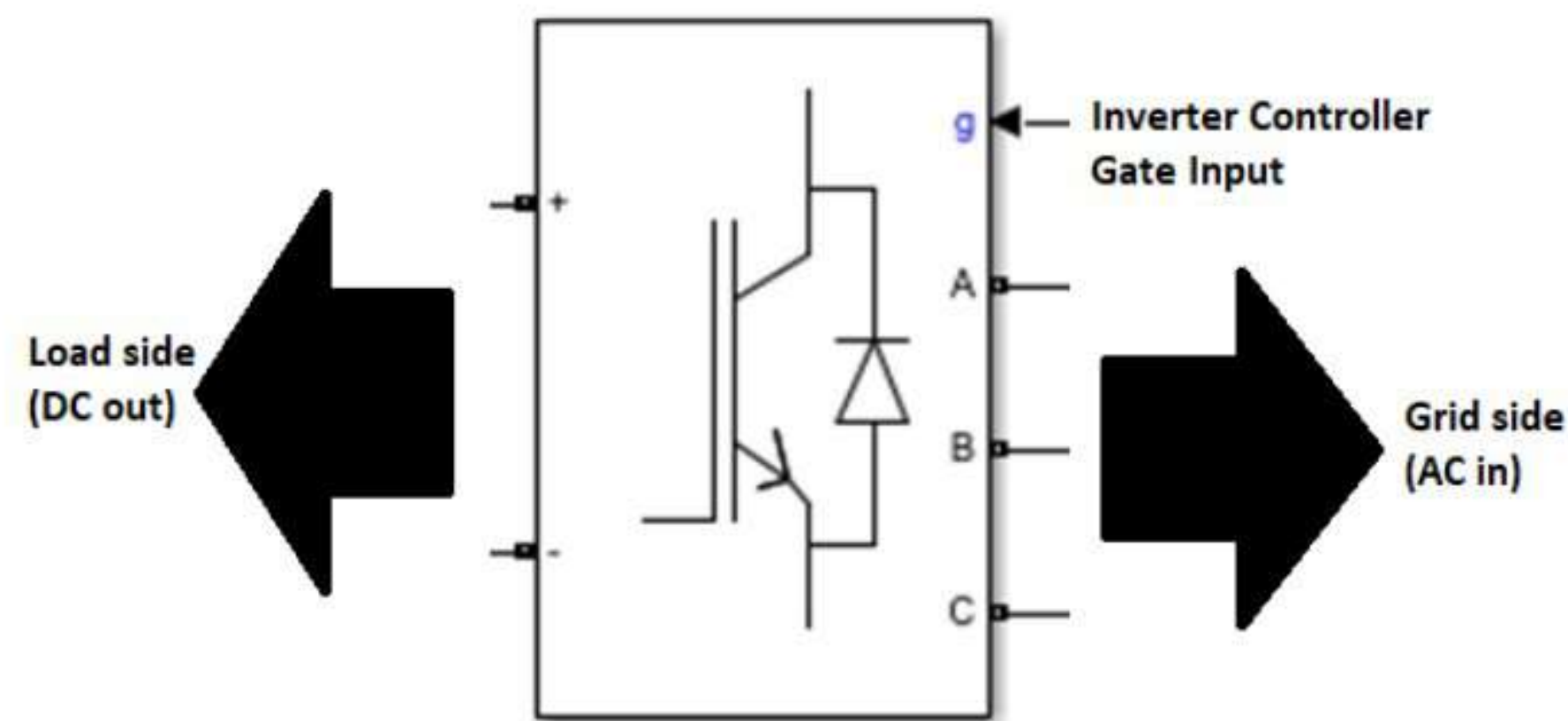


Figure (3-7) MATLAB/Simulink block three-phase inverter.

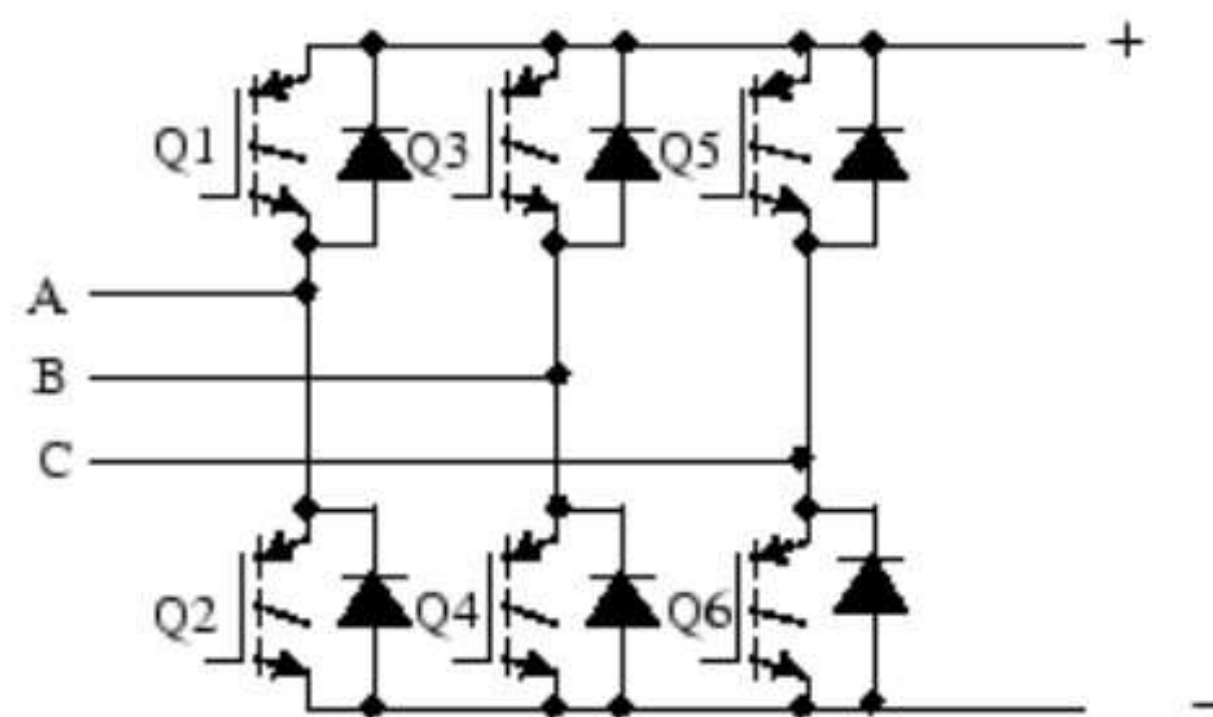


Figure (3-8) Three-phase inverter configuration (AC/DC converter).

3.8 Voltage Oriented Control [24]

Voltage Oriented Control (VOC) depends on arrange transformations amidst stationary α - β and synchronous turning d-q reference framework. It guarantees snappy transient reaction and high performance in relentless state. Because of VOC utilizes an inside current control loops last execution of the framework unequivocally relays on used current control strategies.

The run of the mill VOC framework (Fig. 4) utilizes synchronous current control in pivoting reference arranges, as showed in (Fig. 5). An important development for this kind of current controller is signals processed in two arrange frameworks. The first is stationary α - β and the second one is synchronously turning d-q coordinates framework. Three phases estimation value are swung in to equal 2- ϕ framework α - β and after that are changed to turning coordinate framework in a block α - β /d-q.

Because of the above data the control values are DC signals. A inverse transforming, d-q/ α - β work and it gives an outcome on rectifier reference motions in stationary coordinate:

The angles of our voltage vector us characterised as:

In voltage arranged d-q co-ordinate, the AC line current vector i_c is partitioned into two rectangular segments $i_c = [i_{cd}, i_{cq}]$ as in **(Figure (3-9))**. The part i_{cd} sets up real power(P), where i_{cq} settles on choice about reactive power stream. Hence the real and the reactive power can be controlled autonomously by methods for real&reactive parts of line current vector i_c . The UPF condition is met when the line current vector, i_c , is co-ordinated with the line voltage vector, u_s . By setting the d-axes of the rotating co-ordinates on line voltage vector u_s a disentangled powerful example can be gotten .

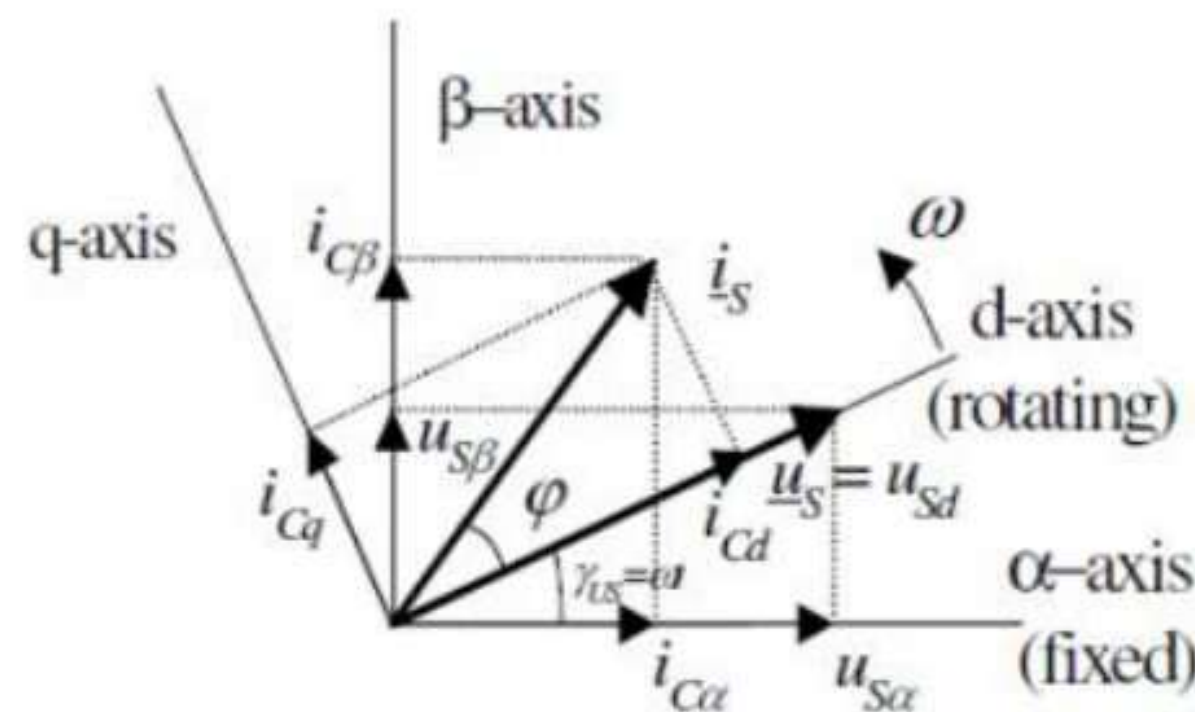


Figure (3-9) Vector graph of VOC.

