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M.Sc. in Electrical and Electronics Engineering

Jamal Abras

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GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES

**DESIGN OF 100 KW THREE-PHASE BIDIRECTIONAL AC-DC
MATRIX CONVERTER FOR FAST CHARGING OF
ELECTRICAL VEHICLES**

M.Sc. THESIS

IN

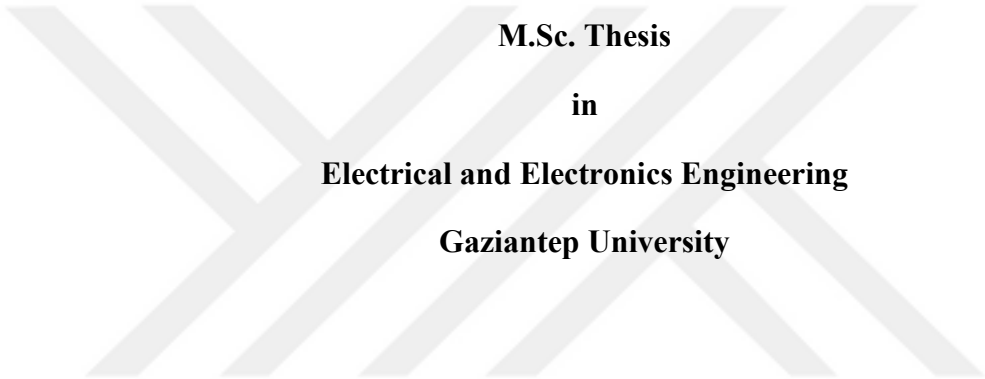
ELECTRICAL AND ELECTRONICS ENGINEERING

BY

JAMAL ABRAS

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ELECTRICAL VEHICLES**



**M.Sc. Thesis
in
Electrical and Electronics Engineering
Gaziantep University**

**Supervisor
Prof. Dr. Ahmet Mete VURAL**

**by
Jamal ABRAS
February 2025**



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**DESIGN OF 100 KW THREE-PHASE BIDIRECTIONAL AC-DC MATRIX
CONVERTER FOR FAST CHARGING OF ELECTRICAL VEHICLES**

submitted by **Jamal ABRAS** in partial fulfillment of the requirements for the degree
of Master of Science in **Electrical and Electronics Engineering, Gaziantep
University** is approved by,

Prof. Dr. Çiğdem AYKAÇ
Director of the Graduate School of Natural and Applied Sciences

Prof. Dr. Ergun ERÇELEBİ
Head of the Department of Electrical and Electronics Engineering

Prof. Dr. Ahmet Mete VURAL
Supervisor, Electrical and Electronics Engineering
Gaziantep University

Exam Date: 04 February 2025

Examining Committee Members:

Prof. Dr. Ahmet Mete VURAL
Gaziantep University

Assist. Prof. Dr. Ali Osman ARSLAN
Gaziantep University

Assist. Prof. Dr. Hasan A M ABUMETEIR
Gaziantep Islam Science And Technology University

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Jamal ABRAS

ABSTRACT

DESIGN OF 100 KW THREE-PHASE BIDIRECTIONAL AC-DC MATRIX CONVERTER FOR FAST CHARGING OF ELECTRICAL VEHICLES

ABRAS, Jamal

M.Sc. in Electrical and Electronics Engineering

Supervisor: Prof. Dr. A. Mete VURAL

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This study addresses the growing need for efficient and rapid electric vehicle (EV) charging solutions by presenting the design and simulation of a 100 kW bidirectional AC-DC matrix converter optimized for fast charging. The system features a three-phase matrix architecture, PI controllers with Pulse Width Modulation (PWM) control strategies, and bidirectional power flow management. Key findings include a charging duration of 55 minutes from 10% to 90% SOC using constant current (CC) charging at 200 A and 630 V DC, achieving an efficiency of 83.5% with minimal 3% current ripple. In constant voltage (CV) mode, charging took 40 minutes at 635 V DC and an initial current of 630 A, attaining 97.35% efficiency. During battery discharge from 100% to 90% SOC, the system achieved an efficiency of 98% with THD voltage and current values of 0.34% and 5.42%, respectively, ensuring high power quality. These results demonstrate the converter's effectiveness in maintaining a power factor of 1, minimal THD (voltage: 0.51%, current: 2.96%), and robust performance in various scenarios. This comprehensive design enhances the EV charging infrastructure, contributing to advancements in sustainable transportation technologies.

Key Words: Electric Vehicle, Power Electronics, Bidirectional AC-DC matrix converter, Control Strategies, Fast Charging.

ÖZET

ELEKTRİKLİ ARAÇLARIN HIZLI ŞARJI İÇİN 100 KW ÜÇ FAZLI ÇİFT YÖNLÜ AC-DC MATRİS KONVERTÖRÜNÜN TASARIMI

ABRAS, Jamal

Yüksek Lisans Tezi, Elektrik-Elektronik Mühendisliği

Danışman: Dr. Öğr. Üyesi A. Mete VURAL

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82 sayfa

Bu çalışma, elektrikli araçların hızlı ve verimli şarj ihtiyacını karşılamak için, hızlı şarj için optimize edilmiş 100 kW çift yönlü AC-DC matris dönüştürücünün tasarımı ve simülasyonunu sunmaktadır. Sistem, üç fazlı matris mimarisi, PI kontrolörleri ile Darbe Genişlik Modülasyonu (DGM) kontrol stratejileri ve çift yönlü güç akışı yönetimi içermektedir. Temel sonuçlar, 10% ile 90% SOC arasında sabit akım modunda 200 A ve 630 V DC kullanılarak 55 dakikalık şarj süresi, 83.5% verimlilik ve 3% akım dalgalanması olduğunu göstermektedir. Sabit voltaj modunda, şarj 40 dakikada 635 V DC ve başlangıç akımı 630 A ile gerçekleştirilmiş, 97.35% verimlilik elde edilmiştir. Bataryanın %100'den %90'a deşarjında, 0.34% THB voltajı ve 5.42% THB akımı ile %98 verimlilik sağlanmıştır. Bu sonuçlar, sistemin güç faktörünü 1 olarak koruduğunu, düşük THB değerleri (voltaj: 0.51%, akım: 2.96%) sunduğunu ve çeşitli senaryolarda güçlü bir performans gösterdiğini kanıtlamaktadır. Bu kapsamlı tasarım, EV şarj altyapısını geliştirmekte ve sürdürülebilir ulaşım teknolojilerine katkı sağlamaktadır.

Anahtar Kelimeler: Elektrikli Araç, Güç Elektroniği, Çift Yönlü AC-DC Matris
Dönüştürücü, Kontrol Stratejileri, Hızlı Şarj.



“Dedicated to my family.”

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TABLE OF CONTENTS

	Page
ABSTRACT	i
ÖZET.....	ii
DEDICATION.....	iii
ACKNOWLEDGEMENTS.....	iv
TABLE OF CONTENTS.....	v
LIST OF TABLES	vii
LIST OF FIGURES	viii
LIST OF ABBREVIATIONS	x
CHAPTER 1 INTRODUCTION	1
1.1 Background and Context	1
1.2 Research Motivation.....	5
1.3 Research Objectives	7
1.3.1 Designing a 100 kW Bidirectional AC-DC MC for Fast EV Charging:	8
1.3.2 Investigating Two Charging Modes:	8
1.3.3 Exploring the Suitability of the Topology for (V2G) Applications:.....	8
1.4 Research Scope.....	8
1.4.1 In-depth Analysis of the Design and Control of a Three-Phase Bidirectional AC-DC MC:.....	8
1.4.2 Simulation-based Verification of the Proposed Design:.....	9
1.5 Thesis Structure	10
CHAPTER 2 LITERATURE REVIEW	12
2.1 Introduction to Energy Conservation and EV Infrastructure:	12
2.1.1 EVs Charging Infrastructure:	12
2.1.2 EVs Charging Requirements:	12
2.1.3 Significance of EVs:	12
2.2 Fast Charging Stations:	13

2.3 Battery Technologies and Charging Modes.....	14
2.3.1 EV Batteries.....	14
2.3.2 Charging Modes for EVs	16
2.4 Power Electronics in EV Charging.....	17
2.4.1 Converter Topologies for EV Charging.....	17
2.4.2 Two-Stage vs Single-Stage Converter Designs	18
2.5 Bidirectional AC-DC MC	19
2.6 Control Strategies.....	23
CHAPTER 3 PROPOSED EV CHARGING SYSTEM.....	25
3.1 System Description.....	25
3.2 MC Topology	28
3.3 The Pulse Width Modulation (PWM)	31
3.4 Input AC filter	33
3.5 Output DC filter.....	35
3.6 Proposed Control Strategies	36
CHAPTER 4 SIMULATION RESULTS AND ANALYSIS.....	40
4.1 Simulation Environment.....	40
4.1.1 Simulation Framework for Power Electronics	40
4.1.2 Setting up the Simulation	40
4.1.3 Modeling of Bidirectional AC-DC MC.....	41
4.2 Simulation Results.....	52
4.2.1 Charging the battery from 10% to 90% using CC charging.....	52
4.2.2 Charging the battery from 10% to 90% using CV charging.....	57
4.2.3 Hybrid CC-CV charging mode	61
4.2.4 Discharging the battery from 100% to 90%	65
4.2.5 Step change in CC charging mode.....	68
4.2.6 Step change in CV charging mode.....	71
CHAPTER 5 CONCLUSIONS.....	74
5.1 Comments and Conclusions on Results.....	74
5.2 Recommendations and future work.....	75
REFERENCES.....	77
CURRICULUM VITAE.....	82

LIST OF TABLES

	Page
Table 2.1 Battery technical specifications [19]	14
Table 2.2 Charging stations schemes [SAE standard J1772] [23]	16
Table 2.3 Main power electronics converters [19]	17
Table 2.4 Comparison of application, control strategy, and research methodology for some previous studies	21
Table 2.5 Comparison of key features, advantages, and missing focus areas for some previous studies	21
Table 3.1 Parameters for each component of the schematic	27
Table 3.2 Main controllable switches comparison	28
Table 3.3 Space vector of AC-DC MC	32
Table 3.4 Parameters of AC filter and DC filter	35
Table 4.1 Parameters used for AC-DC MC simulation	52
Table 4.2 Comparison between CC charging and CV charging modes	61

LIST OF FIGURES

	Page
Figure 1.1 Global carbon emission per year in million tons from 1959 to 2023[7]....	5
Figure 2.1 Impact of DOD and temperature on battery cycles [22].	15
Figure 2.2 Topologies of buck type AC-DC conversion single-stage.	22
Figure 3.1 The proposed EV charging system.	25
Figure 3.2 Different bidirectional switch cell (a) diode bridge bidirectional switch cell (b) anti-parallel reverse blocking IGBT (c) common emitter anti-parallel IGBT (d) common collector anti-parallel IGBT [45].	29
Figure 3.3 Topology of AC-DC MC.	30
Figure 3.4 Topology of AC-DC MC converter in charging mode.	31
Figure 3.5 Topology of AC-DC MC in discharging mode.	31
Figure 3.6 Output voltage.	32
Figure 3.7 Topology of PWM scheme.	33
Figure 3.8 (a) Input AC filter (b) Output DC filter.	34
Figure 3.9 The proposed control strategies in this study.	36
Figure 3.10 The PWM signal.	39
Figure 4.1 Three-Phase AC-DC MC for fast EV charging system model.	43
Figure 4.2 Three-Phase AC source and measurement at the AC side model.	44
Figure 4.3 Three-Phase input AC filter model.	45
Figure 4.4 Three-Phase AC-DC MC model.	46
Figure 4.5 The output DC filter model.	47
Figure 4.6 The battery model.	47
Figure 4.7 The electrical battery parameters model.	48
Figure 4.8 Active and reactive power measurement at the AC side model.	48
Figure 4.9 The output DC power measurement at the DC side model.	49
Figure 4.10 The segmentation of the input source model.	49
Figure 4.11 The twelve switching signals model.	50
Figure 4.12 The six switching signals model.	50
Figure 4.13 Proposed control strategies model.	51

Figure 4.14	The electrical parameters at the AC side in CC charging mode.....	54
Figure 4.15	The electrical parameters at the DC side in CC charging mode.....	55
Figure 4.16	The battery charging from SOC 10% to 90% in CC mode.....	56
Figure 4.17	The electrical parameters at the AC side in CV charging mode.....	58
Figure 4.18	The electrical parameters at the DC side in CV charging mode.....	59
Figure 4.19	The battery charging from SOC 10% to 90% in CV mode.	60
Figure 4.20	The electrical parameters at the AC side in CV, CC charging modes...	62
Figure 4.21	The electrical parameters at the DC side in CV, CC charging modes...	63
Figure 4.22	The battery charging from SOC 10% to 90% in CV, CC modes.	64
Figure 4.23	The electrical parameters at the AC side in discharging mode.....	66
Figure 4.24	The battery discharging from SOC 100% to 90%.	67
Figure 4.25	The electrical parameters at the battery side in unit step change in CC charging mode.	69
Figure 4.26	The electrical parameters at the AC side in unit step change in CC charging mode.	70
Figure 4.27	The electrical parameters at the battery side in unit step change in CV charging mode.	72
Figure 4.28	The electrical parameters at the AC side in unit step change in CV charging mode.	73

LIST OF ABBREVIATIONS

AC	Alternating Current
CC	Constant Current
CV	Constant Voltage
DC	Direct current
DMC	Direct Matrix Converter
EVs	Electric Vehicles
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
I_{dc}	DC Current
IGBT	Insulated Gate Bipolar Transistor
IMC	Indirect Matrix Converter
MC	Matrix Converter
MOSFET	Metal Oxide Field Effect Transistor
P	Active power
P_{dc}	DC Power
PF	Power Factor
PFC	Power Factor Correction
PHEV	Plug-in Hybrid Electric Vehicle
PI	Proportional Integral
PID	Proportional Integral Derivative
PQ	Power Quality
PU	Per unit
PWM	Pulse Width Modulation
Q	Reactive power
RC	Resistor-Capacitor
RMS	Root Mean Square
SOC	state of charge
SPWM	Sinusoidal Pulse Width Modulation

SVPWM	Space Vector Pulse Width Modulation
THD	Total Harmonic Distortion
V2G	Vehicle-to-Grid
V_{dc}	DC Voltage



CHAPTER 1

INTRODUCTION

1.1 Background and Context

The transition to sustainable energy sources is a global imperative, driven by environmental concerns, energy security, and the need to reduce greenhouse gas emissions. At the forefront of this transition is the electrification of transportation, and electric vehicles (EVs) have emerged as a significant component of this transformation. With zero tailpipe emissions and the potential to be powered by renewable energy sources, EVs offer a clean and sustainable solution to the environmental challenges posed by conventional internal combustion engine-based vehicles [1].

With the accelerating global shift towards sustainable transportation, EVs have emerged as a key solution to reduce greenhouse gas emissions and dependency on fossil fuels. EVs use high efficiency electric motors and controllers producing a cleaner, efficient, and more environmentally friendly transportation system [2].

EVs have made substantial progress in recent years, with growing popularity and advancements in technology. However, some challenges still need to be addressed to make EVs more practical and convenient for consumers. Among these challenges are the issues of long charging times and range anxiety. Traditional slow AC charging methods can be time-consuming, and concerns about running out of charge during longer trips have deterred potential EV owners. Fast charging stations offer a compelling solution to these problems [3].

Fast charging stations are designed to significantly reduce charging times, making EVs more attractive and practical for daily use and long journeys. These stations can charge an EV in less than an hour, depending on their power rating. Unlike slow chargers, fast charging stations are typically designed as offboard systems where the charging equipment is mounted on the ground, separate from the vehicle.

As the number of EVs on the road continues to rise, there is an urgent need for robust and efficient charging infrastructures to support their widespread adoption. Efficient and rapid charging solutions play a pivotal role in enhancing the practicality and acceptance of EVs. One of the critical components in this charging infrastructure is the power converter, responsible for transforming electrical energy between the grid and the vehicle's battery when the EV is parked at peaks of consumer energy demand [4].

The core component of a fast-charging station is the converter, responsible for converting the grid's alternating current AC into direct current DC to charge the EV's batteries. The efficiency and cost-effectiveness of this converter play a pivotal role in the overall performance of the fast charging station. The converter design and its control system are essential factors in achieving efficient, reliable, and cost-effective EV charging.

Traditionally, a two-stage approach is used in these converters, where AC power is first converted to DC using an AC-DC converter (or an uncontrolled rectifier), followed by a DC-DC converter at the output. The DC-DC converter must be continuously controlled to meet the desired charging and discharging characteristics. This two-stage method, while functional, can be complex and may result in a larger converter size and increased overall costs.

In contrast, a single-stage bidirectional topology can be utilized to perform the required charging and discharging functions more efficiently and with reduced size and complexity. In such a topology, the control scheme is of paramount importance to meet the desired control characteristics.

Traditional charging methods often face limitations in terms of charging speed and adaptability to varying grid conditions. Derived from the popular matrix converters (MCs), AC-DC MCs have attracted a lot of interest recently as a novel kind of converter. They have several of MCs' intrinsic benefits, including high power density, compact architecture, variable input power factor, sinusoidal input current, and four-quadrant operation [5].

An AC-DC MC is a bidirectional, one-stage, current-source buck rectifier. It is extensively used in many different fields, including battery energy storage systems, EVs, renewable energy generation, and AC-DC microgrids [6].

This research is motivated by the necessity to overcome the limitations of existing charging infrastructures. The study focuses on the design and implementation of a 100 kW bidirectional AC-DC MC, which is a critical component in the power conversion process. This converter is intended to facilitate fast charging of EVs while providing bidirectional power flow capabilities, allowing energy to be transferred both from the grid to the vehicle and vice versa. While substantial research has been conducted on AC-DC converters for EV charging, there remains a notable gap in the design and implementation of high-power bidirectional converters, especially those utilizing a three-phase matrix architecture. The primary objective of this research is to design a bidirectional AC-DC MC, capable of efficiently handling high power (100 kW) for fast charging applications.

Additionally, two charging modes, CC charging and CV charging will be studied. This single-stage bidirectional topology is also well-suited for Vehicle-to-Grid (V2G) applications. The study will demonstrate the capability of the converter to transfer energy from vehicles to the grid and highlight the voltage, current, and power profiles during V2G operation.

All aspects of the design, including the control system, will be developed and validated in a simulation environment suitable for power electronics and control applications.

Specific goals include optimizing control strategies and ensuring reliable bidirectional power flow. By addressing the outlined objectives, this research contributes to the ongoing efforts to advance EV charging infrastructure, making strides towards a sustainable and efficient transportation ecosystem.

The major challenges encountered when designing a bidirectional AC-DC MC for fast EV charging include:

1. The requirement for low harmonic distortion close to an ideal sinusoidal waveform at the input, this necessitates the design of a passive filter, either of the LC or LCL type, to be integrated at the input side of the converter. This filter is designed to reduce harmonic distortion and ensure that the input current waveform closely resembles an ideal sinusoidal waveform.

2. The requirement for unity power factor operation at the input, achieving a unity power factor at the input is crucial to ensure efficient power transfer from the grid to the EV. Unity power factor operation minimizes reactive power and optimizes the utilization of available power.
3. The requirement for reduced ripple at the output. Output voltage and current ripple should be minimized to provide a stable and reliable charging process for the EV. High ripple can lead to voltage and current variations, affecting the safety and performance of the charging process.

To address the challenge of harmonic distortion at the input, a passive filter design is essential. The choice of filter type, whether LC or LCL, is a critical decision. The design parameters of this filter, such as inductance and capacitance values, must be carefully determined to achieve the desired reduction in harmonic distortion while ensuring efficient operation.

To tackle the other challenges, an independent real-reactive power control scheme will be proposed. This control scheme will effectively manage the charging and discharging modes of the converter and the associated reactive power requirements. Additionally, the modulation techniques for generating switching signals for the power semiconductors, such as space vector or pulse width modulation (PWM), will be explored and selected based on their suitability for the design.

Depending on the required power level of 100 kW, the power circuit will be designed at the component level. This includes selecting the appropriate power semiconductors, which could be metal-oxide-semiconductor field-effect transistors (MOSFETs), insulated gate bipolar transistors (IGBTs), or integrated gate-commutated thyristors (IGCTs). The design will ensure that the components can handle the power and voltage levels necessary for fast charging.

Simulation results will be conducted and presented to verify the effectiveness of the proposed design. These results will demonstrate the converter's performance, including its harmonic distortion, power factor, and output ripple. This research aims to contribute to the development of efficient and high-performance DC fast charging stations for electric vehicles, ultimately supporting the adoption of EVs and sustainable energy practices.

1.2 Research Motivation

The motivation for this research arises from the critical need for sustainable and environmentally responsible transportation solutions. EVs have emerged as a promising answer to the environmental challenges posed by conventional internal combustion engine vehicles.

Global fossil fuel emissions primarily result from the combustion of coal, oil and natural gas. Coal is responsible for more emissions than any other fossil fuel, representing approximately 41% of global fossil CO₂ emissions in 2023. Oil is the second largest contributor at 32% of fossil CO₂, while gas rounds out the pack at 21%.

As shown in Figure 1.1 global CO₂ emissions from different fuels over time, covering coal (grey shading), oil (red) and gas (blue), as well as cement production (yellow) and other sources (purple). While coal emissions increased rapidly in the mid-2000s, it has largely plateaued since 2013. However, coal use increased significantly in 2021 and modestly in 2022 and 2023.

Annual CO₂ emissions by fuel, 1959-2023

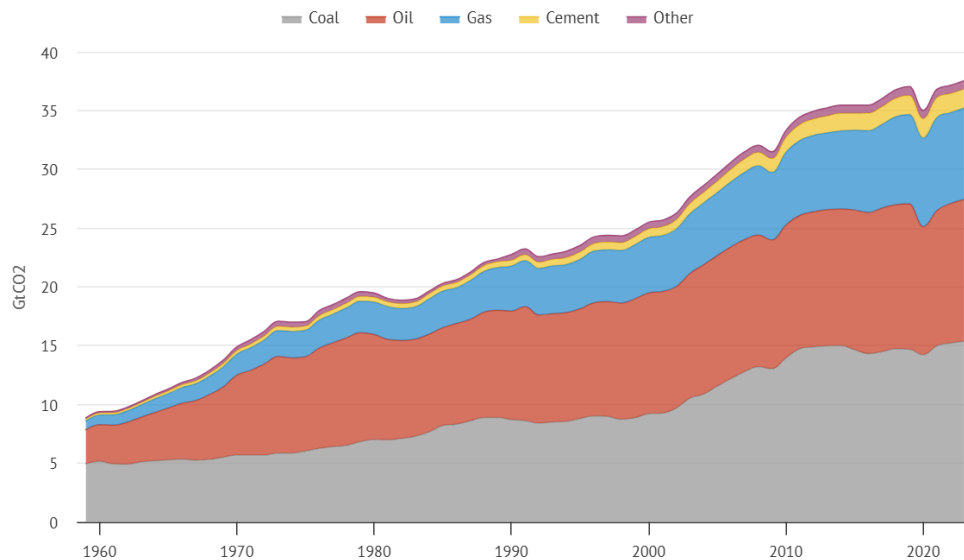


Figure 1.1 Global carbon emission per year in million tons from 1959 to 2023[7].

