OPTIMIZING CHARGING COSTS FOR ELECTRIC VEHICLES THROUGH BIDIRECTIONAL CHARGING

A Thesis

by

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To my Family...

ABSTRACT

Electric vehicles (EVs) have gained much attention recently due to their potential environmental and economic benefits. With the growing adoption of EVs, the need for efficient and cost-effective charging infrastructure is becoming increasingly important. Bidirectional charging, which allows EVs to draw power from the grid and supply power back to the grid or other applications, is a promising technology that can help address some of the challenges associated with EV charging. This thesis focuses on developing and evaluating a bidirectional charging system for EVs to reduce charging costs.

A simulation model was developed using Simulink and Simscape to study the behavior of a bidirectional charging system consisting of an electric vehicle charging controller (EVCC), battery, grid, and application software. The simulation model investigated the performance and interactions of various system components and control strategies. The study also examined the potential cost savings associated with bidirectional charging by calculating the hourly price and comparing it to unidirectional charging scenarios.

This thesis contributes to the existing literature on bidirectional EV charging and charging cost optimization by presenting a detailed simulation model and evaluating the performance of different charging strategies.

ÖZETÇE

Elektrikli araçlar (EV'ler), potansiyel çevresel ve ekonomik faydaları nedeniyle son zamanlarda büyük ilgi görmüştür. EV'lerin giderek daha fazla benimsenmesiyle, verimli ve uygun maliyetli şarj altyapısına duyulan ihtiyaç giderek daha önemli hale geliyor. EV'lerin şebekeden güç çekmesine ve şebekeye veya diğer uygulamalara güç sağlamasına izin veren çift yönlü şarj, EV şarjı ile ilgili bazı zorlukların üstesinden gelmeye yardımcı olabilecek umut verici bir teknolojidir. Bu tez, şarj maliyetlerini azaltmak için EV'ler için çift yönlü bir şarj sisteminin geliştirilmesine ve değerlendirilmesine odaklanmaktadır.

Bir elektrikli araç şarj kontrolörü (EVCC), batarya, şebeke ve uygulama yazılımından oluşan çift yönlü bir şarj sisteminin davranışını incelemek için Simulink ve Simscape kullanılarak bir simülasyon modeli geliştirilmiştir. Simülasyon modeli, çeşitli sistem bileşenlerinin ve kontrol stratejilerinin performansını ve etkileşimlerini araştırdı. Çalışma ayrıca, saatlik fiyatı hesaplayarak ve bunu tek yönlü ücretlendirme senaryolarıyla karşılaştırarak çift yönlü ücretlendirmeyle ilişkili potansiyel maliyet tasarruflarını da inceledi.

Bu tez, ayrıntılı bir simülasyon modeli sunarak ve farklı şarj stratejilerinin performansını değerlendirerek çift yönlü EV şarjı ve şarj maliyeti optimizasyonu hakkındaki mevcut literatüre katkıda bulunuyor.

ACKNOWLEDGEMENTS

I want to express my deepest gratitude to my supervisor, Özkan Bebek, for his invaluable guidance, support, and encouragement throughout my studies. His expertise and insights have been instrumental in shaping my understanding of bidirectional charging in electric vehicles and have helped me navigate the challenges I encountered during this journey.

I am also profoundly grateful to my family for their unwavering support, love, and understanding. Their belief in my abilities and the sacrifices they have made for my education has provided me with the motivation and strength to persevere through difficult moments.

Additionally, I extend my heartfelt appreciation to my friends, who have been a constant source of encouragement, camaraderie, and inspiration. Their companionship and support have played a vital role in making this experience enjoyable and rewarding.

Lastly, I acknowledge the academic and research community working on electric vehicles. Their dedication to advancing our understanding of this technology has paved the way for sustainable transportation solutions that will undoubtedly shape our future.

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CHAPTER I

INTRODUCTION

1.1 Background

The history of electric vehicles (EVs) dates back to the late 19th and early 20th centuries when EVs competed with gasoline-powered vehicles for market dominance [2]. However, due to technological limitations and the rise of the internal combustion engine, EVs lost popularity until recent years, driven by advances in battery and power electronics technology and increasing environmental concerns [3].

Electric car sales reached a record high in 2021, despite supply chain bottlenecks and the ongoing COVID-19 pandemic. Compared with 2020, sales nearly doubled to 6.6 million (a sales share of nearly 9%), bringing the total number of electric cars on the road to 16.5 million. The sales share of electric cars increased by four percentage points in 2021. The Net Zero Emissions by 2050 Scenario sees an electric car fleet of over 300 million in 2030, accounting for 60% of new car sales. Getting on track with the Net Zero Scenario requires their sales share to increase by less than 6% percentage points per year. According to International Energy Agency, figure 1 indicates registrations and car sales between 2016-2021. [4]

This figure highlights the anticipated growth in sales year-over-year, emphasizing the rising demand for electric vehicles. As a result, robust and efficient charging infrastructure will become increasingly critical to support this expansion. The need for adequate charging solutions will play a vital role in fostering the widespread adoption of electric vehicles and ensuring a sustainable, environmentally friendly future for transportation.

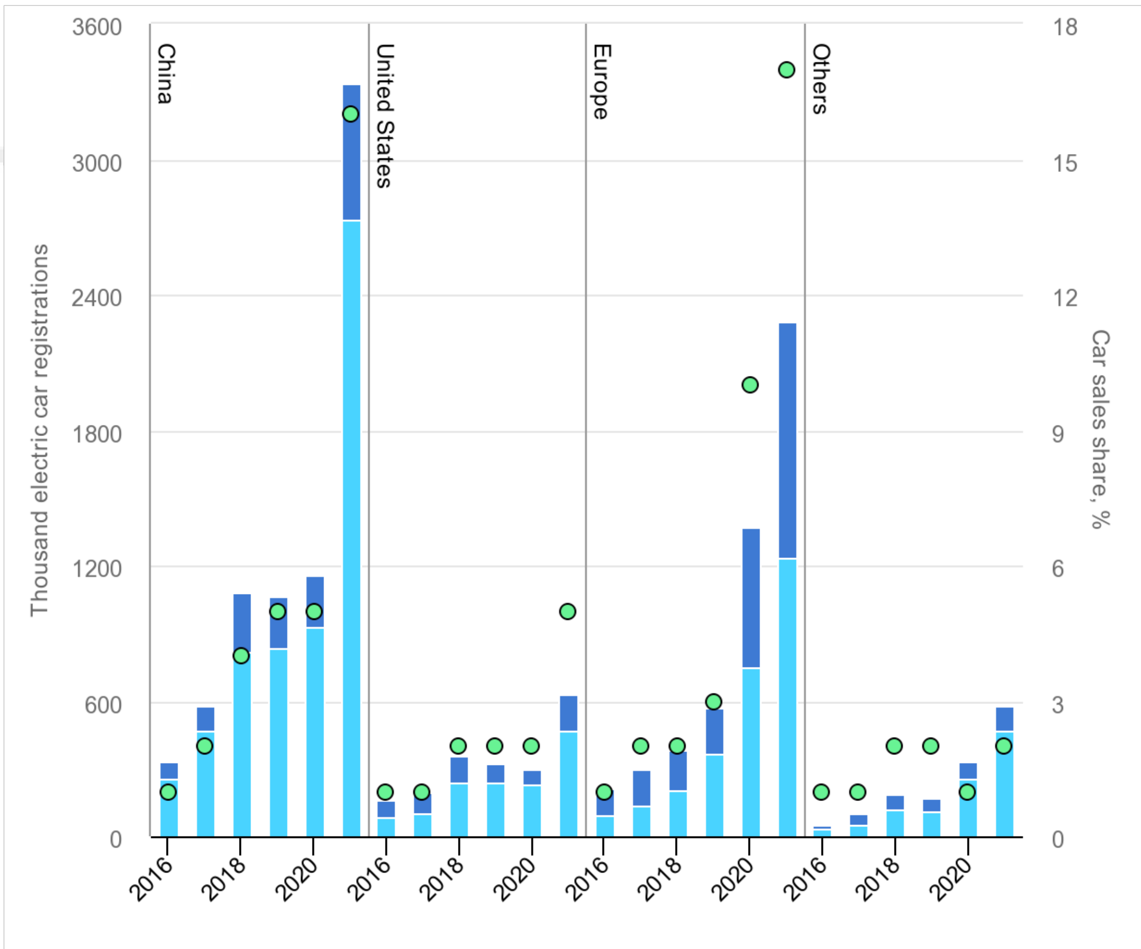

Figure 1: Electric car registrations and sales share in China, United States, Europe, and other regions, 2016-2021 [4]

There are several benefits associated with the adoption of electric vehicles, including:

- **Environmental benefits:** EVs produce zero tailpipe emissions, reducing local air pollution and contributing to improved air quality in urban areas [5]. Furthermore, EVs can potentially reduce greenhouse gas emissions when powered by renewable energy sources [6].
- **Energy efficiency:** EVs are generally more energy-efficient than internal combustion engine vehicles, as electric motors convert a higher percentage of the stored energy into usable power [7].
- **Reduced operating costs:** EVs often have lower operating costs than conventional vehicles due to the lower cost of electricity compared to gasoline or diesel, as well as reduced maintenance requirements [8].

There are also some disadvantages of electric vehicles, such as:

- **Mileage:** EVs use the battery as a source of energy; hence current technology is limited and because of the battery's capacity will not allow drivers to travel long distances.
- **Long charge times:** Charging EVs could take longer if the special chargers are not used. Even with the fast DC chargers, it may take up to one hour to fulfill the battery.
- **Initial buying cost:** Since EVs use a couple of high-tech components such as the battery, high voltage harness, and e-machine that reflect the vehicle's price.

Electric vehicles (EVs) have gained significant attention in recent years due to their potential to reduce greenhouse gas emissions, decrease dependence on fossil fuels, and improve air quality in urban environments [9]. As EV adoption increases, the demand for charging infrastructure also rises. Consequently, developing efficient and cost-effective charging solutions is essential to support widespread EV adoption [10].

There are several methods for charging the vehicle. Direct-current (DC) and alternating-current (AC) charging are the most common ways. DC charging is a method of charging that facilitates rapid energy transfer from the electric grid to plug-in vehicles. This charging method allows significantly more current to be drawn by the vehicle versus lower-rated AC systems. A combination of vehicles that can accept high-current dc charge and the dc supply equipment that provides it has led to the use of terminology such as "fast charging," "fast charger," "DC charger," "quick charger," etc. [11]

Bidirectional charging, also known as vehicle-to-grid (V2G) or vehicle-to-home (V2H), is a technology that allows EVs to not only draw power from the grid during charging but also supply power back to the grid or other applications when required [12]. This innovative approach has several potential benefits, including grid stability, reduced peak load, and increased utilization of renewable energy sources [13].

One of the primary concerns for EV owners is the cost of charging their vehicles [14]. Bidirectional charging could help lower these costs by enabling EV owners to supply energy back to the grid during peak demand periods, when electricity prices are high, and charge their vehicles during off-peak hours when prices are lower. By optimizing charging and discharging schedules, EV owners can minimize energy costs and contribute to a more efficient and sustainable energy system [15]. Tesla company already provided a solution for storing excess energy from solar panels in their Powerwall product. Powerwall is an integrated battery system that stores your solar energy for backup protection so your power stays on when the grid goes down. Your system detects outages and automatically recharges with sunlight to keep your appliances running for days. [16]

Several studies have explored the potential of BDC for reducing charging costs.

Tachikawa et al. [17] conducted a feasibility analysis of BDC and demonstrated that BDC could lessen the demand for grid power during peak hours and potentially lower the costs of EV charging. Similarly, Pearre and Ribberink [18] reviewed BDC technology and its potential applications, highlighting its benefits for grid stabilization, energy management, and load balancing.

Another critical factor in the adoption of EVs is their economic viability. Several studies have investigated the financial aspects of EV adoption, including the cost-effectiveness of charging infrastructure and the potential for revenue generation through BDC. Muratori et al. [19] assess the existing tools used to model future mobility systems and their interactions with other energy systems. The study highlights the need for modeling integrated mobility-energy systems with the infrastructure requirements and transportation energy needs for creating cost opportunities.

In summary, BDC is a promising technology that can significantly eliminate the costs associated with EV charging, improve the economic viability of EVs, and provide benefits for grid stabilization, energy management, and load balancing. This study builds upon this body of literature by providing a simulation-based analysis of BDC and evaluating its potential for reducing charging costs in EVs.

1.2 Research Problem and Objectives

Bidirectional charging technology can potentially optimize charging costs and improve grid stability [12,20]. However, there are still challenges to address, such as developing effective control strategies and understanding the impacts of bidirectional charging on battery life [21]. Furthermore, there is a need to assess the potential benefits and trade-offs associated with different modes of bidirectional charging, such as scheduled and dynamic charging [20].

The main objectives of this study are:

1. To develop a Simulink model with Simscape to simulate the behavior of bidirectional charging in electric vehicles, considering the components such as the EVCC, battery, grid, and application software.

2. To investigate the potential for reducing charging costs using bidirectional charging technology by calculating the price per hour and comparing the costs with and without bidirectional charging.

3. To assess the effectiveness of the scheduled mode in bidirectional charging and examine its impact on cost optimization.

4. To discuss the potential limitations and challenges of implementing bidirectional charging technology in real-world scenarios and recommend future research directions.

1.3 Scope of the thesis

This study focuses on the following aspects of bidirectional charging in electric vehicles:

1. **Simulation model:** The research is based on a Simulink model with Simscape, developed to simulate the behavior of bidirectional charging in electric vehicles. The model includes the EVCC, battery, grid, and application software components.

2. **Charging cost reduction:** The study's primary goal is to investigate the potential for reducing charging costs using bidirectional charging technology. This will be achieved by calculating the hourly price and comparing the costs with and without bidirectional charging.

3. **Modes of bidirectional charging:** Despite the existence of two modes, this

study will focus on evaluating the performance of the scheduled mode in bidirectional charging while exploring its implications for cost optimization. The rationale behind this choice is that, in dynamic mode, the charging station assumes the operation's control. This is to be avoided in this study, as the intention is to control the entire charging sequence for the research.

4. **Limitations and challenges:** The research will also address the potential limitations and challenges of implementing bidirectional charging technology in real-world scenarios. This includes assessing the impacts of bidirectional charging on battery life and the need for effective control strategies.

It is important to note that this study does not cover all aspects of electric vehicle charging or grid integration. The primary focus is bidirectional charging and its potential benefits and challenges for cost optimization.

1.4 Thesis Structure

The remainder of this thesis is organized as follows: Chapter 2 presents a literature review on electric vehicles, charging infrastructure, bidirectional charging technology, charging cost optimization strategies, and using Simulink and Simscape in EV research. Chapter 3 describes the methodology, including developing the simulation model and calculating the hourly price. Chapter 4 presents the results and analysis, including validating the simulation model, comparing charging costs, and evaluating scheduled and dynamic modes for bidirectional charging. Chapter 5 discusses the study's key findings, implications, and potential contributions. Finally, Chapter 6 concludes the thesis with a summary of the research and recommendations for future work.

The literature review in Chapter 2 will provide a comprehensive overview of the existing research in electric vehicles, charging infrastructure, and bidirectional charging technology. It will also cover charging cost optimization strategies and the application of Simulink and Simscape in EV research.

In Chapter 3, the methodology section will detail the simulation model's development using Simulink and Simscape, including the description and implementation of the critical components such as the EVCC, battery, grid, and application software. The calculation of the price per hour and the performance of a scheduled mode for bidirectional charging will also be discussed.

In Chapter 4, the results and analysis section, the simulation model validation will be presented, along with comparing charging costs between bidirectional and unidirectional charging. Additionally, the performance of the scheduled mode in bidirectional charging will be analyzed, offering insights into the most effective strategies for minimizing charging expenses.

In Chapter 5, the discussion section will synthesize the key findings from the study and their implications for EV users, charging infrastructure providers, and policymakers. The potential contributions of the research to the existing literature will also be highlighted.

Lastly, Chapter 6 will conclude the thesis with a summary of the research, recommendations for future work, and potential research directions in bidirectional EV charging and cost optimization.