3.9 VOC with active filtering function:[24]

As an active filter, PWM rectifiers can compensate higher harmonics in a grid current taken by the entire load[6]. Keeping in mind the end goal for compensation of higher harmonics additional control block(AFF) must be joined with standard VOC methodology . The disturbed currents i_{1a} , i_{1b} , i_{1c} are conveyed to the abc/dq change, where a fundamental (50 Hz) harmonic turns into a DC quantity and other harmonics are non-DC values. Next all together, those signals are conveyed to the High-Pass Filter (HPF), which delivers the higher harmonic signals derivations. At that point higher harmonic compensated signals i_{d_fr} , i_{q_fr} are joined with a contrary sign to the standard VOC reference signals i_{cd} and i_{cq} gives the last signals i_{d_err} , i_{q_err} conveyed to PI current controllers. A similar plan is taken after for every portrayed harmonics.

3.10 Voltage Oriented Control 'VOC' :

The conventional control system utilizes closed-loop current control in the rotating coordinate system. Its general structure is shown in Figure (III.1).

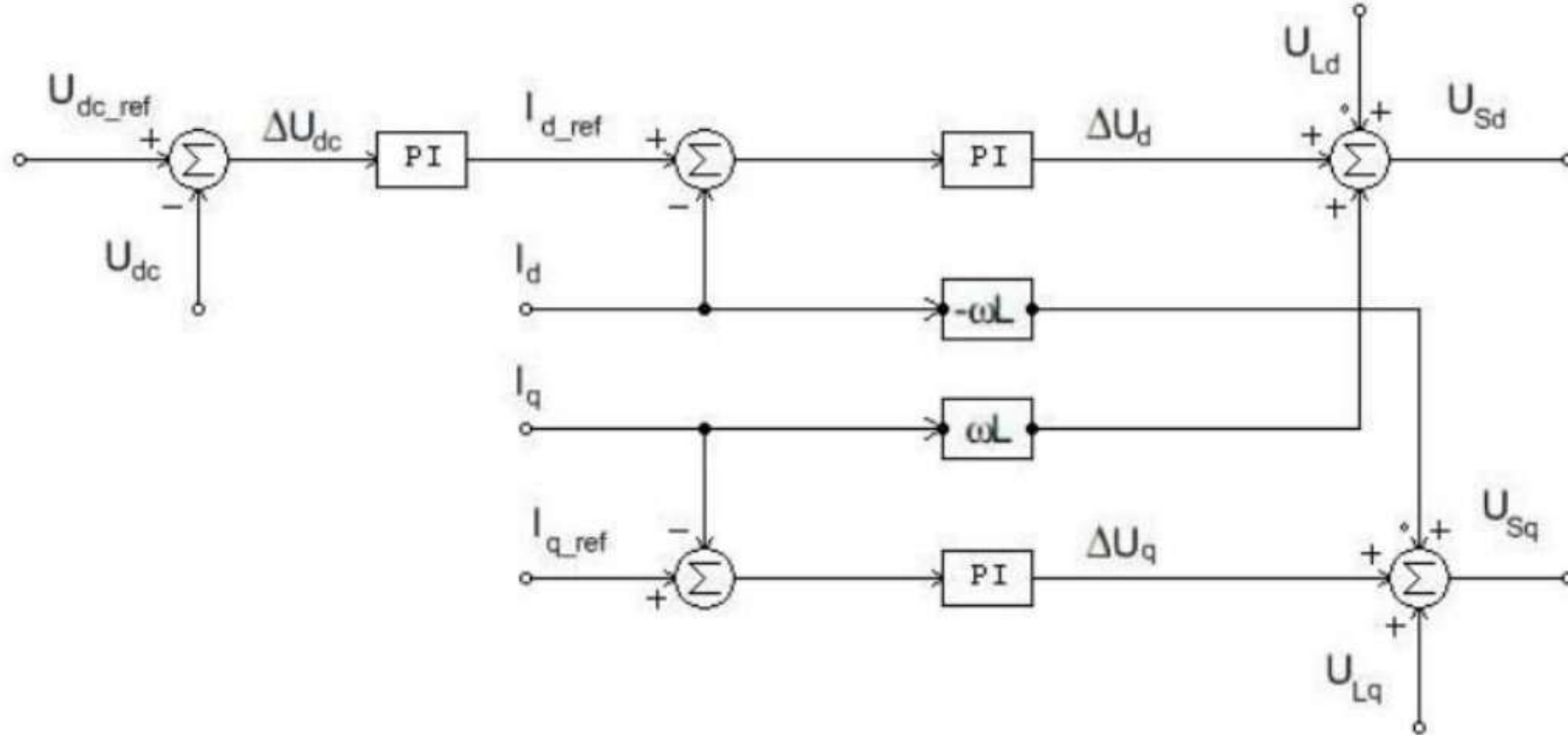


Figure (3-9) Voltage Oriented Control structure.

The characteristic of this current control device is based on transformations between two coordinate systems. The first is the α - β coordinate system, and the second is the d - q rotating coordinate system. The measured values of the three phases are converted into an equivalent two-phase α - β system and then transformed into the d - q rotating coordinate system:

$$\begin{bmatrix} k_d \\ k_q \end{bmatrix} = \begin{bmatrix} \cos \gamma_{UL} & \sin \gamma_{UL} \\ -\sin \gamma_{UL} & \cos \gamma_{UL} \end{bmatrix} \begin{bmatrix} k_\alpha \\ k_\beta \end{bmatrix} \quad (3-1)$$

Thanks to this type of transformation, the control variables become DC signals. An inverse α - β / d - q transformation is performed at the output of the control system, providing the reference signals of the rectifier in fixed coordinates:

$$\begin{bmatrix} k_\alpha \\ k_\beta \end{bmatrix} = \begin{bmatrix} \cos \gamma_{UL} & -\sin \gamma_{UL} \\ \sin \gamma_{UL} & \cos \gamma_{UL} \end{bmatrix} \begin{bmatrix} k_d \\ k_q \end{bmatrix} \quad (3-2)$$

For both coordinate transformations, the voltage vector angle γ_{UL} is defined by:

$$\begin{aligned} \sin \gamma_{UL} &= U_{L\beta} / \sqrt{U_{L\alpha}^2 + U_{L\beta}^2} \\ \cos \gamma_{UL} &= U_{L\alpha} / \sqrt{U_{L\alpha}^2 + U_{L\beta}^2} \end{aligned} \quad (3-3)$$

In the d - q rotating frame, the current vector i_L has two perpendicular components $\mathbf{I}_L = [I_{Ld} \ I_{Lq}]$. The component I_{Lq} determines the reactive power, while i_{Ld} concerns the active power. Thus, active and reactive powers can be controlled independently. The condition for a unity power factor is obtained when the current vector i_L is aligned with the grid voltage vector U_L . By placing the d-axis of the rotating coordinate plane on the grid voltage vector, a simplified dynamic model can be obtained.

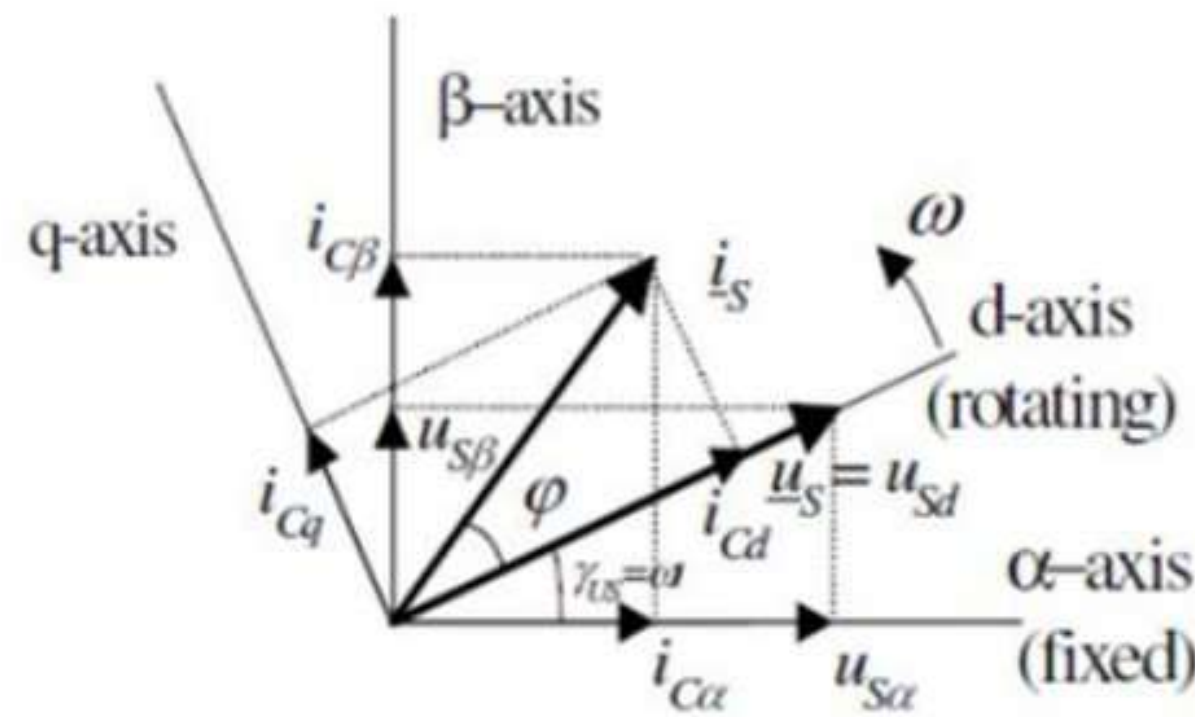


Figure (3-10)