The primary factors driving this research include:

1. **Environmental Concerns:** Issues such as air quality and climate change necessitate a shift towards cleaner transportation. Conventional gasoline and diesel vehicles significantly contribute to air pollution and greenhouse gas emissions. In contrast, EVs produce zero tailpipe emissions, reducing the environmental impact.
2. **Climate Change and Urban Air Quality:** The urgent need to mitigate climate change effects and improve urban air quality strongly motivates the widespread adoption of EVs. Efficient and fast charging solutions are essential for promoting the transition from traditional vehicles to electric ones.
3. **Range Anxiety:** The fear of running out of battery before reaching a destination or charging station has been a significant psychological barrier to EV adoption. Fast-charging stations address this concern by offering rapid charging capabilities, making longer journeys feasible and convenient for EV drivers, this is a significant motivation for developing fast-charging infrastructure.
4. **Sustainable Energy and Transportation Goals:** Broader EV adoption is crucial for achieving sustainable energy and transportation objectives. To encourage consumers to choose EVs over conventional vehicles, the charging experience must be efficient, convenient, and accessible. Fast charging stations are vital in making EVs more attractive and practical for a diverse range of consumers.
5. **Economic and Energy Security:** Reducing dependence on fossil fuels offers economic and energy security benefits. EVs can be powered by domestically generated electricity, decreasing reliance on imported oil and enhancing energy independence. This has geopolitical and economic implications that further motivate the development of EV infrastructure, including fast charging stations.
6. **Technological Advancements:** Progress in power electronics, control systems, and materials has made it feasible to design and deploy efficient and high-power fast charging stations. These advancements enable innovative EV charging solutions and optimize the overall charging experience.
7. **Future-Proofing Infrastructure:** As the number of EVs on the road increases, it is essential to future-proof charging infrastructure. Fast charging stations with

advanced features can meet the needs of next-generation EVs, which are expected to have larger batteries and greater power requirements.

8. DC Fast Charging Stations: These stations are crucial for providing rapid charging, significantly reducing the time required to charge an EV. The ability to charge an EV in less than an hour transforms EVs into a practical mode of transportation for both daily commutes and long-distance travel. This research focuses on the design and optimization of DC fast charging stations, which are key to making EVs more appealing and competitive.
9. Efficiency and Cost-Effectiveness: The efficiency and cost-effectiveness of EV charging systems are linked to the design and control of power converters within these systems. Efficient power conversion ensures maximum electrical energy transfer from the grid to the EV's battery, minimizing energy losses, improving overall performance, reducing operating costs, and lowering environmental impact.
10. Cost Considerations: Making EVs and their charging infrastructure financially accessible is vital for broader adoption. The design and control of power converters impact the size, complexity, and overall cost of the charging system. An efficient design and control strategy can lead to more affordable charging stations, supporting the affordability and accessibility of EVs.

In summary, this research aims to overcome the challenges of long charging times and range anxiety in EV adoption. DC fast charging stations play a central role by providing rapid charging capabilities. The efficient design and control of the power converter are critical for reducing charging times, minimizing operational costs, and ensuring the affordability of EV charging solutions. This research is driven by the need to support and accelerate the transition to sustainable transportation through the development of fast charging infrastructure, addressing environmental concerns, enhancing EV ownership convenience, and contributing to energy security and economic benefits. Additionally, it leverages technological advancements to create efficient and future-proof solutions for the evolving EV market.

1.3 Research Objectives

This research is guided by the following key objectives:

1.3.1 Designing a 100 kW Bidirectional AC-DC MC for Fast EV Charging:

The primary objective of this research is to design a bidirectional AC-DC MC with a power rating of 100 kW. This converter will serve as a fundamental component of fast EVs charging stations. The design process will encompass various critical aspects, including the choice of converter topology, component selection, and control strategy. The aim is to create an efficient and high-power converter capable of significantly reducing EV charging times.

1.3.2 Investigating Two Charging Modes:

The CC and CV: Another key objective of this research is to explore and analyze two distinct charging modes: CC charging and CV charging. These modes are integral to the charging process of EVs and have different implications for battery health, charging efficiency, and user experience. The investigation will provide valuable insights into the performance of the designed converter under varying charging scenarios, contributing to the development of versatile and adaptable charging infrastructure.

1.3.3 Exploring the Suitability of the Topology for (V2G) Applications:

The third objective of this research is to evaluate the suitability of the chosen bidirectional AC-DC MC topology for V2G applications. V2G technology enables bidirectional energy flow between EVs and the electrical grid, allowing EVs to serve as energy resources during peak demand and grid stabilization. Understanding how this converter topology can support V2G applications is essential for the future integration of EVs into the broader energy ecosystem. These research objectives are designed to address the critical challenges associated with EV charging, enhance the performance of charging stations, and pave the way for broader EV adoption and their potential integration into smart grid systems.

1.4 Research Scope

This research is focused on detailed exploration within the following defined scope:

1.4.1 In-depth Analysis of the Design and Control of a Three-Phase Bidirectional AC-DC MC:

The primary scope of this research involves a comprehensive examination of the design and control aspects of a three-phase bidirectional AC-DC MC. The analysis

will delve into the intricacies of selecting the appropriate converter topology, sizing components, and developing a robust control strategy. Special attention will be given to meeting the specific requirements of fast EVs charging, including power rating, efficiency, and adaptability to different charging scenarios. The design analysis will consider factors such as harmonic distortion reduction, unity power factor operation, and output ripple minimization. It will also explore the challenges and considerations associated with achieving bidirectional power flow for both charging and discharging modes.

1.4.2 Simulation-based Verification of the Proposed Design:

To validate the efficacy of the proposed design, simulation-based verification will be conducted. This involves implementing the designed three-phase bidirectional AC-DC MC in simulation software. The simulation will emulate various operating conditions, load profiles, and input variations to assess the converter's performance. Simulation results will be analyzed to verify the converter's ability to meet the defined objectives, including low harmonic distortion, unity power factor operation, and reduced output ripple. The simulation-based approach provides a controlled environment to evaluate the converter's behavior under different scenarios.

This research, while ambitious in its objectives, is specifically scoped to the design and simulation verification phases. Practical implementation, hardware testing, and field deployment fall beyond the current scope but may be considered for future research endeavors. By focusing on the design intricacies and utilizing simulation for verification, this research aims to contribute valuable insights into the development of efficient and high-performance bidirectional AC-DC MC for fast EVs charging.

This research addresses the growing need for efficient and high-power fast EV charging solutions by proposing a 100 kW bidirectional AC-DC MC. The study explores advanced power conversion techniques to enhance charging speed, efficiency, and grid interaction, particularly for Vehicle-to-Grid (V2G) applications. By focusing on converter design, control strategies, and performance optimization, this research contributes to the development of sustainable and reliable EV charging infrastructure, ultimately supporting the widespread adoption of electric vehicles.

1.5 Thesis Structure

The structure of this thesis is organized to provide a coherent and logical progression of the research. Each chapter contributes to the overall understanding of the design and control of a three-phase bidirectional AC-DC MC for fast EVs charging. The following is an overview of the chapters and their respective content. This thesis ensures a systematic and coherent presentation of the research, facilitating a clear understanding of the design and control of the bidirectional AC-DC MC for fast EV charging. Each chapter contributes to the overall narrative, guiding the reader through the research process and its outcomes.

Chapter 2: Literature Review

This chapter conducts an extensive review of existing literature relevant to bidirectional AC-DC MCs, fast EV charging, and related control strategies. It explores previous research, industry standards, and emerging trends in power electronics for EV applications. This chapter serves as the foundation for understanding the current state of the field and identifying gaps that the current research aims to address.

Chapter 3: Proposed EV Charging System

In this chapter, the detailed methodology for designing the bidirectional AC-DC MC is outlined. It covers aspects such as converter topology selection, component sizing, and the development of the control strategy. The methodology also explains the rationale behind investigating CC and CV charging modes and outlines the parameters considered for simulation-based verification. This pivotal chapter delves into the intricacies of the design and control aspects of the three-phase bidirectional AC-DC MC. It discusses the theoretical foundations, design considerations, and challenges encountered in achieving bidirectional power flow. The chapter also introduces the selected control strategy and modulation techniques, shedding light on the decisions made to optimize converter performance.

Chapter 4: Simulation Results and Analysis

The focus of this chapter is on the simulation-based verification of the designed bidirectional AC-DC MC. It details the simulation setup, scenarios considered, and the analysis of simulation results. This chapter serves to validate the effectiveness of the proposed design under various operating conditions and load profiles. Building upon the verification results, this chapter presents a comprehensive analysis of the findings.

It discusses the performance of the bidirectional AC-DC MC in meeting the specified objectives. Additionally, the chapter explores any observed limitations and potential areas for further improvement.

Chapter 5: Conclusion and Future Work

The final chapter summarizes the key findings, implications, and contributions of the research. It concludes with reflections on the designed converter's effectiveness for fast EV charging. Furthermore, the chapter outlines potential avenues for future research, including hardware implementation, testing, and integration into practical EV charging infrastructure.



CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Energy Conservation and EV Infrastructure:

The relevant authorities have understood the need for energy conservation and emission reduction due to the increasingly severe energy shortages and environmental pollution challenges reduction.

2.1.1 EVs Charging Infrastructure:

EVs charging infrastructure is a critical component in the widespread adoption and success of electric mobility. This section provides an overview of EV charging requirements and the infrastructure that supports the growing ecosystem of EVs.

2.1.2 EVs Charging Requirements:

EVs as an eco-friendly alternative to traditional internal combustion engine vehicles, rely on a charging infrastructure that caters to their unique energy needs. Unlike conventional vehicles fueled by gasoline or diesel, EVs are powered by electricity stored in high-capacity batteries. Charging these batteries requires specialized infrastructure that aligns with the diverse charging preferences and requirements of EV users.

2.1.3 Significance of EVs:

The aforementioned problems can be resolved effectively by creating electric or plug-in hybrid automobiles [8], [9]. V2G technology will soon play a crucial role in EVs market [10], [11]. EV is one of the strongest legs for the world's transition to sustainable energy.

The EV industry is seen to be an emerging solution for the environmental problems associated with conventional internal combustion engine-based vehicles. Thereby, EVs are an emission-free and silent solution for future transportation systems [12].

2.2 Fast Charging Stations:

DC fast charging station design for EVs is inevitable for today's living standards to cope with the issues of long charging time and range anxiety [13].

Besides charging a battery car to 80% of its SOC in typically 15 minutes [14], fast charging also decreases operating costs and increases productivity [15]. Fast charging stations play a pivotal role in the evolution of the EVs landscape. Their significance can be understood through several key aspects:

1. **Reduced Charging Times:** Fast charging stations drastically reduce the time required to charge an EV. While slow charging may take several hours, fast charging can deliver a substantial amount of energy in a much shorter duration, making it feasible for users with time constraints.
2. **Long-Distance Travel:** Fast charging is essential for enabling long-distance travel with EVs. It addresses the limitations imposed by the range of EVs, allowing drivers to recharge quickly during extended journeys.
3. **Enhanced Convenience:** The convenience of faster charging aligns with modern lifestyles where time is a valuable commodity. Fast charging stations cater to the needs of drivers who may not have the luxury of waiting for extended periods during their journeys.
4. **Increased Adoption:** The availability of a robust fast charging infrastructure contributes to increased confidence and adoption of EVs. It addresses one of the primary concerns of potential EV buyers—range and charging times.
5. **Versatility for Urban and Suburban Areas:** Fast charging stations are adaptable to various settings, including urban areas where quick top-ups are advantageous for daily commuting, and suburban or rural areas where long-distance travel is more common.

During rapid charging, vehicle batteries experience temperature increases due to resistive (Ohmic) losses and electrochemical reactions occurring during both charging and discharging processes.[16]

To enhance the cooling process and extend battery life in the automotive sector, the use of Thermoelectric Generators (TEG) has been proposed. These coolers can be installed between the terminals of a cell pair or a plate pair. Additionally, a power-

flow management algorithm has been developed to ensure all energy storage devices reach their specified State of Charge SOC before the system operates. [17]

A hybrid PWM method has also been introduced to mitigate temperature rise in converters without significantly increasing switching losses. In this approach, half of the switches operate at a high frequency (tens of kHz), while the other half switch at the system frequency (50 or 60 Hz). This method has proven highly effective [18].

In summary, understanding the requirements of EV charging and recognizing the significance of fast charging stations is crucial for developing an efficient and accessible charging infrastructure. This knowledge informs the design and deployment of charging solutions that cater to the evolving needs of the growing EVs market.

2.3 Battery Technologies and Charging Modes

2.3.1 EV Batteries

A battery is a device that converts chemical energy into electrical energy and vice versa [19]. The parameters shown in Table 2.1 can be found on any battery data sheet provided by the manufacturer. For the purposes of this research, the key parameters are briefly explained below [19]:

Table 2.1 Battery technical specifications [19]

Parameter	Unit	Parameter	Unit	Parameter	Unit
Nominal voltage	V	Power density	W/l	Internal resistance	Ω
Cut-off voltage	V	Maximum continuous discharge current	A	Specific power	W/kg
Capacity	A.h	Maximum 30-sec discharge pulse current	A	Energy density	W.h/L
Energy	W.h	Charge voltage	V	Specific energy	W.h/kg
Cycle life	(unitless)	Float voltage	V	Charge current	A

1. Nominal Voltage: This is also known as the reference voltage of the battery.
2. Cut-off Voltage: This is the voltage level at which the battery is considered depleted.
3. Charging Voltage: This is the maximum permissible voltage for charging the battery.
4. Nominal Energy: This represents the available energy in Watt-hours (calculated as power in watts multiplied by time in hours).
5. Charging Current: This is the optimal current value at the initial stage of charging the battery in constant current until approximately 70% SOC is reached.

The primary chemistries for Plug-in Hybrid EV (PHEV) batteries include Lead-acid, lithium-ion (Li-ion), and Nickel-Metal Hydride (NiMH) [20]. Among these, Lead-acid batteries are the most widely used due to several advantages [21]:

1. They are highly suitable for fast charging technology.
2. Fast charging enhances their life cycle.
3. The pulsed-type algorithm, which will be utilized later in this thesis, effectively maintains the optimal oxide morphology throughout the battery's life cycle.

The longevity of battery life cycles is influenced mainly by the battery temperature and Depth of Discharge (DOD) [22]. As illustrated in Figure 2.1, batteries that operate at lower DODs and temperatures exhibit a higher number of life cycles.

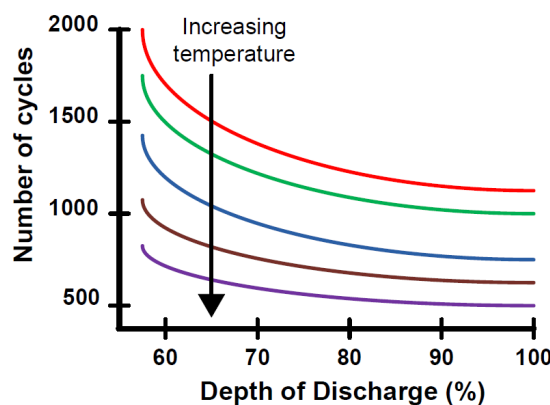


Figure 2.1 Impact of DOD and temperature on battery cycles [22].

2.3.2 Charging Modes for EVs

Charging modes for EVs as shown in Table 2.2 typically include:

1. **Slow Charging (AC):** This is the conventional mode where EVs are plugged into standard electrical outlets for overnight charging. While suitable for daily commuting, it may not address the needs of long-distance travel or situations where rapid charging is imperative.
2. **Fast Charging (AC):** Fast charging stations are designed to deliver a higher amount of electric power to the EV's battery, significantly reducing charging times. This mode is crucial for addressing range anxiety and making EVs more practical for various applications.
3. **Rapid Charging (DC):** Rapid charging stations go a step further in delivering even higher power levels, allowing for quicker charging sessions. These are often strategically located along highways and busy routes to facilitate long-distance travel.

Table 2.2 Charging stations schemes [SAE standard J1772] [23]

Power level	Voltage and current	Location	Max. power (kW)	Charging time (hrs)
Level 1	120 Vac-15 A,	1/–	1.4	4–11
	120 Vac-20 A	On-board	1.9	11–36
Level 2	240 Vac-40 A,	1-phase/3-phase-	4	1–4
	400 Vac-80 A	On-board	8	2–6
			19.2	2–3
Level 3	208 Vac-80 A, 200A	3-phase- -Off-board	38.4	0.4–1
	600 Vac-80A, 200A		130	0.2–0.5
Level 4	400–800 Vdc	Off-board	50–500	0.1–0.2

AC fast charging systems come in two levels and have higher power ratings: Level 3 AC fast charging systems use an off-board AC charging infrastructure to directly charge the vehicle's battery.

The DC fast charger has a maximum power rating of 500 kW and can offer 400–800V DC voltage. DC fast charging systems use an off-board DC charging infrastructure to directly charge the vehicle's battery with a current rating of up to 200A.

DC fast charging stations can charge an EV less than an hour depending on the station power rating [24]. On the contrary to a slow (AC) charging station, DC fast charging

station is designed as offboard where the charging system is mounted on the ground. A bidirectional battery charger is essential to V2G technology. The battery charger provides electrical energy to EVs; however, when the EV is parked during periods of peak consumer energy demand, energy stored in the battery may be returned to the grid to support the system [25].

2.4 Power Electronics in EV Charging

The integration of power electronics is pivotal in EV charging systems, influencing the efficiency and performance of energy transfer between the grid and the vehicle's battery. The conversion from AC to DC (or vice-versa) and among them is done through the converters mentioned in Table 2.3 below [26], [27].

Table 2.3 Main power electronics converters [19]

Conversion	AC to AC	DC to DC	AC to DC	DC to AC
Topology	AC Controller	Chopper	Rectifier	Inverter

This section delves into the various converter topologies employed in EV charging and conducts a comparative analysis between two-stage and single-stage converter designs.

2.4.1 Converter Topologies for EV Charging

1. **Uncontrolled Rectifiers (AC-DC):** This basic converter topology involves the direct conversion of AC from the grid into DC without sophisticated control mechanisms. While simple, it may introduce harmonic distortions and efficiency challenges.
2. **DC-DC Converters:** These converters are essential for accommodating varying voltage levels within the EV charging process. They ensure efficient power transfer from the grid to the EV battery by adapting the voltage characteristics to the requirements of the charging system.
3. **AC-DC MC:** Representing a more advanced solution, AC-DC MC offers bidirectional power flow capabilities. This is crucial for facilitating both charging and discharging of the EV battery. The bidirectional AC-DC MC serves as a versatile and efficient solution for fast-charging scenarios.

The critical part of the charging station is its converter part in which the electrical power is converted from AC to DC form to charge the EV batteries. The efficiency and the cost of the system are primarily based on the critical converter design and its control. Usually, the AC power is first converted to DC form with an AC-DC converter (or an uncontrolled rectifier) and then a DC-DC converter is connected at the output of the AC-DC converter.

Even more complex converter topologies are suggested in [28], [29], which use current source rectifiers following an inverter step to produce good PQ but necessitate massive electrolytic capacitors. The diodes connected in series with the switches in a current source rectifier may result in higher power losses. There has been a discussion of further concepts pertaining to numerous single phase PFC stages in the system, active power filters, and line commutated rectifiers [30].

It has been seen, therefore, that employing these controls for the converters results in a larger, more complex system with a decrease in total system efficiency [31].

2.4.2 Two-Stage vs Single-Stage Converter Designs

The DC-DC converter is needed to be controlled continuously to meet the desired charging/discharging characteristics. On the contrary of this 2-stage method, a bidirectional single-converter topology can also be utilized to meet the required charging/discharging functions with reduced size and complexity. With this regard, the control scheme for such a single-converter topology should be designed to meet the required control characteristics.

Two-Stage Converter Designs: In this approach, the EV charging process involves two sequential stages. Initially, AC from the grid is converted to DC using an AC-DC converter. Subsequently, a DC-DC converter adapts the voltage level for optimal charging of the EV battery. While providing flexibility, this approach can introduce additional components and complexity.

Single-Stage Converter Designs: The single-stage approach, exemplified by bidirectional AC-DC MCs, integrates both the AC-DC and DC-DC conversion functionalities into a unified system. This streamlined design aims to enhance efficiency, reduce component count, and simplify control strategies. The bidirectional

MC is particularly advantageous for its ability to handle bidirectional power flow efficiently.

The choice between two-stage and single-stage converter designs involves careful consideration of factors such as overall system efficiency, cost-effectiveness, and the complexity of the charging infrastructure. Single-stage designs, especially bidirectional AC-DC MC, are gaining prominence for their potential to streamline EV charging systems and improve overall performance.

This exploration of converter topologies and the comparative analysis of two-stage and single-stage designs provide valuable insights into the evolving landscape of power electronics in EV charging, offering solutions that balance efficiency, cost, and complexity.

2.5 Bidirectional AC-DC MC

Bidirectional AC-DC MCs play a pivotal role in modern EV charging and V2G systems. These converters offer bidirectional power flow, enabling energy transfer to and from the grid. This capability is essential for scenarios where an EV not only draws power from the grid but also feeds excess energy back into it. The bidirectional AC-DC MC serves as a versatile solution, contributing to the efficiency and flexibility of EV charging infrastructure.

Most battery chargers on the market now contribute significantly to the problem of electromagnetic interference, harmonic losses, and enormous amounts of current harmonics in the power grid. As power electronics technology advances, more researchers are beginning to concentrate on better battery chargers based on bidirectional converters. The following qualities must be present in a charger converter to comply with the V2G application requirements. With a high-quality sinusoidal current at the grid interface and a configurable power factor (ideally unity), the power flow can change quickly to fulfill the space limitation in EVs, high efficiency, simple design, and high-power density are usually used. Battery chargers for EVs frequently use voltage-source-type PWM rectifiers since they permit bidirectional energy flow and the PWM technique considerably enhances the quality of their input currents. However, because it essentially functions as a boost converter, a separate chopper circuit is required to match the battery's charging voltage characteristics, which raises

the weight, costs, and lowers the efficiency of the device. Recent years have seen a lot of interest in MCs as a new topology of converters. A new MC that supports V2G power transmission is further reviewed in [32]. It is suggested that the problems caused by the current high power PHEV battery charging power systems can be solved by this new MC. MCs are known to be easier to design, more efficient, and able to be used with quick switching power devices. MCs provide a plethora of benefits to circumvent the current restrictive setups for EV chargers: Bidirectional power flow from V2G, because MCs are direct converters and do not require a capacitor on the converter side, the number of components in the system is reduced, achieving unity input power factor is possible, it is possible to acquire high-quality DC output voltage, which reduces the size of the DC-link filter, and well-maintained and high-quality battery current. The ideas of the AC-AC MC are covered in [33], [34], which also show a configuration with fewer switches to enable the converter to function as an AC-DC rectifier. These papers also discuss how MC can use the approach SVPWM to control the output voltage and achieve unity power factor. This thesis focuses on employing MCs to improve the grid's power quality. The study in [35] uses the SVPWM modulation approach for a three-phase MC rectifier with bi-directional power flow and power factor correction capabilities that can regulate the output voltage in a wide range. It has numerous advantages, including controlled input power factor, sinusoidal input and output waveforms, four-quadrant operation, no requirement for massive energy storage components, and more. The MC is frequently used in the distributed generation, new energy production, and variable-frequency drive industries. Inheriting several benefits from the AC/AC MC, the AC-DC MC is a converter that evolved from the indirect MC. It is a bidirectional current-source type rectifier with built-in capabilities for one-stage buck conversion and direct current synthesis. Tables 2.4, 2.5 provide a comparative analysis of previous. They outline key aspects such as control strategies, switching techniques, advantages, research methodology, and areas not emphasized in each study. This comparison offers valuable insights into the strengths and limitations of different approaches, aiding in the selection of optimal design considerations to improve efficiency and stability in bidirectional power conversion applications.