CHAPTER II

LITERATURE REVIEW

2.1 Electric Vehicles and Charging Infrastructure

The rapid growth of electric vehicle (EV) adoption has been driven by technological advancements, environmental concerns, and supportive policies [9]. Electric vehicles (EVs) have gained significant attention in recent years due to their potential to reduce greenhouse gas emissions and dependence on fossil fuels [22]. EVs offer several advantages over conventional internal combustion engine vehicles, including lower greenhouse gas emissions, reduced reliance on fossil fuels, and improved air quality in urban areas [9]. As EV adoption increases, there is a growing need for efficient and reliable charging infrastructure to support the expanding EV fleet [10]. This infrastructure includes charging stations, communication systems, and grid integration technologies, which enable efficient and convenient charging of EVs [23]. Figure 2 shows a sample charging infrastructure [1]. A medium voltage(MV) network is connected to a power converter in the figure. In the power converter, the power electronics unit converts AC to DC and feeds that into the charging dispenser. From the charging dispenser, it can be connected to electric vehicles.

2.2 Bidirectional Charging Technology and Benefits

Bidirectional charging, also known as vehicle-to-grid (V2G) or vehicle-to-home (V2H), is an innovative technology that allows EVs to not only draw power from the grid during charging but also supply power back to the grid or other applications when required [22]. This technology has several potential benefits, including grid stability,

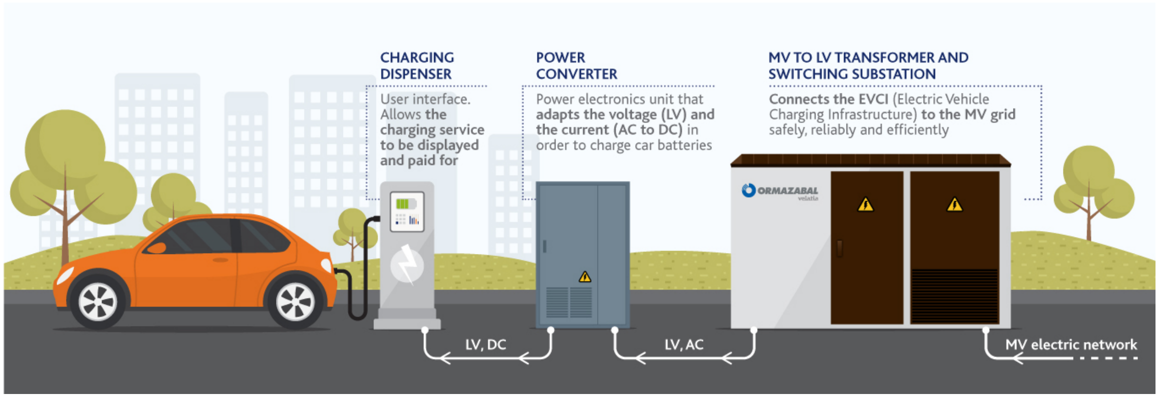

Figure 2: Sample Charging Infrastructure [1].

reduced peak load, and increased utilization of renewable energy sources [13]. By allowing EVs to act as distributed energy resources, bidirectional charging can improve the flexibility and resilience of the power grid, helping to integrate higher levels of renewable energy generation [24]. This capability can help stabilize the grid, support the integration of renewable energy sources, and reduce the overall cost of electricity for EV owners [25]. Figure 3 shows a sample V2H and V2G application [26]. Green arrows show the energy income from solar panels and wind turbines. The red arrow shows that excess energy is fed into the vehicle. With this setup, electric vehicles can be charged with energy from the environment without any cost.

2.3 Charging Cost Optimization Strategies

The charging cost is a significant concern for EV owners and can influence EVs' adoption and usage patterns [10]. Electricity costs are related to fuel prices, although less commonly incorporated in analyses. Those two factors combine to determine most EV operating expenses, impacting adoption rates. Bidirectional charging offers potential cost savings by enabling EV owners to supply energy back to the grid during peak demand periods when electricity prices are high and charge their vehicles during off-peak hours when prices are lower [14]. Various optimization strategies

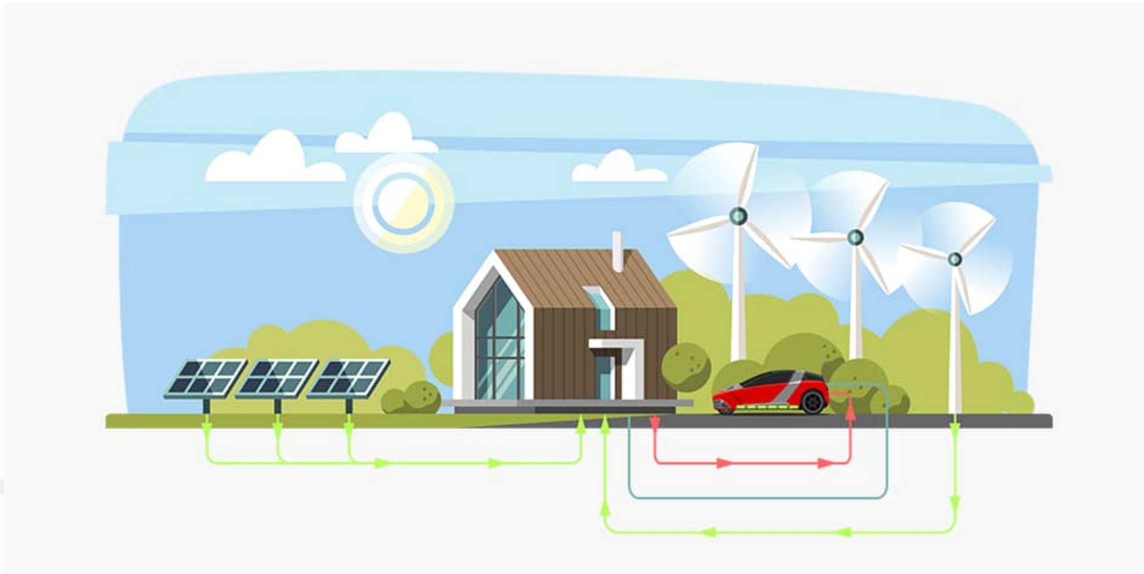

Figure 3: Sample V2H and V2G Application

have been proposed to minimize charging costs and maximize the benefits of bidirectional charging, including intelligent charging algorithms, dynamic pricing schemes, and demand response programs [27]. These strategies aim to optimize charging and discharging schedules based on factors such as electricity prices, grid conditions, and user preferences. Developing effective charging cost optimization strategies is crucial for maximizing the benefits of bidirectional charging and promoting its widespread adoption. As depicted in Figure 4, electricity prices fluctuate and can be optimized for charging purposes. [28] Publicly available wholesale market data taken from Monitoring Analytics. [29]

2.4 Software Tools in Electric Vehicle Research

Simulink and Simscape are powerful simulation tools developed by MathWorks that are widely used in various engineering fields, including EV research [13]. Simulink and Simscape have been particularly useful in developing and evaluating bidirectional charging systems. They allow for the simulation of complex interactions between EVs,

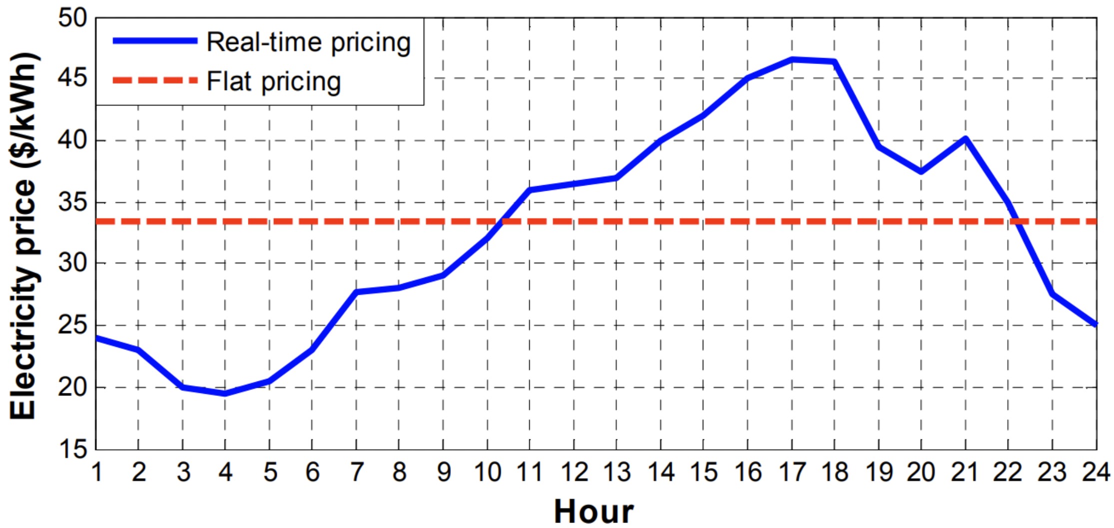

Figure 4: 24-hour electricity price [28]

charging infrastructure, and the electric grid [30]. These tools have significantly contributed to advancing bidirectional charging and electric vehicle research knowledge. Simulink provides a graphical environment for modeling, simulating, and analyzing dynamic systems, while Simscape extends Simulink with tools for modeling physical components and multi-domain systems. These tools can create detailed simulation models of EVs and their associated charging infrastructure, enabling researchers to investigate the performance and interactions of various system components and control strategies [15]. Simulation models can also evaluate bidirectional charging technology's potential benefits and limitations, providing valuable insights for researchers, policymakers, and industry stakeholders. Adhikary et al. [31] developed bi-directional EV charging for grid-to-vehicle and vehicle-to-grid and battery monitoring systems using IoT in Simulink. They designed the bidirectional converter and used it for the charging station to charge the battery of the EV. With the help of Simulink, they monitor the different parameters.

CHAPTER III

METHODOLOGY

3.1 System Overview

The bidirectional charging system for electric vehicles consists of several key components that interact to enable efficient charging and discharging of the vehicle's battery and grid support services. The system's main components are the electric vehicle charge controller (EVCC), battery, grid, and application software [20]. Figure 5 provides a system overview of the bidirectional charging system.

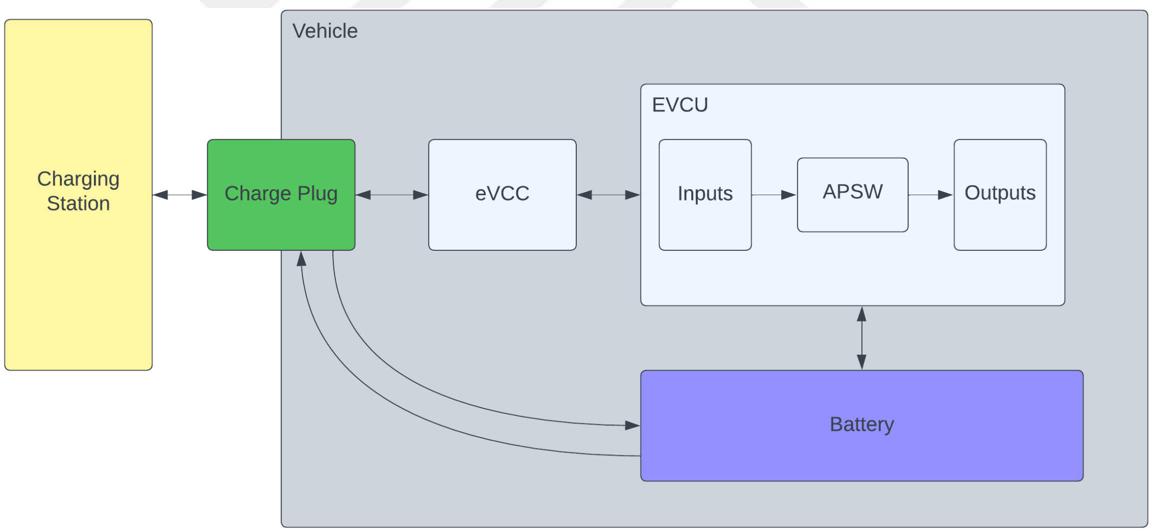

Figure 5: System overview of the bidirectional charging system

- **EVCC:** The EVCC is responsible for managing the charging and discharging process of the vehicle's battery according to the charging procedure. It communicates with the grid and the vehicle to ensure optimal power flow, considering factors such as battery state of charge, grid conditions, and user preferences [12].

- **Battery:** The battery is the energy storage device within the electric vehicle. Its capacity and chemistry play crucial roles in determining the efficiency and performance of bidirectional charging. The battery's state of health, temperature, and charging history are important factors to consider when implementing bidirectional charging [21].

- **Grid:** The grid provides the electrical power needed for charging the vehicle's battery and receives power from the battery during discharging events. Bidirectional charging can support the grid by providing ancillary services such as demand response, frequency regulation, and voltage support [12].

- **Application software:** The application software is the user interface for managing the bidirectional charging process. It allows users to set preferences for charging and discharging, monitor battery health and performance, and optimize charging costs through various algorithms and strategies [20].

The bidirectional charging system is designed to significantly benefit cost optimization, grid stability, and renewable energy integration. However, challenges and limitations must be addressed, such as the impacts on battery life and the development of effective control strategies [21]. Figure 6 provides an overview of the architecture inspired by the existing literature on EV charging systems and bidirectional charging technology [12,15]. In the case of vehicle-to-grid (V2G) charging, the charging station must be outfitted with additional components to enable seamless connections between the home and the vehicle. This configuration facilitates not only the charging of the vehicle but also the utilization of the vehicle's stored energy to power the house when needed.

3.2 Model development

As electric vehicle sales are projected to grow year-over-year, the importance of robust and efficient charging infrastructure will become increasingly critical. This growth in demand for electric vehicles emphasizes the need for effective charging solutions to

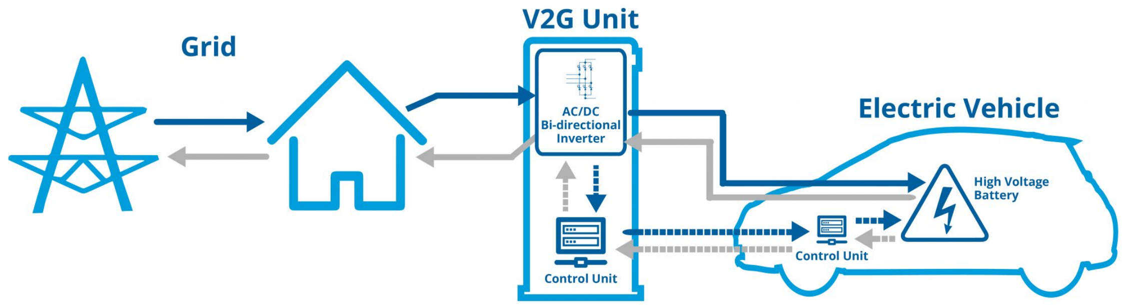

Figure 6: Architecture of the bidirectional charging system

foster their widespread adoption and ensure a sustainable, environmentally friendly future for transportation. The following subsections will briefly outline each component of the bidirectional charging system and the respective modeling approach. For this purpose, the simulation model development involved utilizing Simulink and Simscape, which are widely employed across diverse engineering domains, including electric vehicle (EV) research [15]. These powerful tools facilitated the construction of an accurate representation of the bidirectional charging system and its constituent elements.

3.2.1 Electric Vehicle Charging Controller (EVCC)

The EVCC is responsible for managing the charging and discharging processes of the EV battery in terms of charging. It communicates with the grid and application software to obtain information about electricity prices and user preferences and then determines the optimal charging and discharging schedule. There are two modes of bidirectional charging in the EVCC: [32]

- In Dynamic mode, EVSE will take over the charging control within the energy limits that EV announces. During this phase, the target current and target voltage values that EV requests over the vehicle will not affect the EVSE. However, EVSE will honor the maximum/minimum EV declares current/Voltage/Power values to EVCC over the vehicle. The main target parameters during dynamic mode are the energy requests from the EV. In addition, the EVSE may not terminate the dynamic session even if the EV target amount of Energy is already transferred.

- In Scheduled mode, EV controls charging current and voltage. However, EVCC will clip the EV-requested target current or target voltage if these values exceed the limits set by EVSE min/max current, max voltage, min/max power, and the offered scheduled power profile from EVSE.