The voltage equations in the rotating d-q reference frame are:

$$U_{Ld} = R i_{Ld} + L \frac{di_{Ld}}{dt} + U_{sd} - \omega L i_{Lq} \quad (3-4)$$

$$U_{Lq} = R i_{Lq} + L \frac{di_{Lq}}{dt} + U_{sq} + \omega L i_{Ld} \quad (3-5)$$

The current is assumed to be zero in all cases for unity power factor control. As for it is calculated through the voltage loop and controls the flow of active power between the grid and the DC bus. Equations (III.3-4) can be simplified for a negligible resistance as follows:

$$U_{Ld} = L \frac{di_{Ld}}{dt} + U_{sd} - \omega L i_{Lq} \quad (3-6)$$

$$0 = L \frac{di_{Lq}}{dt} + U_{sq} + \omega L i_{Ld} \quad (3-7)$$

Assuming that is properly regulated to a zero value, the following equations can also be considered valid:

$$U_{Ld} = L \frac{di_{Ld}}{dt} + U_{sd} \quad (3-8)$$

$$0 = U_{sq} + \omega L i_{Ld} \quad (3-9)$$

3.11 Study of the AC-side current loop :

The use of PI controllers in a three-phase frame presents application problems. Indeed, AC components are found in the errors at the inputs of the PI controllers. These AC quantities cause uncompensated static errors by PI controllers. To solve this problem, Park transformations in the frame rotating at the frequency of the grid voltages are used. Thus, the AC variables of the currents are transformed into continuous d and q components as soon as these signals have the same frequency as the grid. Therefore, knowledge of the reference angle of the grid voltages is necessary for calculating the transformations.

However, there is coupling between the axes of the Park transformation; thus, a variation in i_{Ld} causes a variation in i_{Lq} , and vice versa.

The decoupling between the d and q axes is achieved by the variables ΔU_d et ΔU_q :

$$\begin{aligned} u_{sd} &= u_{Ld} + \omega L i_{Lq} + \Delta u_d \\ u_{sq} &= u_{Lq} - \omega L i_{Ld} + \Delta u_q \end{aligned} \quad (3-10)$$

où

$$\begin{aligned} \Delta u_d &= k_{pi}(i_d^* - i_d) + k_{ii} \int (i_d^* - i_d) dt \\ \Delta u_q &= k_{pi}(i_q^* - i_q) + k_{ii} \int (i_q^* - i_q) dt \end{aligned} \quad (3-11)$$

alors

$$\begin{aligned} \Delta u_d &= u_{Ld} + \omega L i_{Lq} - u_{sd} = L \frac{di_d}{dt} + R i_d \\ \Delta u_q &= u_{Lq} - \omega L i_{Ld} - u_{sq} = L \frac{di_q}{dt} + R i_q \end{aligned} \quad (3-12)$$

The decoupled state system is therefore represented by:

$$\begin{bmatrix} \frac{di_{Ld}}{dt} \\ \frac{di_{Lq}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 \\ 0 & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix} \begin{bmatrix} \Delta u_d \\ \Delta u_q \end{bmatrix} \quad (3-13)$$

It becomes possible to control i_a and L independently by acting on Δu_a and Δu_g ; thus, it becomes easier to design the regulators.

The current controllers used are of the PI type. The parameters k_p and k_i are calculated as follows:

$$k_{pi} = a_i L \quad (3-14)$$

$$k_{ii} = a_i R \quad (3-15)$$

$$\text{Où } a_i = \frac{2\pi f_s}{10}. \quad (3-16)$$

3.12 DC Bus Voltage Regulation Loop :

The dynamic model of the DC bus circuit assists in calculating the transfer function of the DC bus voltage; it is represented by Figure (III.4).

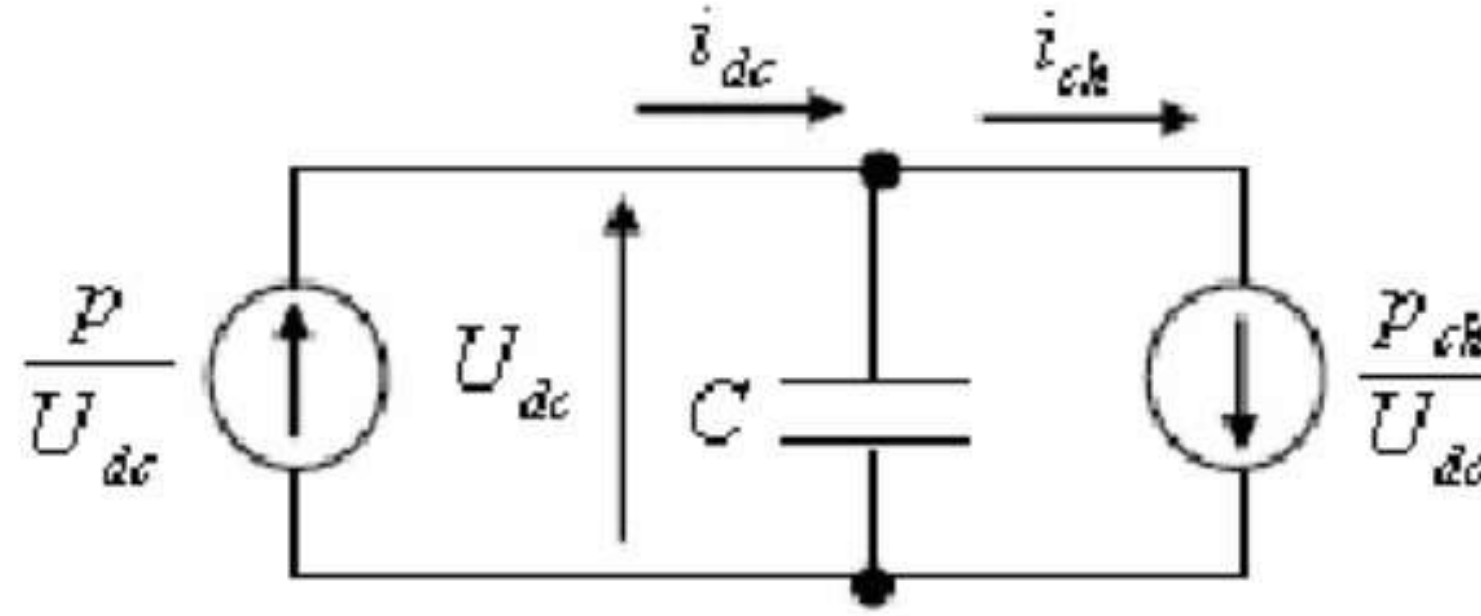


Figure (3-11) Modèle dynamique du circuit du bus continu.

$$C \frac{dU_{dc}}{dt} = i_{dc} - \frac{U_{dc}}{R_L} \quad (3-17)$$

Donc,

$$G(s) = \frac{U_{dc}}{i_{dc}} = \frac{R_L}{CR_L s + 1} \quad (3-18)$$

Et alors, nous pouvons en déduire la fonction de transfert du régulateur :

$$F(s) = \frac{a_v}{s} G^{-1}(s) = \frac{a_v}{s} \frac{CR_L s + 1}{R_L} = k_{pv} + \frac{1}{s} k_{pi} \quad (3-19)$$

En simplifiant on trouve :

$$k_{pv} + \frac{1}{s} k_{pi} = a_v C + \frac{1}{s} \frac{a_v}{R_L} \quad (3-20)$$

D'où :

