People's Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

University M'Hamed BOUGARA- Boumerdes

Institute of Electrical and Electronic Engineering

Department of Power and Control Engineering

Project Report Presented in Partial Fulfilment of

the Requirements of the Degree of

'MASTER'

In Electrical and Electronic engineering

Option: Power Engineering

Title:

DESIGN AND IMPLEMENTATION OF ELECTRIC VEHICLES BIDIRECTIONAL CHARGER

Presented By:

- **Anouar Cherif GHODBANE**
- **Youcef Islem MALKI**

Supervisor:

Prof. Aissa KHELDOUN

Co-supervisor:

Mr. Soufian KHETTAB

Registration number:....../2023

Author's Declaration of Originality

We hereby certify that we are the sole authors of this thesis. All materials used, references to the literature, and the work of others have been properly acknowledged and attributed. This thesis has not been submitted for examination or assessment in any other academic institution or context.

Authors :
Anouar Cherif Ghodbane
Youcef Islem Malki

06-07-2023

Dedication

I have a great pleasure to dedicate this modest work to my beloved parents and grand parents, my dear brothers, and sisters. All my family, all my friends. All my teachers from primary to this year.

Anouar Cherif Ghodbane

I dedicate this work to my beloved parents whose unwavering support and encouragement have been the driving force behind my academic journey, to my dear brothers, my sister and all family members.
This work is dedicated to all my teachers from primary until now, my dear colleagues and friends.
Finally I warmly dedicated this project to esteemed members of IEEE Student Branch University of Boumerdes members whom have been a second family during my time at the university.

Youcef Islem Malki

Acknowledgments

We acknowledge with gratitude the blessings and strength from Allah that have enabled us to successfully complete this thesis. We would like to extend our sincere appreciation to our supervisor, Professor Aissa Kheldoune, for his unwavering guidance and support throughout this project. His expertise and valuable advice have been instrumental in shaping our work at every stage of the writing process.

We would also like to express our special thanks to our co-supervisor, Mr. Sofiane Khettab, for his valuable assistance, insightful tips, and valuable remarks. His contributions have played a significant role in enhancing the quality and depth of our research.

The dedication and support of both our supervisor, Professor Aissa Kheldoune, and co-supervisor, Mr. Sofiane Khettab, have been invaluable in making this work possible. We are truly grateful for their involvement and encouragement throughout this journey.

Abstract

This project aims to enhance the design and implementation of a bidirectional electric vehicle (EV) charger, a vital component in modern energy systems. The bidirectional charger not only facilitates charging and discharging of energy to and from the grid or energy storage systems but also enables efficient energy management and utilization. Additionally, it can serve as a shunt active power filter, effectively mitigating harmonics generated during power conversion, thereby reducing total harmonic distortion (THD) and ensuring grid reliability.

To regulate the operation of this power electronic device, two control techniques were investigated: hysteresis current control (HCC) and model predictive control. Through comprehensive simulation studies, the results obtained from both techniques were presented and compared. Furthermore, real-time evaluations were conducted to validate the efficacy of the employed control techniques.

By improving the bidirectional EV charger's design and employing advanced control strategies, this project contributes to the development of more efficient and reliable energy systems while addressing power quality concerns through harmonic reduction.

List of Abbreviations and Terms

DC	Direct current
AC	alternating current
EV’s	Electric vehicles
PEV’s	plugged in electric vehicles
PHEV’s	plugged in hybrid electric vehicles
LSEVs	Low speed electric vehicles
ICEVs	Internal combustion engine vehicles
GHG	Green house gases
DER	Distributed energy resources
V2G	Vehicle to grid
G2V	Grid to vehicle
V2H	Vehicle to home
V4G	vehicle four grid (filtering)
PI	proportional integrator controller
SAPF	shunt active power filter
HCC	hysteresis current control
MPC	Model predictive control
PQ	Power quality
p-q	Instantaneous Active and Reactive Power
UPS	Uninterruptible Power Supply
VSI	voltage source inverter
CSI	current source inverter
THD	Total harmonics distortion
PWM	Pulse width modulation
CC-CV	constant current constant voltage
SOC	battery state of charge
SOH	battery state of health
BMS	battery management system
PSO	Particle swarm optimization
NEVS	Swedish automotive company

Table of Contents

List of Figures

List of Tables

General Introduction

The convergence of electric vehicles (EVs) and smart grid technologies has revolutionized the way we think about transportation and energy management. The integration of EVs with the power grid has the potential to address the challenges associated with power system quality and pave the way for a more sustainable and efficient energy future. this project deals with the design and implementation of EVs bidirectional charger which enable a more dynamic and efficient energy ecosystem by maximizing the utilization of renewable energy, supporting grid stability, and empowering EVs to actively participate in the energy system.

The architecture of the bidirectional charger is based on advanced power electronic converters and control algorithms. It typically consists of a power conversion stage, which includes AC/DC and DC/DC converters, along with a sophisticated control system in our work we have demonstrated two control methods technique: Hysteresis current control and predictive control to get the optimal control technique that leads to the best results. The AC/DC converter facilitates the charging of the battery or energy storage system from the grid, while the DC/DC converter enables power flow in the reverse direction for discharging energy back to the grid.
The bidirectional charger operates in different modes to meet the varying energy requirements. The primary operation modes include Vehicle-to-Grid (V2G), Grid-to-Vehicle (G2V), vehicle-to-home (V2H) and power filtering (V4G) [1]. In V2G mode, the bidirectional charger enables the electric vehicle (EV) to feed energy back to the grid during peak demand periods, supporting grid stability and power quality. In G2V mode, the charger supplies power from the grid to charge the EV battery.In (V2H) mode,power is supplied from the battery to the load during a grid power outage. The energy filtering mode involves compensating for harmonics and reactive power to ensure a clean and efficient energy exchange between the charger and the grid. the report start by a literature review where we explore the fundamental aspects of smart grids in the power system, focusing on the challenges of power system quality and the mitigation of electric harmonics.the integration of EVs in smart grids is examined, including the different operation modes and the significance of charging infrastructure with brief study about battery technology. Next we delve into the control strategies and algorithms employed in the design of EVs' bidirectional chargers. It begins by providing an understanding of power electronics, including AC to DC inverters and DC to DC converters. Algorithms and control techniques such

as Proportional Integral Controller (PI), Hysteresis Current Control (HCC), and Model Predictive Control (MPC) and PQ theory reference extraction method are examined in detail. Additionally, the design of charging infrastructure is addressed to ensure seamless integration and operation of EVs in the smart grid ecosystem than those control strategies were examined by presenting the simulation and the hardware implementation results of the control strategies where we compare the outcomes of Hysteresis Current Control and Model Predictive Control techniques in terms of grid voltage, grid current, DC link voltage, inverter current, load current,THD and power flow. The discussion and comparison of these results provide valuable insights into the practical application and performance of the control strategies in simulation and in real-world scenarios.

In conclusion, this research encompasses a comprehensive study of electric vehicles chargers to improve power quality problems and ensure grid stability,the project can contribute to the ongoing development and advancement of bidirectional chargers, Charting the course for their widespread adoption and integration into the evolving electric vehicle and smart grid ecosystem.

literature review

1. Exploring Electric Vehicles and Smart Grid Integration

Air pollution, specifically the emission of carbon dioxide and greenhouse gases (GHGs), has been significantly exacerbated by the increased utilization of oil and gas in the transportation sector to meet the growing demand. In response to this challenge, the adoption and introduction of Electric Vehicles (EVs) and Plug-in Hybrid Electric Vehicles (PHEVs) have been pursued as viable solutions [2]. Notably, EVs exhibit enhanced efficiency and reduced maintenance requirements compared to conventional vehicles powered by internal combustion engines. Consequently, they are regarded as more sustainable and environmentally friendly alternatives. Nonetheless, the widespread implementation of EVs necessitates careful consideration of their potential impact on electrical power systems. To mitigate this impact, the development of advanced power electronics technologies for EV battery charging systems assumes crucial significance. These innovative technologies hold the potential to integrate EVs as valuable assets within future smart grids, thereby fostering a more efficient and sustainable energy ecosystem. It is important to acknowledge that EVs themselves are becoming increasingly power- intensive and are now equipped with larger battery capacities. Consequently, there is a growing demand for the installation of high-power, fast DC battery chargers. For instance, notable automaker Tesla has achieved remarkable power delivery rates of up to 250kW with the introduction of their third version of superchargers. However, it is imperative to recognize that high peak power delivery is not the sole desirable feature in battery chargers. Manufacturers and researchers are also focusing their efforts on the development of chargers with bidirectional power flow capabilities. These chargers enable the utilization of EV batteries as storage devices and facilitate the efficient utilization of excess battery power by feeding it back into the grid [3]. Moreover, meticulous attention must be paid to ensuring optimal power quality at the point of interconnection with the grid, particularly considering that charging stations typically house multiple high-power chargers that operate on the same grid connection. This consideration assumes even greater importance in the context of bidirectional chargers this literature will explore power systems challenges such as harmonics and how EV's play a crucial solution in increasing power quality and ensure grid stability.

1.1 Smart grid in power system

A smart grid is an advanced electricity network that uses digital communication and control technology to monitor and manage the flow of electricity from power plants to consumers, with the goal of optimizing energy efficiency, reliability, and sustainability [4]. Unlike traditional power grids, which rely on a one-way flow of electricity from power plants to consumers, smart grids incorporate two-way communication and real-time monitoring to enable a more dynamic and responsive system. This allows for better integration of renewable energy sources, more effective demand response management, and improved grid stability and resilience. Smart grids also enable the use of new technologies, such as electric vehicles and energy storage systems, as distributed energy resources that can both consume and supply power back to the grid. Overall, smart grids are designed to be more adaptive, efficient, and sustainable than traditional power grids, helping to create a more reliable and affordable energy future.

1.1.1 Power system quality challenges

There are several factors that can affect the quality of power in a power system. One major factor is the presence of harmonics, which are distortions of the fundamental frequency of the electrical signal. These harmonics can cause voltage fluctuations, increased power losses, and equipment overheating, all of which can lead to reduced power quality. Another factor is voltage sags and surges, which occur due to sudden changes in load or faults in the system. These events can cause equipment failure and downtime, leading to reduced system reliability [5]. Additionally, the use of renewable energy sources can also impact power system quality, as their variable output can create fluctuations in power supply that require careful management. Proper monitoring, control, and mitigation strategies can help to maintain high power system quality and prevent negative impacts on equipment and consumers.