Table 2.4 Comparison of application, control strategy, and research methodology for some previous studies

Reference	Application	Control Strategy	Research Methodology
[32]	EV-grid integration	Conventional control	Analytical survey and case study
[34]	High-power applications	DSP-based Control	Experimental prototype and testing
[35]	Distributed generation and renewable energy	SVPWM with PFC	Simulation and theoretical validation
[36]	Improved dynamic performance, reduced harmonics, and high-power factor.	PID - SPWM	Simulation & experimental
[37]	Battery energy storage	Modulation and control strategy SVM	Simulation-based study
[38]	Fast EV charging and grid integration	Grid-connected control	Experimental validation with real-world testing

Table 2.5 Comparison of key features, advantages, and missing focus areas for some previous studies

Reference	Key Features	Advantages	Missing Focus Areas
[32]	Discusses PEV impact on the grid and V2G capabilities	Reduces the impact of EV charging on the grid, increases energy efficiency	No detailed analysis on converter topology
[34]	High-frequency isolation, four-quadrant operation	Reduces harmonics, improves conversion efficiency	No detailed efficiency analysis
[35]	Power factor correction, bi-directional operation	Minimizes the need for large energy storage components, smooth output voltage control	No transient response evaluation
[36]	Explores control techniques for single-phase MC	Control of single-phase matrix converters in renewable energy and industrial systems	Limited application to three-phase systems
[37]	Battery energy storage application, improved efficiency	High conversion efficiency, reduced power losses, improved grid stability	No discussion on bidirectional energy flow challenges
[38]	V2G integration, bidirectional power flow	Enhances power quality, reduces harmonics, supports the grid during peak demand	Limited focus on filter design impact

Designing an efficient bidirectional AC-DC MC presents unique challenges:

1. **Harmonic Distortion Reduction at the Input:** Achieving a current waveform close to ideal sinusoidal form, minimizing harmonic distortions during energy transfer. THD is a crucial indicator of power quality, and it must remain within permissible limits according to global standards to ensure the efficiency and stability of electrical systems. The limits vary based on voltage levels and system type. According to IEEE 519-2014, voltage THD should not exceed 5%, while current THD can range from 5% to 20%, depending on the rated current. IEC 61000-3-2 specifies a voltage THD limit of up to 8% for household devices, with varying limits for current based on device categories. Meanwhile, IEC 61000-3-6 sets stricter limits, allowing a maximum of 3% voltage THD in distribution systems and 5% in transmission systems.
2. **Unity Power Factor Operation:** Ensuring that the converter operates with a power factor close to unity, optimizing the use of electrical power from the grid. This also involves managing reactive power effectively to maintain grid stability and improve overall power quality.
3. **Output Ripple Reduction:** Minimizing fluctuations in the output voltage or current to ensure stable and reliable charging and discharging of EV batteries.

Recent research focuses on bidirectional single-converter topologies that reduce size and complexity while maintaining the necessary charging/discharging characteristics for V2G applications as shown in Figure 2.2. The topologies of buck type AC-DC conversion single-stage offer attributes like quick power flow control responsiveness and high efficiency, which make this solution extremely desirable in V2G applications.

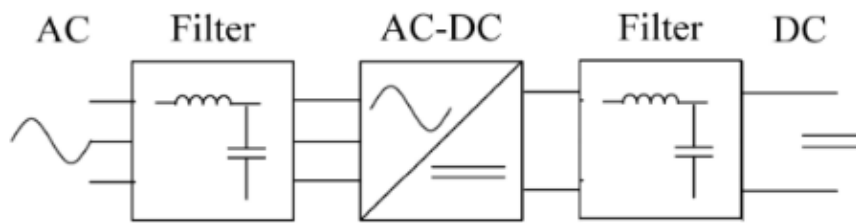


Figure 2.2 Topologies of buck type AC-DC conversion single-stage.

2.6 Control Strategies

Effective control strategies are essential for optimizing the performance of bidirectional AC-DC MC. First, passive filters, such as LC or LCL filters, are incorporated to reduce harmonic distortions at the input, enhancing power quality. Second, an independent control scheme for real and reactive power enables precise management of charging and discharging modes, along with reactive power flow. Lastly, advanced modulation techniques like space vector modulation or pulse width modulation are utilized to generate efficient switching signals, ensuring controlled and optimized energy transfer. The literature review reveals a significant gap in the research related to high-power bidirectional AC-DC MCs for fast EV charging. Existing studies often focus on lower power ratings or address specific aspects of bidirectional converters without providing a holistic solution applicable to fast charging infrastructure. Given the limitations identified in the literature, this study seeks to bridge the gap by presenting a detailed design of a 100 kW bidirectional AC-DC MC. By addressing the current research void, this work aims to contribute to the advancement of efficient and rapid EV charging infrastructure.

In this research, such a single-converter-based topology which is named "three-phase bidirectional AC-DC MC" will be considered for the design of a 100 kW DC fast charging station for EVs. This topology makes both charging and discharging possible [6]. In the research, also, two charging modes; namely, CC charging and CV charging will be also studied. Such a bidirectional single-stage topology is also well suited for V2G applications [39]. All the designs together with the control part will be completed and verified in a simulation environment that is suitable for power electronics and control applications. The major issues when designing a bidirectional AC-DC MC are as follows: The requirement for low harmonic distortion (close to ideal sinusoidal waveform) at the input, the requirement for unity power factor operation at the input, and the requirement for reduced ripple at the output. To cope with the harmonic distortion problem, a passive filter (LC or LCL type) design will be made at the input side of the converter. For the other issues, an independent real-reactive power control scheme will be proposed to effectively control the charging/discharging modes and the reactive power. Space vector or PWM modulation scheme can be preferred to generate the switching signals of the power semiconductors. Depending on the required power level (100 kW), the power circuit will be designed on the semiconductor (MOSFET,

IGBT, or IGCT) component level. Simulation results will be presented to verify the effectiveness of the proposed design.

This chapter reviewed existing literature on bidirectional AC-DC MCs, fast EV charging, and control strategies. It highlighted industry standards, emerging trends, and research gaps that this study aims to address. In the subsequent chapters, the proposed system architecture, control strategies, results, and overall contributions of this research to the field will be thoroughly examined.



CHAPTER 3

PROPOSED EV CHARGING SYSTEM

3.1 System Description

The proposed EV charging system is illustrated in Figure 3.1. This section provides a detailed insight into the components, topology, and operational principles of the system architecture. The system is fed from a low voltage three-phase AC $f=50$ Hz source through an input filter. This filter is a second-order LC one which is used to stop both the transmission of high frequency harmonic currents produced by the converter into the grid and the disruption of the converter by high frequency harmonics in the grid. The heart of the system is a three-phase MC with direct AC-AC conversion capability without the need for an intermediate DC link. This topology reduces the number of components, enhancing overall system reliability and efficiency. The output filter is connected between the MC output and the EV battery to smooth the charging current.

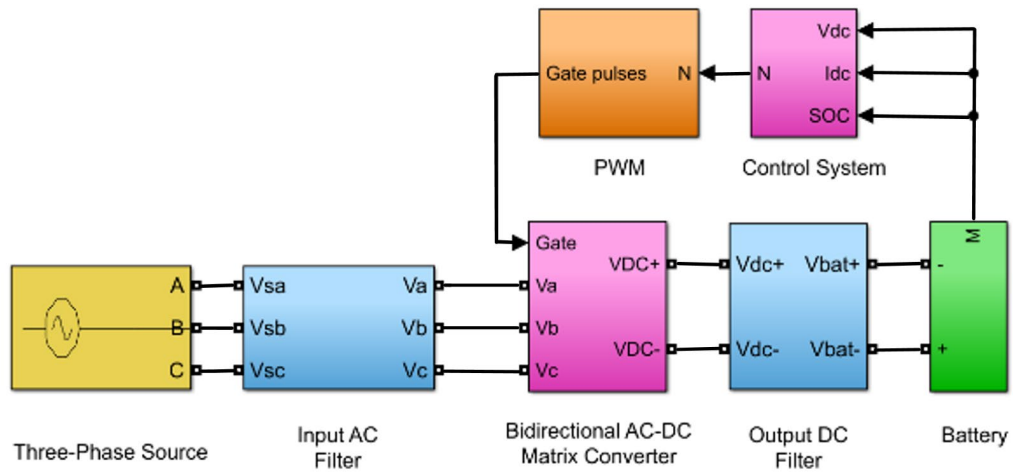


Figure 3.1 The proposed EV charging system.

1. Three-Phase Source is the main AC power supply, commonly from the electrical grid. It provides three-phase alternating voltage (V_a , V_b , V_c) at 50 Hz. The three-phase structure ensures stable power delivery and is well-suited for high-power systems, making it ideal for EV charging applications.

2. Input AC Filter second-order LC filter plays a critical role in ensuring power quality. It filters out high-frequency harmonic currents generated by the MC, preventing them from flowing back into the grid, which could cause disturbances, and shields the converter from high-frequency harmonics present in the grid, ensuring the input to the converter remains clean and stable. This improves overall system efficiency and protects sensitive components downstream.
3. The bidirectional AC-DC MC is the core component of the system, facilitating direct conversion from three-phase AC to DC without requiring an intermediate DC link. This design minimizes component usage, improving reliability and reducing losses. It supports bidirectional energy flow for both charging and discharging modes, making it suitable for V2G and G2V applications. Control is achieved through PWM-based gate signals to manage the switching of IGBTs, ensuring efficient operation.
4. The PWM and gate pulses are central to controlling the system, dictating the precise timing of the MC switches. This ensures efficient energy transfer by regulating both the voltage magnitude and frequency for optimal performance during charging and discharging. PWM has various advantages, including reduced filtering requirements, less computing overhead, and more effective power transmission [36].
5. The output DC filter stabilizes the voltage and smooths out current fluctuations. The inductor reduces ripple in the charging current, while the capacitor stabilizes the DC voltage before it reaches the battery, ensuring safe and efficient operation.
6. The battery serves as the energy storage unit. During charging, the converter provides regulated DC voltage, while in discharging, the stored DC energy is converted to AC and supplied back to the grid. The charging and discharging processes are carefully monitored to ensure efficiency and longevity.
7. The control system monitors key parameters such as the pre-filter DC voltage V_{dc} , charging current I_{dc} , and SOC. This ensures the converter operates reliably under varying grid and battery conditions, optimizing performance and protecting system components.

Table 3.1 illustrates the parameters for each component of the converter's structure.

Table 3.1 Parameters for each component of the schematic

Component	Parameter Name	Description
Three-Phase source	V_a, V_b, V_c	Phase voltages from the electrical network.
	Frequency (f)	Frequency of the AC supply.
	Phase sequence	Order of the three-phase voltages (ABC or CBA).
Input AC filter	L, C (Input filter)	Inductor and capacitor to filter high-frequency harmonics.
	Filter type	Second-order LC filter.
AC-DC MC	Gate signals	PWM-based signals controlling the switches.
	Switch states (ON/OFF)	States of the bidirectional switches.
	V_{dc+} / V_{dc-}	DC output voltage before filtering.
	Input currents	Currents from each phase (I_a, I_b, I_c).
Output DC filter	L_o (Inductor)	Smooths the charging/discharging current ripple.
	C_o (Capacitor)	Stabilizes the output DC voltage.
Battery	V_{bat}	Regulated DC voltage at the battery terminals.
	I_{dc}	Charging or discharging current.
	State of charge (SOC)	Battery charge level indicator.
Control system	V_{dc} (Pre-filter voltage)	Feedback voltage for regulation.
	N (Switching frequency)	Frequency for PWM control of switches.
	I_{dc} (Battery current)	Monitored for safe charging/discharging.

The battery is Li-ion type, nominal voltage 600V, maximum capacity 228 Ah, cut-off voltage 450V, fully charged voltage 645V, nominal discharge current 100A. On the other hand, the control system is designed to effectively control the charging and discharging modes. In this study, two charging modes are considered. These are CC charging and CV charging modes. A traditional PWM approach is used to provide fine digital control over switching commutation within power converters. Its simplicity has led to its adoption across a variety of power converter topologies, establishing its broad use in industrial applications

3.2 MC Topology

The MC topology includes a set of bidirectional switches, forming a matrix of controllable paths for power flow. The most popular controllable static switches used in the design of power electronic converters are displayed in Table 3.2. MOSFET (Metal Oxide Semiconductor Field-Effect Transistor): Operates efficiently at high frequencies, typically in the range of 20 kHz to 1 MHz, making it ideal for low to medium voltage applications. IGBT (Insulated Gate Bipolar Transistor): Has a lower switching frequency, generally between 1 kHz and 20 kHz, suitable for high-power applications. IGCT (Integrated Gate Commutated Thyristor): Designed for very high power but low switching frequency, typically under 1 kHz, often used in industrial systems. These switches, implemented using advanced power electronics devices, enable precise control over the conversion process. The insulated-gate bipolar transistor (IGBT) tends to be the best option for the design of the MC circuit in terms of cost. An IGBT converter typically operates with an efficiency of around 90% [40].

Table 3.2 Main controllable switches comparison

Device	Power Capability	Switching Speed
MOSFET	Low	Fast (20 kHz to 1 MHz)
IGCT	High	Slow (under 1 kHz)
IGBT	Medium	Medium (1 kHz and 20 kHz)

The AC-DC MC must operate in two modes for V2G applications: charging mode and discharging mode. In essence, this converter enables power to flow in both directions. However, no such device is available, instead, unidirectional devices are used to construct a bidirectional switch cell.

Generally, there are four different ways to build bidirectional switch cells as shown in Figure 3.2 [41], [42]. Figure 3.2(a) depicts a diode bridge switch containing an IGBT and four diodes, allowing current flow in both directions with high conduction loss and uncontrolled current direction. Alternatively, Figure 3.2(b) shows an anti-parallel reverse blocking IGBT that controls current flow but experiences high voltage and current spikes during switching. Figure 3.2(c) features a common-emitter anti-parallel IGBT switch with two IGBTs and two diodes, offering controlled current direction

and reduced conduction loss. Lastly, Figure 3.2(d) presents a common collector switch with similar conduction loss to the common emitter.

The common emitter anti-parallel IGBT configuration has the potential to use one isolated power supply for two IGBT gate drivers. Two IGBTs are used to provide the current path, and two diodes are connected to provide the reverse blocking capability. The current direction can be controlled, and only one IGBT and one diode are conducted at each conduction path. Therefore, the common-emitter configuration is preferable for a MC [43], [44].

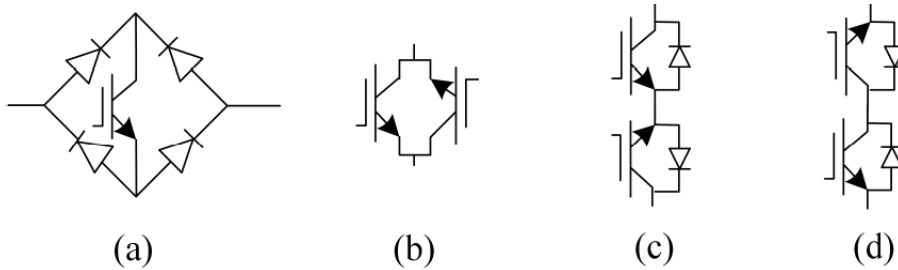


Figure 3.2 Different bidirectional switch cell (a) diode bridge bidirectional switch cell (b) anti-parallel reverse blocking IGBT (c) common emitter anti-parallel IGBT (d) common collector anti-parallel IGBT [45].

The AC-DC MC can be streamlined to a simple topology as illustrated in Figure 3.3. The interaction between the grid voltage, the converter, and the battery in a bidirectional AC-DC MC system. The grid voltages V_a , V_b , V_c represent the three-phase input from the electrical network. The output voltage of the converter V_{dc} denotes the DC voltage measured before the output filter, which is a crucial stage for stabilizing the DC output. After passing through the output filter, the voltage V_{bat} emerges, which corresponds to the regulated DC voltage across the battery terminals.

$S_{1(a,b)}, S_{2(a,b)}, \dots, S_{6(a,b)}$ Two IGBTs with anti-parallel gates typically implement the bidirectional switches. A free-wheeling diode and a common emitter are coupled in series [46].

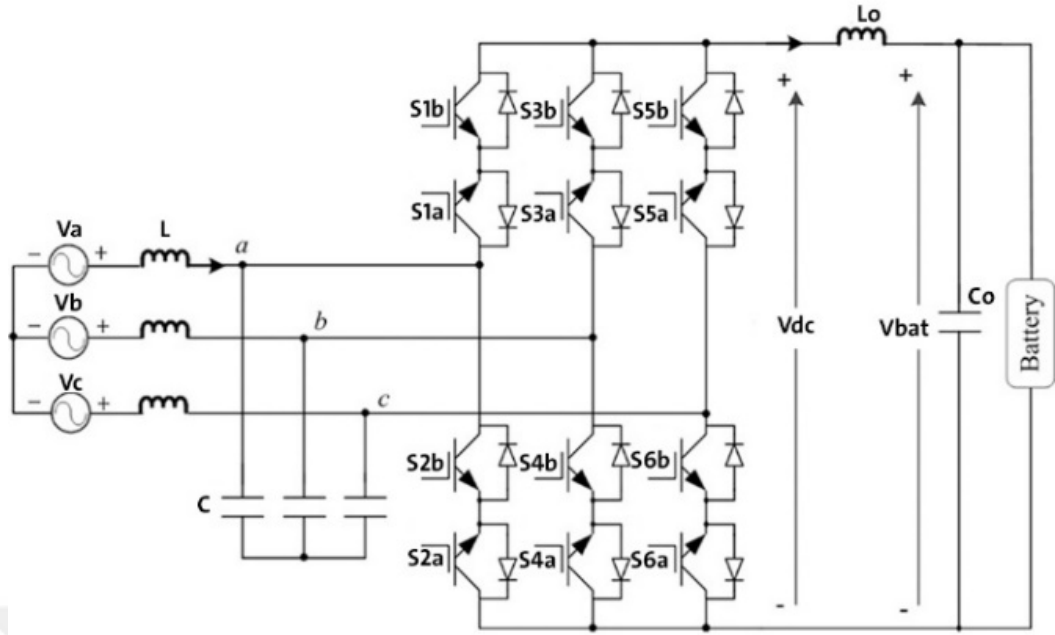


Figure 3.3 Topology of AC-DC MC.

To stop high frequency harmonic currents generated by the converter from entering the grid and to prevent the grid's high frequency harmonics from interfering with the converter, a second-order LC input filter is employed.

The output filter's inductor, L_o , and capacitor, C_o , are there to smooth out the charging current. The AC-DC MC must operate in both the charging and discharging modes in V2G applications. This converter essentially permits bidirectional power flow.

In the charging mode of an AC-DC MC, switches $S_{1a}, S_{2a}, \dots, S_{6a}$ are turned ON, while switches $S_{1b}, S_{2b}, \dots, S_{6b}$ remain OFF. This configuration enables the transfer of energy from the grid to the battery. The three-phase AC input voltages V_a, V_b, V_c are converted into a DC voltage V_{dc} through the converter. Before reaching the battery, this DC voltage passes through an output filter comprising an inductor and a capacitor which stabilizes it as V_{bat} as shown as Figure 3.4.

In discharging mode, the roles of the switches are reversed $S_{1b}, S_{2b}, \dots, S_{6b}$ are turned ON, and $S_{1a}, S_{2a}, \dots, S_{6a}$ are turned OFF. Here, the converter facilitates the flow of energy from the battery back to the grid as shown as Figure 3.5.

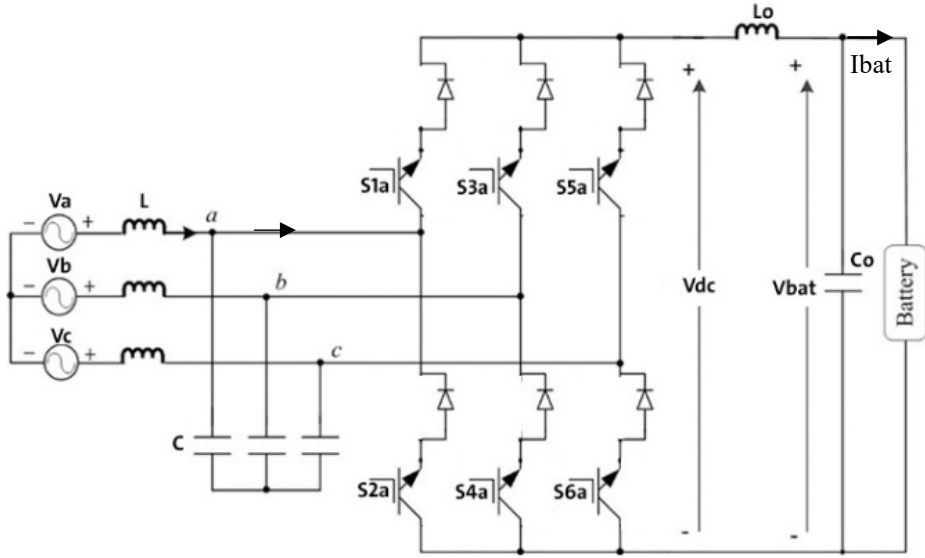


Figure 3.4 Topology of AC-DC MC converter in charging mode.

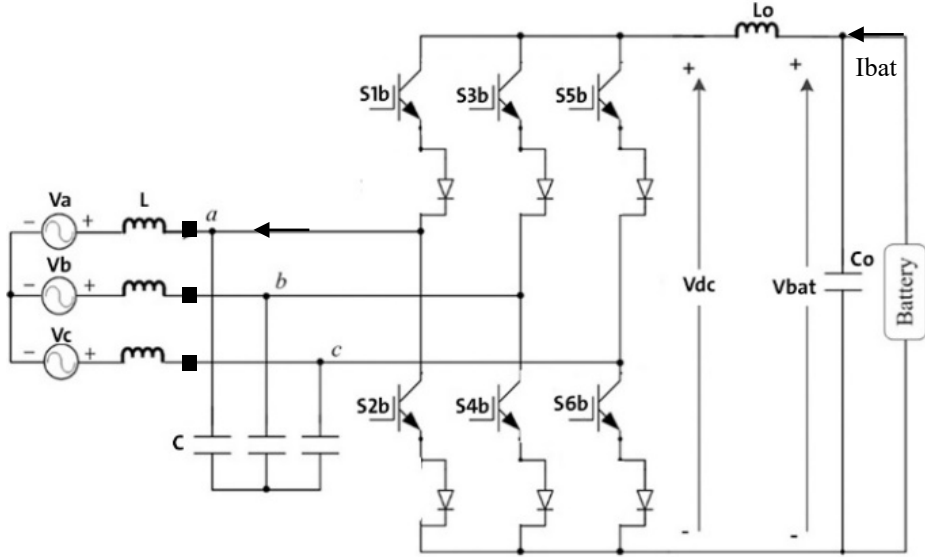


Figure 3.5 Topology of AC-DC MC in discharging mode.

3.3 The Pulse Width Modulation (PWM)

The PWM scheme is illustrated in Figure 3.7, the mathematical model of the converter can be obtained by combining the states of six bidirectional switches into a single vector. Hence, the output voltage $V=[V_p-V_n]$ as shown as Figure 3.6 directly depends on the input voltages (V_a , V_b , and V_c) and the current switch states (S_1 to S_6). [36]. The PWM method is applied in this type of modulation, having various advantages such as reduced filtering requirements, fewer mathematical computations, and better transmission of effective power as shown as Figure 3.7. The modulation system has two essential components: the first is responsible for implementing the PWM system,

generating a modulated signal that matches the reference waveform via a control system.

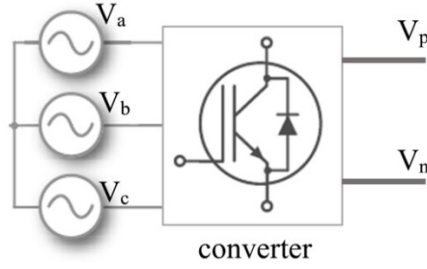


Figure 3.6 Output voltage.

The second section focuses on dividing the three-phase input source to identify different voltage areas defined by various line-to-line voltage combinations. For a three-phase input source, identifying distinct voltage regions is critical for choosing the devices to be switched using Table 3.3.