In this study, the scheduled mode is simulated and evaluated due to having full control of the charging process. EVCC referenced Pi Innovo's solution in the simulations, implemented according to its specifications. Figure 7 shows the EVCC state machine for charging. [32]

3.2.2 Battery

The battery model represents the energy storage system of the EV. It was modeled using a generic lithium-ion battery model available in Simscape, including capacity, state of charge (SOC), and charging and discharging efficiency [15]. The battery model interacts with the EVCC, receiving charging and discharging commands and updating its SOC accordingly. The simulation uses a generic lithium-ion battery with the characteristics shown in Table 1.

Table 1: Electric Vehicle Battery Characteristics

Battery Type	**Lithium-Ion**
Maximum Capacity(Ah)	200
Fully Charged Voltage(V)	814.791
Cut-off Voltage(V)	525
Nominal Discharge Current(A)	86.9565
Internal Resistance(Ohms)	0.035
Capacity(Ah) at Nominal Voltage	180.8696

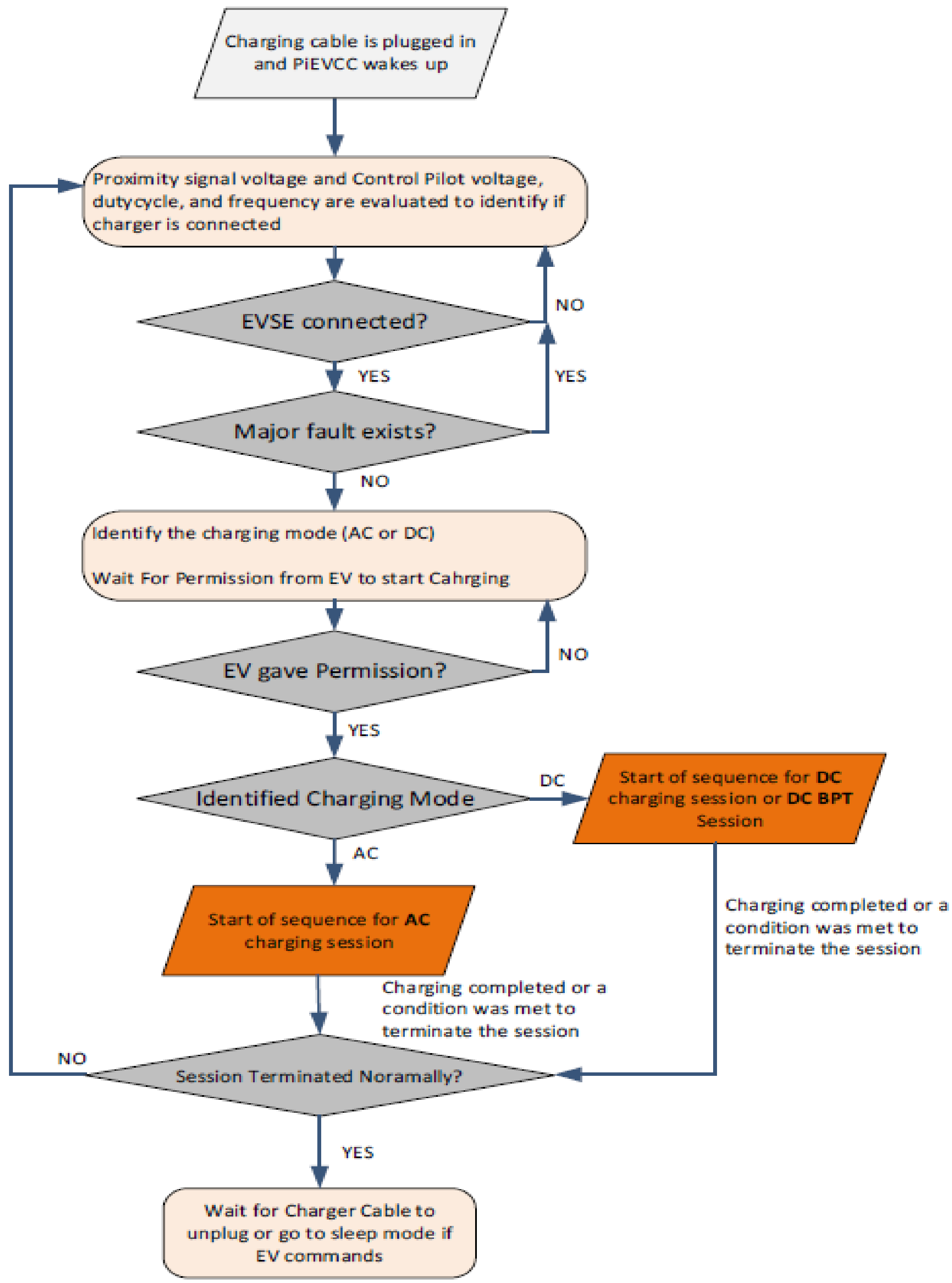

Figure 7: Pi Innovo EVCC State Machine

3.2.3 Charging Station Grid

The grid model serves as the power supply for the bidirectional charging system. It was implemented as a controlled DC voltage source in Simscape, receiving the voltage input from the Electric Vehicle Charge Controller (EVCC). The grid model plays a crucial role in facilitating the bidirectional charging process by providing power to the electric vehicle's battery during the charging phase and receiving power from the battery during the discharging phase. This bidirectional power flow optimizes charging costs, grid stability, and renewable energy integration, contributing to more efficient and sustainable charging infrastructure for electric vehicles. Figure 8 shows a structure for the grid. Target voltage and current are calculated from application software and fed into the system. Based on the target current, the variable resistor value is set by the 1D map. Figure 9 shows changes in resistor values for bidirectional charging. Moreover, Figure 10 shows changes in resistor values for unidirectional charging.

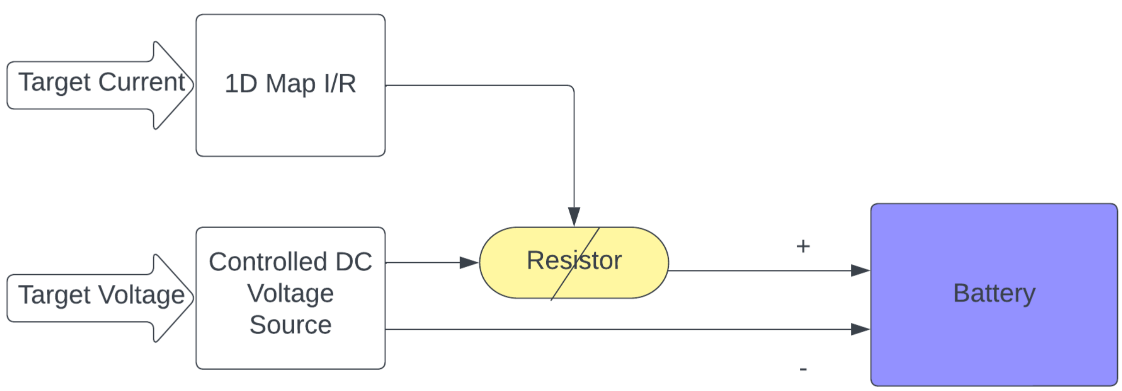

Figure 8: Grid Structure in the Model

3.2.4 Application Software

The application software serves as the user interface for the bidirectional charging system, allowing users to input preferences such as desired SOC, charging start and end times, and preferred charging mode (scheduled or dynamic). In this study, only

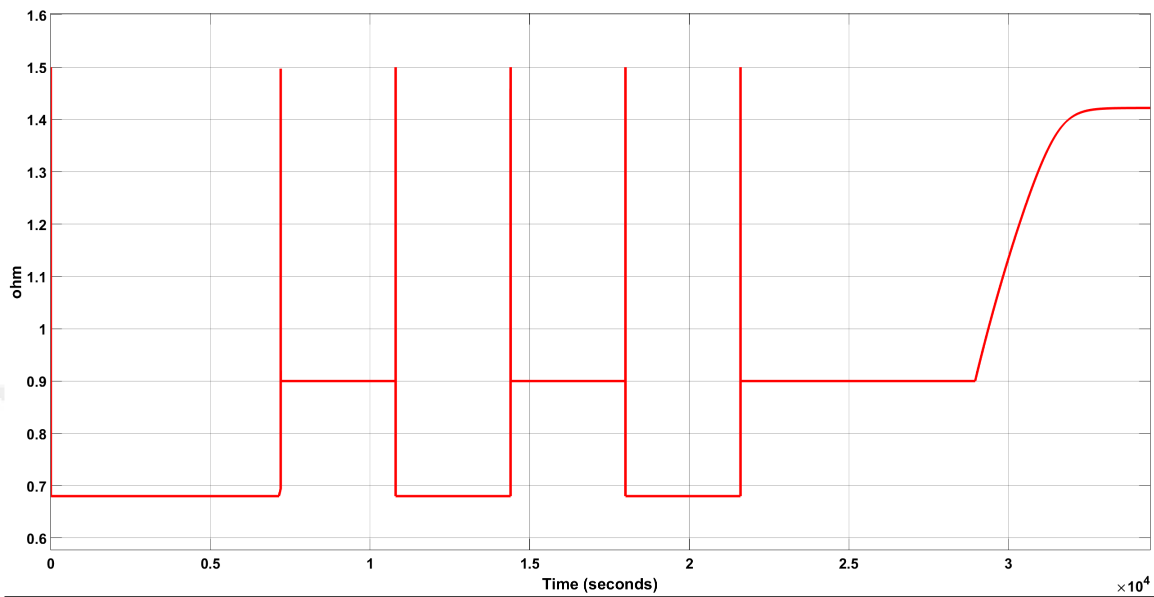

Figure 9: Resistor values for bidirectional charging scenario

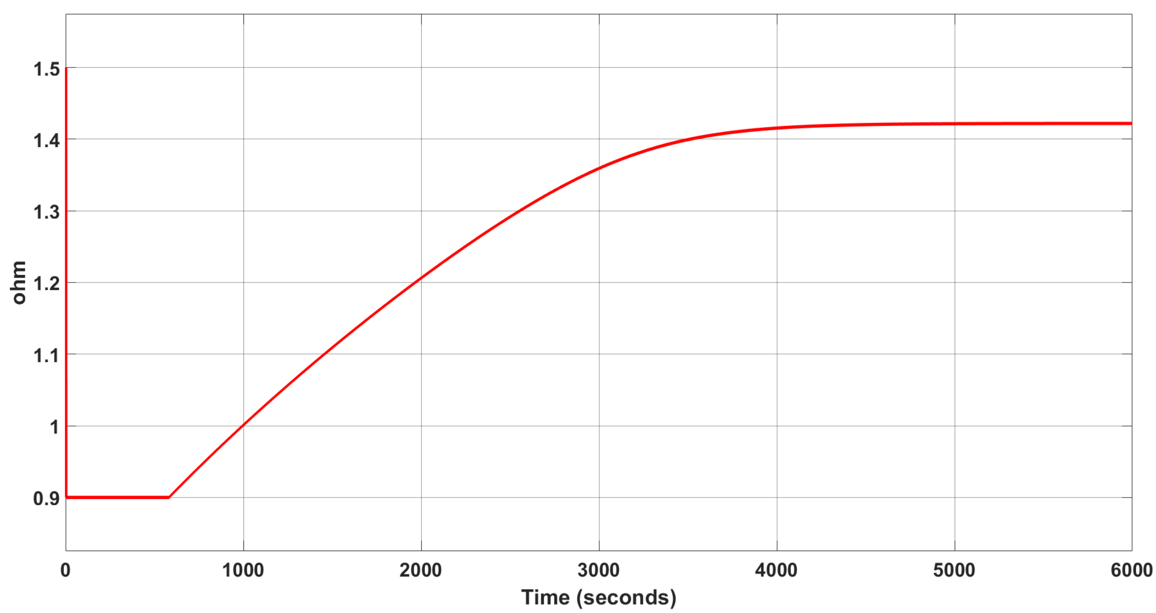

Figure 10: Resistor values for unidirectional charging scenario

the scheduled mode is selected for testing. The application software communicates this information to the EVCC, which then uses it to determine the optimal charging and discharging schedule [14]. Application software has a state machine that checks all conditions to allow the vehicle to charge. The target voltage and current are calculated based on the charging mode and limits if the needs are met. Figure 11 shows the state flow within application software for the charging process.

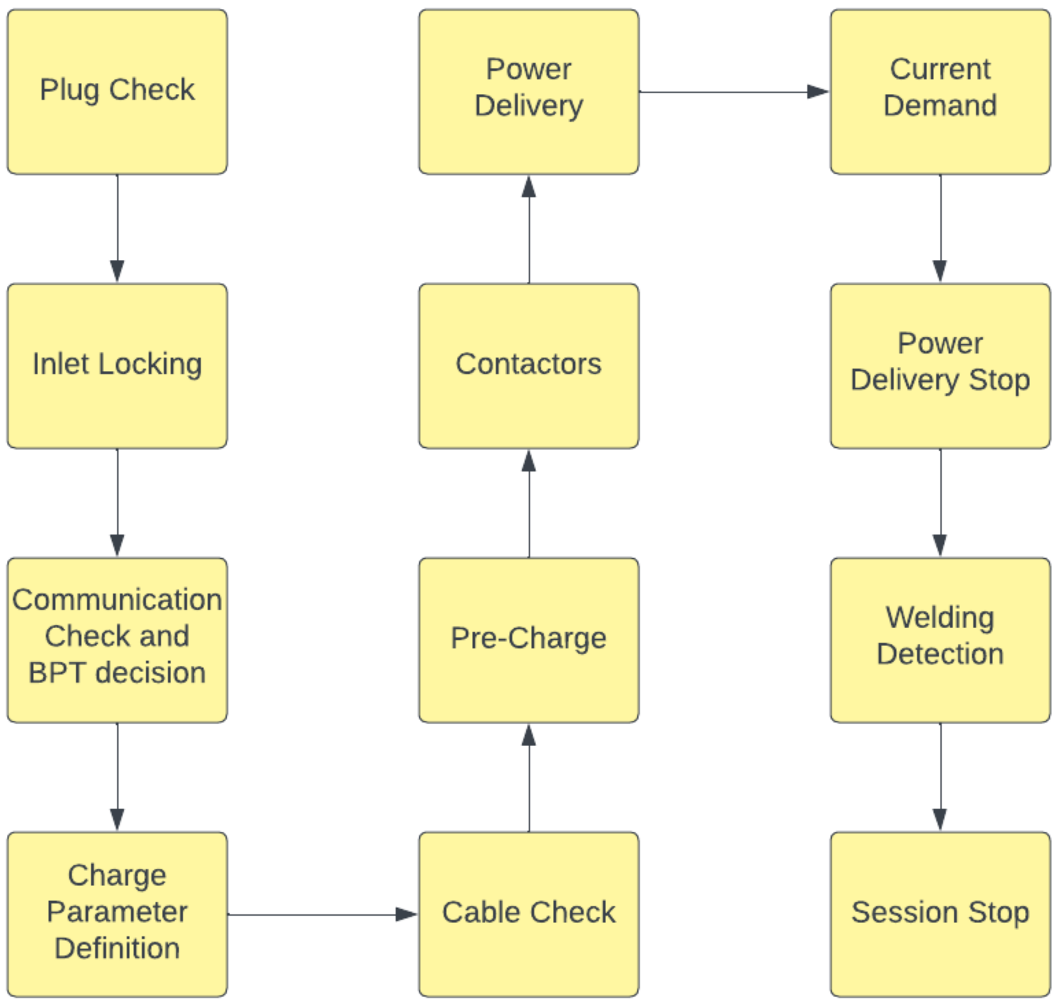

Figure 11: Charging Stateflow in Application Software

3.3 Simulation setup and scenarios

The simulation model was used to investigate the performance of the bidirectional charging system under various scenarios, including different electricity price profiles, user preferences, and grid conditions, as suggested by the existing literature [15]. A baseline scenario with unidirectional charging was also simulated for comparison. The key performance metric for this study was the charging cost, which was calculated based on the price per hour of electricity and the energy consumed during charging. Simulink Test creates a test harness from the model and simulation inputs Signal Editor gives. In the Signal Editor, signals generated are charging mode, control pilot, proximity, and time. These signals are read by the EVCC and processed in the state machine as outputs of EVCC; the current mode of the charging system, plug condition, and limits from the charging station is sent to the EVCC. EVCU has a state machine that checks all requirements to allow vehicles to charge, and if the conditions are met, the target current and the target voltage are calculated based on the charging mode and limits. Figure 12 shows a process flow for Simulink Test. [?]