1.2 Harmonics

Non-linear loads, such as electronic devices with power supplies that use switching circuits, can introduce harmonics into the power system. Harmonics are multiples of the fundamental frequency and can cause distortion in voltage and current wave-forms. This distortion has negative impacts on power quality and performance of electric grid due to the generated harmonics [6].

1.2.1 Effect of harmonics on smart grid

Harmonics have a lot of effect on smart grid [7] among those effects we can mention :

- Additional power losses: Harmonics can cause power losses that reduce the efficiency of the grid and lead to increased operating costs.
- Equipment overheating: The presence of harmonics can cause transformers, motors, and other electrical equipment to overheat, resulting in premature failure and downtime.
- Voltage fluctuations: Harmonics can also cause voltage fluctuations that affect the quality of power delivered to consumers and damage equipment.
- Interference with communication systems: Communication systems used in smart grids can be interfered with by harmonics, which can impact the reliability of data transmission and control signals.
- Reduced power factor: Harmonics can reduce the power factor of the system, leading to penalties and higher operating costs for utilities.

Smart grids can utilize advanced technologies, such as power electronics to actively monitor and control the flow of power and reduce the negative effects of harmonics, among those technologies the integration of EV's in smart grid. By reducing harmonic distortion, the stability and reliability of the grid can be maintained.

1.2.2 Current and voltage harmonics

The terms "current harmonics" and "voltage harmonics" are frequently interchanged, and in many cases, only "harmonics" is mentioned without specifying whether it pertains to current or voltage. To distinguish between the two, it is necessary to consider their respective origins. Harmonics always originate as current harmonics and voltage harmonics are the results of current harmonics.

1.2.3 Origins of current and voltage harmonics

Current harmonics originate because of the presence of non-linear loads like variable speed drives, inverters, UPS,television sets, PCs, semiconductors circuits, welding sets, arc furnaces in the system. They act as harmonic current sources.The resulting current waveform can be quite complex depending on the type of load and its interaction with other components of the system. Non-linear loads do not produce voltage harmonics directly; rather, current harmonics (in the form of distorted wave-forms) pass through the system's impedance (including source and line impedance), resulting in a harmonic voltage drop across the impedance. As a consequence, the supply voltage waveform becomes distorted, generating voltage harmonics. Factors such as long cable runs and high impedance transformers can increase the source impedance, resulting in higher voltage harmonics.

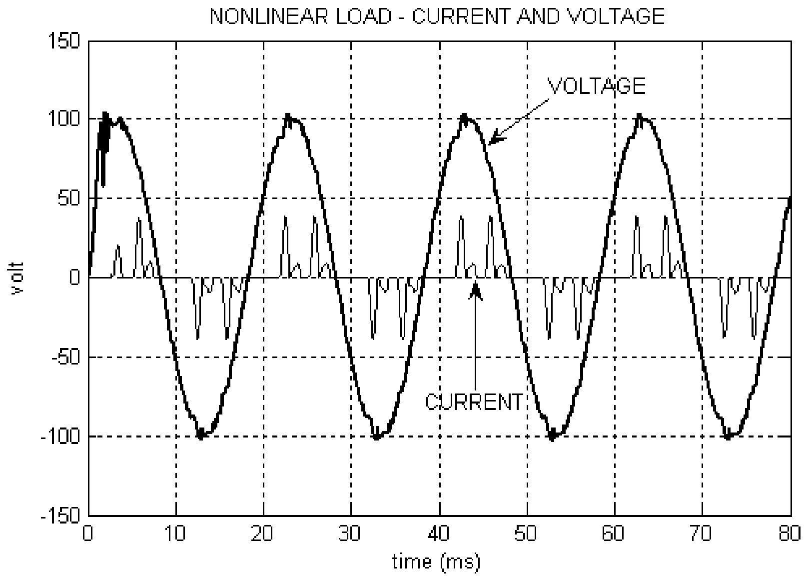

Figure 1. Voltage and currents of non linear loads

1.2.4 Understanding Total harmonic distortion (THD)

The overall level of current and voltage harmonics in a system is commonly represented by the metric of Total Harmonic Distortion (THD). THD measures the extent of harmonic distortion present and is expressed as the ratio of all harmonic components to the fundamental component. The formula for calculating THD is as follows:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_{n\_rms}^2}}{V_{fund\_rms}} \tag{1.1}$$

1.2.5 Mitigation of electric harmonics

Power harmonics filters are series or parallel resonant circuits designed to either block harmonic currents from flowing through electrical power distribution systems or locally isolate and cancel them [8]. Specifically, harmonic filters are designed to have low impedance to ensure that the harmonic currents are flowing between the loads and the filters, rather than reaching the power source and the other components of the electrical power generation and distribution systems. There are three main classifications of filters: (1) passive, (2) active, and (3) hybrid filters:

1.**Passive filters** are made up of reactive components like capacitors, inducators, and resistors. They are tuned to provide a low impedance path for specific currents with undesirable harmonic frequencies. Some potential issues can occur with passive systems if not properly selected resulting in resonance circuits parallel with power source leading to worse power quality conditions. (see figure 2)

2.**Active filters** rely on active power conditioning electronic devices to compensate for unfavorable harmonic currents. Specifically, active filters correct for the distorted sinusoidal current waves to effectively eliminate harmonics. Active filters have the advantage to respond to dynamic changes in the electrical distribution systems. Therefore, active filters can be considered for more complicated and critical systems because they have a better capability to act in response to drastic disturbances. They are, however, more expensive to install than passive filters. (see figure 3)

3.**Hybrid filters** are combinations of active and passive filters. They are used in specific applications to take advantage of the benefits of both filters.

1.3 Shunt Active Power Filters (SAPF)

Shunt active filters are power electronic devices utilized to mitigate power quality issues and enhance the performance of electrical systems. These filters are connected in parallel (shunt) with the load or power source and actively inject compensating currents to reduce or eliminate undesirable harmonics, reactive power, and other power quality problems.

The primary function of a shunt active filter is to monitor the electrical parameters of the system, such as current and voltage, and generate compensating currents to cancel out specific harmonic components or correct the power factor. It operates through continuous sensing of distorted or unbalanced currents or voltages and generating an appropriate compensation signal [9].

The operation of a shunt active filter involves several key components and control strategies:

Measurement and Sensing: The shunt active filter measures current or voltage signals using sensors or transducers. These measurements provide valuable information about power quality issues and guide the compensation process.

Converter and Energy Storage: An integral part of the active filter is a power electronic converter, such as a voltage source inverter (VSI) or current source inverter (CSI), responsible for generating compensating currents. Energy storage elements, such as capacitors or batteries, are often incorporated to provide the necessary power during compensation.

Control System: The active filter's control system analyzes the measured signals, calculates the required compensating currents, and generates control signals for the power electronic converter. Various control strategies, including hysteresis control, proportional-integral (PI) control, or model predictive control (MPC), can be employed to achieve accurate compensation.

Compensation Generation: Based on the control signals, the power electronic converter generates compensating currents that are injected into the electrical system. These compensating currents help mitigate harmonics, correct the power factor, and balance the system.

Shunt active filters find wide applications in industrial and commercial sectors to improve power quality, reduce harmonic distortion, and enhance the efficiency of electrical systems. They are particularly beneficial in industries with nonlinear loads, such as variable speed drives, welding equipment, and computer data centers, where power quality issues can adversely affect the performance and reliability of sensitive equipment.