Table 3.3 Space vector of AC-DC MC

	Output		sector	Trigger Pulses					
	V _p	V _n		S1	S2	S3	S4	S5	S6
1	V _a	V _b	6	1	0	0	0	0	1
2	V _a	V _c	6	1	0	0	0	0	1
3	V _b	V _c	6	1	0	0	0	0	1
4	V _b	V _a	2	0	1	0	0	0	1
5	V _b	V _c	2	0	1	0	0	0	1
6	V _a	V _c	2	0	1	0	0	0	1
7	V _b	V _a	3	0	1	0	1	0	0
8	V _b	V _c	3	0	1	0	1	0	0
9	V _c	V _a	3	0	1	0	1	0	0
10	V _c	V _a	1	0	0	1	1	0	0
11	V _c	V _b	1	0	0	1	1	0	0
12	V _b	V _a	1	0	0	1	1	0	0
13	V _c	V _a	5	0	0	1	0	1	0
14	V _c	V _b	5	0	0	1	0	1	0
15	V _a	V _a	5	0	0	1	0	1	0
16	V _a	V _b	4	1	0	0	0	1	0
17	V _a	V _c	4	1	0	0	0	1	0
18	V _c	V _b	4	1	0	0	0	1	0

The segmentation of the input source is shown as a function of the provided voltage values over time. These unique sections are represented by the variables $X_1, X_2, \dots, X_6$, which are generated by binary comparators in logic circuit 1 that detect whether the phase voltage exceeds the subsequent phase. The three-phase AC voltage inputs are labeled V_a, V_b , and V_c , representing the phases, each pair of signals (e.g., V_a, V_b , and V_a, V_c) is processed through comparison blocks. These blocks perform necessary calculations or comparisons between phases to derive control signals. The outputs of the comparison blocks are combined, likely through a logical gate or multiplexer, to generate a unified control signal for switching. Finally, using the information provided by the control system (N) and the data from the comparator blocks identifying the sectors of the three-phase input source ($X_1, X_2, \dots, X_6$), the 12 switching signals ($S_{1a}, S_{1b}, \dots, S_{6a}, S_{6b}$) can be obtained, and by applying logic circuit 2 (OR), the switching signals ($S_1, S_2, \dots, S_6$) are derived for the MC converter.

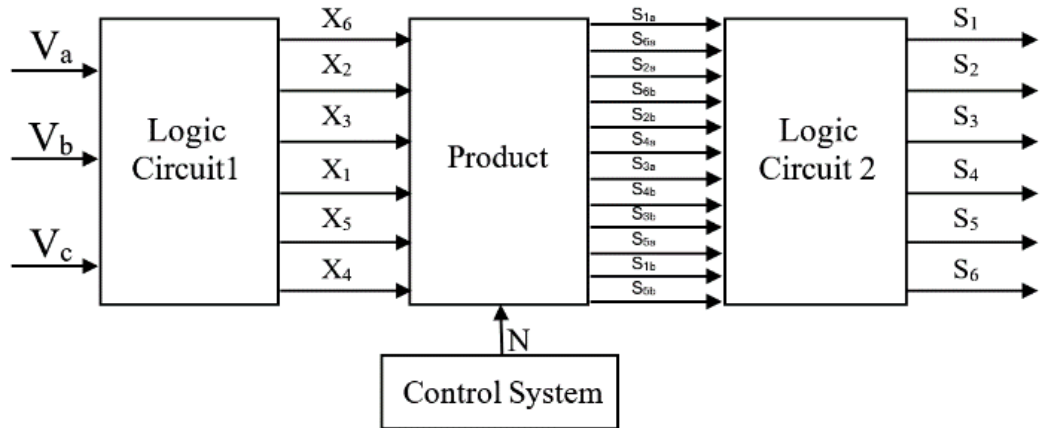


Figure 3.7 Topology of PWM scheme.

3.4 Input AC filter

Input AC filter is designed to ensure compliance with grid standards and reduce harmonic distortion, an input AC filter is incorporated. This filter minimizes high-frequency components and enhances power quality during AC-DC conversion. A passive LC filter is applied in the AC-DC MC as can be seen in Figure 3.8(a). In previous studies, various values for the inductor and capacitor have been selected to optimize filter performance. For instance, reference [37] selected an inductor of 1 mH with a capacitor of 10 μF , and reference [38] applied an inductor of 0.9 mH with a capacitor of 12 mF. Additionally, reference [45] employed different values such as 0.5 mH with 40 μF , 0.3 mH with 30 μF , and 0.3 mH with 20 μF , while reference [46]

utilized an inductor of 6 mH and a capacitor of 30 μ F. These values serve as a foundation for determining appropriate filter parameters in this work. The method for designing a passive LC filter is a general concept based on the principles of designing simple LC filters [47]. As shown by equation (2.1) f_c the cutoff frequency, L and C Inductor and capacitor to filter high-frequency harmonics. The cutoff frequency f_c is determined by considering the grid frequency (50 Hz) and the target for harmonic reduction. Specifically, the objective is to attenuate harmonics above the 3rd order, necessitating the attenuation of frequencies above 150 Hz (3×50 Hz). Consequently, the cutoff frequency f_c is established at 125 Hz, with an initial estimate for the capacitance C set at 4 mF.

$$f_c = \frac{1}{2\pi\sqrt{LC}} \quad (2.1)$$

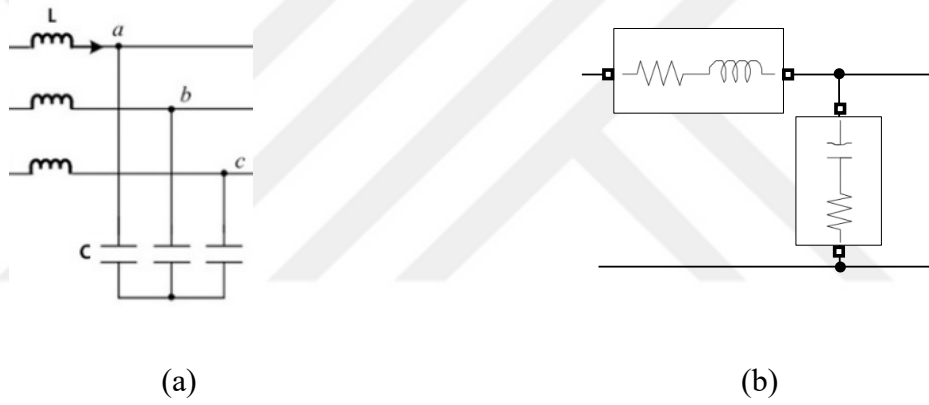


Figure 3.8 (a) Input AC filter (b) Output DC filter.

The necessary inductance L is derived using the equation (1) for the cutoff frequency of an LC filter, where f_c and C are known parameters. $L = 0.4$ mH, in selecting components, commercially available inductors and capacitors that closely match the calculated values are chosen. For instance, a selection might include a 0.4 mH inductor and a 4mF capacitor. It is crucial to ensure that the selected inductance value L remains sufficiently small to avoid impeding the flow of current from the grid to the MC and to prevent a significant voltage drop across the inductor. This consideration helps maintain the MC input voltage at parity with the grid voltage.

3.5 Output DC filter

Output DC filter is integrated for the AC-DC conversion during EV charging. This filter assists in shaping the output waveform and suppressing harmonics, contributing to the charging system's efficiency and stability. A well-designed output filter is required for minimal current ripple and for proper dynamic response.

An LC filter is applied in the AC-DC MC as can be seen in Figure 3.8(b). The design of output filter is based on two considerations: the dynamic response of the system and the suppression of current ripple. The output current response may become slower when using a large LC filter, which is frequently employed to reduce output current ripple. Therefore, a compromise between these two factors needs to be made. In previous studies, various values for inductance (L) and capacitance (C) have been selected to achieve optimal filtering performance. For instance, reference [37] considered configurations like L = 5 mH with C = 20 μ F, and reference [38] examined L = 0.2 mH with C = 2 mF. Additionally, reference [45] utilized L = 5 mH and C values of 110 μ F and 220 μ F, while reference [46] used L = 6 mH with C = 10 μ F. These values provide a reference for selecting appropriate filter components in this study. The method for designing a passive LC filter is a general concept based on the principles of designing simple LC filters [31]. As shown by equation (2.2).

$$f_c = \frac{1}{2\pi\sqrt{LC}} \quad (2.2)$$

The cutoff frequency f_c is established at 300 Hz, with an initial estimate for the capacitance C set at 6 μ F inductance L is 50 mH and with capacitance C set at 10 μ F inductance L is 90 mH. The values are obtained by trial and error for 3% current ripple when a capacitor of 10 μ F and an inductor of 90 mH are used, as the battery presents large capacitive characteristics and has very stable voltage, C can be very small or even removed [46], [48], the Parameters of AC filter and DC filter shown in Table 3.4.

Table 3.4 Parameters of AC filter and DC filter

Component	Parameters
Input AC filter	C= 4 mF , L= 0.4 mH
Output DC filter	C= 10 μ F , L= 90 mH

3.6 Proposed Control Strategies

The control system employs a combination of Proportional-Integral (PI) controllers. The PI controllers regulate the AC-DC conversion processes. Control schemes are created to improve the quality and performance of EV charging systems. The control strategies outlined for the 100 kW bidirectional AC-DC MC are crucial for ensuring efficient and reliable energy conversion in both AC-DC and DC-AC modes. These strategies adapt to the power requirements of the grid and the battery's state of charge SOC to optimize performance.

Figure 3.9 describes the overall diagram of the proposed control scheme; the switching and conversion components are controlled. These converters can employ any modulation techniques such as SVPWM or SPWM that were created for inverters. The converter operates in three modes: charging/discharging, CC, and CV.

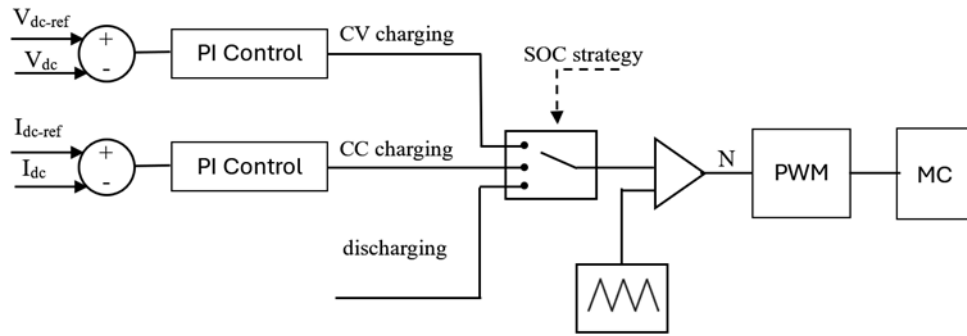


Figure 3.9 The proposed control strategies in this study.

CC and CV modes serve as maintenance modes to safeguard the battery from damage due to excessive charge/discharge. A feedback control loop is necessary to DC control for bidirectional AC-DC MC. The AC side current is directly influenced by the DC current, simplifying active power control. DC current is regulated by adjusting DC voltage or the modulation index N . The system output is the DC output voltage V_{dc} , current I_{dc} and SOC.

The error signal is identified while the converters are under control by comparing the DC output current in CC charging mode I_{dc} with a reference current I_{dc-ref} and the DC output voltage in CV charging mode V_{dc} with a reference voltage V_{dc-ref} . To create a sample, this error is utilized.

The PWM used to drive the switches in the converter is created using this sample waveform. Voltage source current control in CC charging mode or voltage control in CV charging mode are the two methods used to control switching signals. It serves as feedback in several control strategies, including sliding mode control, PID control, and PI controller. In this research, the PI controller was selected due to its suitability for EVs charging applications.

The PI controller provides quick responses and precise control, enhancing system stability and reducing steady-state errors through its integral component, which improves overall efficiency. It is particularly ideal for systems requiring rapid responses and high precision, such as EVs charging. Additionally, PI controllers are straightforward to implement in digital systems, making them easier and quicker to design and execute. While other options like PID controllers exist, the PI controller is sufficient for this context, as the derivative action may not be necessary for enhancing performance. Using the PI controller also simplifies the design while increasing reliability. This choice is further supported by its successful application in various studies on EVs charging, confirming it as a reliable and effective solution [49], [50].

A PI controller regulates the DC bus voltage V_{dc} during AC-DC conversion. It compares the actual V_{dc} with a reference voltage V_{dc-ref} and adjusts bidirectional switch duty cycles to maintain a stable output. And regulates current charging. This precise control accommodates variations in battery SOC and charging demands. The charging control system is unplugged during the discharging mode.

The dynamic response of a PI controller determines how quickly the system reacts to changes or disturbances. The proportional term (P) reacts to the magnitude of the error and provides a fast response. However, it may cause oscillations or overshoot if not tuned correctly. The integral term (I) helps eliminate steady-state errors by accumulating past errors over time but can slow down the response and introduce lag. A well-tuned PI controller eliminates steady-state error completely. The integral term continuously adjusts the control signal until the error reaches zero. However, excessive integral action can lead to instability or overshoot.

Proportional Gain (K_p) determines how aggressively the controller responds to the current error. Higher K_p reduces the rise time but may introduce overshoot and

oscillations. Integral Gain (K_i) This influences the system's ability to correct steady-state errors by considering the accumulated error over time. A higher K_i accelerates error elimination but can cause instability or excessive overshoot if not properly tuned. Tuning these parameters involves balancing speed, accuracy, and stability to achieve the desired system performance.

The triangular waveform in the PWM block represents the carrier signal used for pulse width modulation. It is compared with the control signal to generate gate pulses for the switching devices. The frequency and amplitude of the triangular waveform determine the resolution and switching frequency, directly influencing the system's efficiency and harmonic performance.

The SOC strategy governs whether the system operates in CC or CV charging modes. Depending on the battery's SOC, the control switches between modes to ensure efficient charging and prevent overcharging. The selection of the SOC strategy depends on several factors such as battery health, permissible current and voltage, and efficiency. Therefore, choosing the optimal charging strategy requires analyzing various scenarios to achieve the best possible outcome. The strategy should aim to maximize efficiency, whether in CC or CV modes, ensuring the highest possible efficiency or a combination of both. Discharging is represented as a separate pathway distinct from the charging processes. During discharging, the stored energy in the battery is released and sent back through the system, potentially to the AC grid or other loads. The discharging pathway bypasses the PI controllers for charging modes and connects directly to the PWM block.

The PWM block utilizes the discharging control signal, along with the triangular waveform, to generate gate pulses for the switching devices in the MC. PWM signals are shown in Figure 3.10. This ensures efficient conversion of the battery's DC energy back into AC energy suitable for external use. This signal works in conjunction with the triangular waveform and the PWM block, allowing energy to flow efficiently from the battery to the external load or grid.

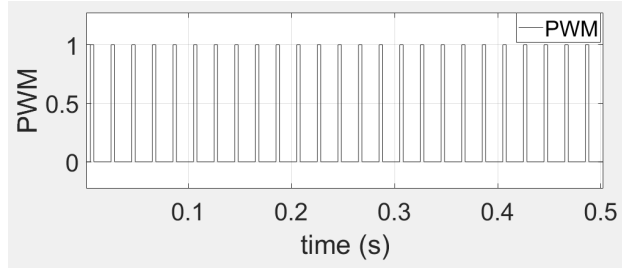


Figure 3.10 The PWM signal.

In our study, the reference charging voltage was established at 635 volts, ensuring it surpasses the nominal voltage of the battery yet remains below its full firing voltage. This selection ensures optimal charging conditions while safeguarding against overvoltage. Similarly, the reference charging current was determined not to surpass the maximum charging current specified by the battery, which in this case is 200 A. This cautious approach ensures safe charging by mitigating risks of excessive current flow.

This chapter outlined the design methodology of the bidirectional AC-DC matrix converter, covering topology selection, control strategies, and charging modes. Key challenges in bidirectional power flow were addressed.

CHAPTER 4

SIMULATION RESULTS AND ANALYSIS

4.1 Simulation Environment

This chapter details the simulation methodology employed to evaluate the performance of the bidirectional AC-DC MC design for fast EV charging. The section includes a description of the simulation software/tools used and the setup process for conducting simulations relevant to power electronics and control applications.

4.1.1 Simulation Framework for Power Electronics

This research employs a comprehensive simulation framework to study and optimize power electronics systems. The approach focuses on leveraging advanced tools to accurately model, simulate, and analyze system dynamics, emphasizing bidirectional power flow in high-power applications. This abstract-level methodology enables detailed examination of voltage, current, and power characteristics under various scenarios, supporting efficient design and validation. The framework's flexibility ensures applicability to complex power electronics challenges, including V2G integration and fast EV charging infrastructure development.

4.1.2 Setting up the Simulation

Setting up the simulation involves configuring the simulation parameters and models to accurately represent the bidirectional AC-DC MC system. The methodology includes:

1. **Model Development:** Developing detailed mathematical models of the converter components, including power semiconductors, passive filters, and control algorithms.
2. **Parameterization:** Assigning appropriate parameters to the models based on the specifications of the bidirectional AC-DC MC design, including component values, operating conditions, and control parameters.

3. **Validation:** Validating the simulation models against theoretical calculations and experimental data to ensure accuracy and reliability.

4.1.3 Modeling of Bidirectional AC-DC MC

Bidirectional AC-DC MC are essential components in modern power applications such as V2G technology as Figure 4.1. These converters enable the efficient bidirectional flow of power between AC and DC sources, crucial for integrating renewable energy sources and stabilizing the grid. Such converters can be modeled using advanced simulation tools, which allow precise analysis and modeling of electrical and electronic systems.

To create a comprehensive model of the bidirectional AC-DC MC, the following key components are necessary:

1. **Switching Circuits:** these circuits include components such as IGBTs, which perform the conversion between AC and DC. These electronic switches are controlled by PWM signals, which regulate the switching of power between the AC and DC sources.
2. **Input and Output Filters:** filters, such as LC filters, are employed to minimize voltage and current ripples, thus improving the quality of the converted power.
3. **Control Units:** control units manage the power flow and ensure that the converter operates efficiently. These units typically employ control techniques such as voltage control or current control to maintain system stability and achieve specific performance objectives like power regulation between the vehicle and the grid.

Simulation Environment is a graphical modeling environment, used to create dynamic system models. The system can be designed as a block diagram representing the real-world elements of the converter.

1. **Building the Core Circuit:** The model typically starts with placing power sources (e.g., AC or DC sources) along with switches like IGBTs. LC filters are added to enhance power quality, and control units such as current or voltage control blocks are introduced to manage system dynamics.

2. **Control Signals Using PWM:** PWM signals are used to control the frequency and magnitude of the electronic switches, ensuring effective switching between the different power sources. The PWM signal generator can be built in Simulation Environment and connected to the switching components to manage the bidirectional flow of power.
3. **Design of Control Units:** Control units are crucial for ensuring that the system operates within its desired parameters, particularly with regard to voltage and current levels. These units are designed using Control blocks in Simulation Environment, which allow for precise tuning and management of the power flow.
4. **Achieving Voltage and Current Balance:** Control units regulate the flow of voltage and current between AC and DC sources. This regulation is based on the chosen control strategy, such as voltage or current control.
5. **Minimizing Voltage Ripple:** Control units also work to adjust signals periodically to ensure that the output voltage is stable and free from large ripples. This improves the efficiency and reliability of the power conversion process.

Once the system and control units are designed, the simulation can be run to evaluate the converter's performance under different scenarios. The following aspects are typically monitored:

1. **Signal Monitoring:** Voltage and current at each stage of the converter (before and after conversion) are measured using Scopes and Displays available within simulation.
2. **Performance Analysis:** The simulation enables a detailed assessment of system performance, focusing on conversion efficiency, stability, and signal quality, such as voltage and current ripple. It also offers valuable insights into critical parameters, including frequency behavior, voltage levels, and power flow dynamics.

Figure 4.2 shows a Three-Phase AC source and measurement at the AC side model. It includes the following components:

1. Three-Phase Source (A, B, C): This represents the input three-phase AC supply.
2. Voltage Measurement (V_{sa} , V_{sb} , V_{sc}): Voltage probes measure the phase voltages with respect to the ground for each phase.
3. Current Measurement (I_a , I_b , I_c): Current sensors monitor the phase currents.
4. Three-Phase V-I Measurement Block: Processes the measured voltage and current signals for further analysis.
5. THD Block: Computes the Total Harmonic Distortion (THD) of the input signals, providing an indicator of signal quality.

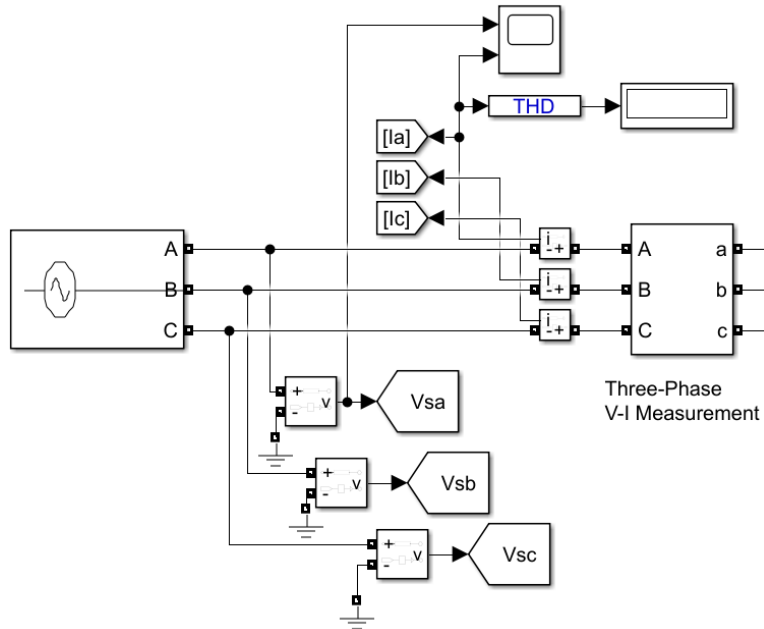


Figure 4.2 Three-Phase AC source and measurement at the AC side model.

Figure 4.3 represents a three-phase AC input filter model designed to improve power quality by minimizing harmonic distortions and electromagnetic interference.

1. Connections (Conn1, Conn3, Conn5): These represent the three-phase AC input lines (A, B, C), carrying the incoming AC signals.
2. Inductor Block: The three inductors filter high-frequency noise and smooth the current flow in each phase.

3. Capacitor Block: The capacitors connected to the ground stabilize the voltage by filtering high-frequency disturbances.
4. Outputs (V_a , V_b , V_c): These are the filtered three-phase voltages provided to the downstream components.

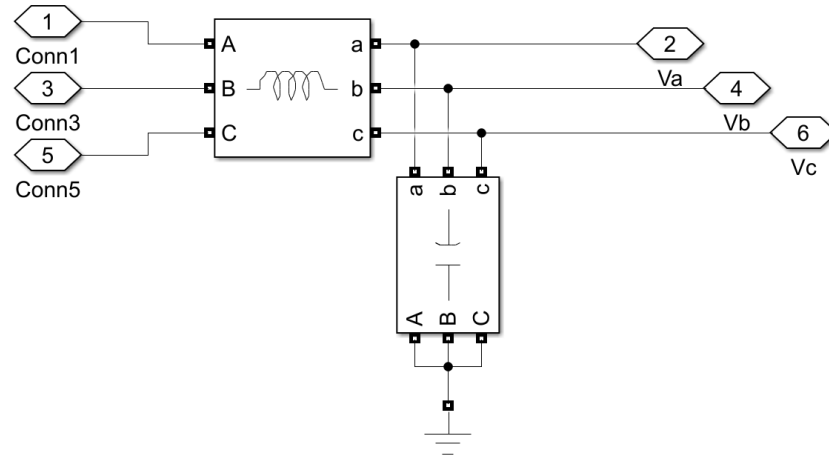


Figure 4.3 Three-Phase input AC filter model.

Figure 4.4 represents a three-phase AC-DC bidirectional MC model, detailing the structure and operation of a bidirectional MC.

1. Switches (S_1 to S_6): These are the power electronic switches (IGBTs) that regulate current flow between the AC and DC sides. Each switch is paired with a diode for reverse voltage protection.
2. Control Inputs (PWM1–PWM6): Pulse Width Modulation signals control the switching behavior, ensuring proper operation for bidirectional energy conversion.
3. AC Side Inputs (V_a , V_b , V_c): Three-phase AC voltage inputs are processed to convert energy to DC.
4. DC Bus (V_{DC+} and V_{DC-}): Outputs represent the DC link for energy storage or usage.