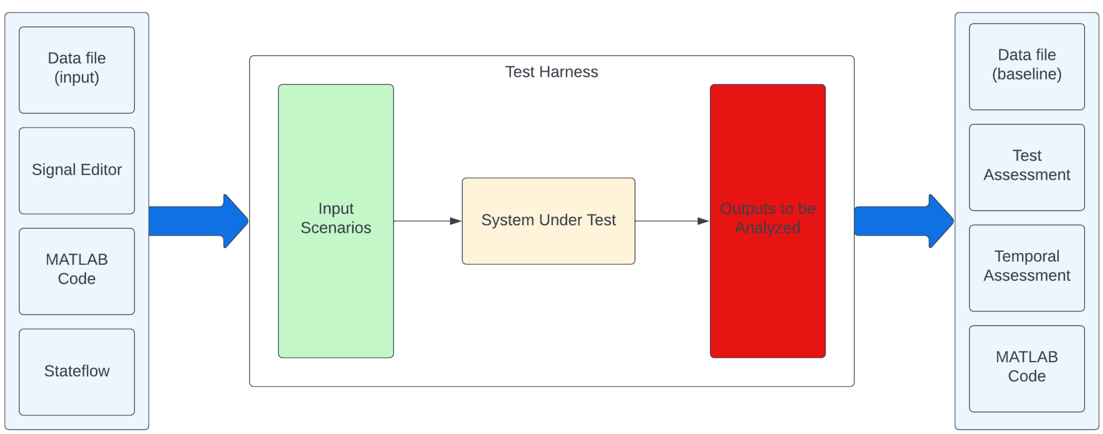

Figure 12: Simulink Test Flow

3.4 Data analysis

The simulation results were analyzed to evaluate the performance of the bidirectional charging system and its potential for cost savings compared to the baseline scenario, following the approaches discussed in the literature [14, 15]. The charging costs for two scenarios were compared, and the factors influencing these costs were examined, such as the effectiveness of the charging schedule and the impact of user preferences. In a scenario implementing unidirectional charging, the process demonstrated an advantage in terms of the time it consumed, with charging completed in a relatively short duration. However, the associated high costs offset this advantage, presenting a potential financial constraint to its application.

Conversely, the process was notably lengthier when employing bidirectional charging, requiring a more extended period to complete the charging and discharging cycles. Despite this apparent drawback, bidirectional charging presented a significant advantage in terms of cost efficiency. The costs associated with this charging method were markedly lower, showcasing its potential for yielding substantial savings, especially when applied over long-term usage.

In summary, while unidirectional charging offers speed, bidirectional charging provides a more sustainable and economically beneficial alternative. Therefore, choosing these two methods would hinge on the user's specific requirements and priorities, such as time availability and cost considerations.

The analysis involves assessing the cost savings obtained through bidirectional charging by comparing standard and scheduled mode bidirectional charging scenarios. In the standard charging scenario, the electric vehicle (EV) obtains power from the grid using a unidirectional charging process. Conversely, in the bidirectional charging (BDC) scenario, the EV either charges from or supplies power to the grid, depending on the electricity price data. It is assumed that the vehicle has different SoC levels of 0%,20%, 50%, and 80%, and the owner wanted to be put in charge overnight from

00:00 to 09:00. Weekly analysis was also done to extend the results. The cost of charging for both scenarios is calculated by using the following equation:

$$J = \frac{1}{3600} \cdot \left[\int (P_{ch} \times k_{wh}) + (z^{-1}) \int (P_{ch} \times k_{wh}) \right] \quad (1)$$

where P_{ch} is the charging power, z^{-1} is a discrete-time unit delay, and k_{wh} is the cost per megawatt-hour of electricity as shown in Fig. 13 and Table 2. In the given equation, the cost is calculated by integrating the power multiplied by cost over 1/s and then summed with the unit delay of that signal. The result is divided by 3600 to obtain an hourly price.

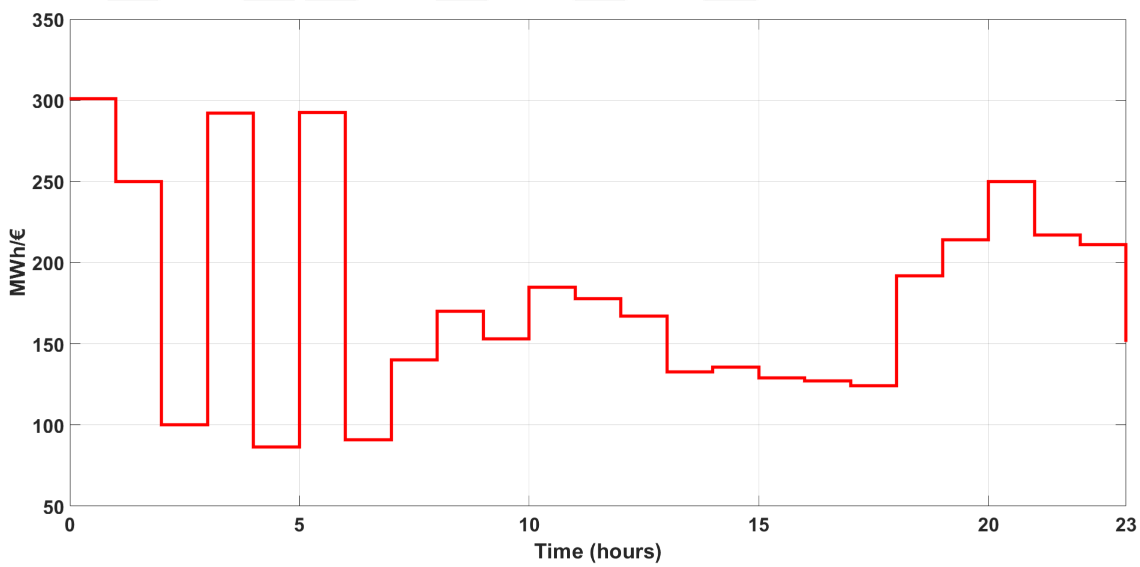

Figure 13: Cost per megawatt-hour of electricity

3.5 Methodology Summary

In summary, the methodology section detailed the development of a simulation model using Simulink and Simscape to study the behavior and performance of a bidirectional charging system for EVs based on existing literature and research approaches [12,15]. The model included an EVCC, battery, grid, and application software and considered the scheduled mode of bidirectional charging. Two scenarios were evaluated which

Table 2: Cost per megawatt-hour of electricity for night

Price (MWh/€)	**Time (hours)**
300.93	00:00-01:00
250.01	01:00-02:00
100.06	02:00-03:00
292.09	03:00-04:00
86.44	04:00-05:00
292.45	05:00-06:00
91.01	06:00-07:00
140.03	07:00-08:00
170.06	08:00-09:00
153.09	09:00-10:00

are unidirectional and bidirectional charging in the scheduled mode for overnight charging and the cost of both scenarios compared.

CHAPTER IV

RESULTS AND ANALYSIS

This section presents the results and analysis of the simulation model developed for bidirectional charging in electric vehicles. The primary aim is to evaluate the performance of the bidirectional charging system, assess its cost-effectiveness, and compare it with the conventional unidirectional charging method. The results obtained from the simulation model offer valuable insights into the advantages and limitations of bidirectional charging and serve as a foundation for potential improvements and future research directions.

The analysis is structured as follows: the simulation model is first validated to ensure its accuracy and reliability. Subsequently, charging costs associated with unidirectional and bidirectional charging are compared, highlighting the potential savings that can be achieved. The performance of the scheduled mode of bidirectional charging is then assessed, considering its implications for cost optimization. Finally, potential limitations are examined, and the system's sensitivity to various factors is discussed.

This comprehensive analysis will better understand bidirectional charging's practical application, its benefits for electric vehicle users, and its implications for charging infrastructure providers.

4.1 Limitations

This study has some limitations that should be considered when interpreting the results.

1. **Assumptions about electricity pricing:** The analysis assumes a simplified

electricity pricing structure. In reality, electricity prices can vary based on time of use, demand, and location [33]. Future studies could consider more complex pricing structures to reflect real-world conditions better.

2. **Battery degradation:** The model does not fully account for the impact of bidirectional charging on battery degradation. While some studies have found that battery degradation may be minimal under certain conditions [21, 34], further research is needed to determine the long-term impacts of bidirectional charging on battery life.

3. **Simulation model:** The study relies on a simulation model, which may not perfectly capture the behavior of real-world systems. Additional research with real-world data and more advanced simulation techniques could provide further insights [35].

4. **Generalizability:** The findings of this study may not be generalizable to all-electric vehicle types, charging infrastructure, and grid conditions. Further research is needed to explore the applicability of the results to different contexts [36].

4.2 Validation of the simulation model

The simulation results demonstrate that bidirectional charging leads to significant cost savings compared to unidirectional charging under various scenarios, as reported in previous studies [12–15]. The cost savings can be attributed to the effective utilization of lower electricity prices during off-peak hours and the ability to sell excess energy back to the grid during peak hours [12].

Figure 14 shows the cost for bidirectional charging when SoC has an initial level of 80%. Figure 15 shows the cost for unidirectional charging when SoC has an initial level of 80%. Figure 16 shows the cost for bidirectional charging when SoC has an initial level of 50%. Figure 17 shows the cost for unidirectional charging when SoC has an initial level of 50%. Figure 18 shows the cost for bidirectional charging when SoC has an initial level of 20%. Figure 19 shows the cost for unidirectional charging when SoC has an initial level of 20%. Figure 20 shows the cost for bidirectional charging when SoC has an initial level of 0%. Figure 21 shows the cost for unidirectional charging when SoC has an initial level of 0%.

Figure 22 shows the state of charge for the bidirectional charging when SoC has an initial level of 80%. Figure 23 shows the state of charge for the bidirectional charging when SoC has an initial level of 50%. Figure 24 shows the state of charge for the bidirectional charging when SoC has an initial level of 20%. Figure 25 shows the state of charge for the bidirectional charging when SoC has an initial level of 0%.

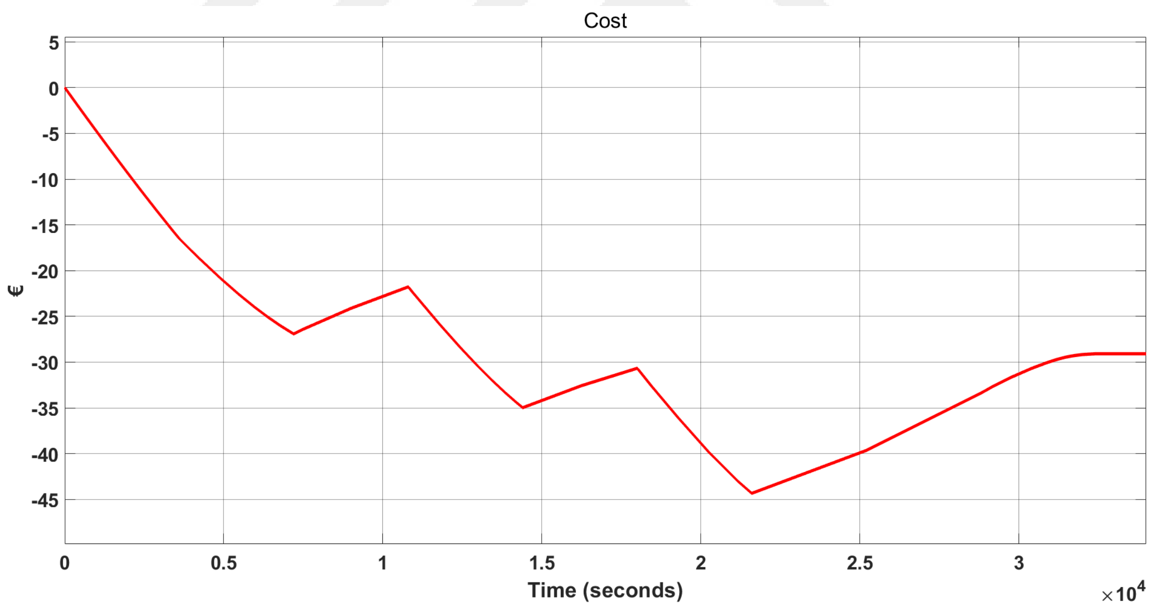

Figure 14: Charging cost for bidirectional charging scenario starting from 80% SoC

Furthermore, Figure 26 shows the bidirectional charging costs for a week together, whereas Figure 27, shows the charging cost for unidirectional within a week.

Figure 28, shows the SoC changes between the days.

Figure 29 show that the range of current values from 80 A to -80 A illustrates the bidirectional power flow between the electric vehicle's battery and the charging

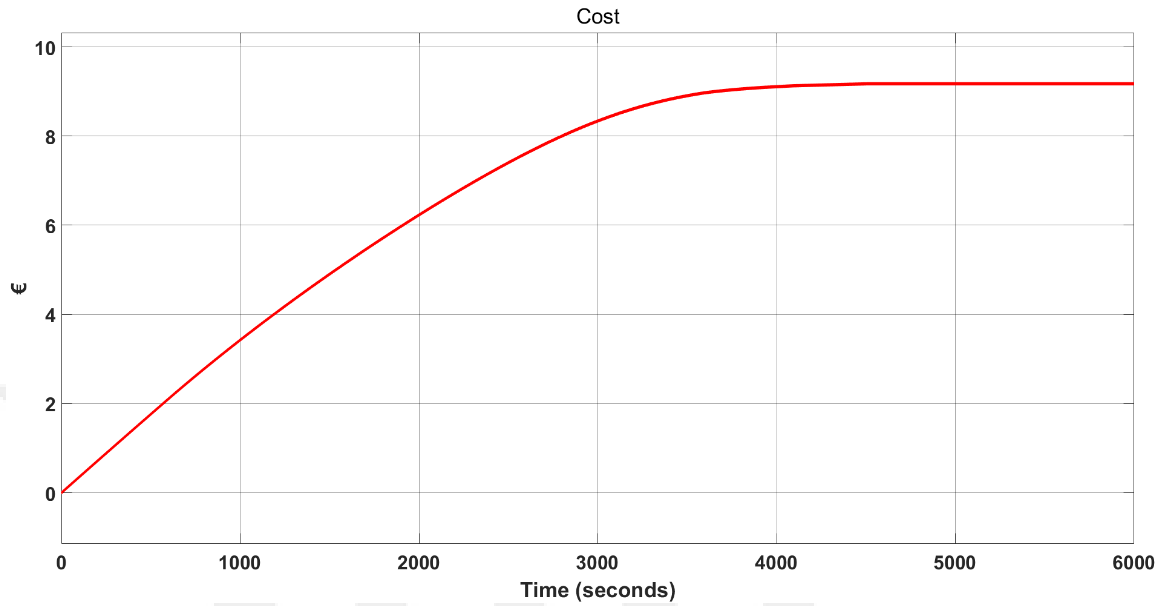

Figure 15: Charging cost for unidirectional charging scenario starting from 80% SoC

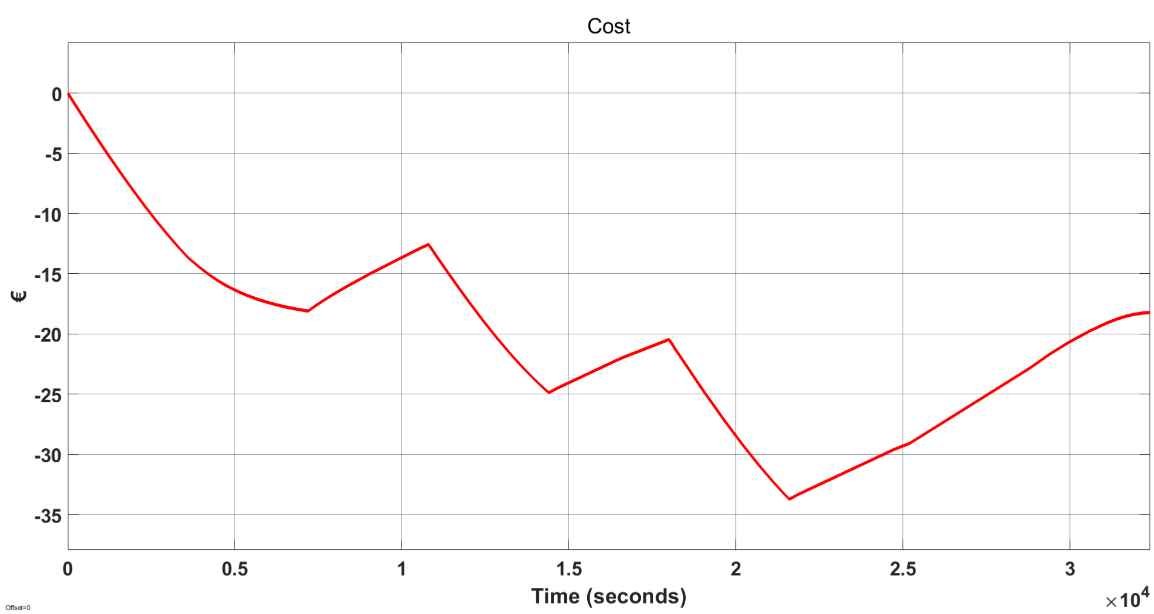

Figure 16: Charging cost for bidirectional charging scenario starting from 50% SoC