$$k_{pv} = a_v C \quad (3-21)$$

$$k_{iv} = \frac{a_v}{R_L} \quad (3-22)$$

$$\text{où } a_v = \frac{a_i}{10}. \quad (3-23)$$

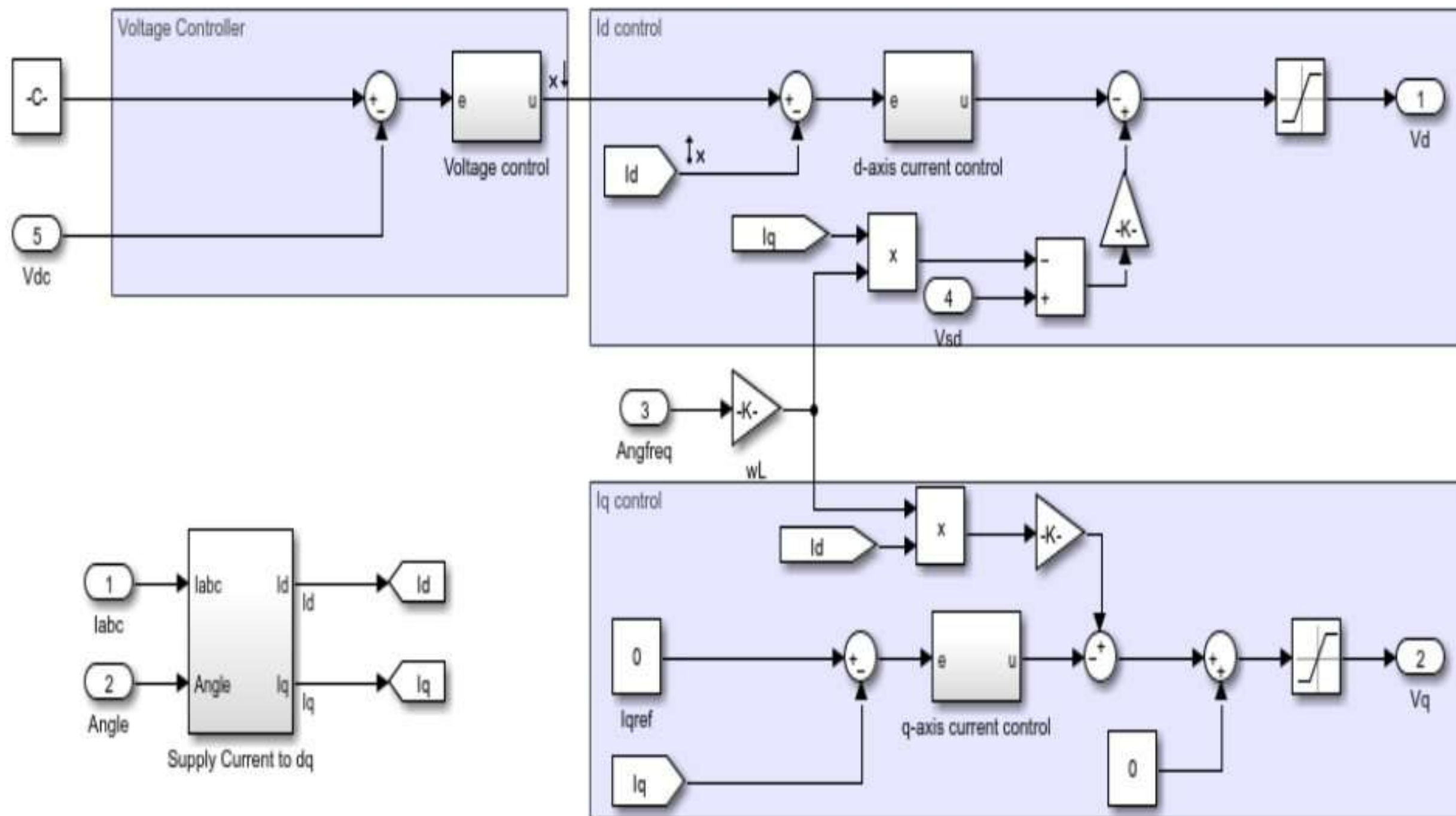


Figure (3-12): Voltage and Current Control

3.13 DC/DC Converter Stage

The DC/DC converter stage creates an interface between the AC/DC rectifier stage and the battery of the EVs, so that the provided intermediate DC voltage from the AC/DC rectifier can be regulated to charge the battery. According to the requirements for galvanic isolation explained above, DC/DC converters are classified as isolated or nonisolated [24]. Figure (3-13) shows the LLC topology of isolated DC/DC converter.

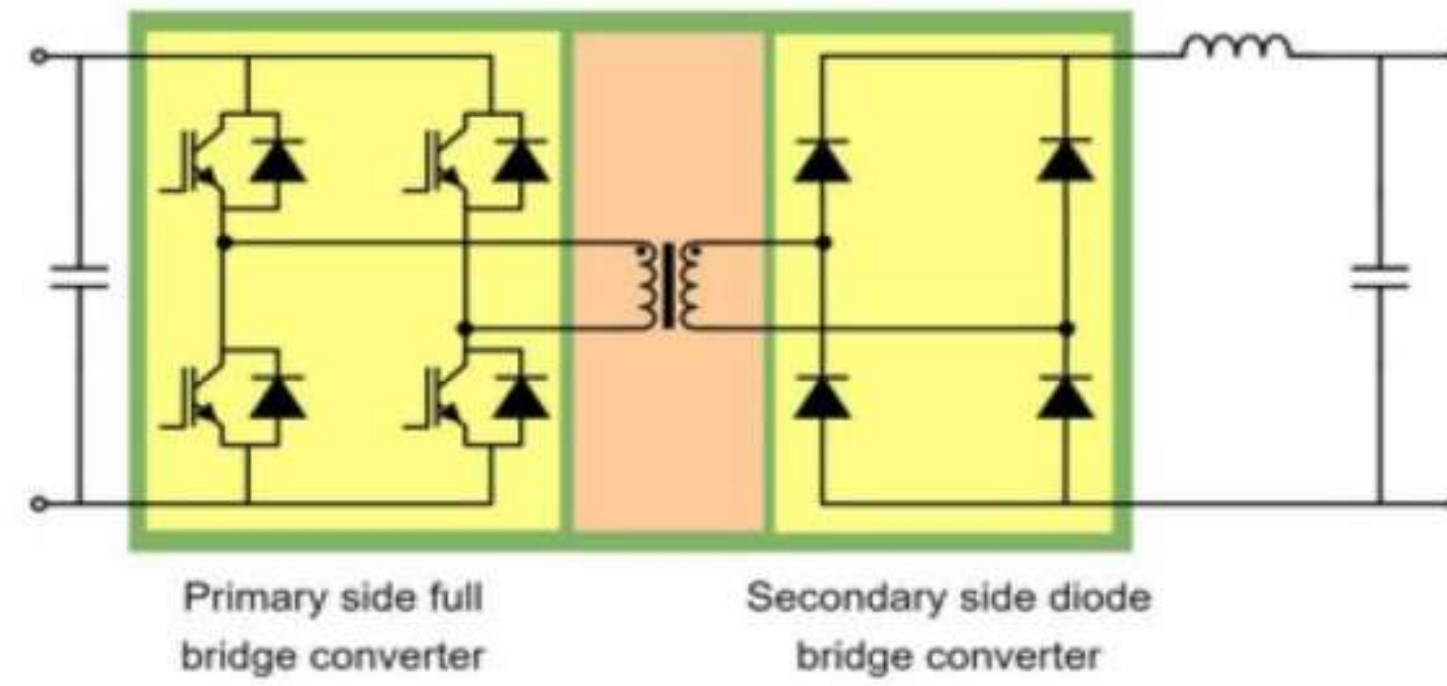


Figure (3-13) PSFB topology of isolated DC/DC converter.

The phase-shifted full bridge (PSFB) converter is a widely utilized advanced DC-DC converter topology, commonly adopted in various fields such as electric vehicles, renewable energy systems, energy storage systems. It is preferred for its attractive features, such as galvanic isolation, fixed frequency operation and simplified control, which contribute to its ease of implementation. Additionally, its compact design, soft switching for all primary devices, as well as scalability and modularity, make it suitable for both low- and high-power applications [25].

3.14 Electric Vehicle Battery

The battery characteristics to be selected in the power system model to be calculated are important. These parameters should be revised according to the desired result as there will be a battery in the system that will draw power as a load. Electric vehicle battery parameters are given in Table 1.

Table 1. Battery Pack Parameters.

Description	Value reference
Battery Technology	Lithium-ion
SOC	20%
Battery Capacity	50Ah
Current Reference	100 A
Series Resistance (R series)	0,0175 Ω
Transient Resistance (R transient)	0,245 Ω
Transient Capacitor (C transient)	8,1 F
Battery Inductance (L b)	0,005 H
Open-Circuit Voltage (V_{oc})	400 V
Minimum Battery Voltage (V min, bat)	250 V
Control Loop	CC/CV(Constant Current/Constant Voltage)

3.15 Simulation result

Input and output parameters of the designed Simulink model are given in Table-3 and Table-4. Provided that these parameters are within the scope of the standards, different values can be selected for the model to be designed and simulation can be performed. After designing the model, it is important to determine the simulation sampling and time values to simulate the model. Making the right decisions about these are the issues that are necessary for the simulation to be carried out correctly. The integration method applied for this study is based on “ode23t”. At least 100 samples should be taken in the period with the fastest frequency of the integration method. The simulation time step is based on “2 μ s” .

Table 2. Simulation Input Parameters for Grid and AC/DC Converter

Description	Value
Phase-Phase Voltage (V_{rms})	415 v
Frequency	50 Hz
Rectifier .DC Current	700; % A
Rectifier .DC Voltage	800 V
F_{sw} (Switch Frequency)	10 kHz

Table 3Simulation Output Parameters DC-DC Converter

Description	Value
Switch Frequency	10e3 Hz
K_p	2
K_i	1
inductance	10e-6 H
transformer. magnetizingL	1 H
transformer. winding Factor	0.5
Voltage Sensor G	1
Voltage Sensor T	$1/(10 \cdot f_{sw})$

The 3-Phase rectifier topology simulation model is implemented using MATLAB/SIMULINK. **Figure (3-14)**. shows the input voltage waveform of the rectifier with 310 V. The Input current of the rectifier is shown in **Figure (3-15)**, with good input current quality at the peak current of 80 A. **Figure (3-16)** shows the output voltage of the Vienna Rectifier with 600 V. **Figure (3-17)** shows the Output current of the Rectifier with 61.22 A. The specifications for the 3-phase Vienna rectifier topology have been shown in [Table 11](#). The power factor of the Vienna Rectifier is 0.9511. **Figure (3-18)** shows the general model of the system