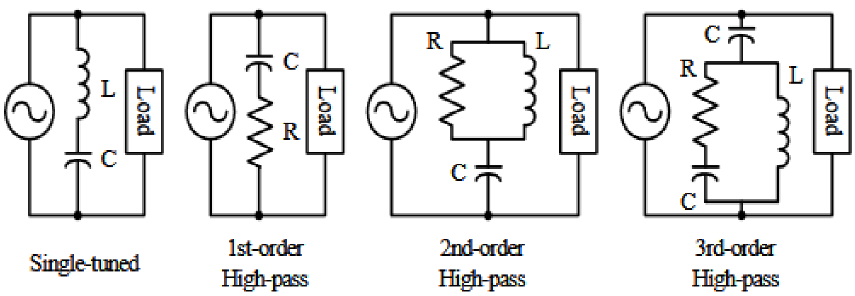

Figure 2. Passive filter types

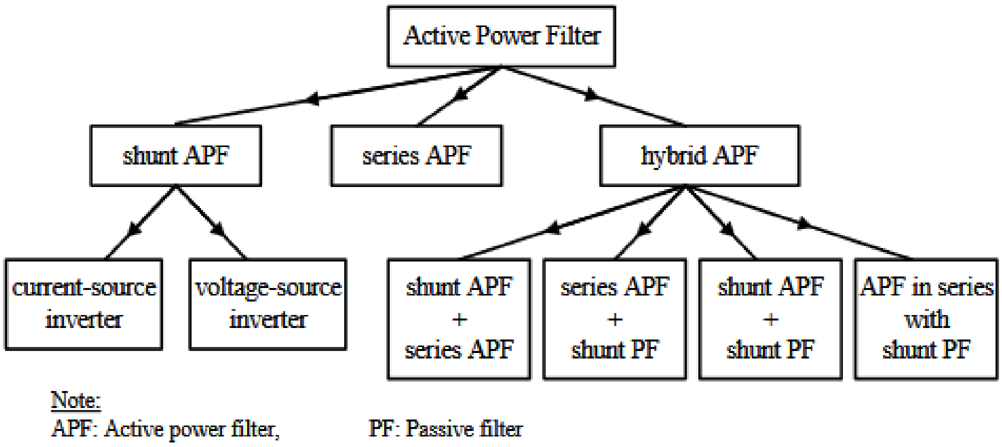

Figure 3. Active filter types

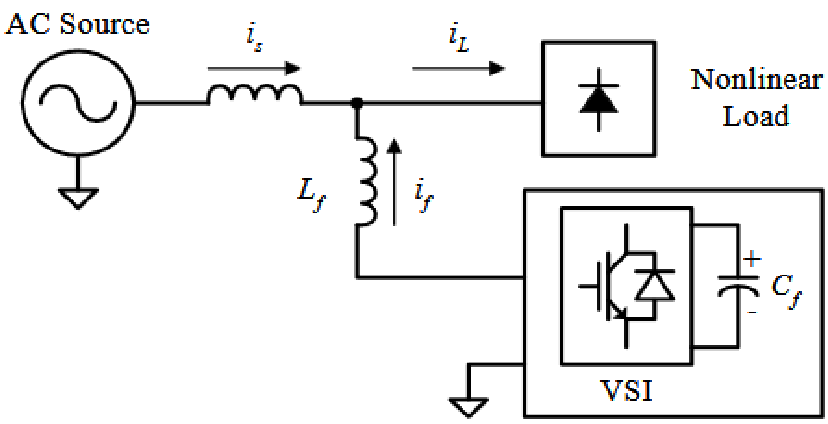

Figure 4. Shunt active filter circuit

1.4 Plugged-in electric vehicles (PEV's)

Plug-in electric vehicles, often abbreviated as PEVs, are a type of electric vehicle that can be charged from an external power source, typically through a plug-in connection. Unlike conventional hybrid vehicles, which rely on gasoline engines and regenerative braking to recharge their batteries, plug-in electric vehicles can be charged from a variety of sources, including standard household outlets, dedicated charging stations, and even solar panels [10]. There are two primary types of PEVs: battery electric vehicles (BEVs), which are powered solely by electricity and have no internal combustion engine, and plug-in hybrid electric vehicles (PHEVs), which combine an electric motor with a gasoline engine to extend their range. PEVs offer a more sustainable and eco-friendly alternative to traditional gasoline-powered vehicles, with the added benefit of being cheaper to operate and maintain over the long term.

1.4.1 Integration of Electric vehicles in smart grids

One of the main benefits of integrating EVs into smart grids is the potential to use them as a distributed energy resource (DER). A DER is a decentralized energy source that can both consume and supply electricity to the grid, such as rooftop solar panels or wind turbines. EVs can be used as a DER by allowing them to charge when electricity demand is low and supply power back to the grid when demand is high. This can help to reduce peak demand, improve grid stability, and increase the use of renewable energy sources.

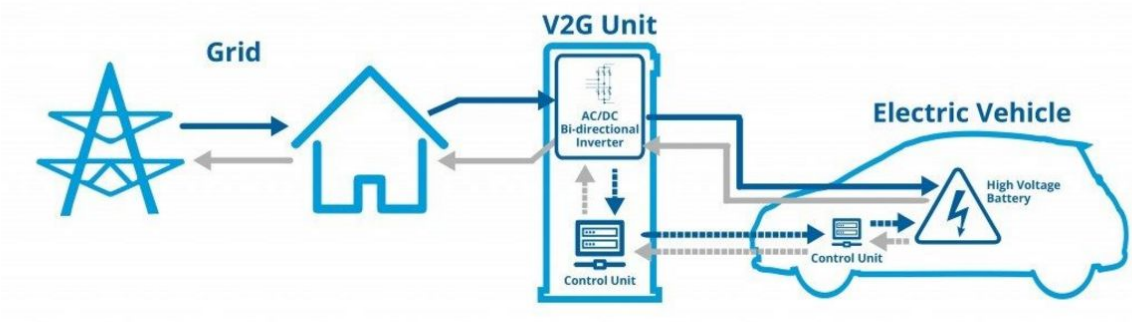

Figure 5. Electric vehicles to smart grid

1.4.2 EV's operation modes in smart grid

There has been increasing interest in the significant potential of electric vehicles (EVs) as highlighted in numerous studies . Typically, EV chargers function in either grid-to-vehicle (G2V) or vehicle-to-grid (V2G) mode, with the additional capability to operate in vehicle-to-home (V2H) mode. In V2H mode, the charger can act as a additional power source by feeding household loads to menimize grid consumption during high energy cost periods. [11].In addition to that EV batteries can be used as static VAR compensators to support the main grid; this is named the vehicle-for-grid (V4G) mode. The types of EV chargers can be classified based on the power flow direction as either unidirectional or bidirectional with on-board or off-board chargers [12] . The PQ coordinate system in Figure displays the complete control area for EV battery chargers. The directions of P and Q represent the power being transferred from the grid to the EVs. The PQ plane can be partitioned into eight operating modes based on the direction of active and reactive power transmission. Modes I-IV are defined by the xy axes of the PQ frame and represent pure G2V, inductive V4G, V2G, and capacitive V4G operations, respectively. The remaining four quadrants show the V2G or G2V operation combined with either the capacitive or inductive V4G operation.(fig 6).

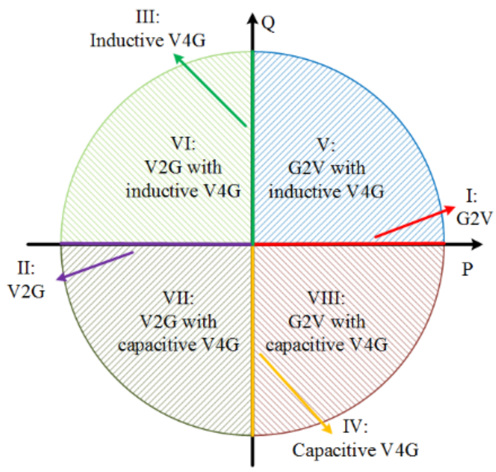

Figure 6. Four-Quadrant Operations of Bidirectional Chargers for Electric Vehicles

1.5 Power converters

Power converters play a pivotal role in modern electrical systems, enabling the efficient and reliable conversion of electrical energy from one form to another. They serve as indispensable components in various applications, including renewable energy systems, electric vehicles, consumer electronics, and industrial machinery. Power converters facilitate the conversion of voltage levels, frequency, and waveform to match the specific requirements of different devices and systems. By efficiently transforming electrical power, they enable seamless integration, distribution, and utilization of energy across diverse platforms. Power converters can be categorized based on the nature of the conversion process and the specific application requirements. Here are some of the key types of power converters [13]:

- AC/DC Converters, also known as rectifiers, play a crucial role in converting alternating current (AC) to direct current (DC). These converters are widely utilized in diverse applications, including electronic device power supplies and battery charging systems.
- DC/AC Converters, commonly referred to as inverters, perform the reverse function by converting DC power into AC power. They play a vital role in applications such as solar photovoltaic systems, where DC power generated from solar panels needs to be transformed into AC power for grid integration or powering household appliances.
- DC/DC Converters are specifically designed to convert one DC voltage level to another, enabling step-up (boost), step-down (buck), or polarity inversion of the voltage. Their applications are prevalent in portable electronic devices, battery systems, and automotive systems, ensuring efficient power management and voltage regulation.

1.6 Battery technology

1.6.1 Lithium-ion batteries technology

A lithium-ion battery is a family of rechargeable battery types in which lithium ions move from the negative electrode to the positive electrode during discharge and back when charging. Most of today's all-electric vehicles and PHEVs use lithium-ion batteries, though the exact chemistry often varies from that of consumer electronics batteries. Research and development are ongoing to reduce their relatively high cost, extend their useful life, and address safety concerns in regard to overheating.[14]

1.6.2 Lead-Acid Battery Technology and Usage in Electric Vehicles

Lead-acid batteries, a mature and established technology, still have a place alongside lithium-ion batteries in the growing electric vehicle (EV) market. This section provides an overview of lead-acid battery technology and its applications in EVs, highlighting advantages, limitations, and current uses

Lead-Acid Battery Technology:

Structure: Lead-acid batteries consist of lead and lead oxide plates immersed in a sulfuric acid electrolyte. Porous separators prevent short-circuits and enable ion flow. Discharge converts lead and lead oxide into lead sulfate, with the reverse occurring during charging.

Advantages of Lead-Acid Batteries:

Cost: Lead-acid batteries are affordable, making them appealing for cost-sensitive applications. Durability: They have a long cycle life and can handle deep discharges, suitable for frequent cycling. Safety: Lead-acid batteries boast a proven safety record and established protocols for handling, transportation, and recycling [15].

Limitations of Lead-Acid Batteries:

Energy Density: Lead-acid batteries have lower energy density than lithium-ion batteries, reducing EV range and payload capacity. This makes them less suitable for long-range applications. Weight and Size: Lead-acid batteries are heavier and bulkier, limiting their use in lightweight EV designs with space constraints. Environmental Impact: Lead-acid batteries contain hazardous materials, necessitating proper management during production, usage, and disposal. Recycling processes exist but have a greater overall environmental impact compared to lithium-ion batteries.

Usage of Lead-Acid Batteries in EVs:

Low-Speed Electric Vehicles (LSEVs) [15]: Lead-acid batteries are extensively used in low-speed EVs and industrial utility vehicles. These vehicles operate at low speeds and short distances with lighter power demands, making lead-acid batteries a cost-effective choice. Hybrid Electric Vehicles (HEVs): Some HEVs incorporate lead-acid batteries to support regenerative braking and power assist functions. The lower energy density and weight demands of HEVs make lead-acid batteries suitable for this application, unlike all-electric vehicles.

1.6.3 Battery parameters

Battery parameters are essential for understanding how batteries work and how to use them effectively. The most important parameters of a battery include capacity, voltage, current, power, energy, and efficiency [16].

Capacity refers to the amount of charge a battery can store and is typically measured in units of ampere-hours (Ah) or milliampere-hours (mAh).

Voltage represents the electrical potential difference between the positive and negative terminals of the battery, measured in volts (V).

Current is the flow of electric charge through a battery, measured in units of amperes (A).

Power is the rate at which energy is transferred and is measured in units of watts (W). For batteries, power is calculated as the product of voltage and current.

Energy is the amount of work that a battery can perform, measured in units of watt-hours (Wh) or (kWh).Energy is calculated as the product of voltage, current,and time.

Efficiency is the ratio of the energy delivered by a battery to the energy put into it during charging, and is usually expressed as a percentage.