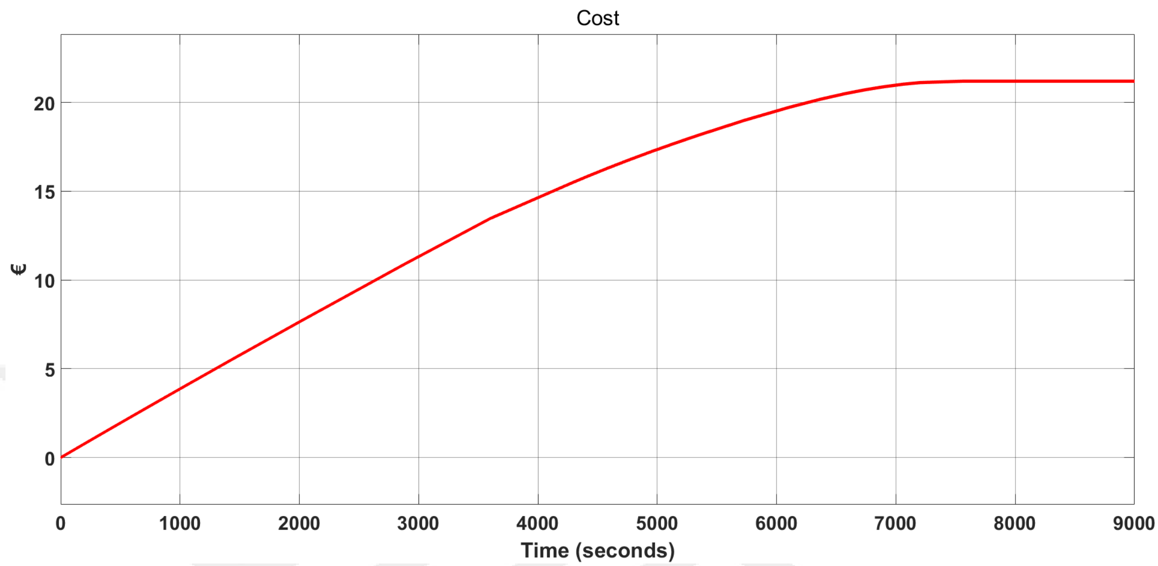

Figure 17: Charging cost for unidirectional charging scenario starting from 50% SoC

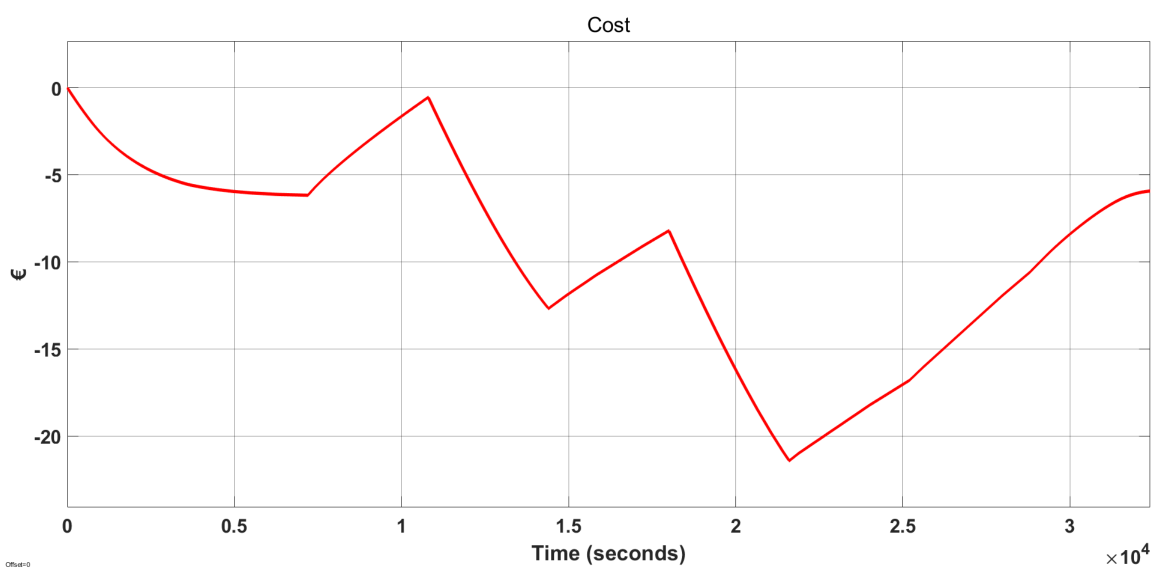

Figure 18: Charging cost for bidirectional charging scenario starting from 20% SoC

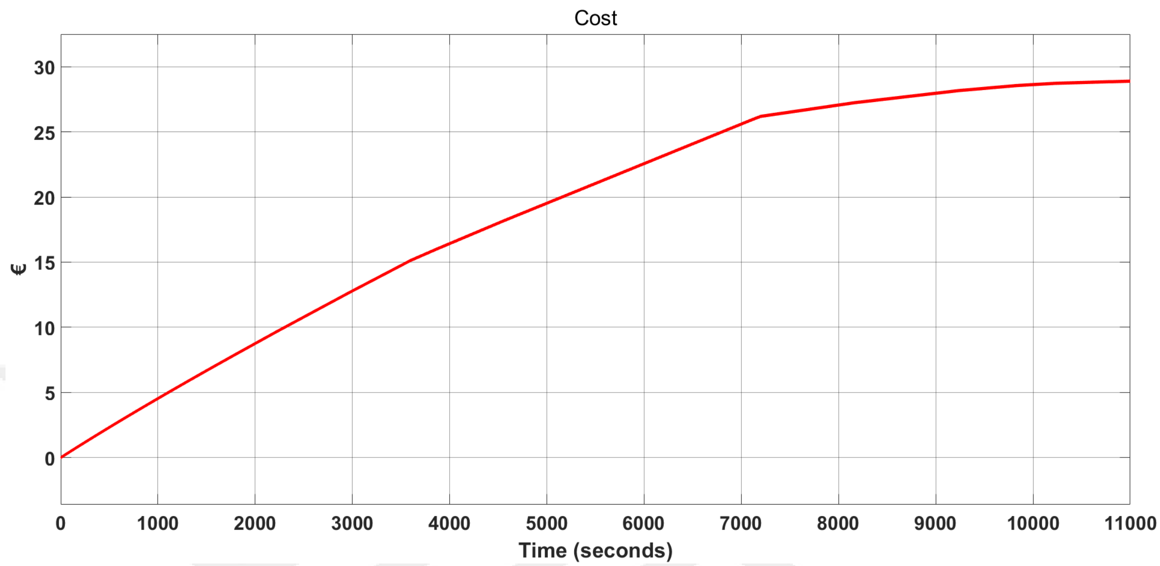

Figure 19: Charging cost for unidirectional charging scenario starting from 20% SoC

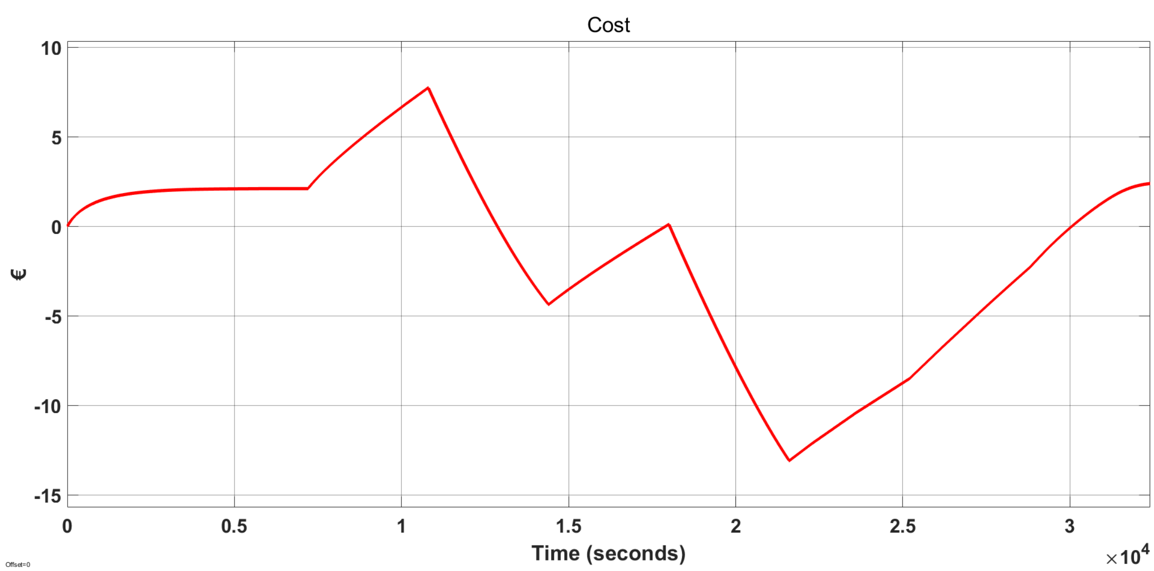

Figure 20: Charging cost for bidirectional charging scenario starting from 0% SoC

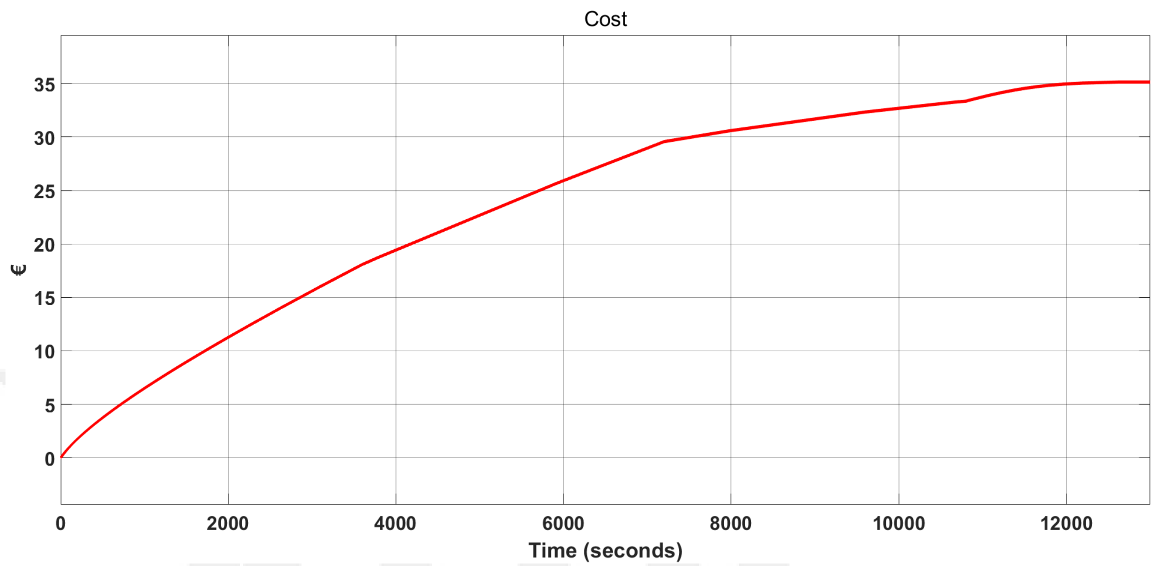

Figure 21: Charging cost for unidirectional charging scenario starting from 0% SoC

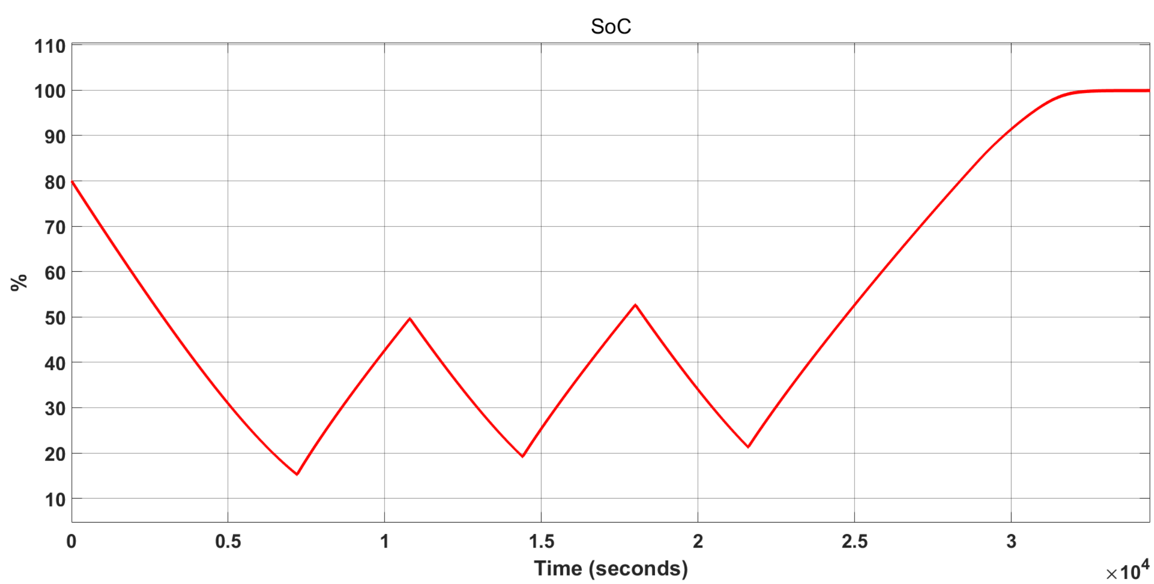

Figure 22: State of charge for bidirectional charging scenario starting from 80% SoC

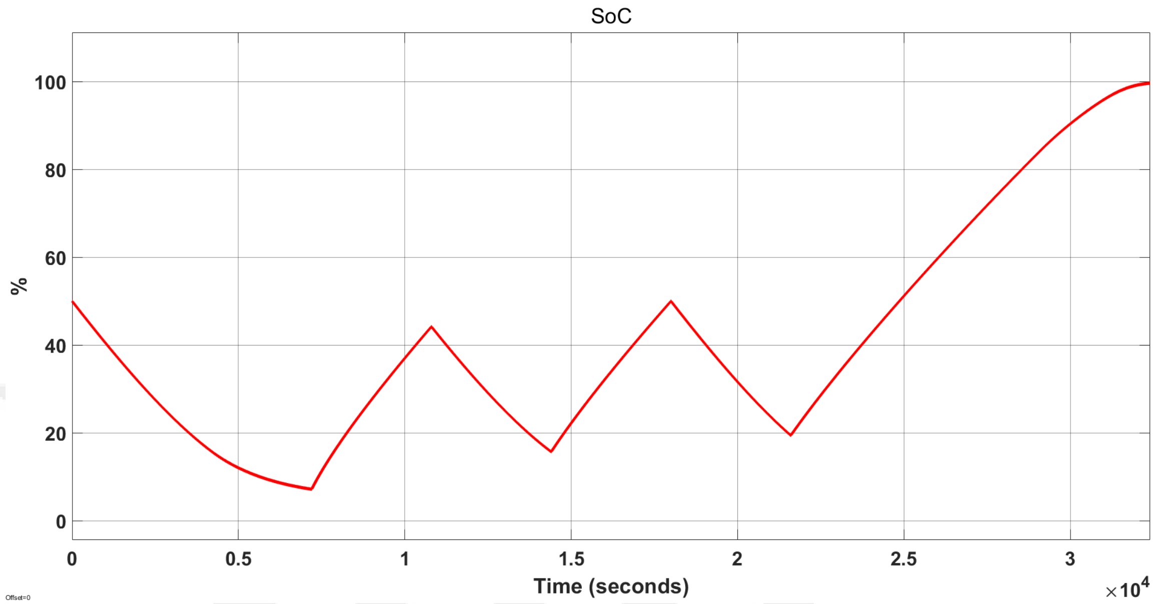

Figure 23: State of charge for bidirectional charging scenario starting from 50% SoC