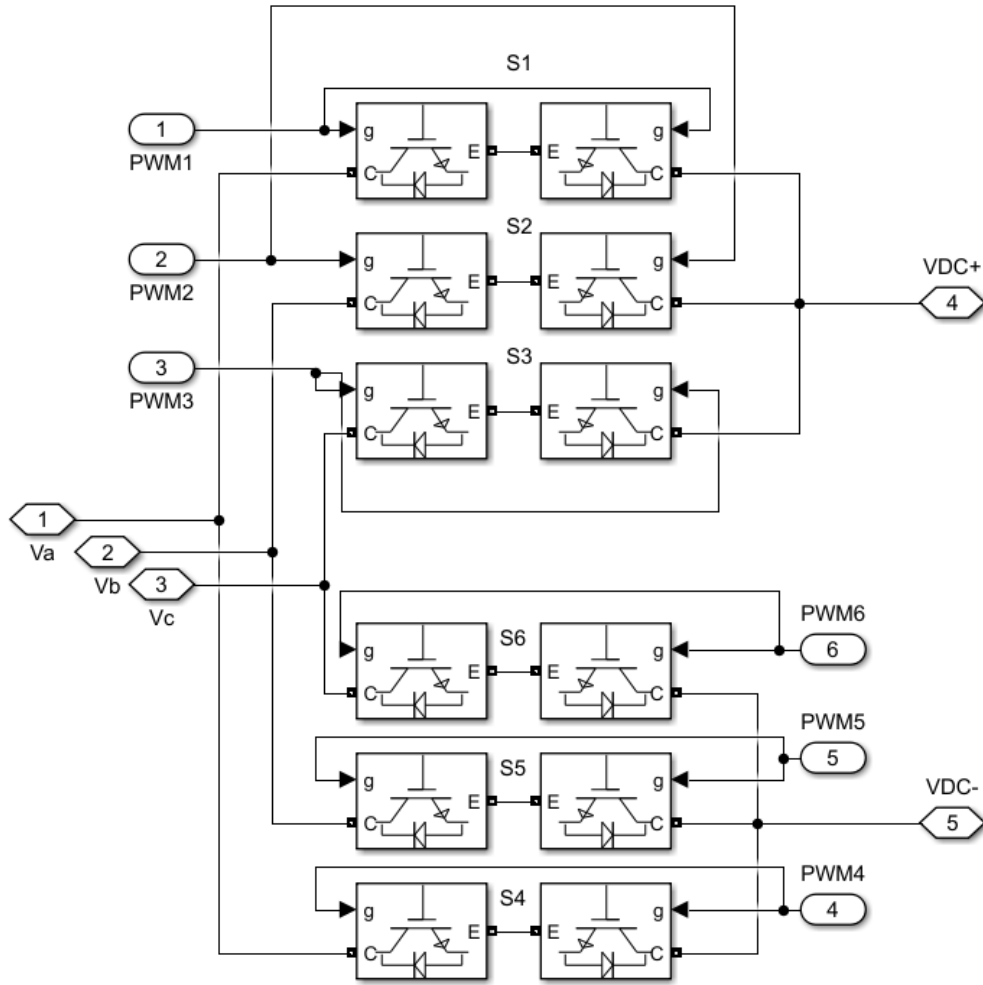


Figure 4.4 Three-Phase AC-DC MC model.

Figure 4.5 represents Output DC Filter Model describes a filtering circuit that smooths the DC output voltage and current.

1. Input (VDC+ and VDC-): The DC voltage provided by the AC-DC converter is fed into the filter.
2. LC Filter: This combination of an inductor (L) and capacitor (C) eliminates ripples in the DC output, ensuring a stable voltage supply.
3. Output (Vbat+ and Vbat-): The filtered DC voltage is delivered to the battery, providing smooth and consistent power for charging or other applications.

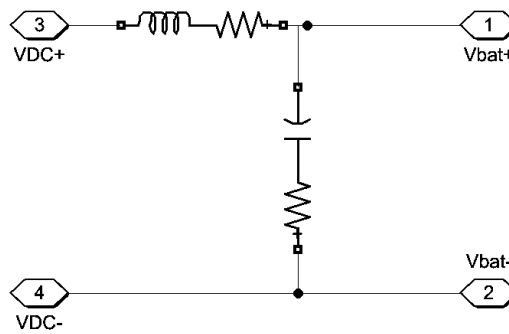


Figure 4.5 The output DC filter model.

Figure 4.6 represents a battery model. It includes:

1. Inputs: The positive terminal (+) and the negative terminal (-), which are connected to the battery.
2. Battery Symbol: The battery is depicted with internal components, possibly representing the electrochemical process or equivalent circuit.
3. Output: A measurement or variable denoted as "m" is generated, which could represent a parameter such as SOC, energy level, or any monitored variable related to the battery.

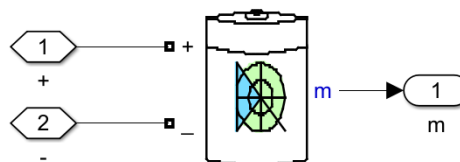


Figure 4.6 The battery model.

Figure 4.7 represents an electrical battery parameters model. It visualizes the key measurable parameters of a battery:

1. SOC: Displays the battery's remaining charge percentage.
2. Battery Current (Ibat): Monitors the current flowing through the battery in amperes.
3. Battery Voltage (Vbat): Measures the voltage across the battery in volts.

These parameters are connected to display blocks for visualization and further monitoring, which facilitates understanding battery behavior during operation and charge/discharge cycles.

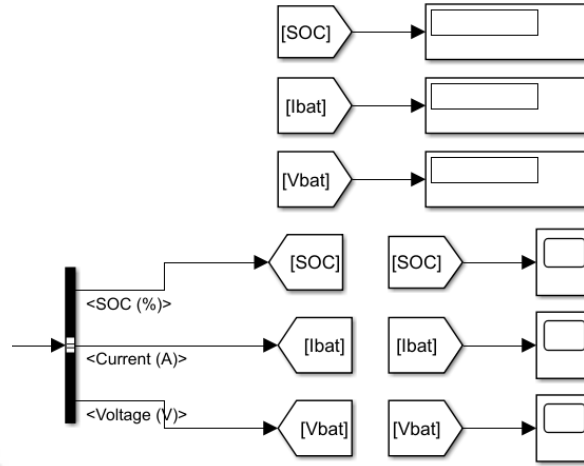


Figure 4.7 The electrical battery parameters model.

Figure 4.8 represents the measurement system for active and reactive power on the AC side of a circuit.

1. Inputs: The three-phase voltage signals V_{abc} , and the three-phase current signals I_{abc} .
2. Process: These inputs are fed into a measurement block that calculates Active power and Reactive power.
3. Outputs: The calculated values are displayed and monitored using the connected visualization blocks to track the power levels and ensure system performance and balance.

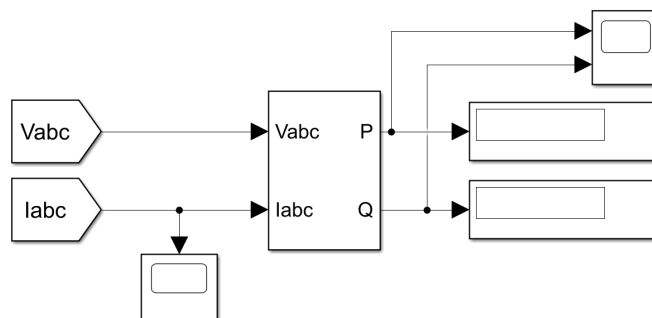


Figure 4.8 Active and reactive power measurement at the AC side model.

Figure 4.9 represents the DC power measurement on the DC side utilizes the inputs VDC (DC voltage) and IDC (DC current) to calculate and monitor the power.

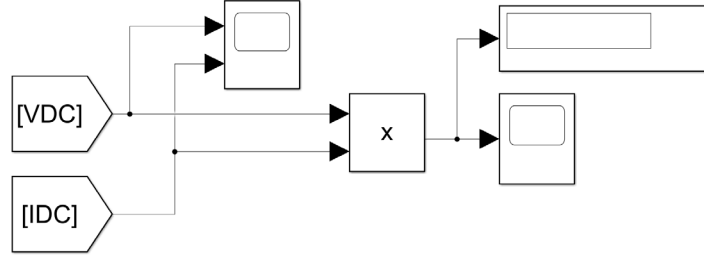


Figure 4.9 The output DC power measurement at the DC side model.

Figure 4.10 represents the segmentation of an input source model in a three-phase system, where the three-phase input voltages V_{sa} , V_{sb} , V_{sc} are compared. The result of the comparison is then integrated into the multiplexer, producing the X6 signal. This process is repeated for other cases, generating signals from X1 to X6 as shown in Table 3.3.

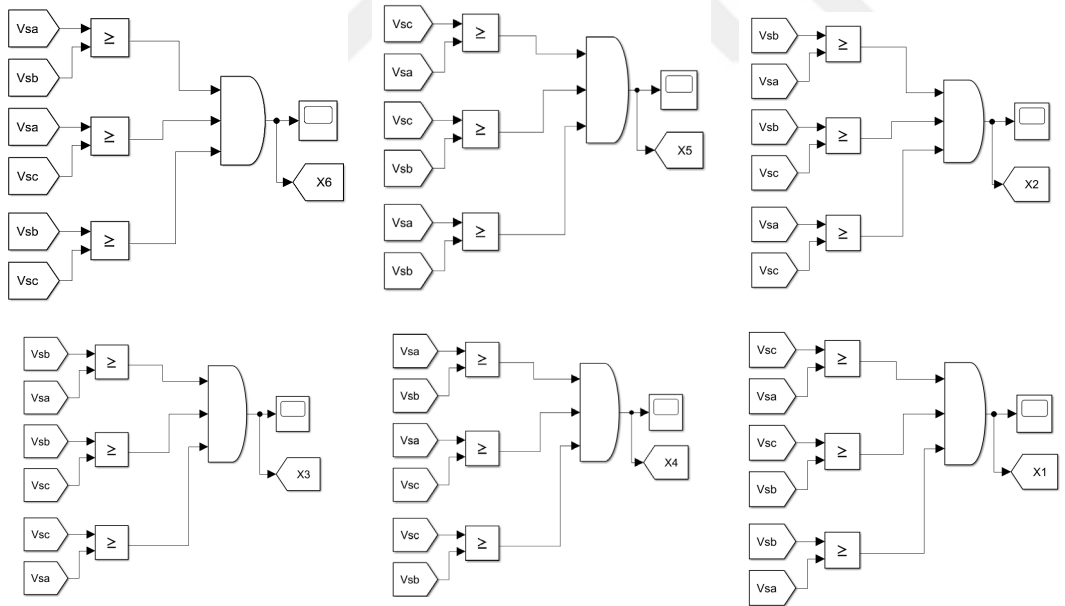


Figure 4.10 The segmentation of the input source model.

Figure 4.11 represent the twelve-switching signals model for a bidirectional AC-DC MC. Each switching signal (e.g., S1a, S1b, S6a, S6b) controls the corresponding

switches, to regulate the power flow between the input and output terminals. This model generates and distributes 12 switching signals (6 upper and 6 lower) within the converter. The switches are activated based PWM, with the necessary pulses being produced by multiplying the controller's output signal N with the signals from the input source segmentation $X1 \dots X6$.

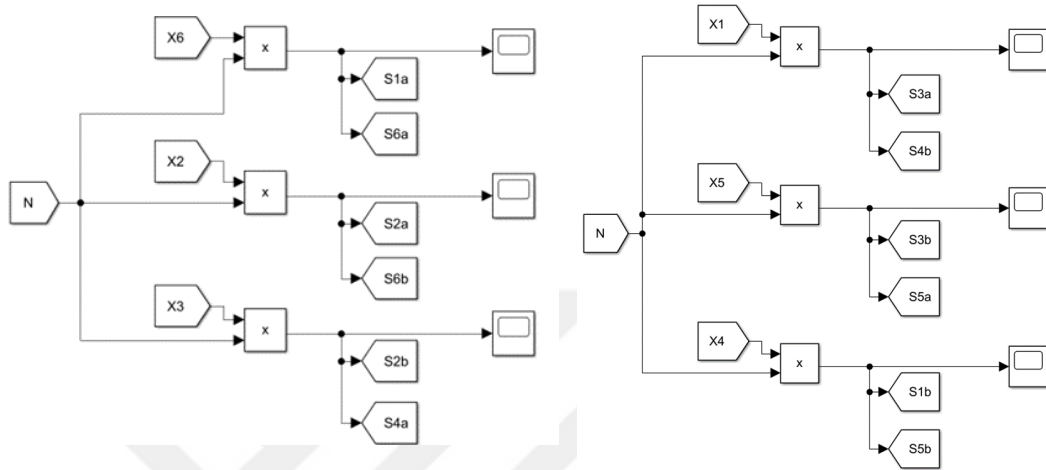


Figure 4.11 The twelve switching signals model.

Figure 4.12 shows a structure of six distinct signals ($S1$ to $S6$), with each pair of signals (e.g., $S1a$, $S1b$) entering separate logical gates.

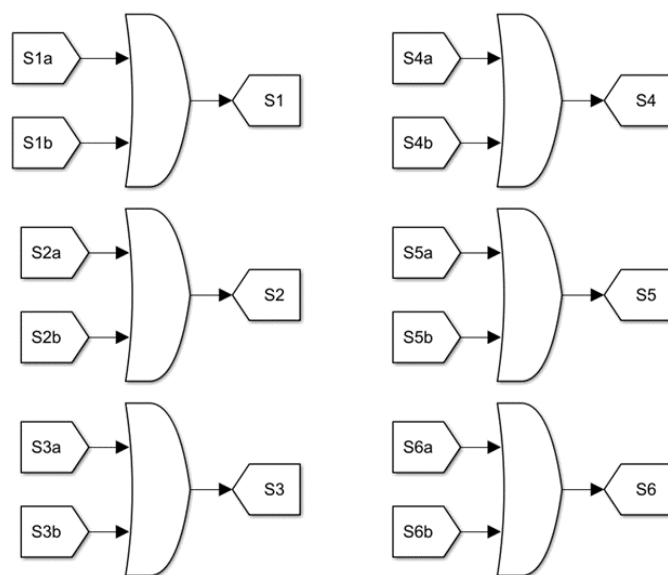


Figure 4.12 The six switching signals model.

Figure 4.13 represents a control strategy model for a battery management system divided into three main sections:

1. CV Charging: This section maintains a constant charging voltage by using a PI controller to adjust the input voltage V_{dc-ref} .
2. CC Charging: In this section, a PI controller ensures a steady current by adjusting the input current I_{dc-ref} .
3. The discharge process is carried out by disconnecting the control of the charging process with CV or CC
4. The reference V_{dc-ref} is compared with the voltage at the converter output. Using the PI controller, a signal is generated and compared with the triangular carrier signal, producing the N signal, which then enters the pulse generation circuit explained in previous diagrams.
5. Similarly, CC charging follows the same process. The charging process, whether CV or CC, is controlled by the SOC strategy. For example, charging is done with CC until the SOC reaches 70%, after which charging continues with CV, depending on the chosen charging strategy.

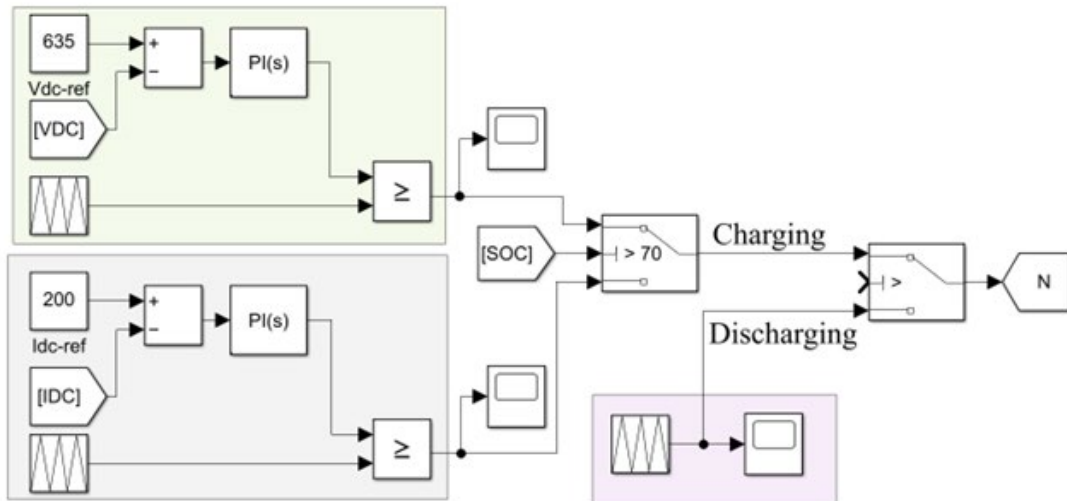


Figure 4.13 Proposed control strategies model.

4.2 Simulation Results

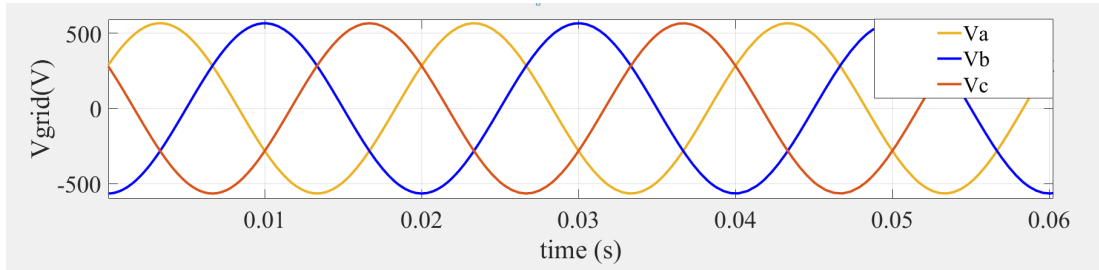
This section presents the outcomes of the simulation studies conducted to evaluate the proposed bidirectional AC-DC MC design. A comprehensive set of experiments was conducted under various conditions to evaluate the performance of the 100 kW bidirectional AC-DC MC included real-time monitoring of critical parameters such as voltage, current, and power flow direction in the simulation environment to validate the suggested method. Table 4.1 contains a list of the parameters of the AC-DC MC used in simulation, while Figure 3.1 displays the schematic representation of the same. In our study, we will present four scenarios for battery charging: Charging the battery from 10% to 90% using CC charging, Charging the battery from 10% to 90% using CV charging., Charging the battery from 10% to 70% using CC charging and using CV charging from 70% to 90%, Discharging the battery from 100% to 90%.

Table 4.1 Parameters used for AC-DC MC simulation

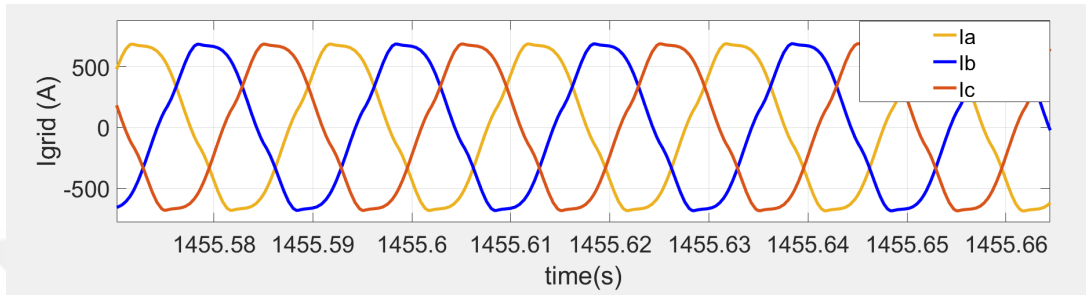
Parameter	Value
Three-Phase AC source	400 Volt – 50 Hz
Input AC filter	0.4 mH – 4mF
Output DC filter	90 mH –10 μ F – 0.001 Ω
Switching and sampling frequency	20 kHz
Battery	100 kW, 100-228 Ah, 600 V Lithium-Ion. Max charge current 200A

4.2.1 Charging the battery from 10% to 90% using CC charging

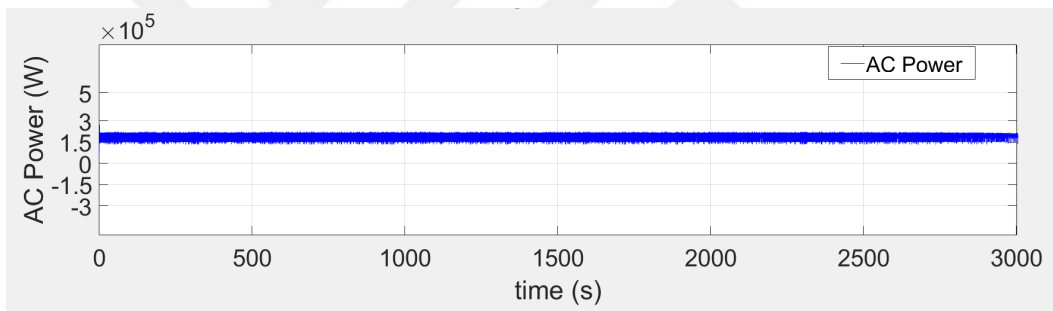
To make the charging process as fast as possible while maintaining battery safety conditions, the I_{dc-ref} will be set to the max permissible charging current for the battery, which is 200A. Figure 4.14 presents the simulated electrical parameters at the AC side of the EV charging station in CC charging mode. Active power of about 150.9 kW flows from the grid to the rectifier side and a reactive power of 0kVAR flows in the system as shown in Figure 4.14 (c-d) respectively. Power factor is 1, THD voltage is 0.51%, and THD current is 2.96% for ten cycles as shown in Figure 4.14 (e-f). THD values are fit to international standards.