Battery state of charge SOC

Battery state of charge (SOC) refers to the amount of energy that is currently stored in a battery as a percentage of its total capacity. SOC is an important parameter for battery management and monitoring, as it provides information on the available energy and remaining run-time of a battery. SOC can be estimated using various methods, such as voltage, current, temperature, and coulomb counting. Voltage is commonly used for SOC estimation, as it is easy to measure and correlates well with SOC. However, voltage-based methods may be inaccurate due to variations in battery chemistry, temperature, and load conditions. Coulomb counting is a more precise method that measures the amount of charge that flows in and out of the battery, but it requires accurate measurement of the current and can be affected by errors and drift over time. Accurate SOC estimation is important for maximizing battery performance, avoiding overcharging or over-discharging, and extending battery lifespan (fig7).

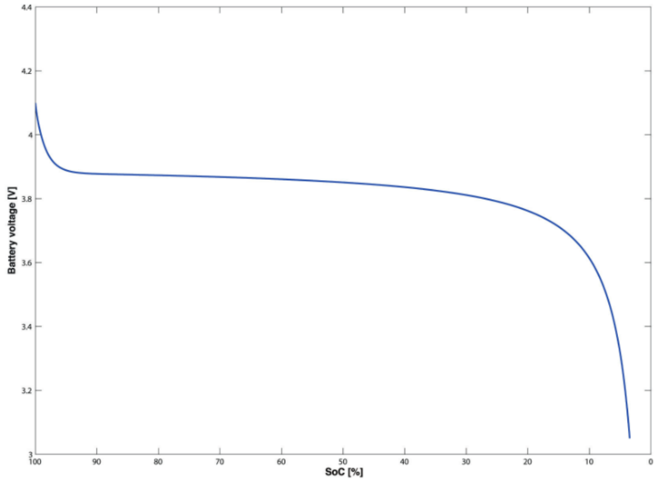

Figure 7. Typical discharge curve used for SoC calculation

Understanding these battery parameters can help in selecting the appropriate battery for a given application, optimizing charging and discharging rates, and ensuring the battery operates effectively and efficiently.

1.6.4 Energy management system

Energy management systems (EMS) are electronic control circuits that monitor and regulate the charging and discharge of batteries. The battery characteristics to be monitored include the detection of battery type, voltages, temperature, capacity, state of charge, power consumption, remaining operating time, charging cycles, and some more characteristics. The task of battery management systems is to ensure the optimal use of the residual energy present in a battery. In order to avoid loading the batteries, EMS systems protect the batteries from deep discharge and over-voltage, which are results of extreme fast charge and extreme high discharge current. In the case of multi-cell batteries, the battery management system also provides a cell balancing function, to manage that different battery cells have the same charging and discharging requirements.

1.6.5 Battery charging methods

Battery charging is the process of restoring energy to a battery that has been depleted through use. Different types of batteries require different charging methods, and the correct method depends on the battery's chemistry, capacity, and other factors [17].

Here are some of the most common battery charging methods:

Constant current charging: This method involves delivering a constant current to the battery until it reaches a certain voltage level. This is a common method used for charging lead-acid batteries, which are commonly found in cars, boats, and other vehicles. This method is effective for charging lead-acid batteries because it ensures that the battery is charged evenly and helps prevent overcharging.

Constant voltage charging: This method involves delivering a constant voltage to the battery until it reaches a certain current level. This is commonly used for charging lithium-ion batteries, which are commonly found in smartphones, laptops, and other portable devices. This method is effective for charging lithium-ion batteries because it helps prevent overcharging and ensures that the battery is charged evenly.

Trickle charging: This method involves delivering a low current to the battery continuously to keep it charged. This method is often used for maintaining batteries that are not in frequent use, such as in cars or boats. It is also used for charging small batteries, such as those found in remote controls or other small electronics. Trickle charging is a slow and steady method that helps prevent overcharging and extends the life of the battery.

Fast charging: This method uses higher currents or voltages to charge the battery more quickly. However, this method can generate more heat and may reduce the overall lifespan of the battery. Fast charging is commonly used for charging electric vehicle batteries, as well as some smartphone and laptop batteries. It is important to use a charger that is specifically designed for fast charging and to follow the manufacturer's recommendations to avoid damaging the battery.

Pulse charging: This method involves using short pulses of high current to quickly charge the battery, followed by a resting period to allow the battery to recover. This method can help extend the life of the battery by reducing the buildup of lead sulfate crystals on the battery plates. Pulse charging is commonly used for charging lead-acid batteries, such as those used in cars, boats, and other vehicles.

Constant current constant voltage (CC-CV): is a widely used method for recharging lithium-ion batteries. This approach involves charging the battery with a steady current until it reaches a specific voltage, followed by maintaining the voltage constant while gradually decreasing the charging current. CC-CV charging is a preferred method for its ability to facilitate fast and efficient charging, while minimizing the risk of overcharging and excessive heat generation. It is also versatile and can be easily incorporated into most charging systems, adapting to various battery types and chemistries. CC-CV charging is commonly used in electric vehicles, portable electronic devices, and renewable energy storage systems, making it an essential and highly effective battery charging method.

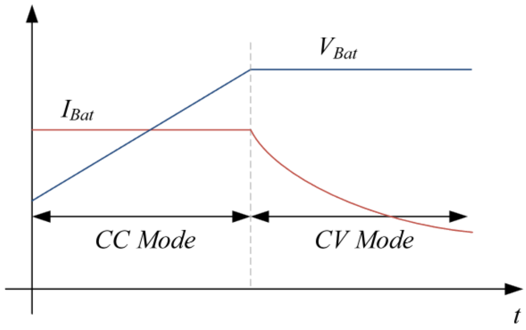

Figure 8. CC-CV charging method

1.6.6 Battery modeling

There are several methods for modeling and comprehending battery behavior. At the system level, batteries are often represented by an ideal voltage source with a fixed value that denotes the EMF of the battery. This approach is straightforward and fairly accurate, as long as the battery's state of charge (SoC) is within the range of 20% to 90%. Beyond this range, the battery's behavior can become more complex and less predictable, requiring more advanced modeling techniques that account for factors such as internal resistance and aging effects. By using accurate battery models, system designers can optimize battery usage, improve system efficiency, and prolong battery lifespan.For most applications the model shown in Figure9 is accurate enough. However when high load currents are applied at nearly empty or nearly full batteries the accuracy of this model goes down. Just as with the EMF of the battery it turns out that the internal resistance of the battery is dependent on the SoC.

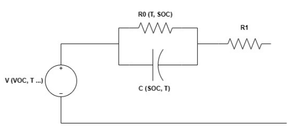

Figure 9. Lead-acid battery modeling 1

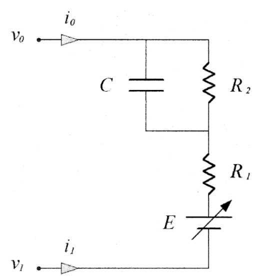

Figure 10. Lead-acid battery modeling2

1.7 Charging infrastructure

BEVs receive their charge from an external source, specifically the electric grid. The BEV battery is charged using a charger, which is essential to facilitate the charging process because the power supplied by the grid is in alternating current (AC) form while the battery requires direct current (DC). The charger is designed to convert the AC power from the electric grid into the appropriate DC power level for charging the BEV battery. A typical EV charger utilizes an AC-DC converter, also known as a rectifier, to perform the necessary power conversion. In the case of fast charging stations, an additional DC-DC converter is incorporated into the design to enhance energy conversion efficiency. Chargers can be installed in two ways: on-board or off-board, depending on the specific configuration and charging capacity.

On-board chargers have distinct design requirements. They need to be compact and lightweight in order to ensure efficient EV propulsion. However, on-board chargers have a limitation in terms of power rating and are generally suitable for slower charging levels. Conversely, off-board chargers are installed at dedicated locations since they tend to be bulkier due to the inclusion of a DC-DC converter that enables fast charging within the charger itself.[18]

1.8 Bidirectional charger

A bidirectional charger, is a type of electric vehicle (EV) charger that allows electricity to flow both ways between the EV battery and the electrical grid. In addition to charging the EV battery, a bidirectional charger can also discharge the battery back into the grid when the vehicle is not in use or when grid demand is high. This enables EVs to function as a distributed energy resource (DER) and provide grid services such as peak shaving, load shifting, and frequency regulation so The bidirectional chargers were able to operate in the V2G/G2V/Filtering modes in smart grids or homes therefore they are a key technology for the integration of EVs into smart grids and the optimization of renewable energy sources.(fig11).[19].

1.9 DC fast charging station

DC fast charging stations are essential for the widespread adoption of electric vehicles (EVs) as they provide a means to quickly charge EV batteries from the electric grid. Unlike slower level 1 and level 2 chargers commonly used for overnight charging, DC fast charging stations enable rapid charging.

In the case of off-board EV charging setups, the charging station and charger handle the conversion of high voltage AC from the grid into DC, as well as the conversion of high voltage DC to low voltage DC. This approach allows for faster battery charging and is a cost-effective alternative to implementing individual on-board power converters in each EV.

Off-board fast charging stations are particularly beneficial in addressing range anxiety for EV owners. By extending the mileage or range that an EV can cover with battery power, these stations help alleviate concerns about running out of charge during a journey. Recent advancements in battery technology have made it possible for EVs to accept fast charging, resulting in significantly reduced charging times compared to older technologies [20].

At a DC fast charging station, the AC voltage from the grid is converted into DC voltage outside the EV. This DC coupling between the vehicle and the charging station enables efficient and rapid charging.

Charging stations also play a vital role in vehicle-to-grid (V2G) technology, where they determine current conversion and power flow direction. A charging station typically consists of two power converters: an AC-DC converter and a DC-DC converter. These converters perform the necessary power conversion tasks and regulate the amount and direction of power flow to or from the EV battery based on predetermined standards and control algorithms.

1.10 Conclusion

In conclusion, the literature has delved into various aspects related to the challenges and mitigation strategies in the context of smart grids, specifically focusing on the issue of harmonics. Harmonics pose a significant challenge in power systems due to the proliferation of non-linear loads, which can distort the quality of electrical signals and impact system performance. Mitigating harmonics is crucial to ensure the reliable and efficient operation of smart grids.

Various techniques for harmonics mitigation have been discussed, including passive filters, active filters. These methods offer effective solutions for reducing harmonic distortion and maintaining power quality within acceptable limits. Implementing harmonics mitigation techniques in smart grids is essential to minimize power losses, prevent equipment damage, and enhance the overall stability and reliability of the grid.