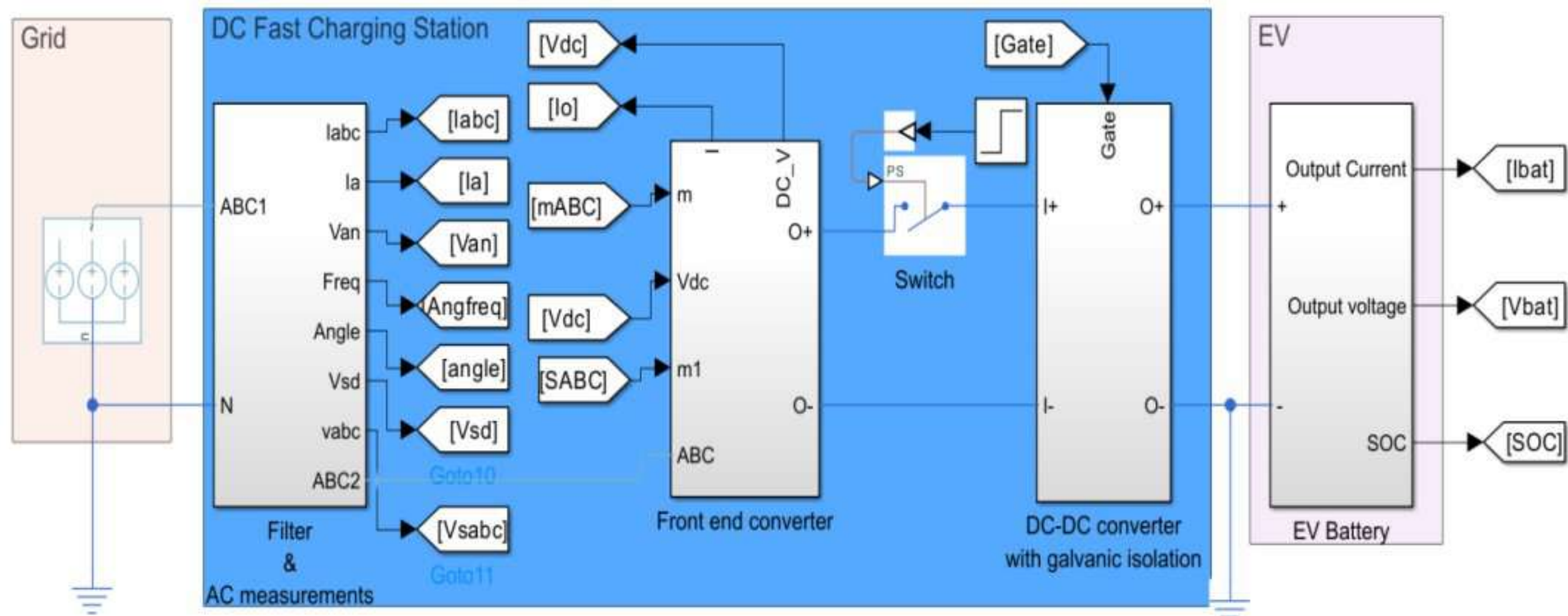


Figure (3-14) Matlab Simulink model for DC Fast charger.