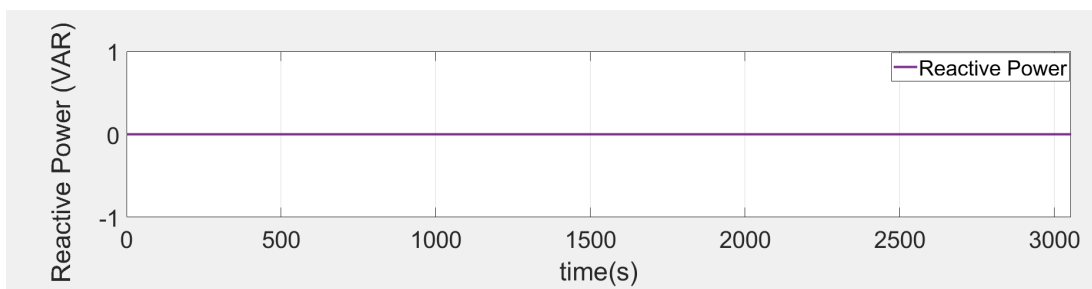
(a) Three-phase line voltages of grid (V)



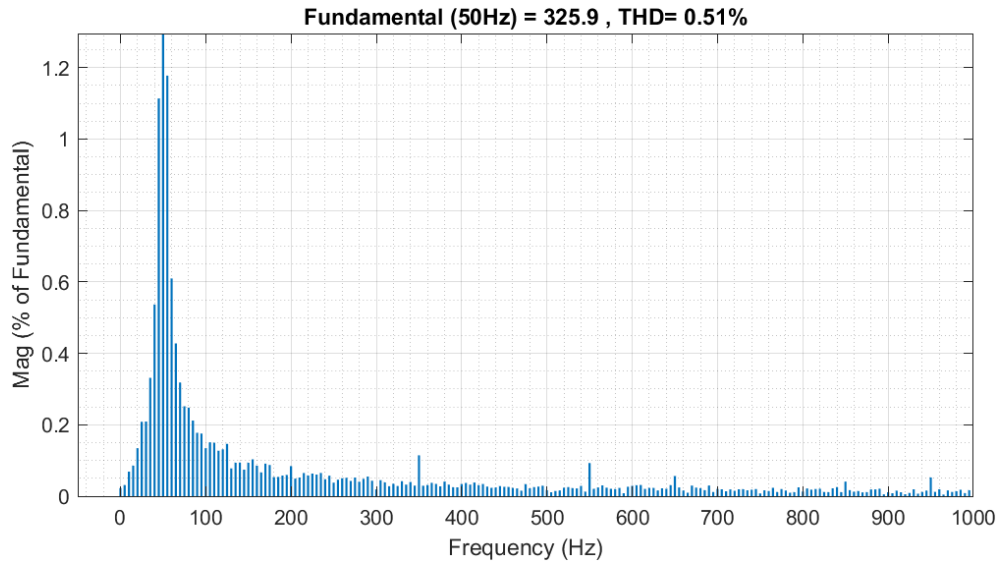
(b) Three-phase line currents of grid (A)



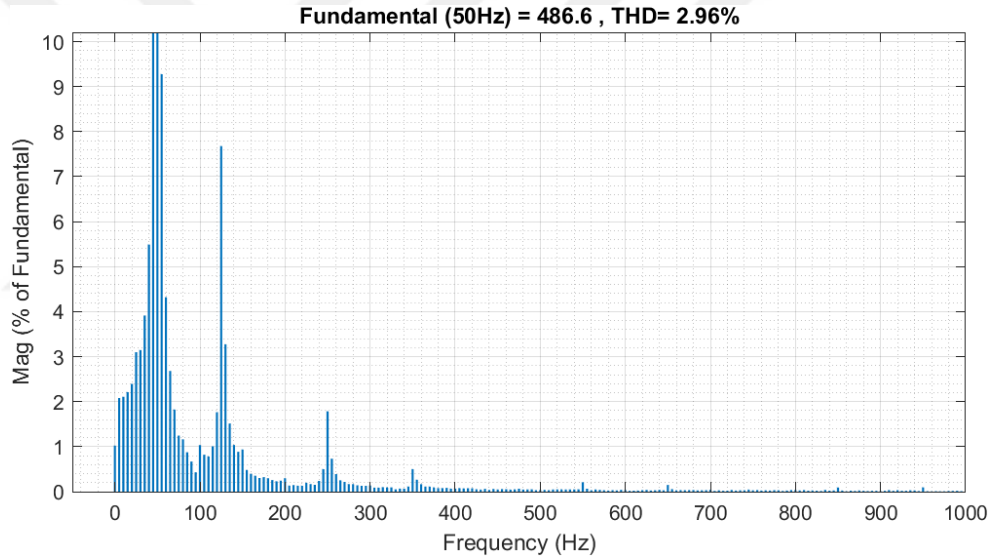
(c) Active power drawn from AC grid (W)



(d) Reactive power drawn from AC grid (VAR)



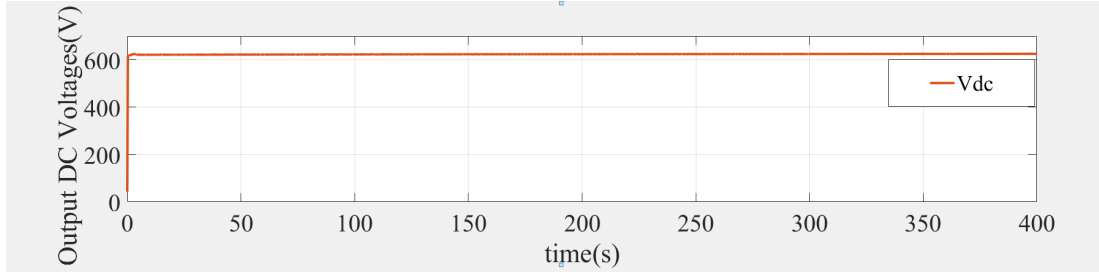
(e) The harmonic spectrum of voltage



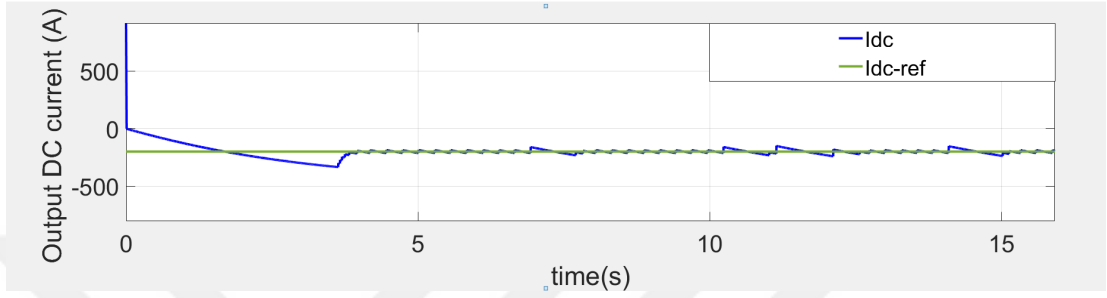
(f) The harmonic spectrum of currents

Figure 4.14 The electrical parameters at the AC side in CC charging mode.

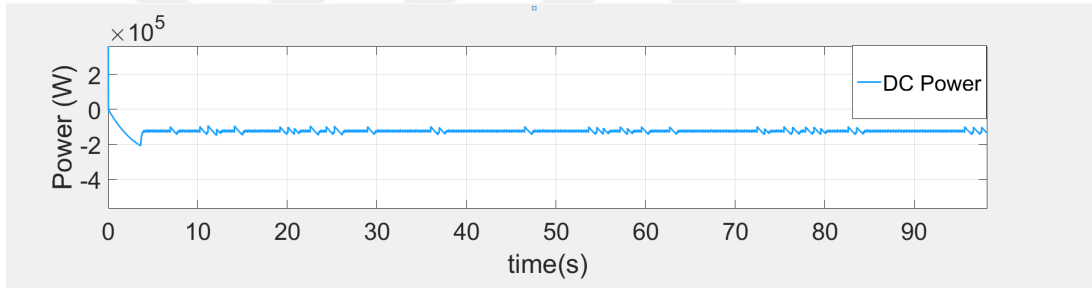
At the DC side, 630V output DC voltage, 200A output DC current, and an output DC power of about 126 kW are maintained, allowing the charging of the battery as shown in Figure 4.15. As for the battery, Figure 4.16 shows charging the battery from 10% to 90%. It is seen that the charging time takes around 55 minutes with 630V DC and 200A DC, provided by the converter.



(a) Output DC Voltage (V)



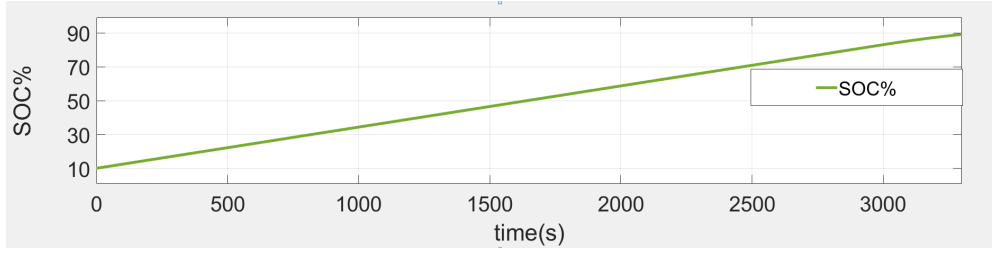
(b) Output DC current (A)



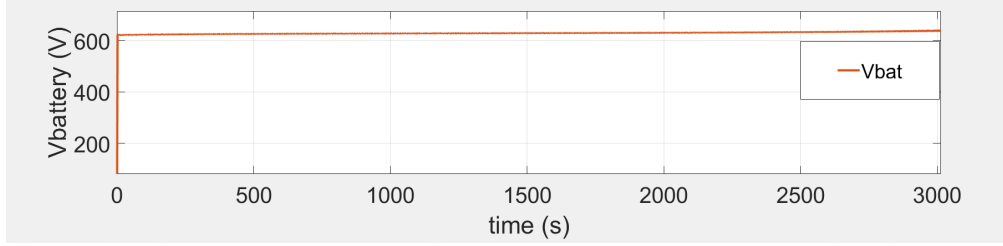
(c) Output DC power (W)

Figure 4.15 The electrical parameters at the DC side in CC charging mode.

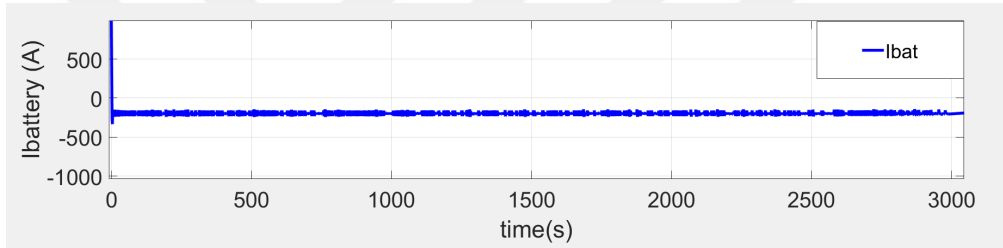
In Figure 4.15, a small ripple is observed in both output power and DC output current, with the ripple percentage being around 3%, which is considered low. The ripple is caused by the periodic switching that occurs due to the switching frequency of the converter. This ripple was reduced to 3% by designing an output filter. High ripples in output and DC current can lead to undesirable fluctuations, affecting battery performance, reducing efficiency, and potentially shortening battery life if not properly controlled. It can also affect the overall power quality of the system.



(a) Battery charging SOC



(b) Battery charging voltage (V)



(c) Battery charging current (A)

Figure 4.16 The battery charging from SOC 10% to 90% in CC mode.

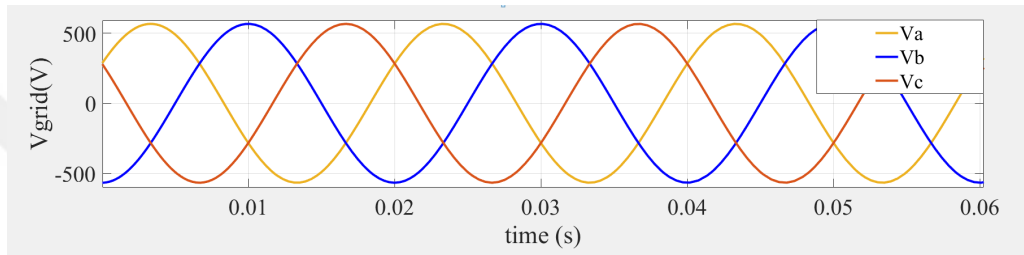
To calculate efficiency in CC charging, the equation is:

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \quad (1)$$

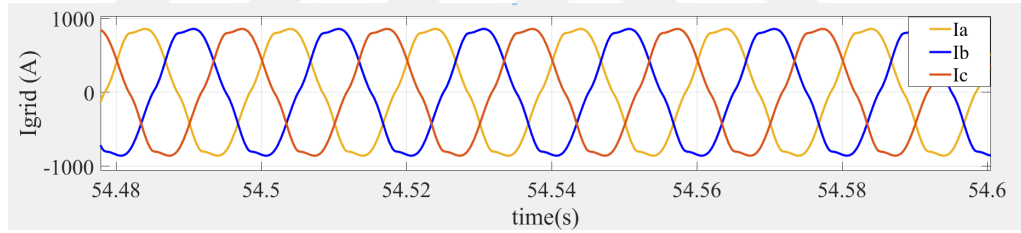
During the CC charging process, power remains constant. Based on Figures 4.14 and 4.15, the input power P_{in} is 150.9 kW, and the output power P_{out} is approximately 126 kW, resulting in an efficiency $\eta = 83.5\%$. The efficiency during CC charging is affected by several factors, leading to lower performance. Internal battery losses, caused by its inherent resistance, result in energy dissipation as heat. Additionally, the AC-DC converter contributes to efficiency loss through switching and conduction losses. Thermal losses in the charging system, particularly under high current conditions, further reduce efficiency.

4.2.2 Charging the battery from 10% to 90% using CV charging

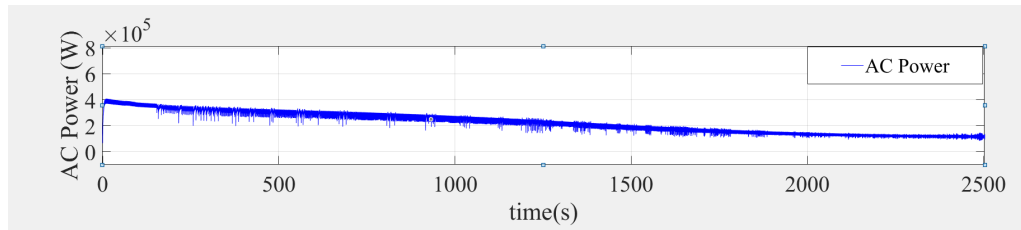
The charging process when there is no current control and charging is CV charging (CV). Figure 4.17 presents the simulated electrical parameters at the AC side of the EV charging station in CV mode. Active power varies significantly at the beginning of charging, starting from 400 kW to reach a small value at the end of charging flows from the grid to the rectifier side and a reactive power of 0kVAR flows in the system as shown in Figure 4.17 (c-d) respectively. The power factor is 1, THD voltage is 0.16%, and THD current is 3.34% for ten cycles as shown in Figure 4.17 (e-f). THD values are fit to international standards.



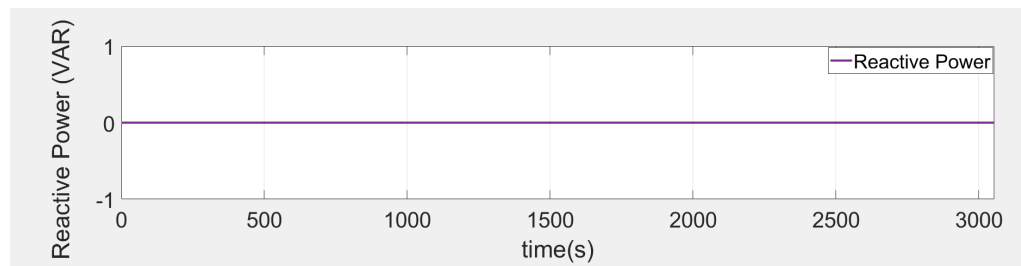
(a) Three-phase line voltages of grid (V)



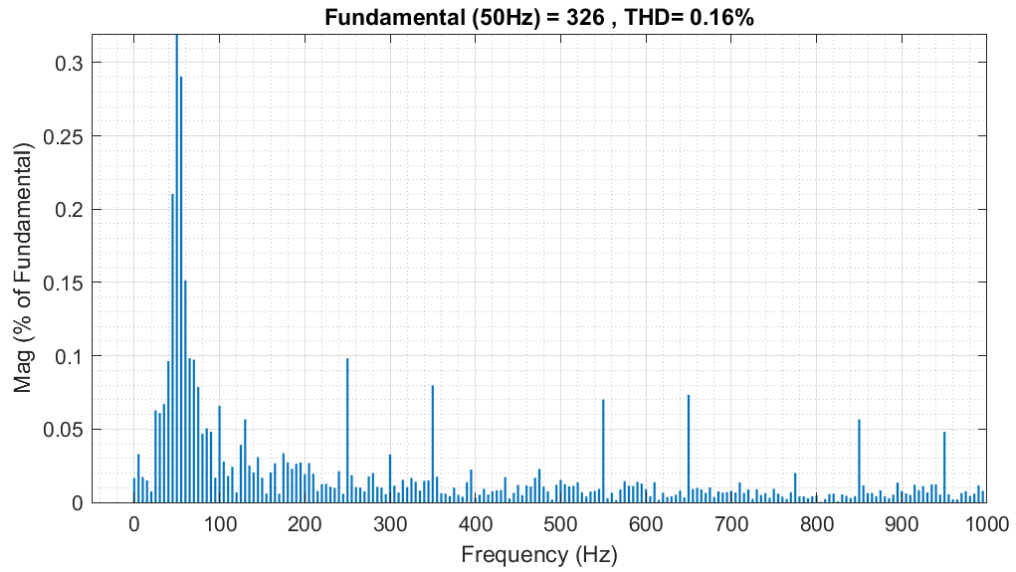
(b) Three-phase line currents of grid (A)



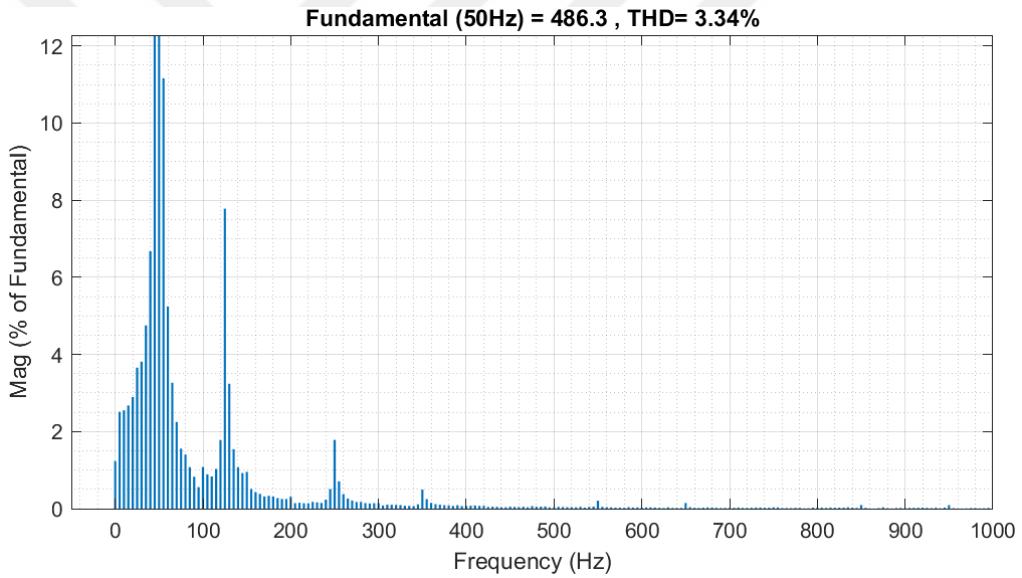
(c) Active power drawn from AC grid (W)



(d) Reactive power drawn from AC grid (VAR)



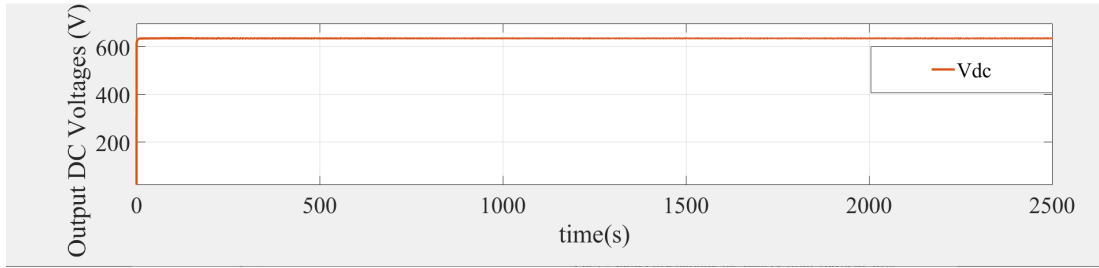
(e) The harmonic spectrum of voltage



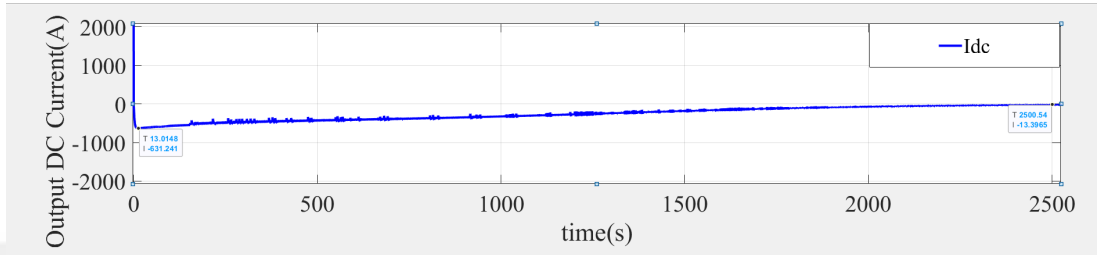
(f) The harmonic spectrum of currents

Figure 4.17 The electrical parameters at the AC side in CV charging mode.

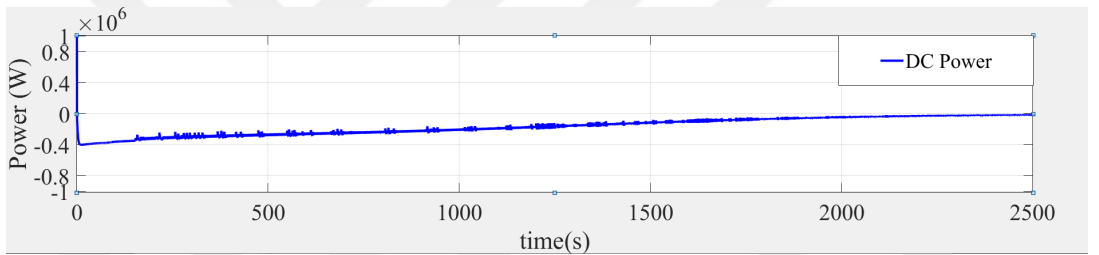
In Figure 4.18 shows the DC side, the value of the charging current at the beginning of charging is approximately 630 A and decreases during the charging process to reach a low value close to zero at the end of the charging as Figure 4.18(b). DC power varies significantly at the beginning of charging, starting from 400 kW to reach a small value at the end of charging.



(a) Output DC voltage (V)



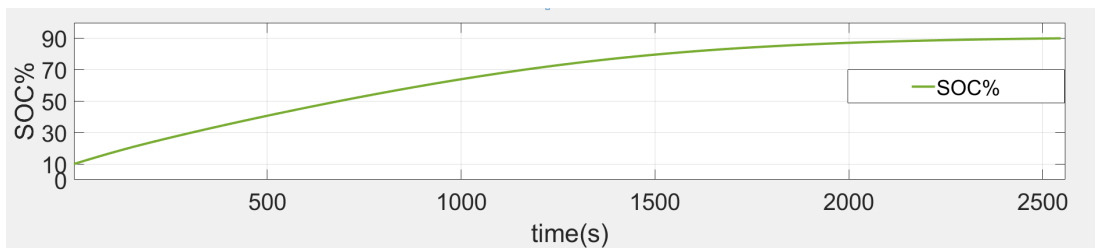
(b) Output DC current (A)



(c) Output DC power (W)

Figure 4.18 The electrical parameters at the DC side in CV charging mode.

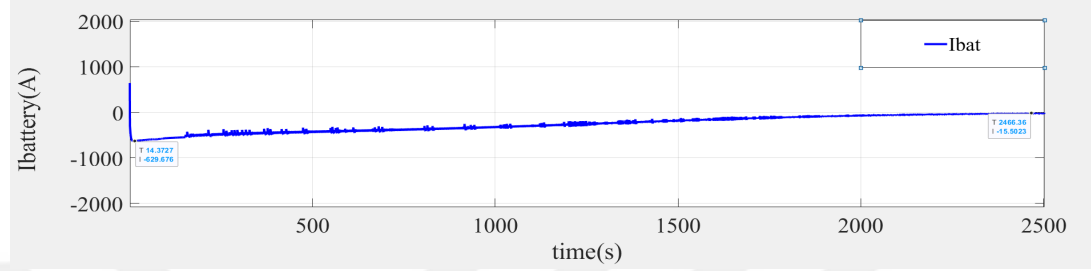
As for the battery, Figure 4.19 shows charging the battery from 10% to 90%, It is seen that the charging time takes around 40 minutes with 635V DC, and the battery current at the beginning of charging is approximately 630 A.



(a) Battery charging SOC



(b) Battery charging Voltage (V)



(c) Battery charging Currents (A)

Figure 4.19 The battery charging from SOC 10% to 90% in CV mode.

During the charging the current decreases to reach a low value close to zero at the end of the charging process provided by the converter. Charging with a CV has several problems, including power instability and significant changes in the charging current value during the process. The current starts from a very high value that exceeds the maximum charge current, causing damage to the battery. Determining the reference value for the CV V_{dc-ref} is difficult. In our study, we chose a reference value close to the battery's full charging voltage, resulting in a very high initial charging current. Choosing a lower reference voltage stops the charging process early, preventing the battery from fully charging.