Power converters play a crucial role in facilitating the integration of EV's into smart grids. They enable efficient and reliable conversion of power between AC and DC, ensuring proper charging of EV batteries from the grid. Moreover, advancements in power converter technology, such as bidirectional operation which offers opportunities for grid support and power flow management.Furthermore, the integration of electric vehicles (EV's) into smart grids has emerged as a significant development in recent years. EV's not only contribute to reducing greenhouse gas emissions but also pose new challenges and opportunities for the power system. the next chapter pertains to the proposed control strategies and algorithms to design an effective EV bidirectional charger.

Control strategies for bidirectional EV charger

2. Control strategies for bidirectional EV charger

The proliferation of electric vehicles (EVs) has prompted the development of efficient and intelligent charging solutions to meet the growing demand for reliable and flexible energy transfer. Bidirectional chargers have emerged as a promising technology, enabling not only the charging of EV batteries from the grid but also facilitating vehicle-to-grid (V2G) and grid-to-vehicle (G2V) power flow, thereby enabling vehicle-to-home (V2H) applications. To ensure effective bidirectional power transfer, advanced control methods and algorithms play a pivotal role in regulating the charger's operation and optimizing its performance. This chapter will provide a comprehensive exploration of control methods and algorithms that we have employed in the design of bidirectional chargers. By understanding and evaluating these techniques, we can enhance Power quality efficiency by mitigating the electric harmonics, thereby facilitating the widespread adoption of electric vehicles and promoting a sustainable and intelligent energy ecosystem.

2.1 Understanding power electronics

2.1.1 AC to DC inverter

In our project we have used AC to DC inverters as a bidirectional inverter it can perform both rectification (AC to DC conversion) and inversion (DC to AC conversion). This allows for power flow in both directions, enabling applications such as energy storage systems and grid support. The equations for a bidirectional inverter can be derived based on the power flow in both directions. Let's consider the following variables:

- $V_{(ac)}$: AC voltage
- $I_{(ac)}$: AC current
- $V(dc)$: DC voltage
- $I_{(dc)}$: DC current
- D is the duty cycle of the PWM signal, ranging from 0 to 1, representing the ON-time of the switching devices.

Rectification (AC to DC Conversion): During rectification, the inverter operates in a way that converts the AC input voltage to a DC output voltage.it can be expressed as follows:

$$V_{dc} = V_{ac} * D \tag{2.1}$$

$$I_{dc} = I_{ac} * D \tag{2.2}$$

Inversion (DC to AC Conversion): During inversion, the inverter converts the DC input voltage to an AC output voltage. The equations for inversion depend on the specific waveform and modulation technique used. One common approach is sinusoidal pulse width modulation (SPWM), which approximates a sinusoidal output waveform. Assuming ideal operation and SPWM:

$$V_{ac} = V_{dc} * D \tag{2.3}$$

$$I_{ac} = I_{dc}/D \tag{2.4}$$

the switching states for a single phase bridge inverter are shown in the following table:

Table 1. Single phase inverter switching states

S1	S2	S3	S4	Va	Vb	Vab
ON	OFF	OFF	ON	Vs/2	-Vs/2	Vs
OFF	ON	ON	OFF	-Vs/2	Vs/2	-Vs
ON	OFF	ON	OFF	Vs/2	Vs/2	0
OFF	ON	OFF	ON	-Vs/2	-Vs/2	0

In this project the inverter is controlled by Hysteresis current control which deliver only two stages as S1 and S4 has the same state while S2=not S1 and S3=not S4 like it is described in the table below

Table 2. HCC inverter switching states

S1	S2	S3	S4	Va	Vb	Vab
ON	OFF	OFF	ON	Vs/2	-Vs/2	Vs
OFF	ON	ON	OFF	-Vs/2	Vs/2	-Vs

2.1.2 DC to DC converter

DC-DC converters are electronic circuits used to convert one DC voltage level to another, providing efficient power conversion in various applications. They are essential components in many electronic devices, ranging from portable electronics to renewable energy systems. The working principle of DC-DC converters involves the use of power switches, inductors, capacitors, and diodes to control the flow of electrical energy and achieve the desired voltage conversion.
1_ Buck Converter: The Buck converter is a DC-DC converter that steps down the input voltage to a lower output voltage. It consists of a power switch (S), an inductor (L), a diode (D), and an output capacitor (C). The operation of the Buck converter can be described mathematically using the following equations:

$$V_{out} = V_{in} * D \tag{2.5}$$

2_Boost Converter: The Boost converter is a DC-DC converter that steps up the input voltage to a higher output voltage. It consists of a power switch (S), an inductor (L), a diode (D), and an output capacitor (C). The mathematical description of the Boost converter is as follows:

$$V_{out} = \frac{V_{in}}{(1 - D)} \tag{2.6}$$

3_ Buck-Boost Converter: The Buck-Boost converter is a DC-DC converter that can step up or step down the input voltage, depending on the duty cycle. It combines the operation principles of both the Buck and Boost converters. The mathematical equations for the Buck-Boost converter are as follows:

$$V_{out} = \frac{V_{in} * D}{(1 - D)} \tag{2.7}$$

These mathematical descriptions provide a quantitative understanding of the voltage conversion process in DC-DC converters. By analyzing these equations and considering the system parameters, you can evaluate the performance characteristics, such as voltage gain, efficiency, and transient response, of the Buck, Boost, and Buck-Boost converters.

2.2 DC link capacitor

The main role of the DC-side capacitor is to serve two major purposes :
a) Maintains a constant DC voltage with small ripples in the steady state.
b) Compensates the real power difference between the load and the source during the transient state.
During steady state, real power supplied by the source is equal to the real power demand of the loads plus a small power to compensate the losses accruing in the active filter.Thus, the DC-link voltage can be maintained at a constant reference value. However, during load variation the real power balance between the mains and the load is disturbed. This real power difference is compensated by the charging/discharging of DC- link capacitor. If the DC-link capacitor voltage is recovered and it attains the reference voltage; real power supplied by the source again becomes equal to that consumed by the load.

2.3 Bidirectional charger composition

Most single-phase battery bidirectional chargers comprise two cascaded stages.The first stage includes an AC/DC converter that ensures unity power factor correction by absorbing sinusoidal current from the grid with low current harmonics.The second stage is based on a DC/DC converter that regulates the current delivered to the battery based on its state of charge (SOC) and matches the difference between the DC-link and battery voltages.Both stages are generally connected by means of a DC-link capacitor.(see figure11)

2.3.1 First stage:AC to DC converters

A bidirectional AC to DC converter is an electronic device that can convert electrical power back and forth between an alternating current (AC) power source and a direct current (DC) power source.

The bidirectional converter has the ability to convert AC power from the source to DC power for charging a battery or powering a DC load, and also to convert DC power from the battery or DC source back to AC power for supplying power to an AC load or exporting excess energy back to the grid.

2.3.2 Second stage DC to DC converter

The second link between the power grid and electric vehicles (EVs) after the AC-DC converter is a bidirectional DC-DC converter that performs both buck and boost conversions.

The DC voltage obtained at the output of the bidirectional AC-DC converter is higher for charging the EV battery and must be converted to a lower value. Similarly, when the EV is supplying power to the utilities, the voltage at the battery terminal is lower than the output of the AC-DC converter, and it must be converted to a higher value for high voltage DC-AC inversion.

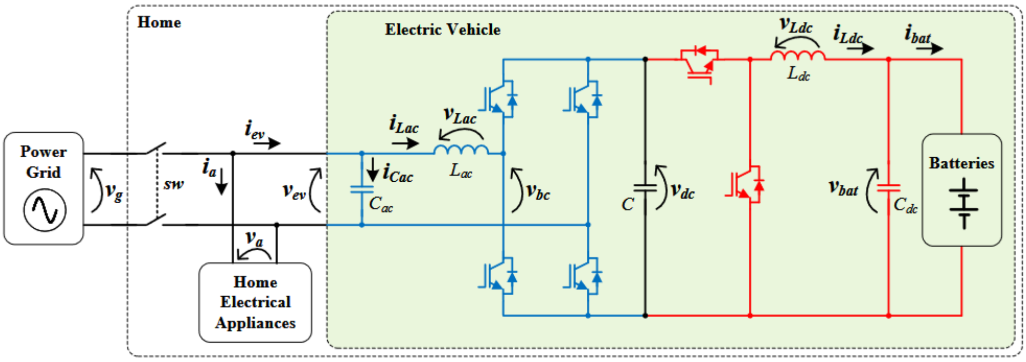

Figure 11. Configuration of a bidirectional charger

2.4 Voltage regulation

2.4.1 Proportional integral controller (PI)

In control systems, the Proportional-Integral (PI) controller is a widely used and effective technique for achieving accurate and stable control. The PI controller combines proportional and integral control actions to regulate the system's output based on an error signal. The PI controller continuously compares the system's output with the desired set-point and generates a control signal to minimize the error. The proportional component of the PI controller produces an output proportional to the current error, while the integral component integrates the error over time. By combining these two control actions, the PI controller addresses both steady-state and dynamic errors, providing a balanced response.

Mathematical Formulation: The mathematical formulation of the PI controller can be described as follows:

Proportional Action: The proportional term generates an output proportional to the error between the set-point and the actual output. It can be expressed as:

$$u(t) = Kp * e(t) \tag{2.8}$$

Integral Action: The integral term accumulates the past errors and adjusts the controller output to eliminate steady-state errors. It can be represented as:

$$u(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(\tau)\, d\tau \tag{2.9}$$

Where:

u(t): is the controller output or control signal.
K_p :is the proportional gain, determining the strength of the proportional action.
K_i :is the integral gain, controlling the responsiveness of the integral action.
e(t): is the error signal, calculated as the difference between the setpoint and the system's output.