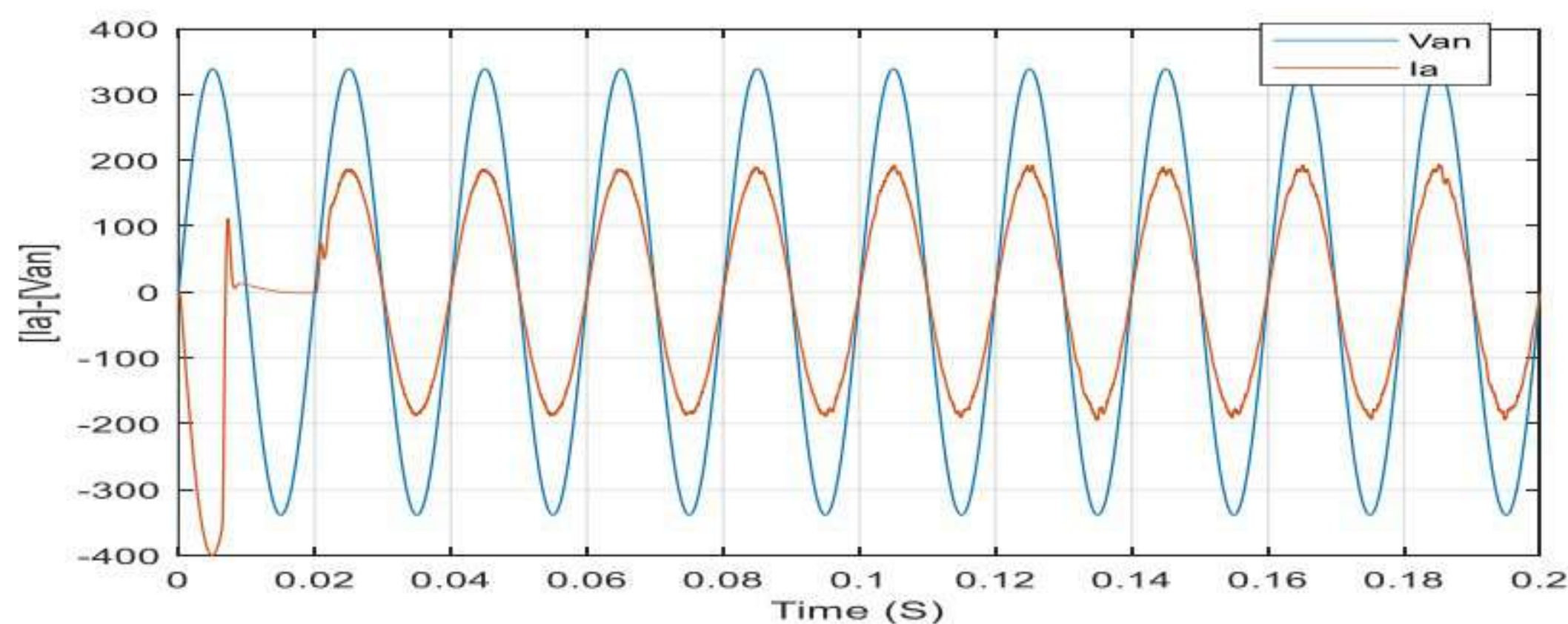


Figure (3-15): AC Voltage and Current

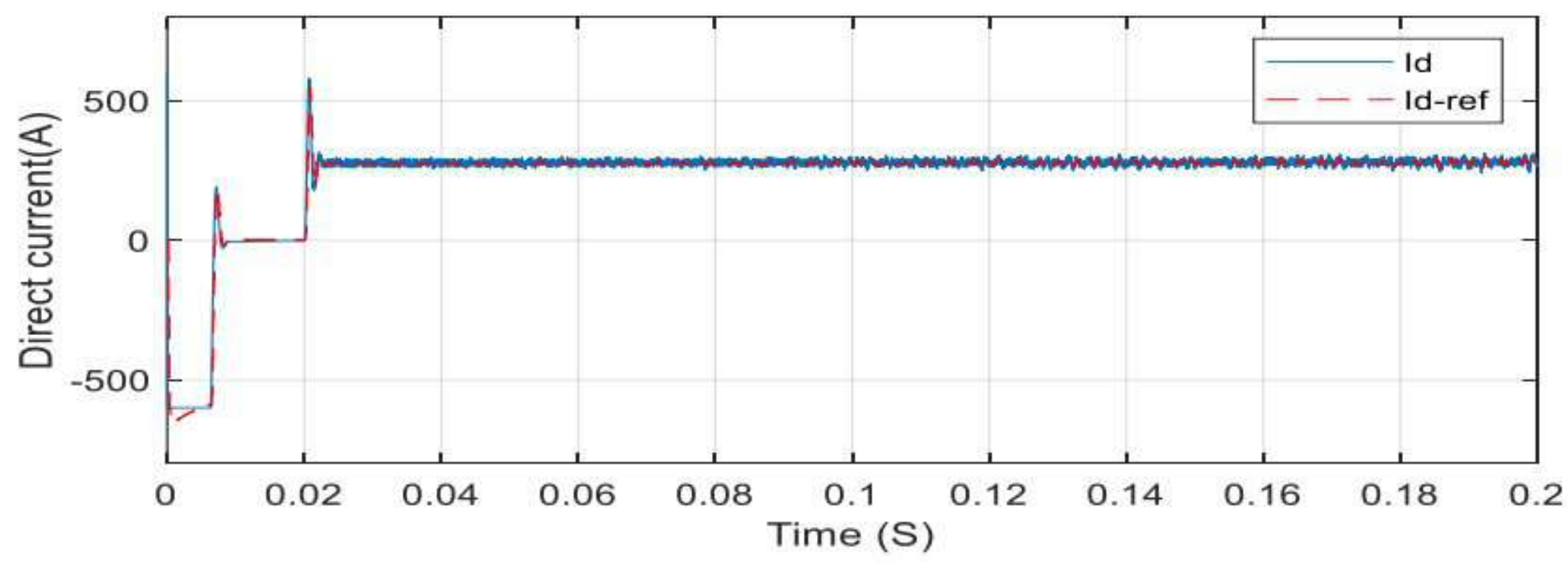


Figure (3-16): DC current response curve for battery charger

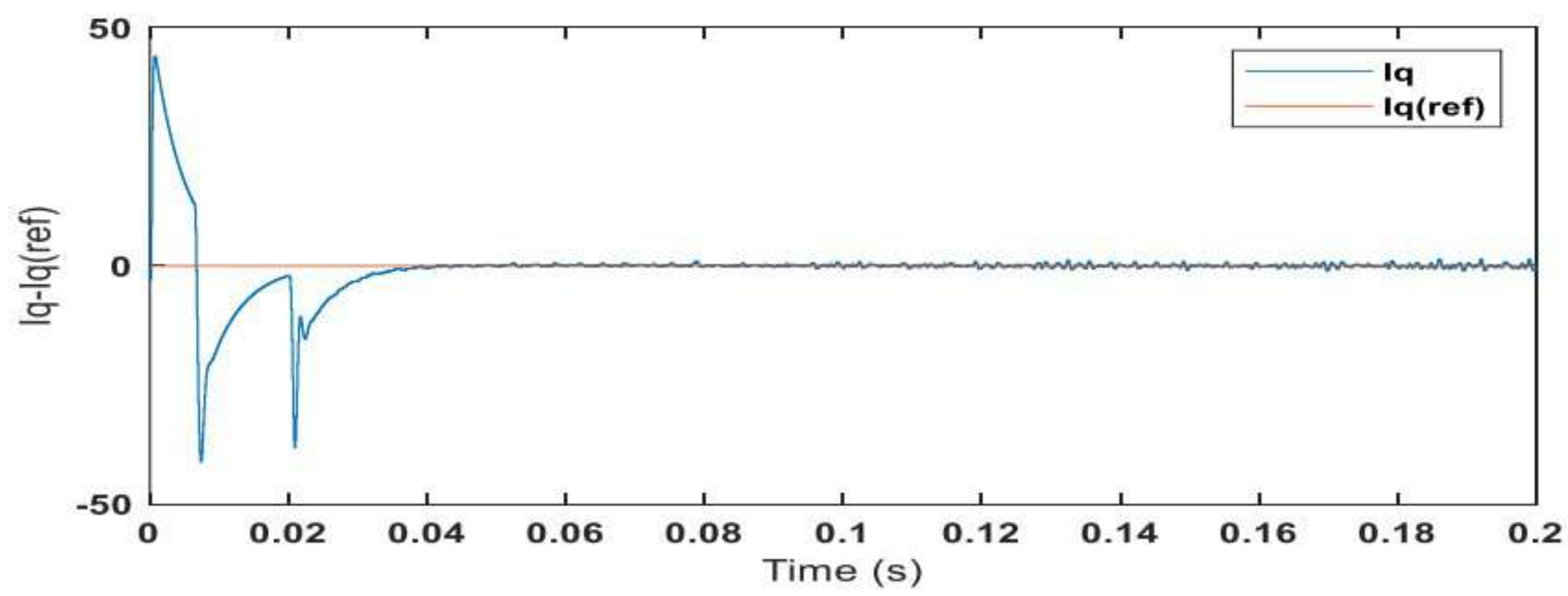
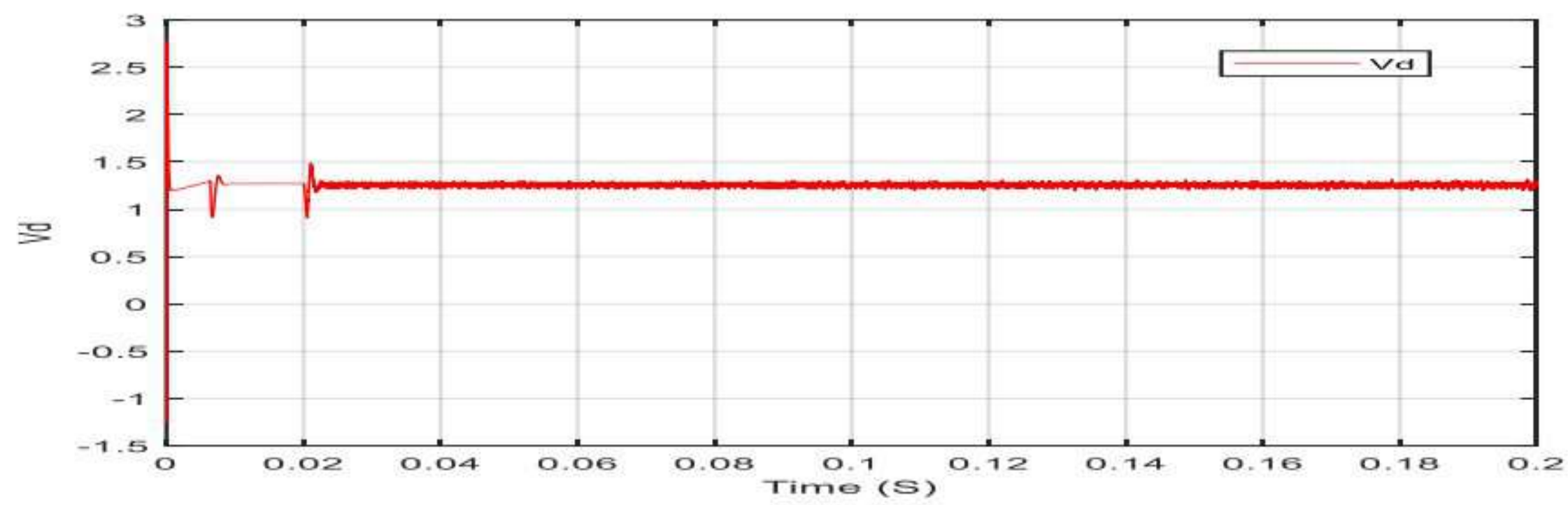
Figure (3-17): Error curve of the vertical axis current tracing (I_q).