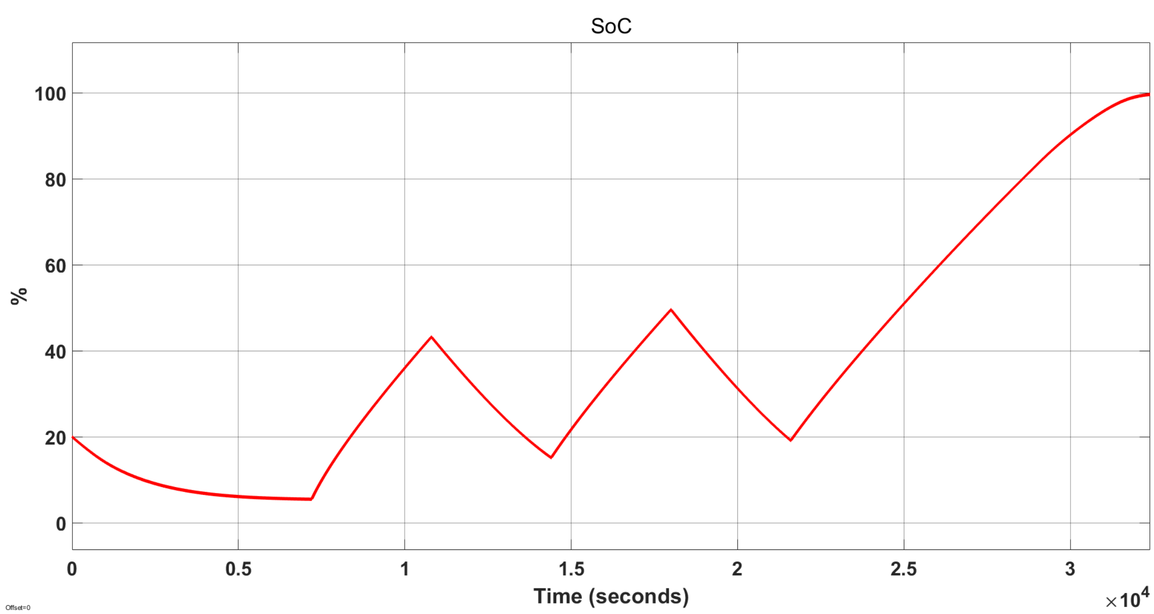

Figure 24: State of charge for bidirectional charging scenario starting from 20% SoC

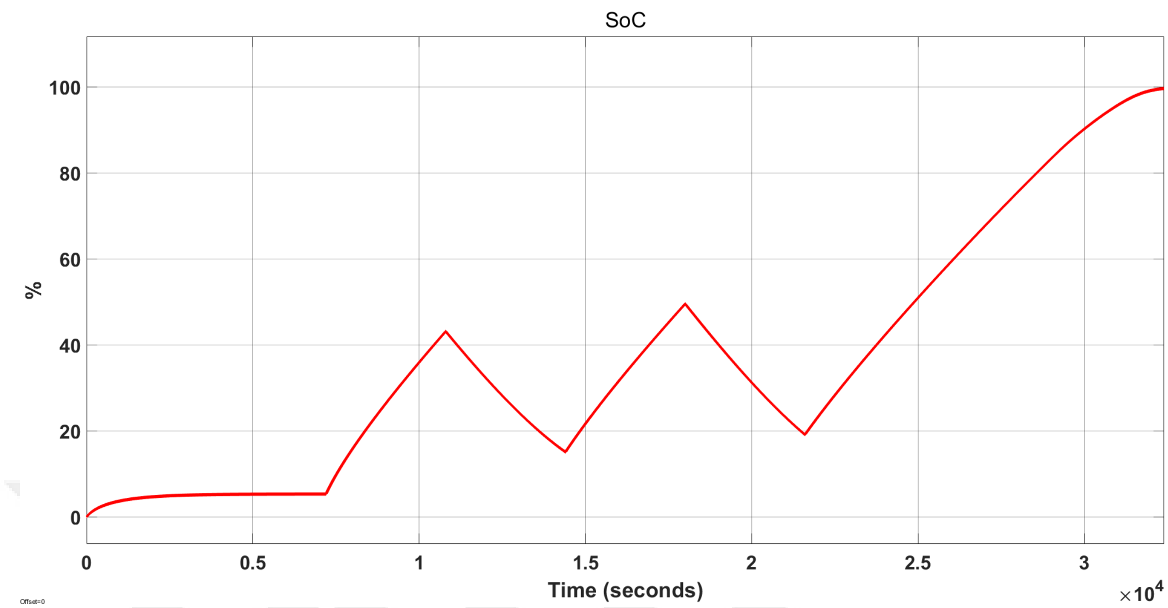

Figure 25: State of charge for bidirectional charging scenario starting from 0% SoC

infrastructure. This bidirectional flow enables the system to optimize charging costs. The overshoots observed at the transition points, where the current briefly reaches -100 A, could be a point of concern. These sudden changes might stress the battery or the charging infrastructure, potentially leading to reduced efficiency, premature wear, or other issues. Further investigation and optimization of the control strategies for bidirectional charging might be necessary to address these overshoots. The decreasing current as the battery approaches its charging limit highlights the importance of robust application software in bidirectional charging. By carefully controlling the charging and discharging current, the application software can help ensure that the bidirectional charging process is safe and efficient and preserves the battery's longevity. The zero current observed when the battery is fully charged demonstrates the essential role of the application software in preventing overcharging. This is particularly important in bidirectional charging systems, where the battery may be subject to more frequent and complex charging and discharging cycles than in unidirectional charging systems.

Figure 30 shows that, based on the current limit and the battery's state of charge,

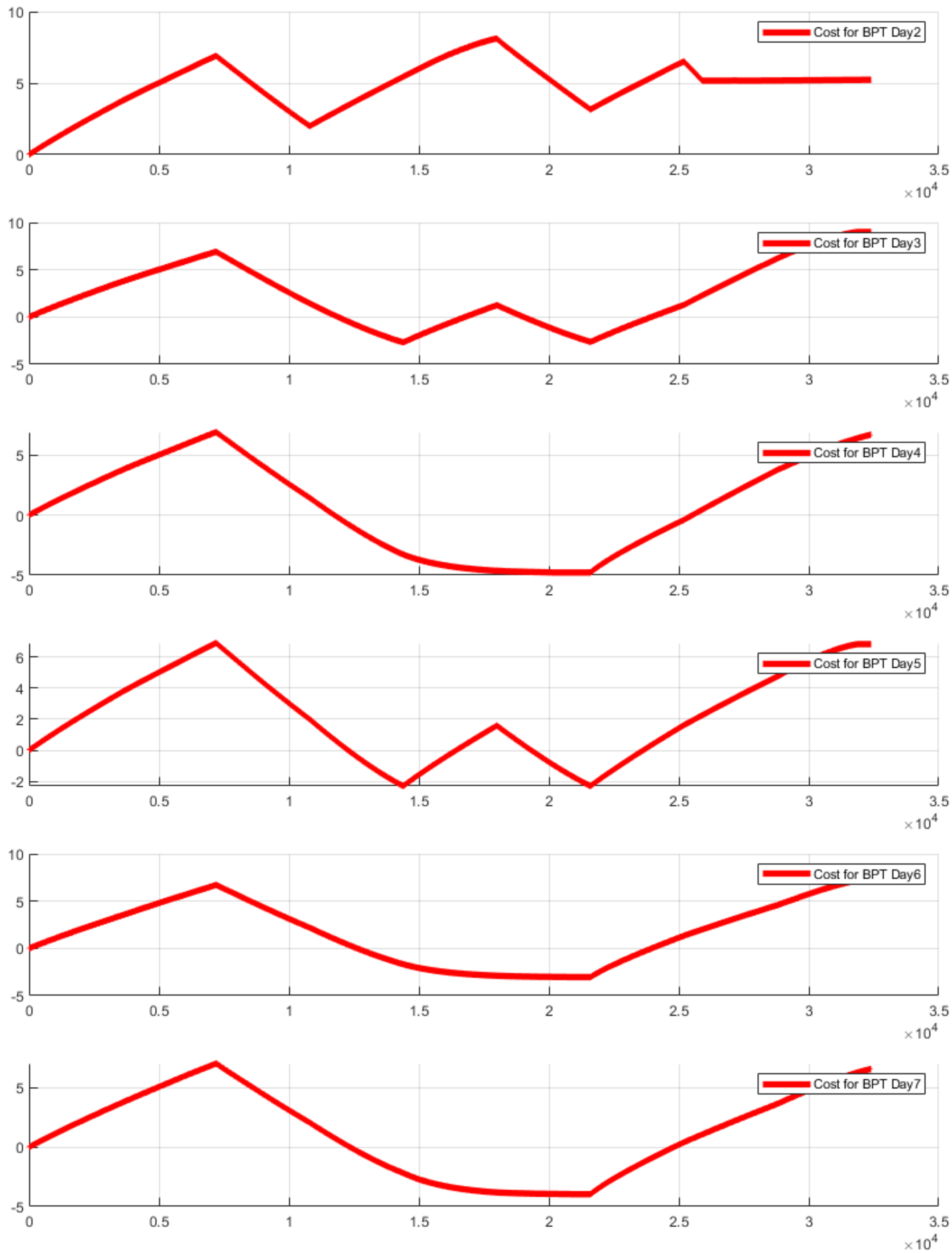

Figure 26: Charging costs for bidirectional charging scenario starting from 20% SoC Weekly

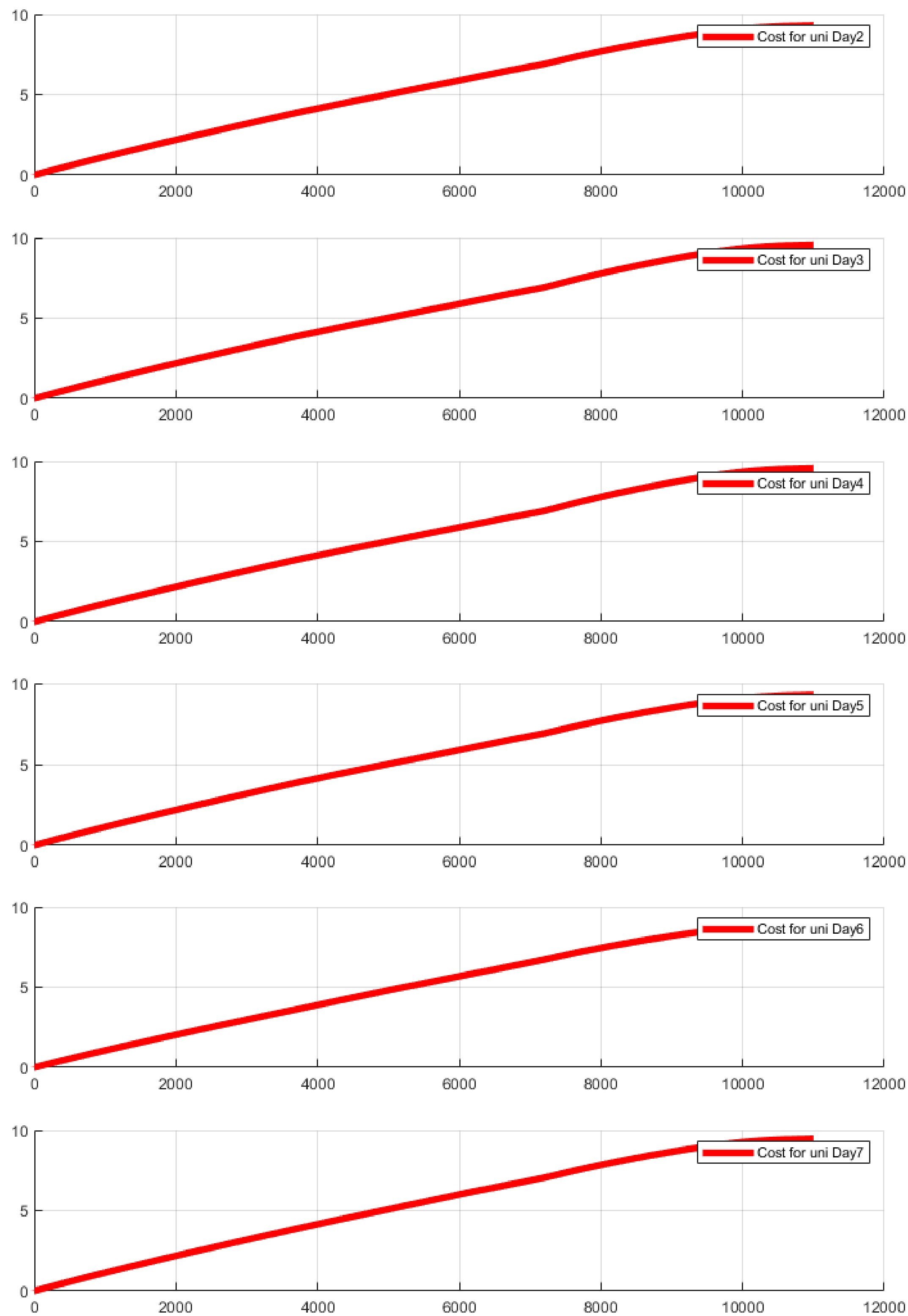

Figure 27: Charging costs for unidirectional charging scenario starting from 20% SoC Weekly