Figure12 The PSO algorithm is used to determine suitable gain values for KI and KP

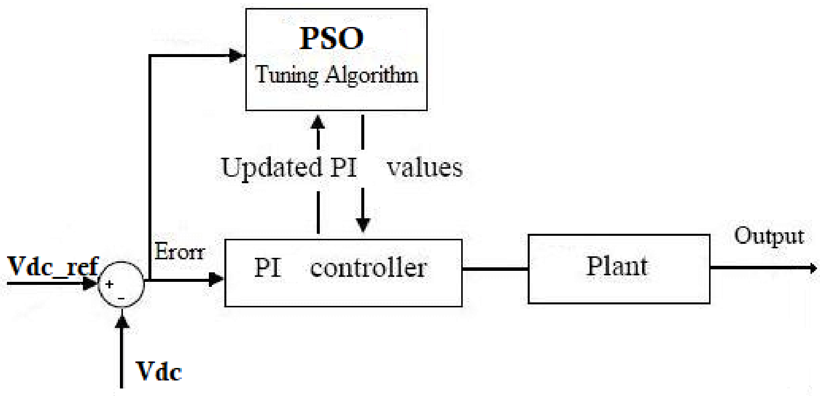

Figure 12. DC link voltage regulation control diagram

2.5 PQ Theory Reference Current Extraction

The PQ Theory, also referred to as the instantaneous power theory, is a control technique widely employed in power electronics applications, particularly in grid-connected inverters. Its primary objective is to regulate the active and reactive power flow between the inverter and the utility grid while ensuring high-quality power transfer.

The PQ Theory operates by analyzing the instantaneous values of voltage and current wave-forms. It utilizes a mathematical transformation known as the Clarke transformation or the $\alpha - \beta$ transformation [21] see figure (13), which converts the three-phase quantities into two orthogonal components: the d-axis component (representing the active power) and the q-axis component (representing the reactive power).Using MATLAB function we can express this PQ calculations in the following equations:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \times \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \tag{2.10}$$

This transformation simplifies the control algorithm and enables independent control of active and reactive power. In PQ Theory control, the reference values for active power (P),and reactive power (Q) are set by the control system. The inverter adjusts its output current (Ih_{ref}) and voltage to maintain the desired power flow. By continuously monitoring the grid voltage and currents (I_α^* and I_β^*) we get the references compensation currents as expressed below

$$\begin{bmatrix} Ic1 \\ Ic2 \end{bmatrix} = \begin{bmatrix} I_\alpha^* \\ I_\beta^* \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \times \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \times \begin{bmatrix} Posc \\ Q_{grid} \end{bmatrix} \tag{2.11}$$

The inverter can regulate the power factor and ensure optimal power transfer[22]. the output current($Ih_{ref} = I_\alpha^*$) is then used in the hysteresis current control diagram in order to control the inverter switches. (see figure 27)

One of the significant advantages of PQ Theory control is its ability to dynamically respond to changes in the grid conditions, such as voltage sags, swells, and harmonic distortions. It can rapidly adjust the inverter's output to compensate for variations and maintain the desired power quality[23].

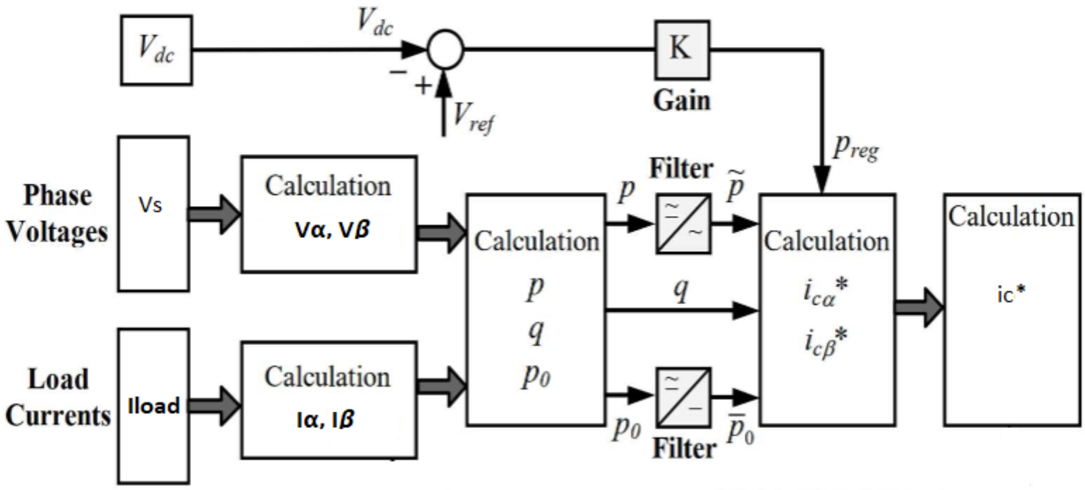

Figure 13. PQ Theory model

2.5.1 p-q Modified Power injection

In addition to harmonics mitigation, we are going to inject active power from the electric vehicle (EV) that will be connected to the inverter through a boost converter. Therefore, we require a specific feedback signal to instruct the control circuit to incorporate power from the EV in its output, alongside harmonics. The selected signal is the power computed from the EV's output, as shown in equation below, which should be included as an additional component to the reference active power, denoted as 'p^*'.

$$P_{bat} = V_b * I_b \tag{2.12}$$

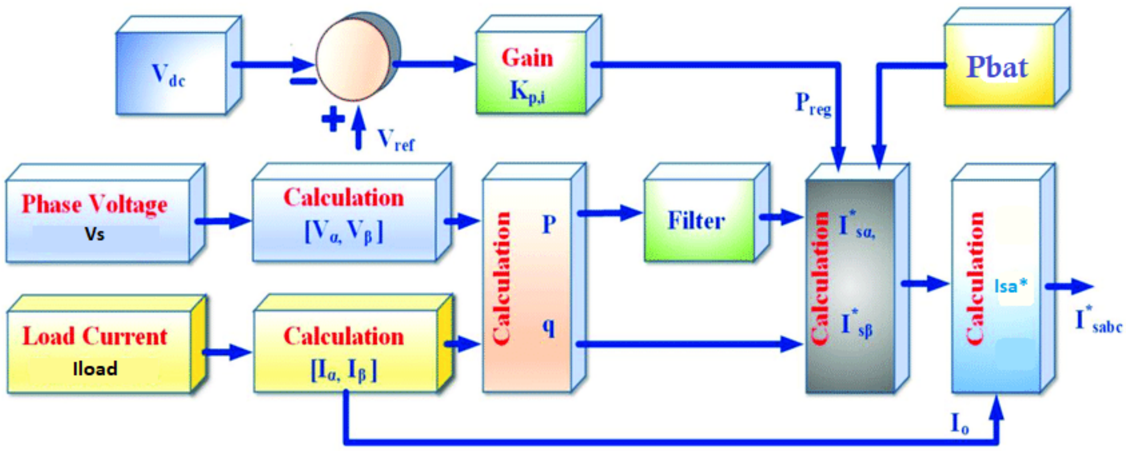

Figure 14. P-Q modified power injection

2.6 Hysteresis Current Control (HCC)

Hysteresis current control is a sophisticated technique used in single-phase inverters to regulate the output current with high accuracy and responsiveness. This control method ensures that the inverter output current tracks the desired reference current waveform within a specified hysteresis band.

In hysteresis current control, the actual output current is continuously compared with a reference current signal. The hysteresis band is defined by an upper threshold $(I_{ref} + H)$ and a lower threshold $(I_{ref} - H)$, where H represents the desired width of the hysteresis band. The switch state of the inverter is determined based on the comparison result as follows:

If the output current exceeds the upper threshold (I_{out} > $(I_{ref} + H)$), the switches are rapidly turned OFF to reduce the current. If the output current falls below the lower threshold (I_{out} < $(I_{ref} - H)$), the switches are promptly turned ON to increase the current. If the output current lies within the hysteresis band ($(I_{ref} - H)$ < I_{out} < $(I_{ref} + H)$), the switch state remains unchanged.

By employing hysteresis current control, the inverter can accurately track the reference current waveform, swiftly adjusting the switch states to maintain the output current within the desired range. This control technique offers excellent dynamic response, enabling precise and stable current regulation in single-phase inverters.

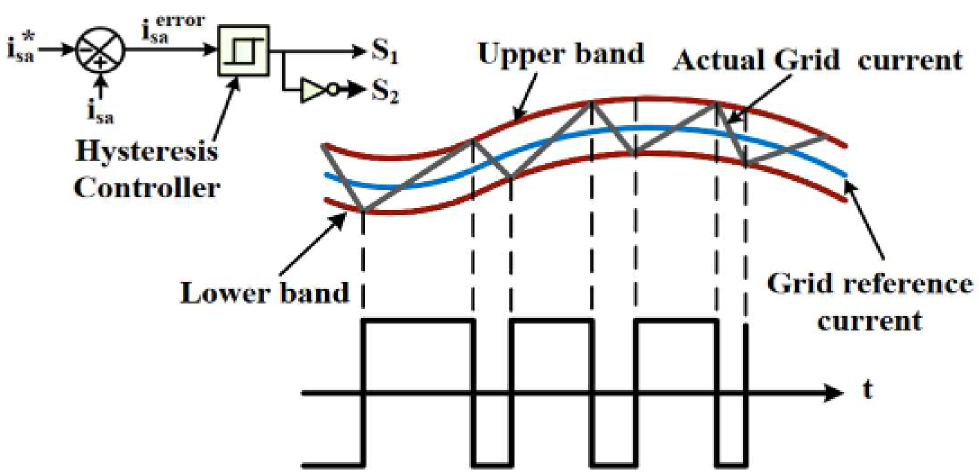

Figure 15. Description of the hysteresis controller

2.7 Model predictive control (MPC)

MPC (Model Predictive Control) is an advanced and effective strategy for power converter control. It utilizes a mathematical model of the system under study to anticipate the future behavior of controlled variables [24]. The proposed predictive control strategy acknowledges that a static power converter can only generate a finite number of possible switching states. By leveraging system models, it becomes possible to predict variable behavior for each switching state. To determine the appropriate switching state, a selection criterion must be established. This criterion involves a cost function that evaluates the predicted values of the variables to be controlled. The prediction of future variable values is computed for each potential switching state, and subsequently, the state that minimizes the cost function is selected.Using the measured values of the current I_{inv} the grid voltage Vs, the reference current I_{ref} estimated from the PQ theory, the DC link voltage (V_{dc}), the predicted value of current $I_{inv}(k+1)$ is calculated for all switching states see figure 1 cases. In order to reduce the computation burden, one variable S_{dc1} is introduced to simplify the use of switching states they are calculated using the following equations :

$$S_{dc1} = S1 - S2; \tag{2.13}$$

The voltage vector that is generated from the inverter can be calculated as follows:

$$V_{inv} = S_{dc1} * V_{dc} \tag{2.14}$$

The dc voltage is given as 2.15:

$$Vdc_{cal} = V_{dc} - ((T_s/C) * (S1 - S2)) * i_{inv} \tag{2.15}$$

Where C is the DC link capacitor.
the generated reference current I_{ref} is calculated as follows :

$$I_{ref.cal} = (1 - R * Ts/Lf) * i_{inv} + (Ts/Lf) * (V_{inv} - V_{as}) \tag{2.16}$$