Figure (3-18): Waveform of the d-axis voltage component

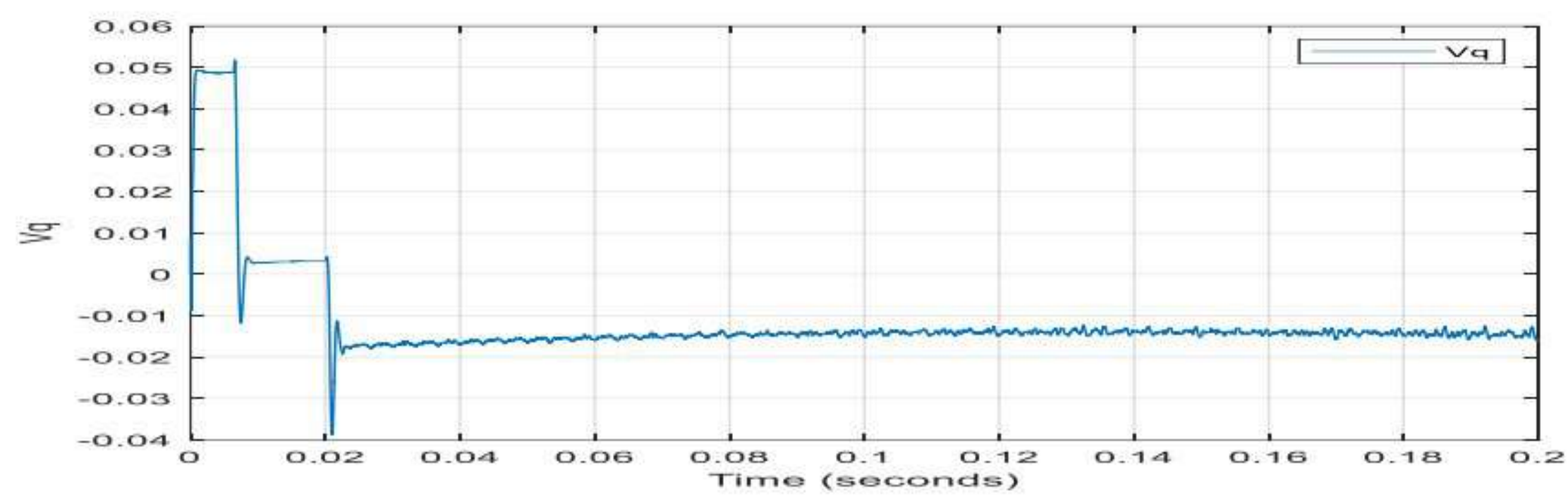


Figure (3-19): Variation of the control voltage component

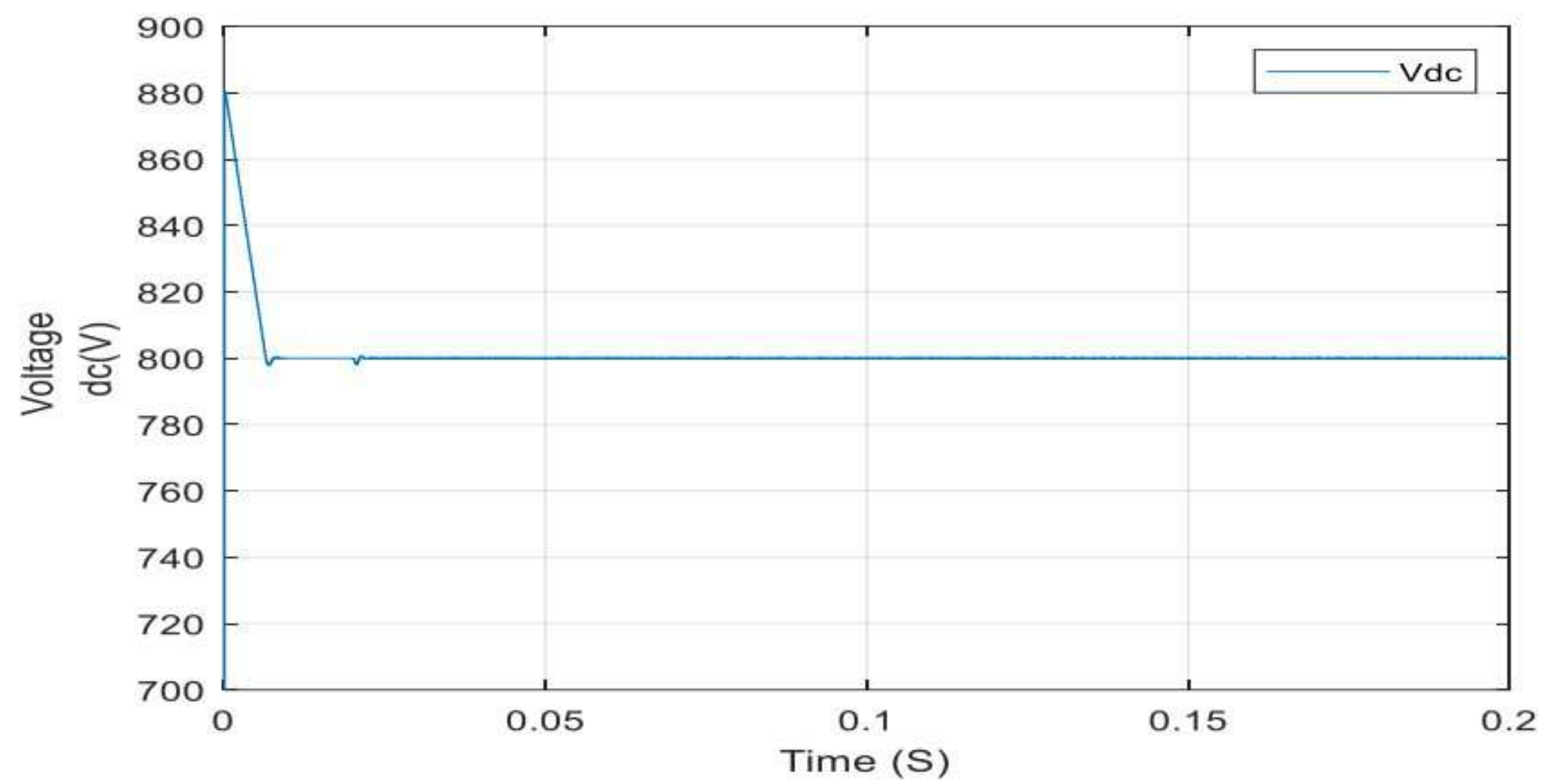


Figure (3-20): Voltage DC Profile

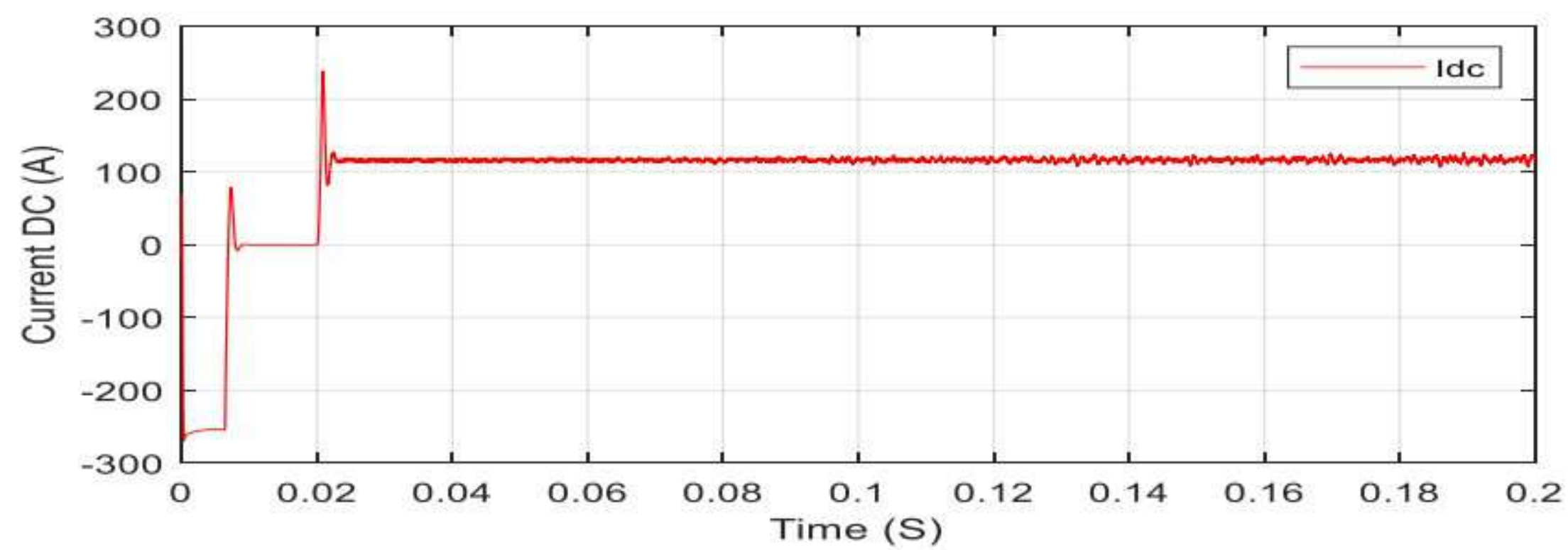


Figure (3-21): Current DC Profile

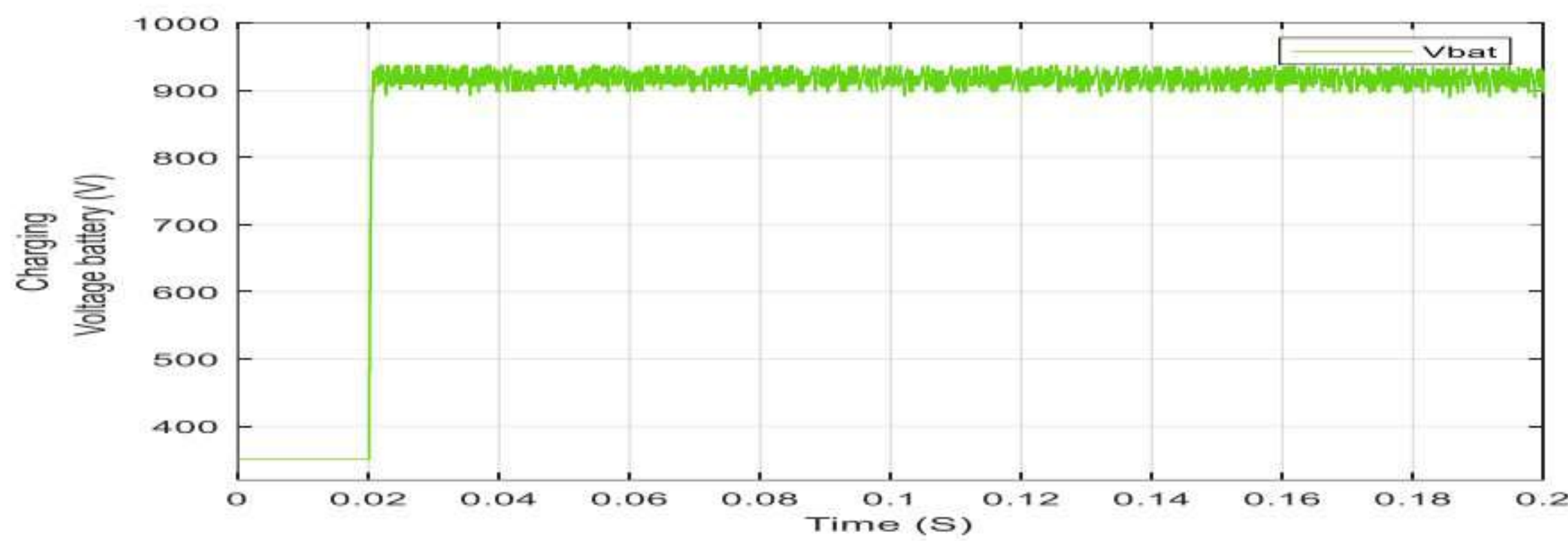


Figure (3-22): Voltage Of Battery

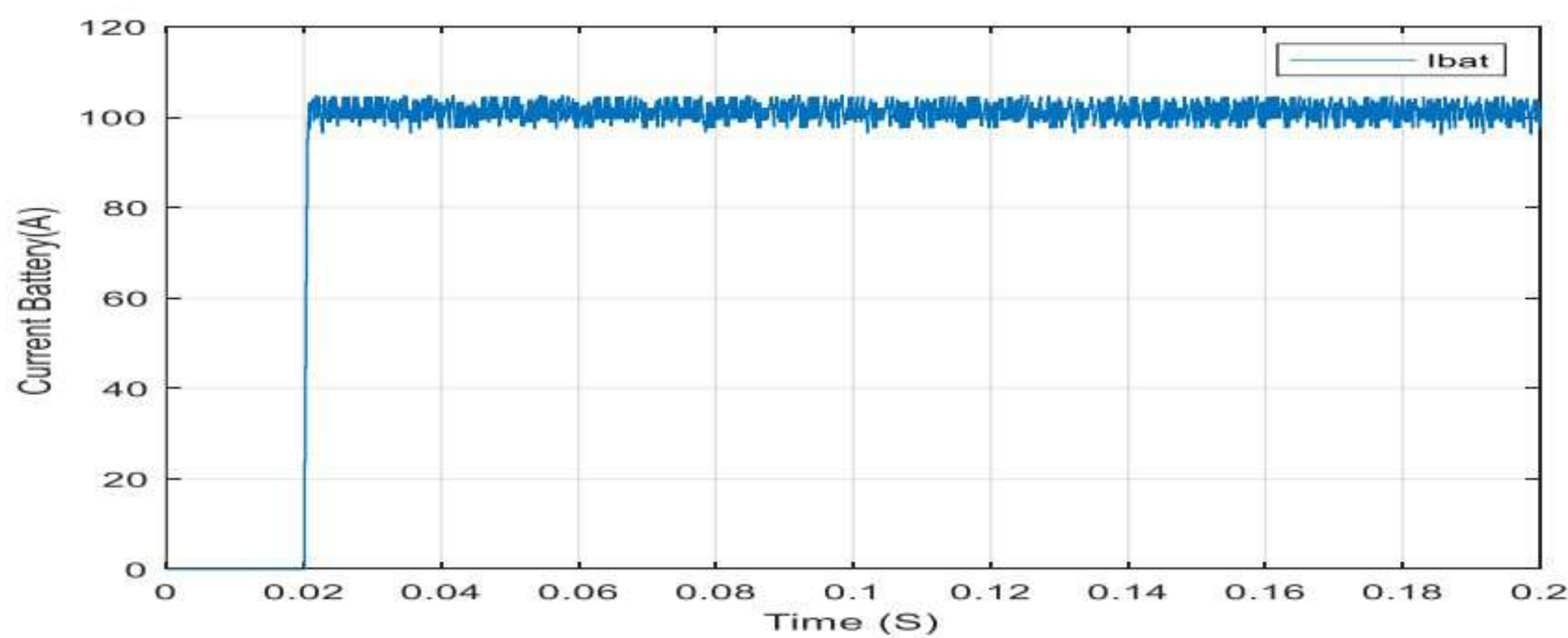


Figure (3-23): Current Of Battery

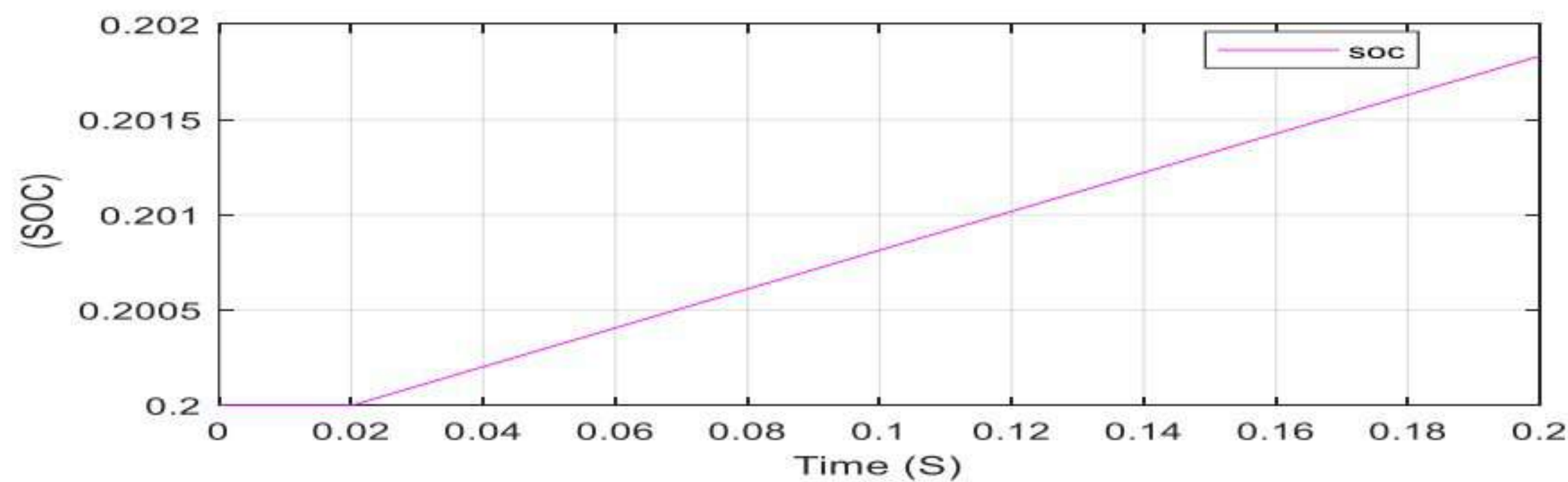


Figure (3-24):SOC Of Battery

3.16 Conclusion

This chapter was dedicated to studying the DC Fast Charging system for electric vehicles (EVs), as it represents one of the fundamental pillars for developing the infrastructure necessary to support the widespread adoption of this type of vehicle. Various charging levels and internationally approved standards were reviewed, alongside a study of the general architecture of fast-charging stations and their constituent power conversion stages, starting from the AC/DC

rectification stage down to the DC/DC conversion stage required to meet battery charging requirements efficiently and safely.

Furthermore, the focus was placed on the Voltage Oriented Control (VOC) strategy, demonstrating its operating principle, basic structure, and its role in the independent control of active and reactive power. This ensures improved power quality, a high power factor, reduced harmonic distortions, and a fast dynamic response for the system. Additionally, some essential associated components, such as LCL filters and galvanic isolation techniques, were studied due to their importance in enhancing overall performance and increasing system reliability.

Based on the simulation model developed using MATLAB/Simulink, the system's performance was evaluated, and the effectiveness of the proposed control strategy was verified. The results demonstrated good stability in voltage and current regulation, an improvement in electrical power quality, and operational characteristics that align with the requirements of modern fast-charging systems.

Consequently, it can be concluded that adopting advanced control techniques—foremost among which is Voltage Oriented Control (VOC)—alongside an appropriate design for the power conversion stages, represents an effective choice for developing EV fast-charging stations. This constitutes a significant step toward building a more efficient and reliable infrastructure capable of keeping pace with the rapid acceleration in electric mobility and supporting the global shift toward more sustainable energy systems.

General Conclusion

The increasing adoption of electric vehicles and renewable energy systems has highlighted the importance of developing efficient and reliable battery charging technologies. In this context, DC fast charging has emerged as a promising solution to reduce charging time and enhance the practicality of battery-powered applications. However, ensuring high charging performance while preserving battery health remains a significant challenge.

This work has focused on the modeling and simulation of battery pack DC fast charging systems. The equivalent circuit contains a voltage source, a series resistor, and a single RC element sufficient to represent the system dynamics. DC fast charging system consists of a single AC/DC inverter connected to the grid, a DC bus, and a DC/DC converter for recharging the electric vehicle batteries. VOC control system is used to control the AC/DC converter. Through simulation studies, it has been possible to evaluate system performance under different operating conditions and to gain a deeper understanding of the factors influencing charging efficiency and stability.

The obtained results demonstrate the effectiveness of modeling and simulation tools in predicting system behavior and supporting the design of advanced charging strategies. These tools offer valuable insights for optimizing charging processes, improving energy management, and reducing development costs before practical implementation.

As battery technologies continue to evolve, future research may focus on integrating thermal effects, advanced battery models, intelligent control algorithms, and real-time optimization techniques to further enhance the performance, safety, and sustainability of DC fast charging systems.

References

- [1] M. A. Ravindran, K. Nallathambi, P. Vishnuram, R. S. Rathore, M. Bajaj, I. Rida, and A. Alkhayyat, "A Novel Technological Review on Fast Charging Infrastructure for Electrical Vehicles: Challenges, Solutions, and Future Research Directions," *Alexandria Engineering Journal*, vol. 82, pp. 260–290, 2023, doi: 10.1016/j.aej.2023.10.009.