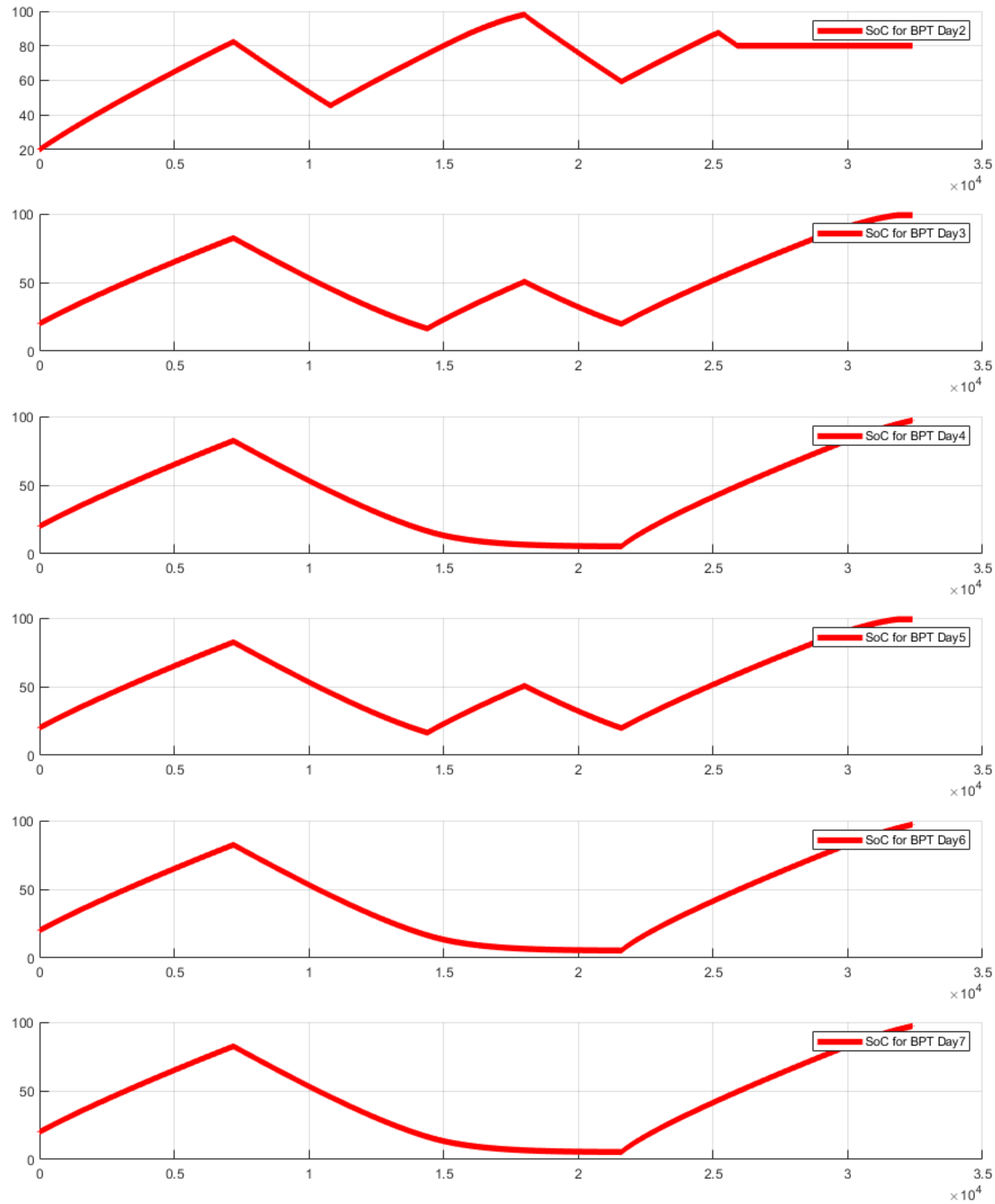

Figure 28: SOCs for bidirectional charging scenario starting from 20% SoC Weekly

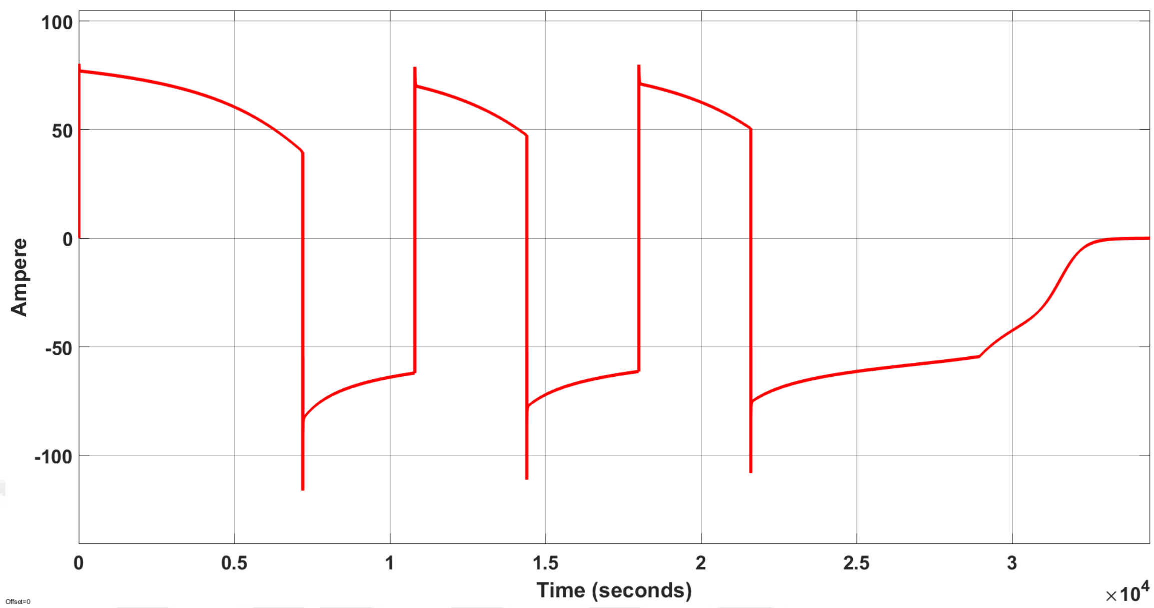

Figure 29: Current flow for bidirectional charging scenario starting from 80% SoC

it decreases as time passes. When the battery is fully loaded, the current becomes zero. Opposite of bidirectional charging, it is much faster because it is only one direction hence only charging the battery.

Figure 31 shows that the application software effectively manages the bidirectional charging process, controlling the power flow between the electric vehicle's battery and the charging infrastructure.

Figure 32 shows that the application software effectively manages the unidirectional charging process, controlling the power flow between the electric vehicle's battery and the charging infrastructure. As the vehicle battery approaches a total state of charge, the current goes to zero, as shown in Figure 30.

Figure 33 shows that the application software highlights the complex nature of the bidirectional charging process, with several voltage fluctuations during charging and discharging cycles. It also emphasizes the role of the electric vehicle charging controller and application software in managing the charging process, particularly when the battery is approaching its fully charged state. Further analysis of the control strategies and system components could help optimize the bidirectional charging

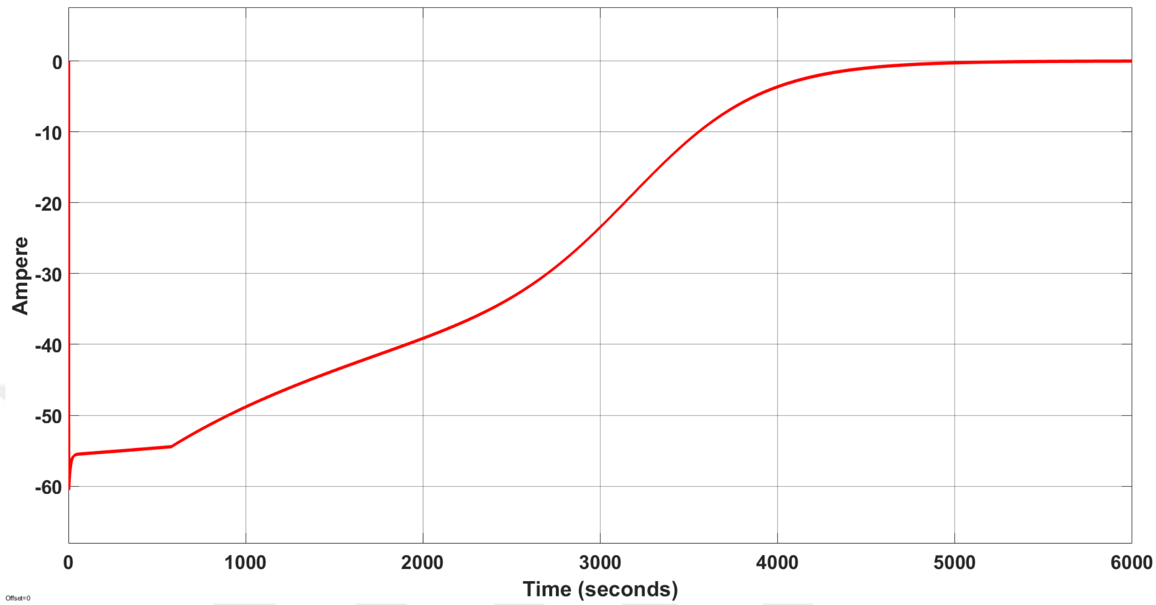

Figure 30: Current flow for unidirectional charging scenario starting from 80% SoC

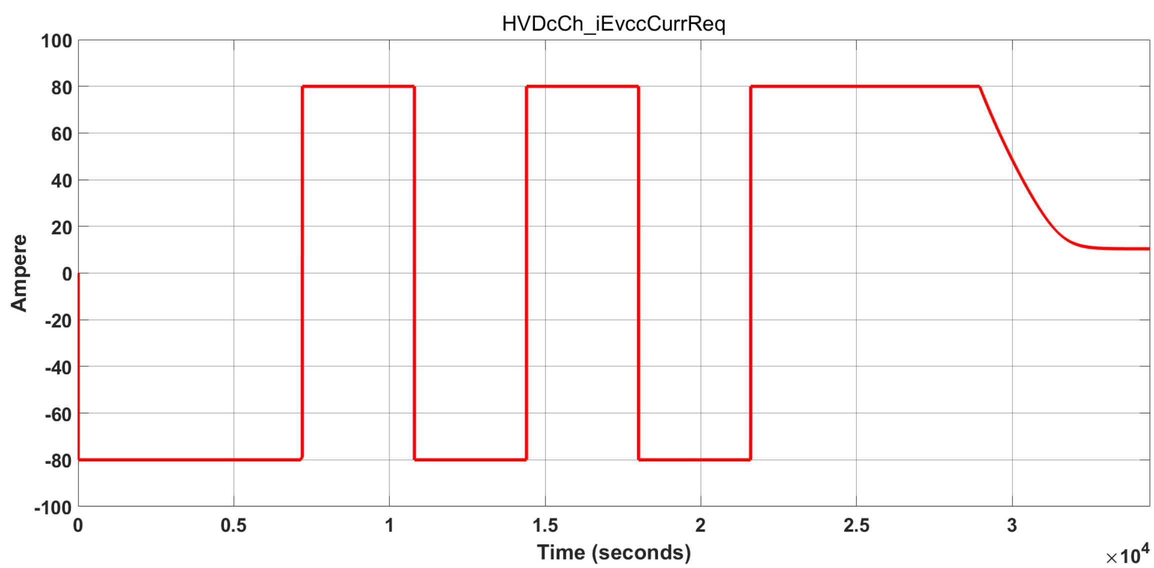

Figure 31: Current request from application software for bidirectional charging scenario starting from 80% SoC

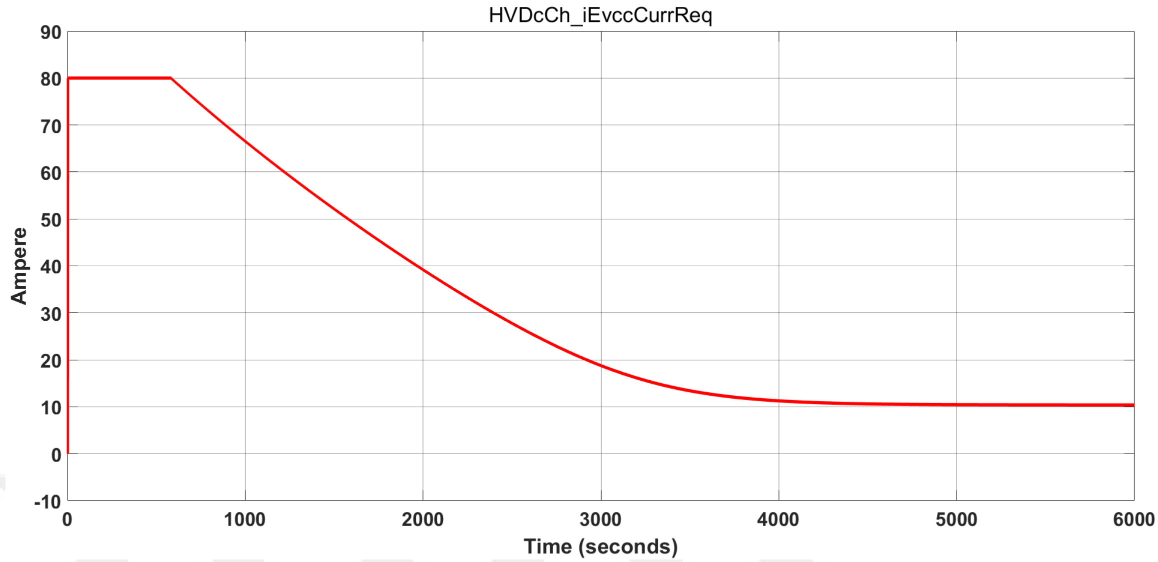

Figure 32: Current request from application software for unidirectional charging scenario starting from 80% SoC

process and improve its efficiency and safety.

Opposite to bidirectional charging, fluctuations are not seen in unidirectional charging. Hence voltage increases until the battery is full. Figure 34 shows that voltage increase is slower when the battery charging is close to complete.

4.3 Results and Analysis

As a result of utilizing unidirectional charging, the charging process demonstrates different characteristics compared to bidirectional charging. In this instance, when the electric vehicle's battery has an initial state of charge (SoC) of 80%, it takes approximately 70 minutes to reach a fully charged state (100% SoC). The cost to charge the vehicle during this period, determined by the hourly rate, is outlined in the accompanying Table 3.

This table presents a comprehensive breakdown of the charging costs for each interval of the 70-minute charging process. It considers various factors that impact the charging costs, such as the prevailing electricity prices, the charging rate, and the battery's state of charge. A deeper understanding of its financial implications

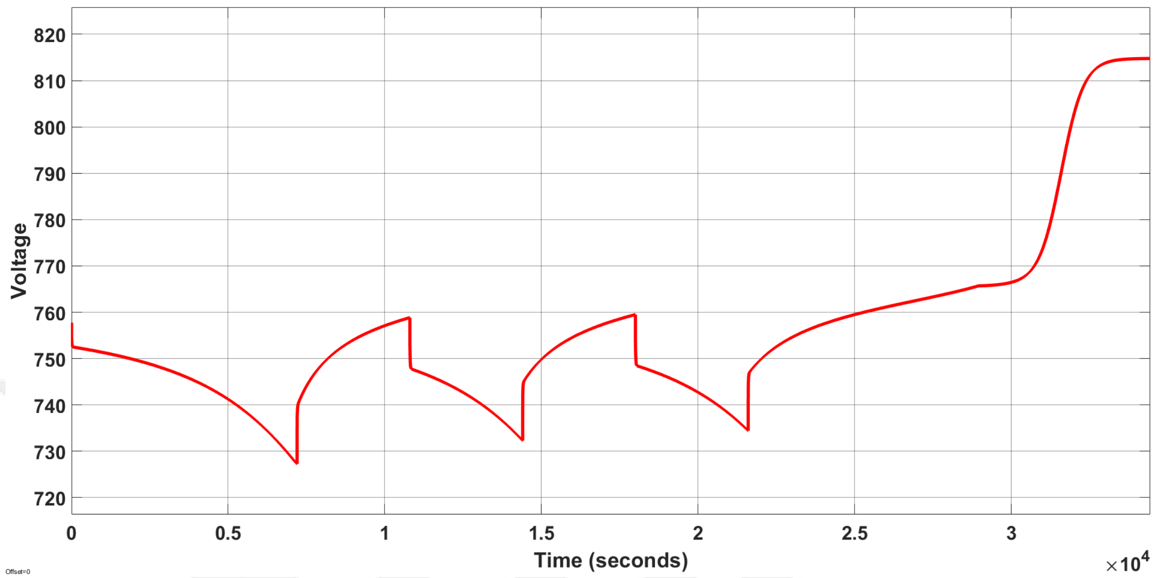

Figure 33: Battery voltage for bidirectional charging scenario starting from 80% SoC

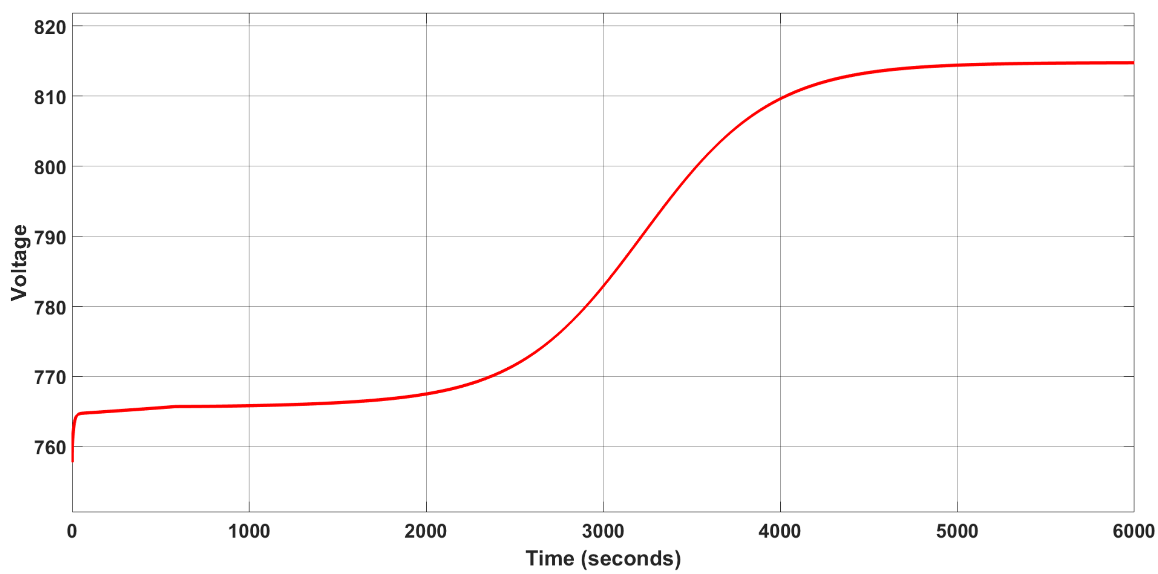

Figure 34: Battery voltage for unidirectional charging scenario starting from 80% SoC

for electric vehicle users can be gained by analyzing charging costs for unidirectional charging.