To calculate efficiency in CV charging, equation 1, since the output power in CV charging varies, a specific point during the charging process is selected for calculation. Based on Figures 4.17 and 4.18 for instance, at a selected moment during charging, for example, at 1000 seconds, the output power P_{out} is 221 kW, and the input power P_{in} is 227 k, resulting in an efficiency $\eta = 97.35\%$ Table 4.2 compares CC charging and CV charging modes, CC charging mode offers a relatively stable and efficient charging process, with a consistent current (200A). However, efficiency is reduced to 83.5% due to internal losses in the battery and power losses in the AC-DC converter. It takes approximately 55 minutes to charge from 10% to 90%. In CV charging mode

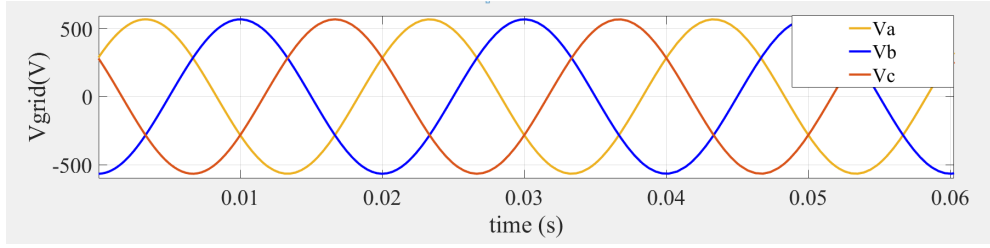
the voltage remains constant, but the current starts high (630A) and decreases over time. This can lead to inefficiencies, particularly at the start of the process, as the current exceeds the battery's safe charging limits. However, the efficiency is significantly higher at 97.35% due to a lower loss rate, with the charging process completed in 40 minutes. The key challenge here is managing the high initial current and choosing an appropriate reference voltage for safe and efficient charging.

Table 4.2 Comparison between CC charging and CV charging modes

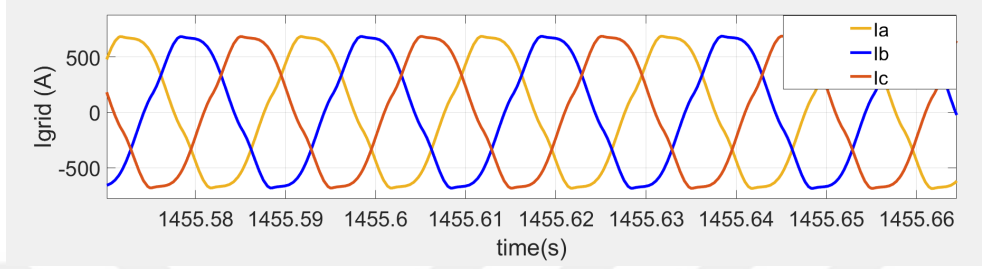
Aspect	CC Charging	CV Charging
Charging method	Maintains a CC throughout the process.	Maintains a CV, with current varying during the process.
Charging time	55 minutes to charge from 10% to 90%.	40 minutes to charge from 10% to 90%.
Input power	150.9 kW (constant)	227 kW (variable)
Output power	126 kW	221 kW (at a specific point, e.g., 1000 seconds)
Efficiency	83.5%	97.35% (at 1000 seconds)
Current profile	Constant 200A throughout the process.	High initial current that decreases to near zero.
Challenges	Lower efficiency due to internal battery losses and converter losses.	Power instability and high initial current that could damage the battery.
Power factor	1 (ideal)	1 (ideal)
THD	2.96%	3.4%

4.2.3 Hybrid CC-CV charging mode

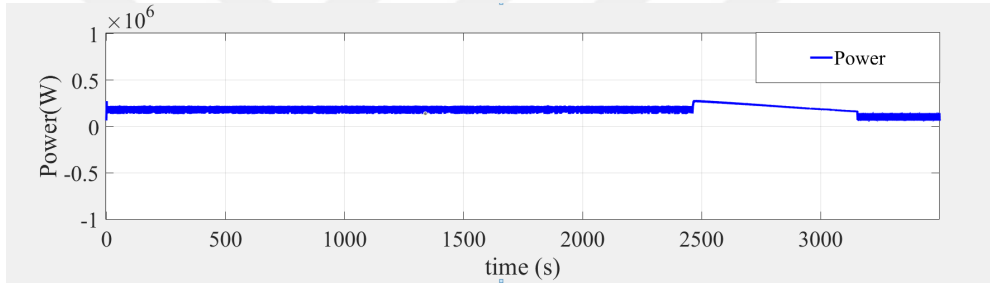
Charging the battery from 10% to 70% in CC charging mode and from 70% to 90% in CV charging mode. Based on previous studies, it was concluded that charging the battery from 10% to 70% is optimal using the CC method. Therefore, it was chosen to apply CC charging from 10% to 70% and then switch to CV charging from 70% to 90%. The CC charging mode maintains stable power and current at an acceptable level, though with moderate efficiency. Meanwhile, CV charging offers high efficiency but involves variable and often large power and current levels. Hence, a hybrid CC-CV charging mode was proposed for better performance. Figure 4.20 presents the simulated electrical parameters at the AC side of the EV charging station.



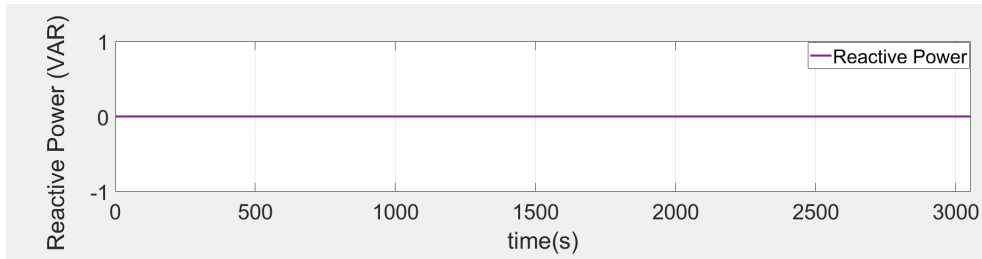
(a) Three-phase line voltages of grid



(b) Three-phase line currents of grid



(c) Active power drawn from AC grid

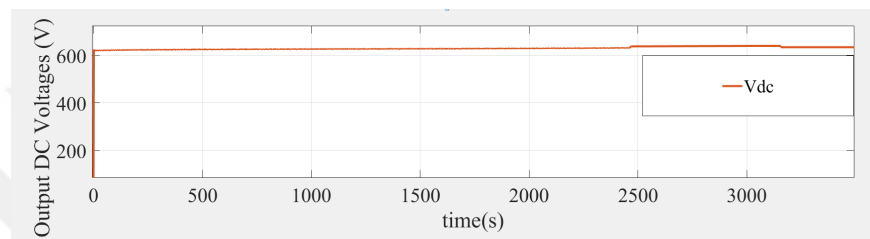


(d) Reactive power drawn from AC grid

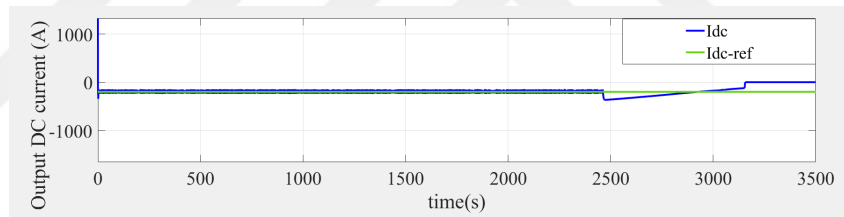
Figure 4.20 The electrical parameters at the AC side in CV, CC charging modes.

Active power of about 150.9 kW flows from the grid to the rectifier side and a reactive power of 0kVAR flows in the system as shown in Figure 4.20 (c-d) respectively. Power factor is 1, THD voltage is 0.51%, and THD current is 2.96% in CC charging mode from 10% to 70%, and THD voltage is 0.16%, and THD current is 3.34% CV charging mode. At the moment when the transition to the charging system with a CV

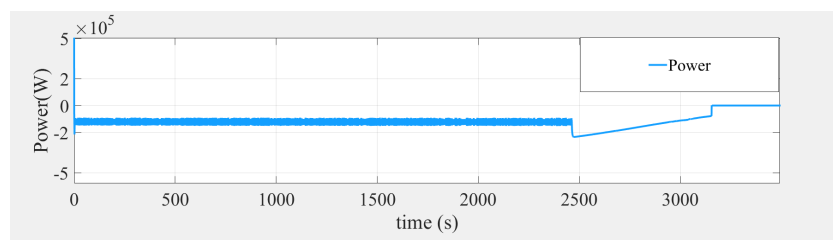
is made, we notice an increase in the actual power to reach a value of more than 200kW and then return to decrease until the end of the charge. At the DC side, 630V output DC voltage, 200A output DC current, and an output DC power of about 126 kW are maintained during CC charging mode from 10% to 70% , When moving to charging with a CV, we notice an increase in the charging voltage to be equal to the reference voltage of 640V, then it begins to gradually decrease to reach 630V at the end of charging, as well as the charging current increases to exceed the maximum charging current and reaches more than 350A, then gradually decreases to reach zero at the end of charging allowing the charging of the battery as shown in Figure 4.21.



(a) Output DC Voltages



(b) Output DC current

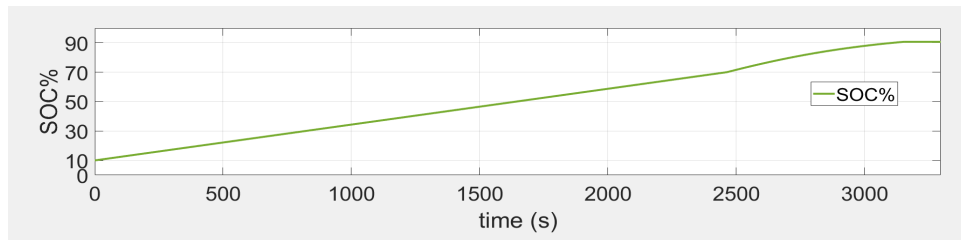


(c) Output DC power

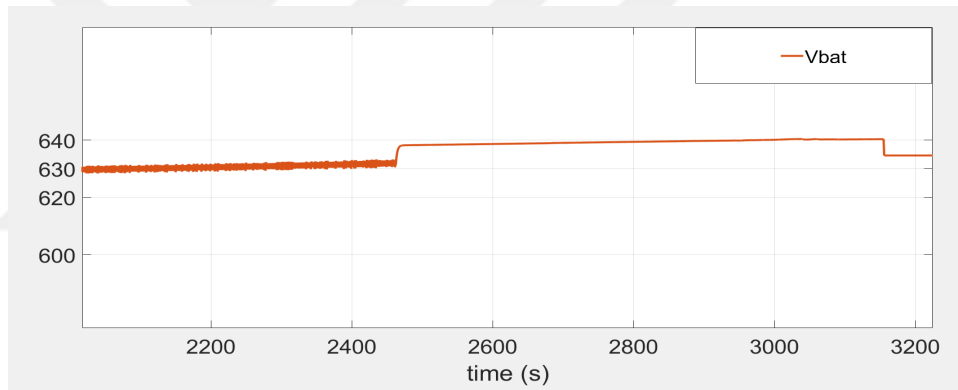
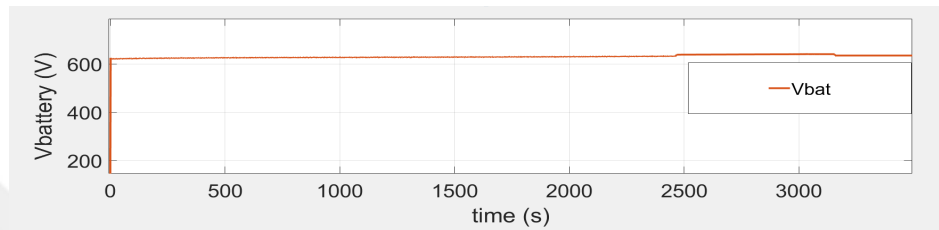
Figure 4.21 The electrical parameters at the DC side in CV, CC charging modes.

During CC charging, the efficiency is around 83.5%, while during CV charging, it increases to approximately 97%. Consequently, the overall efficiency of the hybrid charging mode reaches over 90.25%. As for the battery, Figure 4.22 shows charging

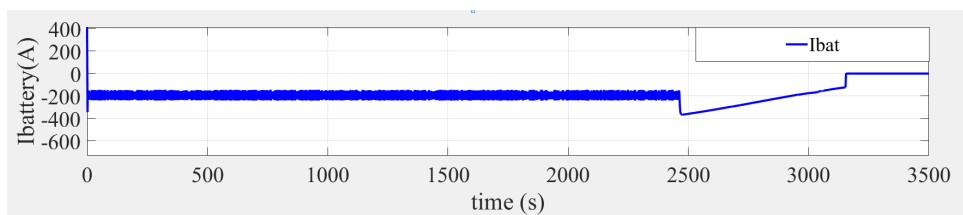
from 10% to 70% using CC charging and using CV charging from 70% to 90%. It is seen that the charging time takes around 55 minutes.



(a) Battery charging SOC



(b) Battery charging Voltage (V)



(c) Battery charging Currents (A)

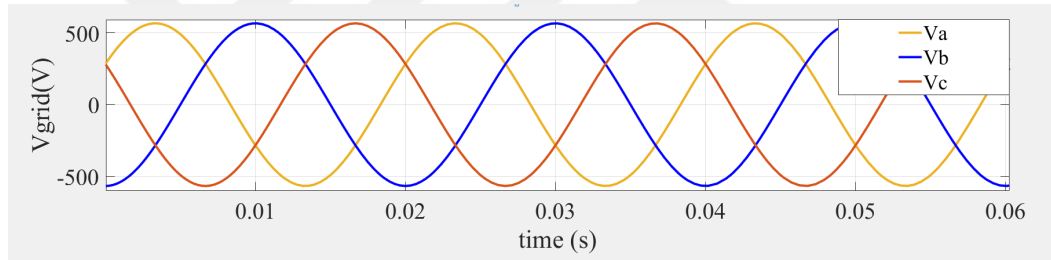
Figure 4.22 The battery charging from SOC 10% to 90% in CV, CC modes.

Hybrid CC-CV charging combines the advantages of stable power and current in the CC phase (10%-70%) with the higher efficiency of the CV phase (70%-90%), optimizing the charging process. However, it has drawbacks, including temporary current surges during the transition to CV, the need for complex control systems, and

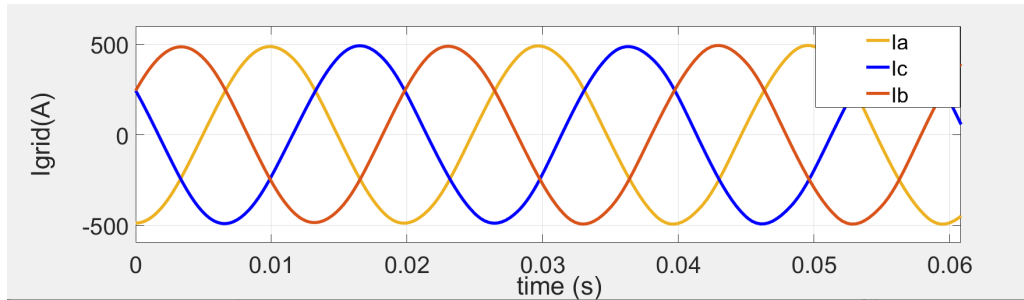
a moderate charging time of about 55 minutes, which may be longer than alternative methods. This approach balances efficiency and safety but requires careful design to mitigate stress on the battery.

4.2.4 Discharging the battery from 100% to 90%

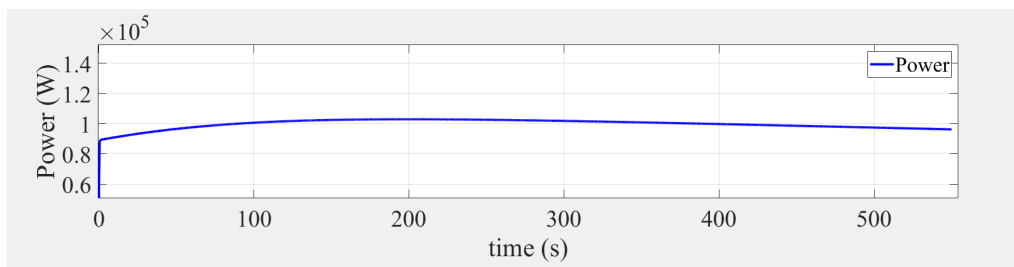
The discharging of an EV battery from 100% to 90% demonstrates the bi-directional capability of Vehicle-to-Grid (V2G) systems, which play a crucial role in energy management and grid stability. V2G allows the energy stored in EV batteries to be sent back to the grid during periods of high demand, enhancing flexibility and reducing dependency on traditional power sources. In this mode, Figure 4.23 illustrates the AC side electrical parameters during discharging. THD values are well within acceptable limits, with THD voltage at 0.34% and THD current at 5.42% over ten cycles. THD values are fit to international standards. This indicates efficient energy transfer with minimal distortion in power quality.



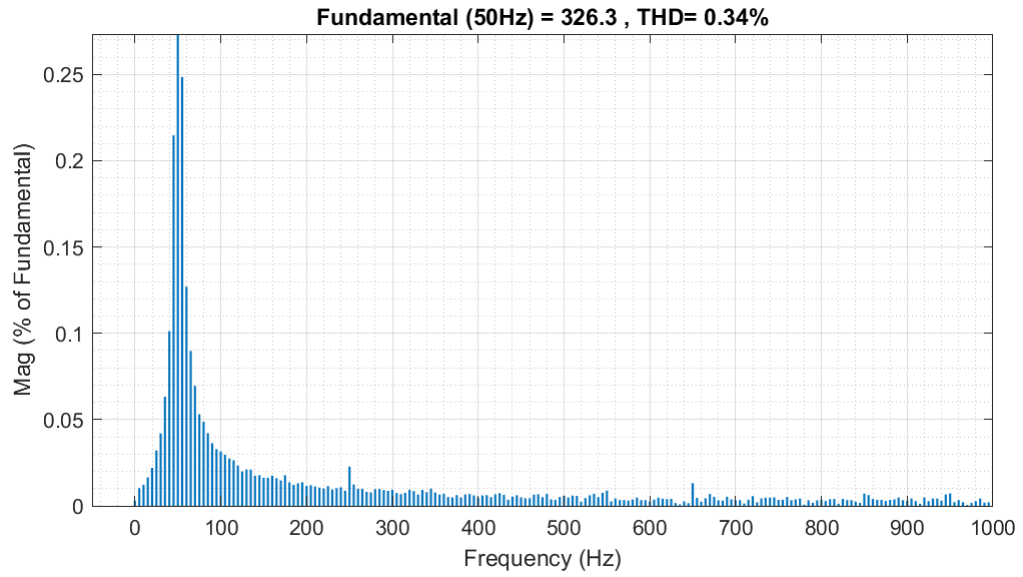
(a) Three-phase line voltages of grid



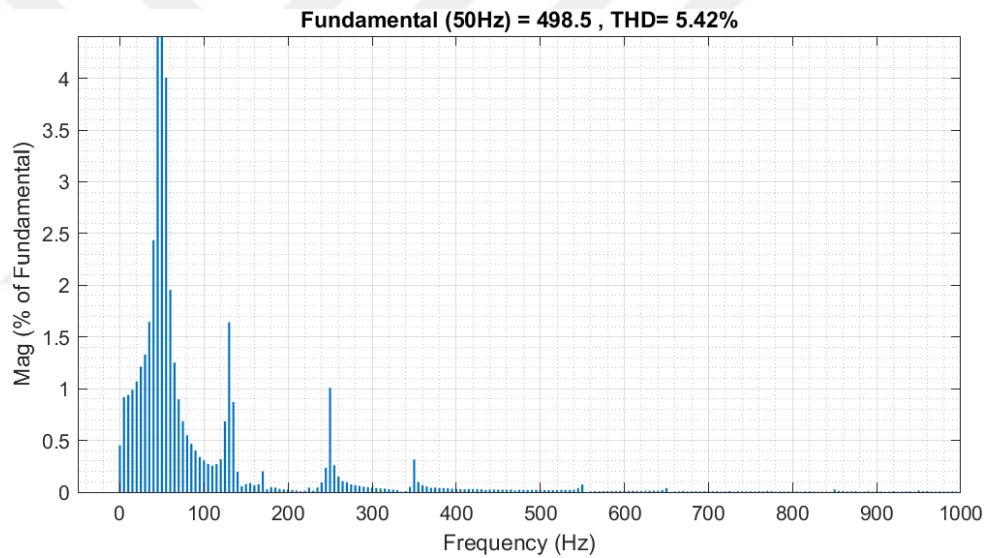
(b) Three-phase line currents of grid



(c) Active power drawn to AC grid



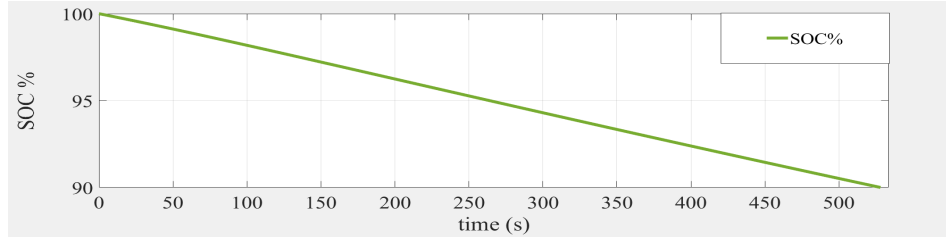
(d) The harmonic spectrum of voltage



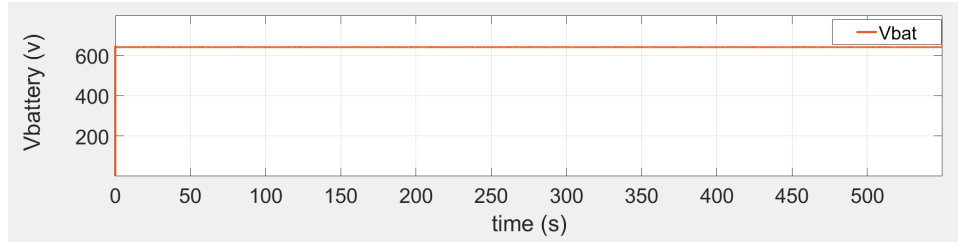
(e) The harmonic spectrum of currents

Figure 4.23 The electrical parameters at the AC side in discharging mode.

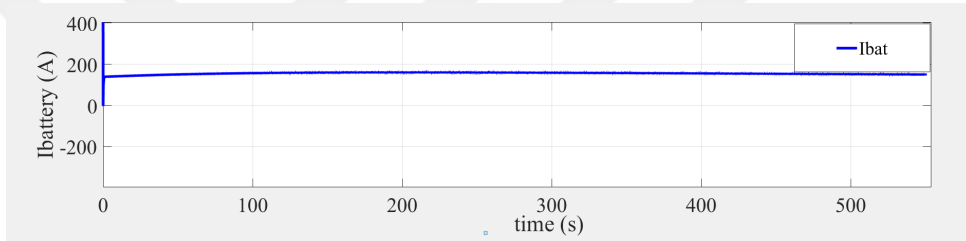
Figure 4.24 depicts the battery discharging from 100% to 90%. During this process, the system maintains a CV of 635V, while the current flow is steady at 150 A, allowing power to return to the grid, the complete discharge of the battery may take approximately 90 minutes. The bidirectional feature ensures that the system can adapt to the operational needs of the grid, providing both energy storage and energy return capabilities.



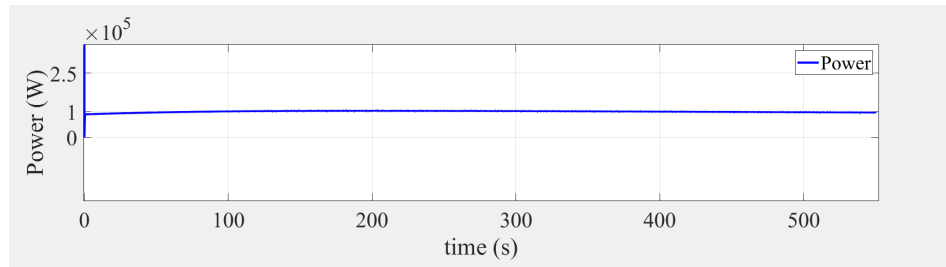
(a) Battery discharging SOC



(b) Battery discharging voltage (V)



(c) Battery discharging current (A)



(d) Battery discharging power (W)

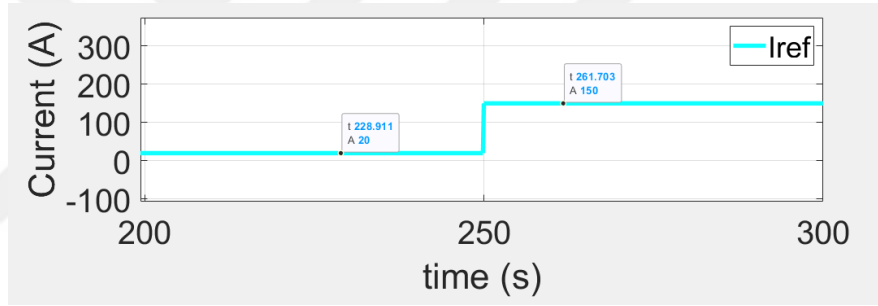
Figure 4.24 The battery discharging from SOC 100% to 90%.