- [2] M. Mathew, "Modeling and State Estimation of Lithium-Ion Battery Packs for Application in Battery Management Systems," Ph.D. dissertation, Department of Chemical Engineering, University of Waterloo, Waterloo, Ontario, Canada, 2018.
- [3] G Marin-Garcia, G Vazquez-Guzman, JM Sosa, Adolfo R Lopez, PR MartinezRodriguez, and D Langarica. Battery types and electrical models: A review. In 2020 IEEE International Autumn Meeting on Power, Electronics and Computing(ROPEC), volume 4, pages 1–6. IEEE, 2020.
- [4] R. Chen, "Battery Pack Design of Cylindrical Lithium-Ion Cells and Modelling of Prismatic Lithium-Ion Battery Based on Characterization Tests," Master's thesis, Department of Mechanical Engineering, McMaster University, Hamilton, Ontario, Canada, Aug. 2022.
- [5] M. I. Meziane, "Modeling and Identification of Lithium-Ion Battery Parameters: Polynomial Approach," Master's thesis, Department of Electronics, Badji Mokhtar University - Annaba, Annaba, Algeria, 2023.
- [6] Yadhukrishnan, "Designing and Optimizing a flexible Battery Pack Manufacturing Process Incorporating Cylindrical and Prismatic Cells: Key Factors and Strategies," Master's thesis, Department of Engineering Technology, University of Twente, Enschede, Netherlands, Sep. 2023.
- [7] Battery module. <https://www.laserax.com/blog/battery-pack-design>, 2023. Accessed: 2023-09-10.
- [8] Iñigo Alonso Fernandez. Trading Off Between Flexibility and Product Platform Constraints for Effective Technology Introduction. PhD thesis Chalmers Tekniska Hogskola (Sweden), 2022.

- [9] Armand, M., & Tarascon, J. M. (2008). Building better batteries. *Nature*, 451(7179), 652-657. DOI: 10.1038/451652a
- [10] Goodenough, J. B., & Park, K. S. (2013). The Li-ion rechargeable battery: a perspective. *Journal of the American Chemical Society*, 135(4), 1167-1176. DOI: 10.1021/ja3091438
- [11] DEKKICHE ABDELILLAH Modèle de batterie générique et estimation de l'état de charge, 2008.
- [12] U.S. Department of Energy - Battery Energy Storage for Renewables: Market Status and Technology Outlook
- [13] A. B. M. Nasiruzzaman, Modeling & Simulation of Battery Performance Parameters for Efficient Electrical Vehicles, Chapter 3, pp. 59–96.
- [14] R. R. Thakkar, "Electrical Equivalent Circuit Models of Lithium-ion Battery," in *Management and Applications of Energy Storage Devices*, IntechOpen, 2022, pp. 1-18. doi: 10.5772/intechopen.78501.
- [15] Low Wen Yao, J. A. Aziz, Pui Yee Kong, and N. R. N. Idris. Modeling of lithium-ion battery using MATLAB/Simulink. In: *Proceedings of Conference of the IEEE Industrial Electronics Society*. Vienna, pp. 1729-1734, Nov.2016.
- [16] Barcellona Simone and Piegari Luigi . Lithium ion battery models and parameter identification techniques. *Energies* 2017;10.
- [17] R. R. Thakkar, Y. S. Rao, and R. R. Sawant. Performance Analysis of electrical equivalent circuit models of lithium-ion battery. In: *2020 IEEE Pune Section International Conference (PuneCon)*, 2020, pp. 103-107. DOI:10.1109/PuneCon50868.2020.9362386
- [18] <https://calce.umd.edu/battery-data> .
- [19] Min Chen and Gabriel A. Rincón Mora. Accurate electrical battery model capable of predicting runtime and I–V performance. *IEEE Transactions on Energy Conversion* 2006;21(2).
- [20]. Jonas, T., Daniels, N., Macht, G.: Electric vehicle user behavior: An analysis of charging station utilization in Canada. *Energies* 16(4), 1592 (2023)

- [21] V. Sawant and P. Zambare, "DC fast charging stations for electric vehicles: A review," *Energy Conversion and Economics* (2024)
- [22] Channegowda, J.; Pathipati, V.K.; Williamson, S.S. Comprehensive review and comparison of DC fast charging converter topologies: Improving electric vehicle plug-to-wheels efficiency. In *Proceedings of the 2015 IEEE 24th International Symposium on Industrial Electronics (ISIE)*, Buzios, Brazil, 3–5 June 2015; pp. 263–268..
- [23] H. Kilicoglu and P. Tricoli, "Technical Review and Survey of Future Trends of Power Converters for Fast-Charging Stations of Electric Vehicles," *Energies* Jul. (2023).
- [24] A. F. Güven and S. B. Akbaşak, "DC Fast Charging Station Modeling and Control for Electric Vehicles," *Karadeniz Fen Bilimleri Dergisi* (2021).
- [25] P. Roja and V. John, "Comprehensive analysis of phase-shifted full-bridge converter for optimal design," *Sādhana*, vol. 50, p. 276, 2025, doi: 10.1007/s12046-025-02793-z.