The cost function is defined to evaluate the performance of the control system. It typically includes terms that represent desired control objectives and penalties for deviations from these objectives.The cost function g is derived as eq :2.17

$$g = k1 * (I_{ref.cal} - i_{ref})^2 + k2 * (Vdc_{cal} - V_{dc})^2 \tag{2.17}$$

2.8 DC-DC and Battery management algorithm

In the previous section,the control algorithms employed in this project for regulating the inverter current was highlighted . Now, we delve into the method utilized for controlling the DC to DC converter, which plays a crucial role in managing the bidirectional power flow and determining the V2G, G2V and V2H operation modes. Controlling the DC to DC converter is essential for efficiently transferring power between the electric vehicle (EV) and the grid in both V2G and G2V modes,also transferring power from battery to home appliances (V2H). The control strategy employed aims to optimize the bidirectional power flow, ensuring smooth and reliable operation while adhering to the desired operation mode. the control algorithm is established using Matlab function as illustrated in the figure (16) below:

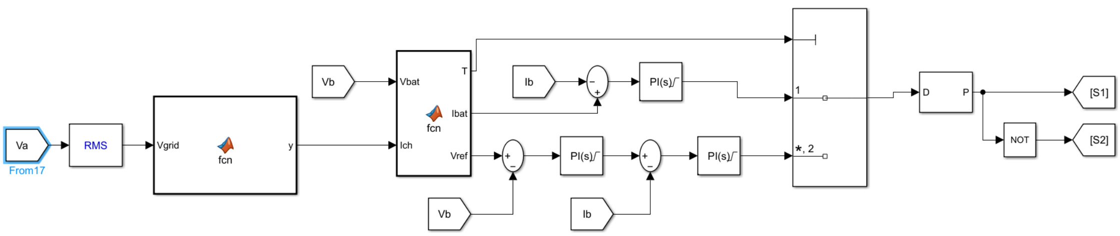

Figure 16. DC to DC converter control model

The algorithm begin by monitoring the status of the grid, starting with the measurement of the grid voltage, denoted as V_s. If V_s is greater than zero, it indicates that the grid is available for charging the battery. The next step involves reading the battery voltage, denoted as V_b. If V_b is below the maximum battery voltage ($V_{b.max}$,V=13.4) and Greater than the minimum required voltage ($V_{b.min}$), the grid receives a command to initiate charging using the constant current (CC) charging technique. Otherwise if the grid has a high demand,the algorithm start reading the status of the battery if $V_{bat} > V_{b.min}$ then the battery will deliver power to grid and the system will operate in V2G mode.In addition if the grid is not available and the battery SOC is greater than SOC_{min} the battery will deliver power to the load and the system will operates in the V2H mode. During the charging process, the battery voltage is continuously monitored, and once it reaches the reference voltage (V_{ref}), the grid is instructed to transition to the constant voltage (CV) charging method. This CC-CV charging technique is employed to ensure the preservation of the battery's state of health (SOH). To regulate both the charging current and voltage, a proportional-integral (PI) controller is utilized.

The buck-boost converter is controlled using pulse width modulation (PWM), which takes the reference battery current as input to generate the necessary control signals for carrying out the charging operation. This configuration allows the DC-DC converter to function as a buck converter during charging or as a boost converter during discharging. The control algorithm diagram is depicted in the figure (17) .

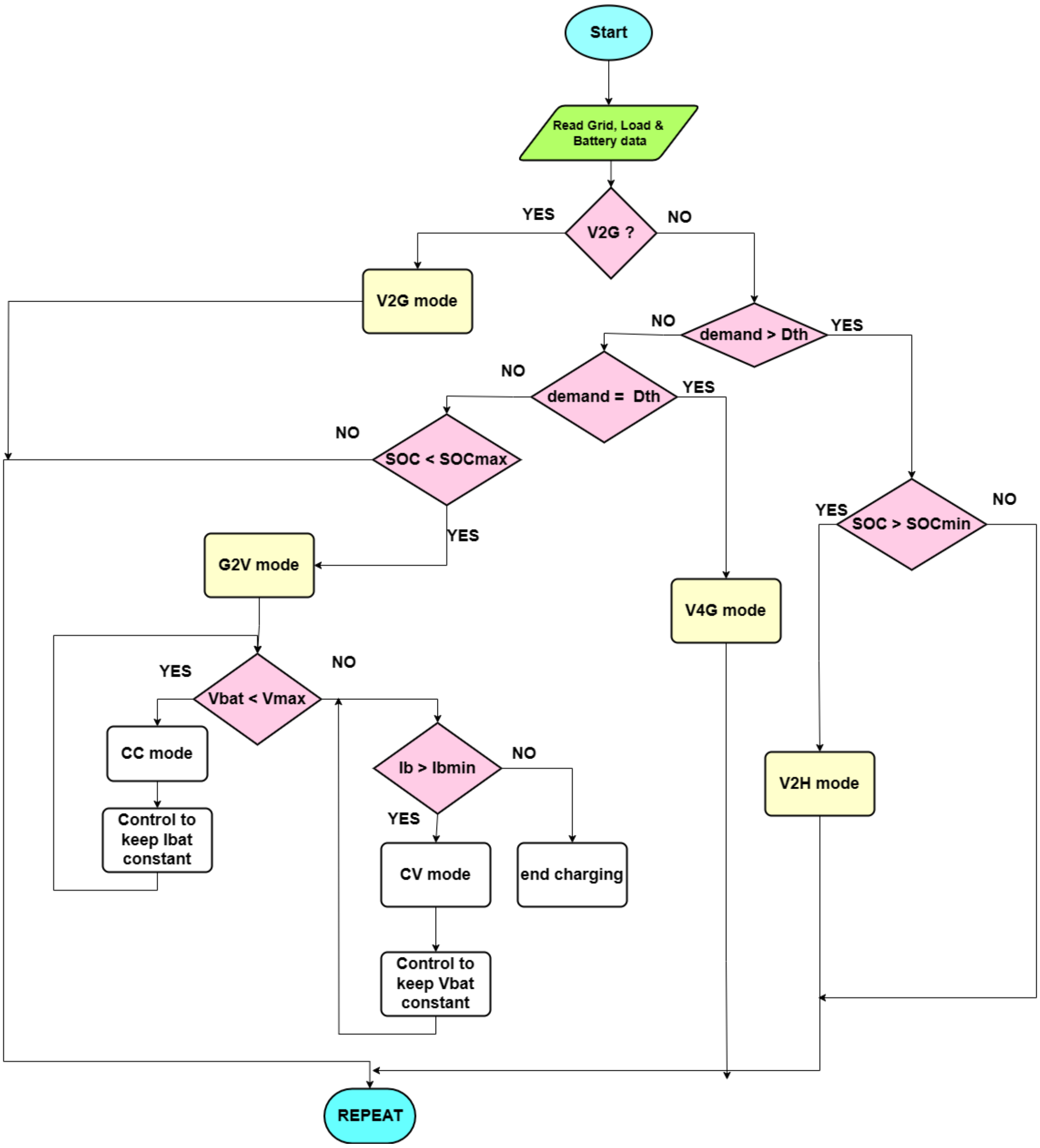

Figure 17. Battery management algorithm

2.9 Conclusion

In conclusion, Chapter two has provided an overview of the control strategies and algorithms involved in designing an electric vehicle's (EV) bidirectional charger. The content covered various aspects of power electronics, including the AC to DC inverter and the DC to DC converter. Additionally, the importance of the DC link capacitor and its role in the bidirectional charger was discussed.

The composition of the bidirectional charger was outlined, highlighting its key components and their functions. Voltage regulation, a crucial aspect of charger design, was examined, with a focus on the proportional integral controller (PI) as a control technique. The PQ Theory technique and its application through p-q Modified Power injection were also introduced.

Furthermore, two specific control methods were explored: Hysteresis Current Control (HCC) and Model Predictive Control (MPC). These methods play a significant role in achieving efficient and precise control of the bidirectional charger.

Lastly, we have presented the control algorithm for a DC-DC converter and battery management algorithm, emphasizing the importance of effective control strategies to ensure optimal charging performance.

By providing insights into control strategies and algorithms, this section serves as a foundation for the subsequent chapters, which will delve deeper into each control method through its modeling and performance analyzing for each control technique .