To calculate efficiency in discharging from SOC 100% to 90%, the equation 1. During the discharging from SOC 100% to 90% process, power remains constant. Based on Figures 4.23 and 4.24, the input power P_{in} is 98.7 kW, and the output power P_{out} is approximately 97 kW, resulting in an efficiency $\eta = 98\%$.

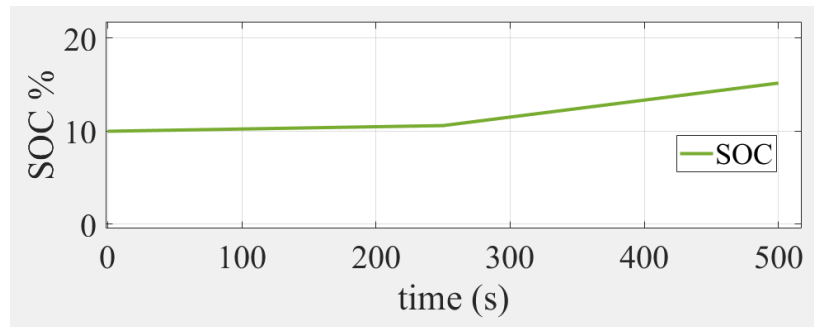
Overall, this capability highlights the potential of V2G systems not only as a means for charging vehicles but also as active participants in energy distribution networks, optimizing energy use and supporting grid reliability.

4.2.5 Step change in CC charging mode

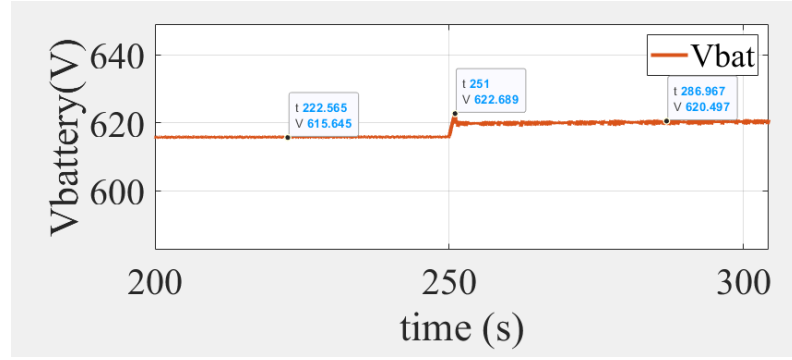
At 250 seconds during CC charging, a reference current change from 20A to 150A was applied, introducing a significant step to clearly observe system behavior. According to Figure 4.25, the battery SOC slope increased post-change, reflecting a rise in charging speed. The battery voltage, initially steady at 615V, briefly peaked at 622V (a 0.3% deviation) before stabilizing at 620V. The charging current surged to 246A within one second before settling at 150A, matching the new reference. Similarly, output power showed a transient rise before stabilization.



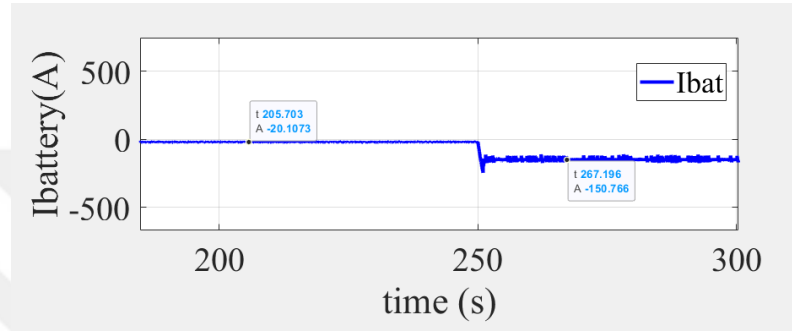
(a) Reference current



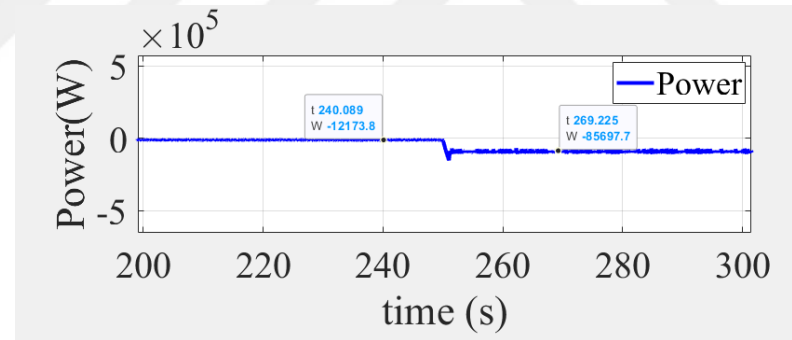
(b) Battery charging SOC



(c) Battery charging Voltage (V)



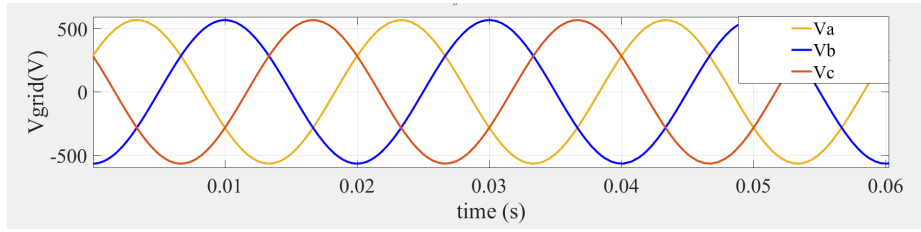
(d) Battery charging Currents (A)



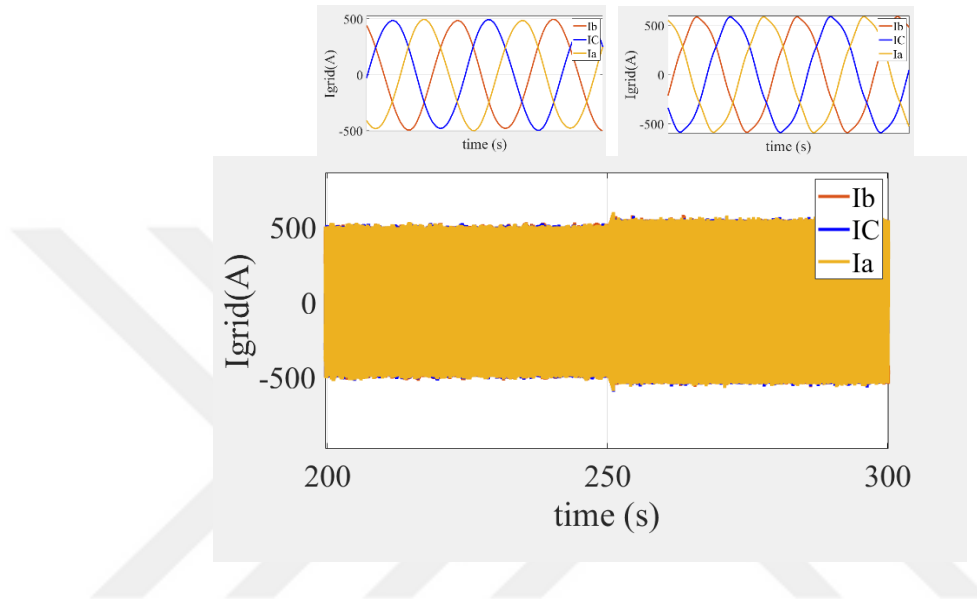
(e) Output DC power (W)

Figure 4.25 The electrical parameters at the battery side in unit step change in CC charging mode.

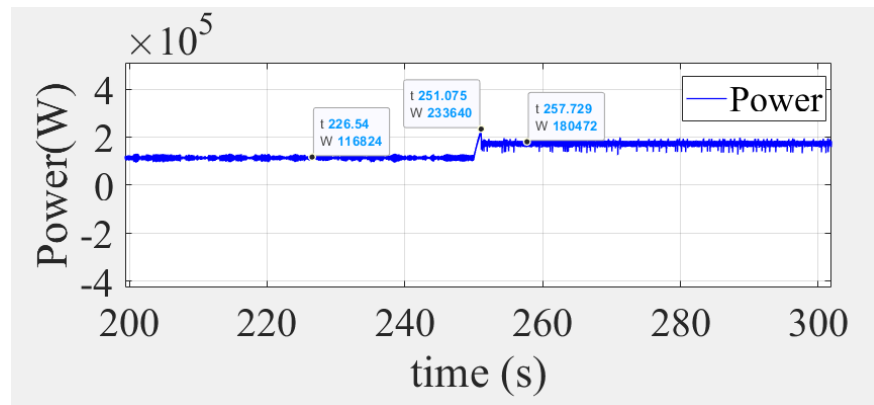
On the AC side, Figure 4.26 shows voltage remained constant while the current adjusted during the transition, stabilizing thereafter. Input power exhibited an initial overshoot before returning to its new steady-state value. The brief current overshoot above the battery's maximum lasted less than a second, demonstrating the system's robustness and stability despite the significant step change in current.



(a) Three-phase line voltages of grid (V)



(b) Three-phase line currents of grid (A)



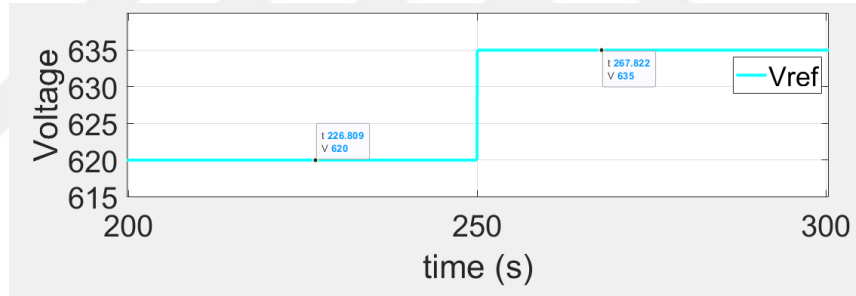
(c) Active power drawn from AC grid (W)

Figure 4.26 The electrical parameters at the AC side in unit step change in CC charging mode.

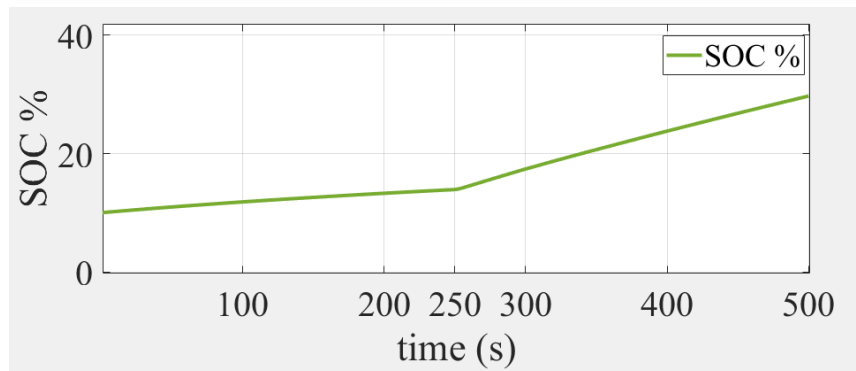
4.2.6 Step change in CV charging mode

A step change in the reference voltage from 620V to 635V was applied at 250 seconds during CV charging to evaluate the system's performance as shown in Figure 4.27. This adjustment was made deliberately to observe the system's dynamic behavior. After the voltage change, the SOC slope increased, reflecting an acceleration in charging speed. Initially steady at 620V, the battery voltage gradually increased to reach the new reference voltage of 635V within a few seconds. The charging current surged from 80A to a peak value of 590A, stabilizing at this higher level. Consequently, the converter's power increased significantly, rising from 49kW to 374kW after the voltage change.

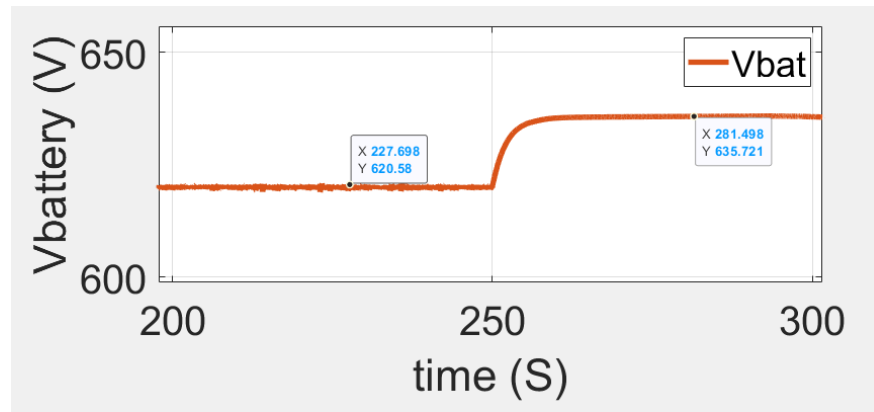
As shown in Figure 4.28, the AC voltage remained constant while noticeable changes occurred in both the current and power. The system demonstrated stability throughout the change. However, the response time was relatively long due to the high capacities and large component values in the converter.



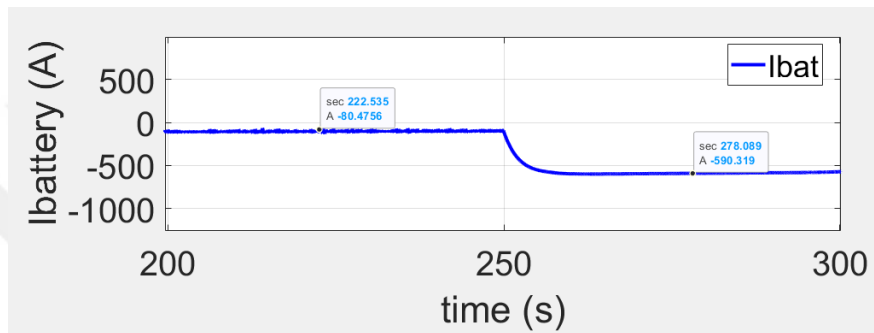
(a) Reference voltage



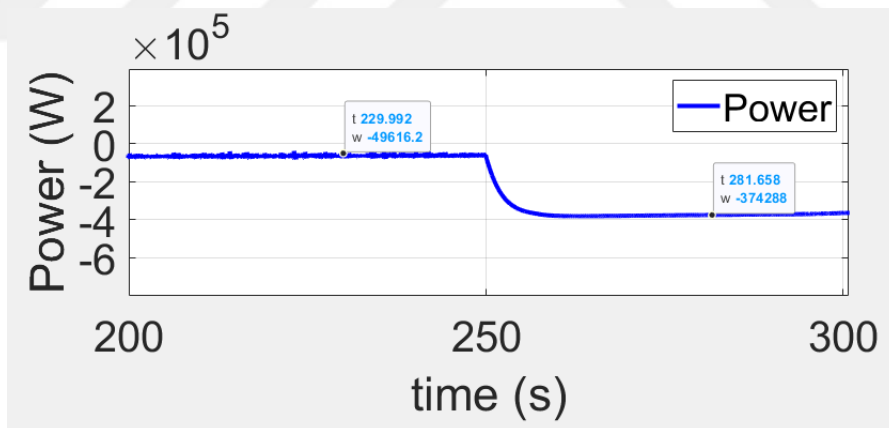
(b) Battery charging SOC



(c) Battery charging Voltage (V)

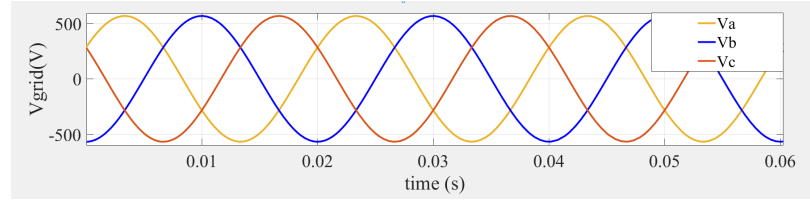


(d) Battery charging Currents (A)

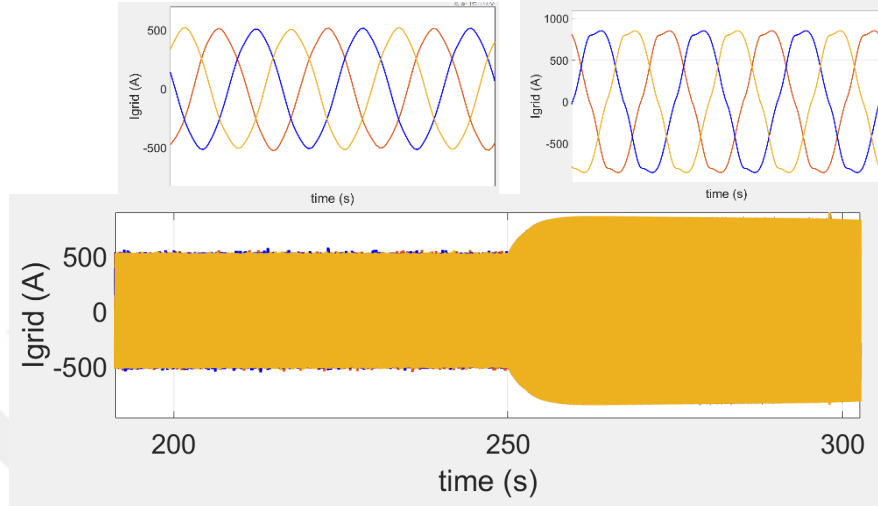


(e) Output DC power (W)

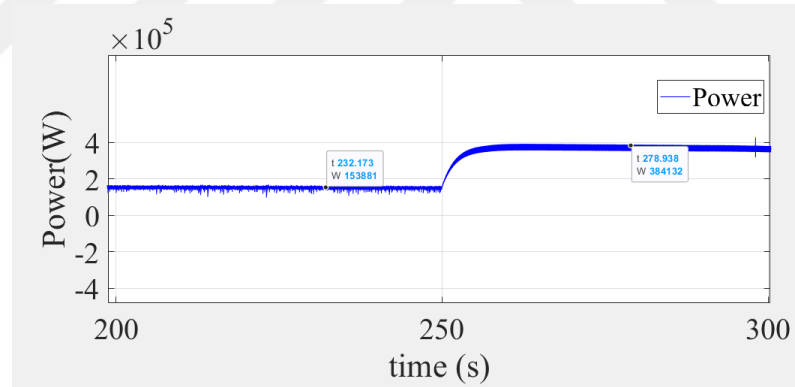
Figure 4.27 The electrical parameters at the battery side in unit step change in CV charging mode.



(a) Three-phase line voltages of grid (V)



(b) Three-phase line currents of grid (A)



(c) Active power drawn from AC grid (W)

Figure 4.28 The electrical parameters at the AC side in unit step change in CV charging mode.

This section presented the simulation and simulation results of the 100 kW bidirectional AC-DC matrix converter. The results demonstrated the system's efficiency and ability to maintain power quality with minimal THD. These findings validate the feasibility of the proposed design for high-power EV charging applications.

CHAPTER 5

CONCLUSIONS

This study developed a 100 kW bidirectional AC-DC MC, marking significant progress in EV charging infrastructure. The design simplifies conversion by eliminating intermediary DC links and integrates a PI controller for precise power management. Simulation results confirmed charging from 10% to 90% SOC within 55 minutes (CC mode, 630 V, 200 A) at 83.5% efficiency and 40 minutes (CV mode, 635 V, 630 A initial current) at 97.35% efficiency. THD values for voltage and current were minimized to 0.51% and 2.96%, respectively. Battery discharging achieved 98% efficiency with voltage and current THD values of 0.34% and 5.42%, maintaining a power factor of 1 and ensuring high power quality.

5.1 Comments and Conclusions on Results

1. CC Charging mode:
 - Strength: Provides stable current and power during the charging process, ensuring predictable and controlled charging behavior.
 - Limitation: Efficiency (83.5%) is moderate, indicating potential energy losses compared to other methods.
2. CV Charging mode:
 - Strength: Achieves high efficiency (97.35%), optimizing energy utilization during charging.
 - Limitation: Initial current and power are very high, which could stress the battery and grid. This issue can be mitigated by setting the reference voltage slightly above the battery voltage (5–10 V) to ensure current stays within permissible limits.
3. Hybrid Charging (CC-CV) mode:
 - Potential: Combining the stability of CC charging and the efficiency of CV charging offers a balanced approach, minimizing stress on both the battery and the grid while optimizing performance.
4. Discharging Efficiency:

- Observation: High discharging efficiency (98%) with minimal THD in voltage (0.34%) and current (5.42%) demonstrates the converter's suitability for V2G applications, supporting grid stability and power quality.
5. Harmonic Distortion and Ripple Control:
- The low THD values across all cases validate the effectiveness of the converter's design, ensuring compliance with regulatory standards. The use of output filters successfully limited the current ripple to 3%, preserving battery health and improving system reliability.

5.2 Recommendations and future work

1. Practical Deployment:
 - Real-World Testing: Conduct pilot projects in commercial EV charging stations to validate the converter's performance under diverse operational conditions (e.g., varying loads, ambient temperatures, and vehicle types).
 - Integration of V2G Technology: Expand capabilities to support vehicle-to-grid (V2G) applications, enabling energy storage from EVs during peak grid demand.
2. Control System Enhancements:
 - Dynamic Control Strategies: Incorporate advanced control techniques, such as Model Predictive Control (MPC) or Adaptive Control, to improve responsiveness and adapt to grid fluctuations, renewable energy integration, and varied charging profiles.
 - Harmonics and Ripple Mitigation: Further optimize THD and ripple reduction methods through innovative modulation techniques like Space Vector Modulation (SVM).
3. Industry Collaboration:
 - Stakeholder Partnerships: Collaborate with EV manufacturers, grid operators, and regulatory bodies to align the technology with industry needs and standards.
 - Mass Production and Cost Reduction: Scale manufacturing to reduce component costs and develop modular designs for compatibility with existing infrastructure.
4. Research Extensions:

- High-Power Applications: Test scalability for larger vehicles (e.g., buses or trucks) requiring higher power levels.
- Energy Storage Systems: Explore integration with renewable energy sources and battery storage systems to enhance grid stability and charging station self-sufficiency.
- Cooling and Durability: Optimize thermal management to ensure reliability and longevity in intensive charging environments.

By addressing these areas, the bidirectional MC can fully realize its potential, becoming a cornerstone of efficient and sustainable EV charging networks.



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CURRICULUM VITAE

Name: Jamal ABRAS

Electrical Power Systems Engineer – IT and Media Expert

- **Education**

Bachelor of Electrical Engineering – Electrical Power Systems Engineering
Aleppo University, Syria | 2009.

- **Professional Experience**

- IT and Media Officer
Excellence and Leadership Academy | Gaziantep, Turkey | 2021 – 2024.
- Training Coordinator
International Academy for Leadership and Specialized Training | Gaziantep, Turkey | 2018 – 2020.
- Office Manager
International Academy for Leadership and Specialized Training | Gaziantep, Turkey | 2016 – 2017.
- Technical Support Specialist
Awj Trading & Industry Co. | Gaziantep, Turkey | 2013 – 2015.
- Project Assistant (Volunteer)
Bulbulzade Association | Gaziantep, Turkey | 2012 – 2013.
- Research Assistant and Lecturer
Aleppo University | Aleppo, Syria | 2009 – 2012.
- Projects Engineer
SSBC Co - Aleppo University | Aleppo, Syria | 2009 – 2012.

- **Languages**

- Arabic: Native.
- English: Upper Intermediate.
- Turkish: Intermediate.