Table 3: Cost per unidirectional charging of electricity starting from 80% SoC

Cost (€)	Time (minutes)
1	4.71
2	9.47
3	14.43
4	19.88
5	25.58
6	31.82
7	38.65
8	46.65
9.1	75

Due to implementing bidirectional charging, the electric vehicle's cost is significantly influenced by the duration the vehicle remains connected to the charging infrastructure. Based on user preferences, a scenario is considered where the vehicle remains connected to the charging station for 9 hours. In this context, the cost of charging the vehicle, as determined by the hourly rate, is presented in the following Table 4.

The table provides a detailed breakdown of the costs associated with bidirectional charging for each hour of the 9 hours. It considers the various factors that impact charging costs, such as fluctuations in electricity prices and the battery's state of charge.

For unidirectional charging, different starting points in Table 5 show charging costs for each case.

Different starting points in Table 6 show charging costs for each case for bidirectional charging.

Based on the obtained results, savings in percentage starting SoC from 80%, 50%, 20%, and 0% (no charge), can be found using the following formula:

Table 4: Cost per bidirectional charging of electricity starting from 80% SoC

Cost (€)	**Time (hours)**
-16.50	1
-26.91	2
-21.77	3
-34.97	4
-30.66	5
-44.33	6
-39.65	7
-33.40	8
-29.08	9

Table 5: Cost per unidirectional charging of electricity for different SoC levels

Total Cost (€)	**Starting SoC (%)**
9.1	80
21.19	50
28.88	20
35.13	0

$$\text{Percentage Savings} = \frac{\text{Savings}}{\text{Unidirectional charging cost}} \cdot 100 \tag{2}$$

$$\text{Savings for 80\% SoC} = (\frac{39.18}{9.1}) \cdot 100 = 388\%$$

$$\text{Savings for 50\% SoC} = (\frac{39.4}{21.19}) \cdot 100 = 185\%$$

$$\text{Savings for 20\% SoC} = (\frac{33.83}{28.88}) \cdot 100 = 117\%$$

$$\text{Savings for 0\% SoC} = (\frac{32.74}{35.13}) \cdot 100 = 93\%$$

Consequently, bidirectional charging leads to approximately 388% savings in charging costs compared to the unidirectional method when the vehicle has initial SoC of 80%. This demonstrates the significant cost advantages of adopting bidirectional charging systems for electric vehicles.

Table 6: Cost per bidirectional charging of electricity for different SoC levels

Total Cost (€)	**Starting SoC (%)**
-29.08	80
-18.21	50
-5.03	20
2.39	0

Further analyzing the weekly results showed more data related to savings as shown in Table 7 and Table 8.

Table 7: Cost per bidirectional charging of electricity for different days

Days	**Total Cost (€)**	**Starting SoC (%)**
1	-5.03	20
2	5.23	20
3	8.99	20
4	6.70	20
5	6.83	20
6	7.52	20
7	6.59	20

Table 8: Cost per unidirectional charging of electricity for different days

Days	**Total Cost (€)**	**Starting SoC (%)**
1	28.88	20
2	9.29	20
3	9.56	20
4	9.56	20
5	9.29	20
6	8.91	20
7	9.46	20

By separating unidirectional charging expenses and bidirectional charging expenses and calculating the average savings for a week, the savings can be easily calculated utilizing the previous formula and weekly results. The following equation can be used for this purpose:

$$\text{Weekly Savings for 20\% SoC} = \left(\frac{48.12}{84.95}\right) \cdot 100 = 56\% \tag{3}$$

The simulation results demonstrate that bidirectional charging leads to significant cost savings compared to unidirectional charging under various scenarios, as reported in previous studies [14,15]. Figure 35 shows that the cost savings can be attributed to the effective utilization of lower electricity prices during off-peak hours and the ability to sell excess energy back to the grid during peak hours. Furthermore, Analyzing the provided graphs offers valuable insights into the bidirectional charging process, its control strategies, and the significance of well-designed functions in the application software. The charts reveal that the application software effectively manages the power flow between the electric vehicle's battery and the electric vehicle charging controller, preventing overcharging and ensuring battery longevity.

However, overshoots at transition points in the current request graph indicate potential areas for further investigation and optimization to improve the system's performance, safety, and efficiency. Additionally, the voltage fluctuations in the voltage graph emphasize the complex nature of bidirectional charging, which involves alternating charging and discharging cycles.

Furthermore, each battery for electric vehicles has approximately 2000 cycles of charging count. The average kWh for battery pack price is 140€ [37]. Approximate battery prices for electric vehicles can be calculated as follows:

$$Price = €140 \cdot \text{kWh} \tag{4}$$

Kilowatt-hours (kWh) measure a battery's energy storage capacity. A kilowatt (kW) is a unit that measures electric energy consumption, and a kilowatt-hour is the energy a 1-kW device consumes in an hour. To calculate a battery's kWh, the following formula can be used:

$$kWh = \frac{Ah \cdot Voltage}{1000} \tag{5}$$

Since the 140 kWh battery used in the test model, it would cost €19,600. Based on the cycle count being 2000, each cycle for battery cost is €9.8. A week-long bidirectional charging testing consumed approximately 7 cycles from the battery's life. Table 9 shows the total cost with included battery degradation. However, battery degradation could be analyzed more extensively for future studies to achieve better results.

Table 9: Cost per bidirectional charging of electricity for different days with battery degradation

Days	**Total Cost (€)**	**Starting SoC (%)**	**Cost with Degradation (€)**
1	-5.03	20	4.77
2	5.23	20	15.03
3	8.99	20	18.79
4	6.70	20	16.5
5	6.83	20	16.63
6	7.52	20	17.32
7	6.59	20	16.39

In conclusion, the graph analysis highlights the critical role of application software's control strategies and robust functions in the bidirectional charging process. Further exploration and optimization of these components can enhance the efficiency and safety of the system.

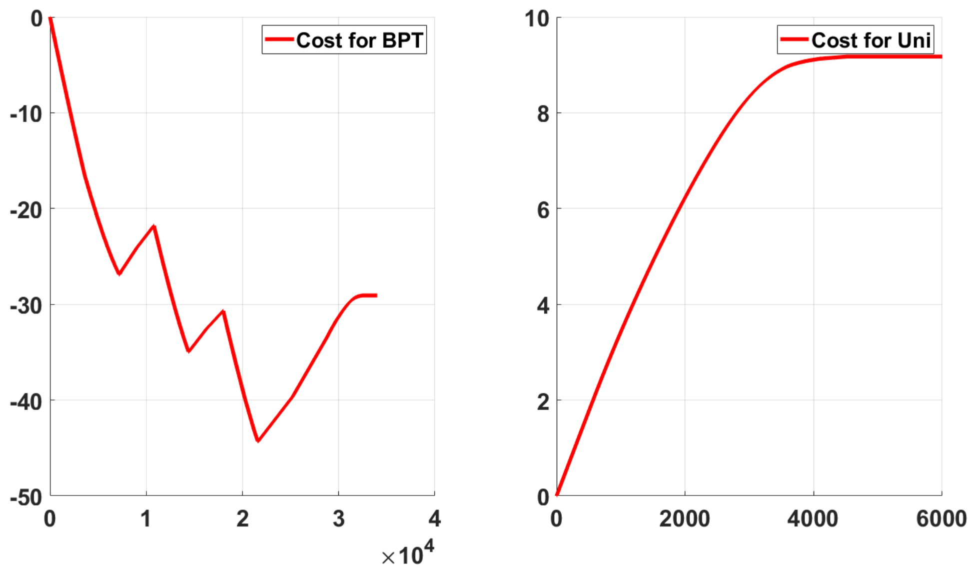

Figure 35: Side by side cost comparison starting from 80% SoC

CHAPTER V

DISCUSSION

5.1 Key Findings from the Study

Our study focused on the potential benefits of bidirectional charging for electric vehicles (EVs), specifically on reducing charging costs. By creating a simulation model using Simulink and Simscape, it can be analyzed the behavior of bidirectional charging under various conditions [14]. Our model incorporated an electric vehicle charging controller (EVCC), a battery, a grid, and application software. By calculating the price per hour for charging, it is determined the potential benefits of bidirectional charging [23]. Utilizing bidirectional charging, it is observed that within specific electricity price ranges, the profitability is significantly increased by 388%. This demonstrates the considerable potential for cost savings and enhanced efficiency that can be achieved when employing bidirectional charging compared to traditional unidirectional charging methods.

Despite the existence of two modes, this study focused on evaluating the performance of the scheduled mode in bidirectional charging while exploring its implications for cost optimization [20].

5.2 Implications of the Results for EV Users, Charging Infrastructure Providers, and Policymakers

The results of our study have important implications for various stakeholders involved in the EV ecosystem. For EV users, bidirectional charging can substantially save electricity costs, making EV ownership more attractive and economically viable [12]. Additionally, the ability to provide grid support through bidirectional charging can also create new revenue streams for EV owners [27].

Charging infrastructure providers can benefit from the increased demand for bidirectional charging equipment and services [24]. Developing and deploying advanced charging infrastructure, including intelligent charging stations and communication systems, will be crucial to successfully implementing bidirectional charging [23].

For policymakers, our findings highlight the potential of bidirectional charging in supporting grid stability and renewable energy integration [12]. By promoting the adoption of bidirectional charging technologies and establishing supportive market and regulatory frameworks, policymakers can further drive the transition towards sustainable transportation and energy systems [22].

5.3 Comparison with Existing Literature and Potential Contributions

Our study builds upon the existing literature on bidirectional charging by providing a comprehensive analysis of its potential benefits in terms of cost reduction [25]. While previous studies have explored the technical aspects of bidirectional charging, such as control strategies and grid integration, our research focuses on the practical implications of this technology for EV users, charging infrastructure providers, and policymakers [14, 27].

Compared to existing literature, our study employs a detailed simulation model to evaluate the performance of bidirectional charging under various conditions [13]. The understanding of bidirectional charging technology involves analyzing both scheduled and dynamic modes. This approach provides insights into the various factors that can impact the potential benefits of this technology. [25].

Overall, our research provides valuable insights into the practical implications of bidirectional charging and offers guidance for EV ecosystem stakeholders to maximize this technology's benefits [22].

5.4 Challenges for Bidirectional Charging

Implementing bidirectional power transfer (BPT) in electric vehicles (EVs) presents several challenges that must be addressed. Some of the main challenges are as follows:

1. **Technical challenges:** Developing efficient and reliable power electronics and control systems is crucial for managing power flow between EVs and the grid [12]. This can increase the complexity and cost of charging infrastructure and EV powertrains.

2. **Battery degradation:** Repeated bidirectional charging and discharging cycles may accelerate battery degradation, reducing the overall lifetime of the EV battery [21]. Further research is required to develop strategies to mitigate battery degradation during BPT.

3. **Standardization and compatibility:** The lack of standardization and compatibility among different EV models, charging infrastructure, and grid systems may hinder the widespread adoption of BPT in the EV market [20].

4. **Regulatory and market barriers:** Existing regulatory frameworks and market structures may not be well-suited to accommodate BPT, as they often do not account for EVs providing grid services [38]. Policymakers and regulators must develop new policies and market mechanisms to support BPT integration.

5.5 Future Research Directions

While this study has provided valuable insights into the benefits of bidirectional charging in reducing charging costs, there are several areas where future research can further expand our understanding of this technology and its implications. Some potential future research directions include:

- Investigating the impact of different battery technologies on the performance and cost-effectiveness of bidirectional charging, as advancements in battery technology may significantly influence the benefits of bidirectional charging [9, 39].

- Integrating renewable energy sources, such as solar and wind power, with bidirectional charging systems to create more sustainable and resilient energy systems [12, 40].

- Developing advanced control strategies and algorithms for bidirectional charging to optimize grid stability, power quality, and user convenience, considering factors such as demand response, time-of-use pricing, and peak shaving [41, 42].

- Evaluating the long-term impact of bidirectional charging on battery degradation and life cycle, as the increased cycling due to bidirectional charging may affect battery performance and lifespan [21, 34].

- Assessing the scalability and feasibility of large-scale implementation of bidirectional charging, considering factors such as grid capacity, market structures, and regulatory frameworks [35, 36].

- It would be interesting to investigate the impact of feed-in tariffs on the widespread adoption of V2G systems. Feed-in tariffs are financial incentives that encourage the production of renewable energy and the use of V2G systems by compensating EV owners for the electricity they provide to the grid [43]. Future research could explore how different feed-in tariff structures and rates affect the profitability of V2G systems for EV owners and the deployment of V2G infrastructure.

- The development of deep learning-based models for battery management could be a promising approach to predicting the SoC and SoH of lithium-ion batteries [44]. Future research could explore the performance of different learning techniques, such as neural networks, for battery state prediction. In addition, transfer learning, which involves training a deep learning model on a large data set and fine-tuning it on a smaller data set, could be investigated to improve the accuracy of battery state prediction for specific EV models and usage patterns.

- Future work could also optimize the charge schedule within a fleet of EVs equipped with bidirectional charging capabilities. This would require the use of optimization algorithms to minimize charging costs and ensure grid stability [45]. In addition, the impact of uncertainties, such as EV arrival and departure times and electricity prices, on the charging and discharging schedule could be investigated.

- The development of standardized communication protocols for V2G systems is essential to ensure interoperability and enable seamless integration with the power grid. The Combined Charging System (CCS) and ISO/IEC 15118-2:2019 are examples of such protocols [46, 47]. Future research could focus on optimizing and improving existing V2G communication protocols to ensure their reliability, security, and scalability.

CHAPTER VI

CONCLUSIONS

This thesis investigates the potential benefits of bidirectional charging in electric vehicles (EVs), focusing on reducing charging costs. Bidirectional charging allows EVs to draw power from the grid for charging and send power back to the grid when needed. This research explores the effectiveness of bidirectional charging in reducing charging costs, which can significantly impact EV adoption and integrate renewable energy into the grid.

This study explored the potential benefits of bidirectional charging in electric vehicles (EVs). The research began by examining the current landscape of EVs and the importance of bidirectional charging technology. A thorough literature review highlighted a gap in understanding the practical implications of this technology, leading to the development of a detailed simulation model using MATLAB's Simulink and Simscape tools. The model, which included components like an electric vehicle charging controller (EVCC), a battery, and a grid, was used to evaluate the possibility of reducing charging costs through bidirectional charging. The results indicated that bidirectional charging could offer significant savings compared to unidirectional charging. The implications of these findings were then discussed from various perspectives, including those of EV users, charging infrastructure providers, and policymakers. The potential of bidirectional charging to reduce charging costs was emphasized, and the study concluded by identifying areas for future research, such as the impact of feed-in tariffs, the use of deep learning for battery management, and the need for standardization of V2G communication protocols. This research provides a good starting point for future exploration into the potential of bidirectional charging to improve the sustainability of electric vehicles.

- A comprehensive analysis of the potential benefits of bidirectional charging in terms of cost reduction is not extensively covered in the existing literature.
- A detailed simulation model using Simulink and Simscape to evaluate the performance of bidirectional charging under various conditions adds to the body of knowledge on bidirectional charging technology.
- Implementing and analyzing the scheduled mode of bidirectional charging contributes to a better understanding of the factors that influence the potential benefits of this technology.
- A thorough examination of the practical implications of bidirectional charging for different stakeholders, including EV users, charging infrastructure providers, and policymakers, guides maximizing the benefits of this technology.
- Comparing the results with existing literature and identifying potential contributions, thus extending the knowledge base on bidirectional charging and its benefits in reducing charging costs for EV users.

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