Simulations Results

3. Simulation results

3.1 Introduction

In this chapter,comprehensive analysis of the simulation and results of the proposed control algorithms to design the EV bidirectional charger is presented (figure 18). Two methods of control are established and compared in order to achieve the best possible outcomes : Hysteresis current control (HCC) and Model predictive control MPC. the chapter tends to begin by outlining the methodology used for the simulation, including the modeling of the bidirectional charger using MATLAB simulink. Next, we delve into the results obtained from the simulation study. We analyze the performance of the bidirectional charger in terms of charging and discharging efficiency, energy transfer capabilities, and its effect on the grid power quality.The results provide insights into the charger's ability to optimize energy flow, mitigate grid harmonics and ensure a reliable and sustainable charging infrastructure

3.2 System Parameters

The values of the used components, elements and other parameters are indicated in the table below 3:

Table 3. System parameters

GRID	RMS peak voltage: 64 volts	frequency : 50 Hz
BATTERY (lead-acid)	V_{bat}: 12 volts	battery Capacity : 7 Ah
LOAD	L = 5 mH	C =1μF
Converter	L= 15 mH	DC link capacitor C =1100μF

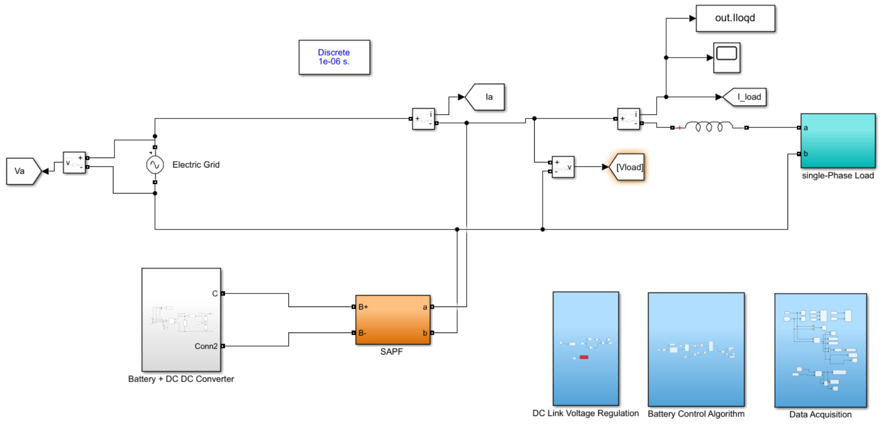

Figure 18. EV bidirectional charger Simulink blocks

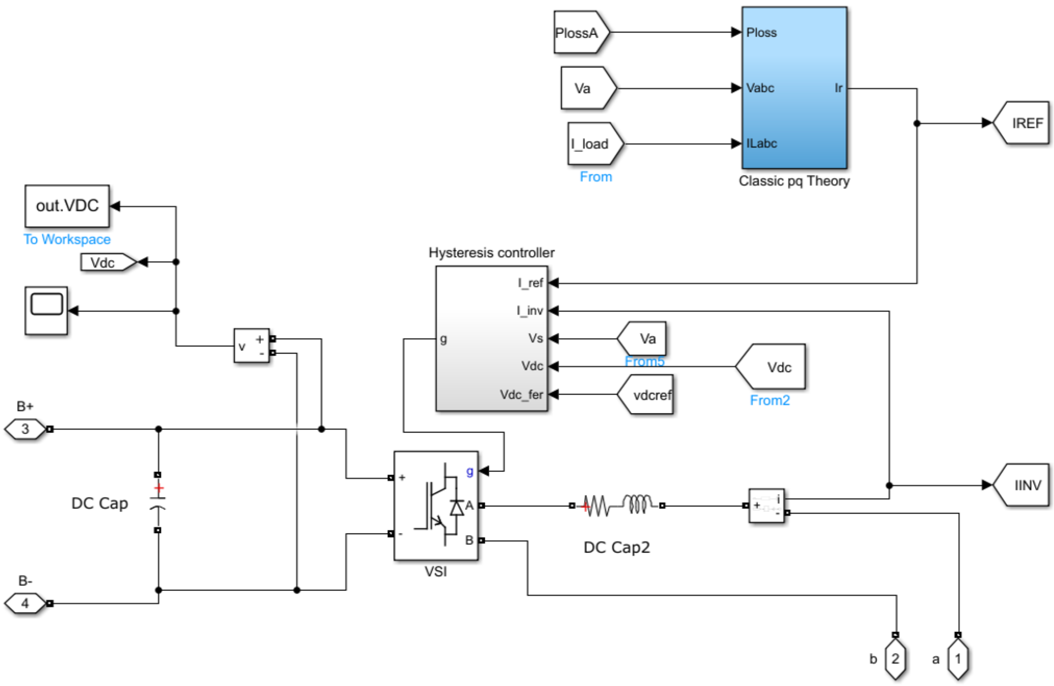

Figure 19. SAPF control Simulink Blocks

3.3 Hysteresis current control (HCC) simulation results:

This section shows the results obtained from the model simulation using the HCC control method the matlab model of the HCC method is shown in figure 19.

3.3.1 Grid voltage (V_s) and Grid current (I_s):

G2V mode (Charging)

The graphs provided bellow figure 20 represents the behavior and characteristics of the Grid voltage and the grid current in the G2V operation mode (charging mode). .

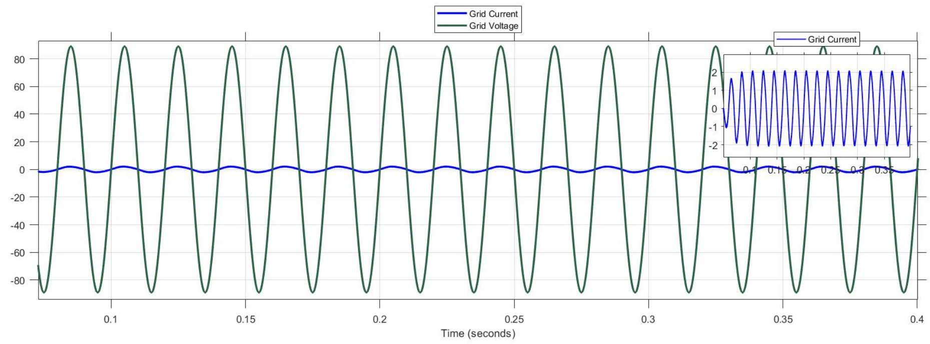

Figure 20. Grid voltage and Grid current during G2V mode

V2H mode (Discharging to the load)

The graphs provided bellow figure 21 represents the behavior and characteristics of the Grid voltage and the grid current in the V2H operation mode (Discharging mode):

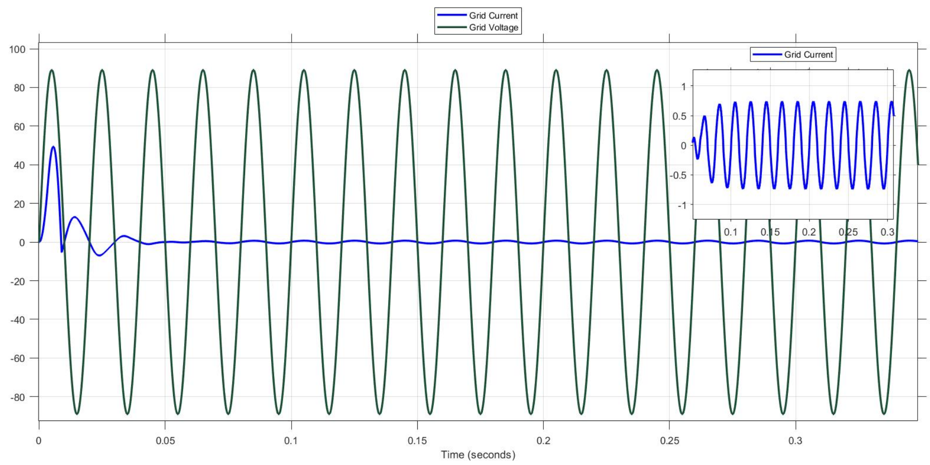

Figure 21. Grid voltage and Grid current during V2H mode

V4G mode (Filtering)

The graphs provided bellow figure 22 represents the behavior and characteristics of the Grid voltage and the grid current in the V4G mode :

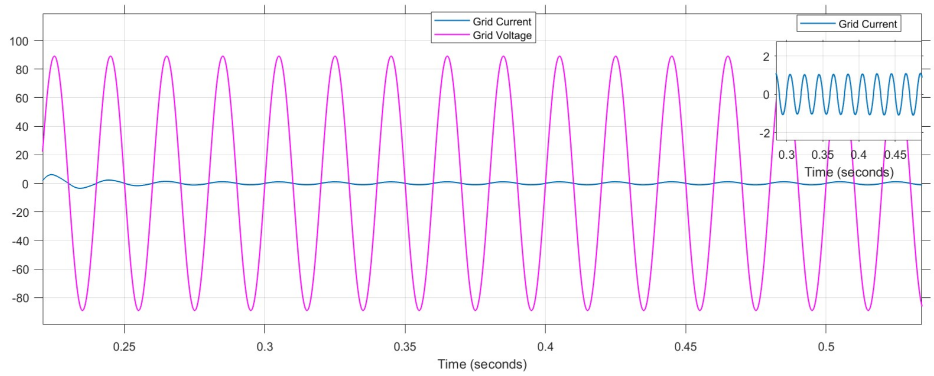

Figure 22. Grid voltage and Grid current during V4G mode

V2G mode (Discharging to grid)

The graphs provided bellow figure 23 represents the behavior and characteristics of the Grid voltage and the grid current in the V2G operation mode (discharging mode) .

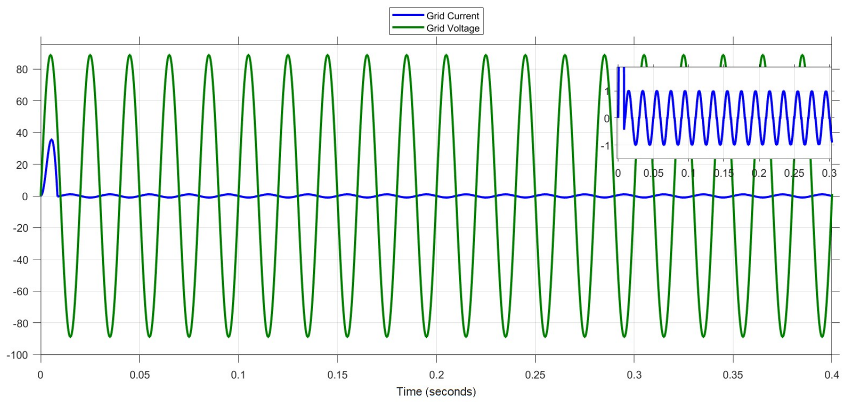

Figure 23. Grid voltage and Grid current during V2G mode

the graph clearly shows that the grid current and the grid voltage are out of phase

3.3.2 DC link Voltage (V_{dc}):

The DC link voltage is regulated using PI controller (fig:24). The proportional part of the PI controller responds to the error between the actual DC link voltage and the desired reference value 100V. It adjusts the control action based on the magnitude of the error. By applying a proportional gain, the controller can quickly respond to changes in the error, ensuring a fast and accurate voltage regulation while The integral part of the PI controller considers the accumulated error over time. It continuously integrates the error and adds a corrective action to the control output. This helps in eliminating steady-state errors and improving the system's steady-state accuracy. The integral action allows the controller to handle steady-state disturbances or biases that might affect the DC link voltage.In order to ensure system stability The PSO algorithm is used to maintain optimal suitable gain values for KI and KP.

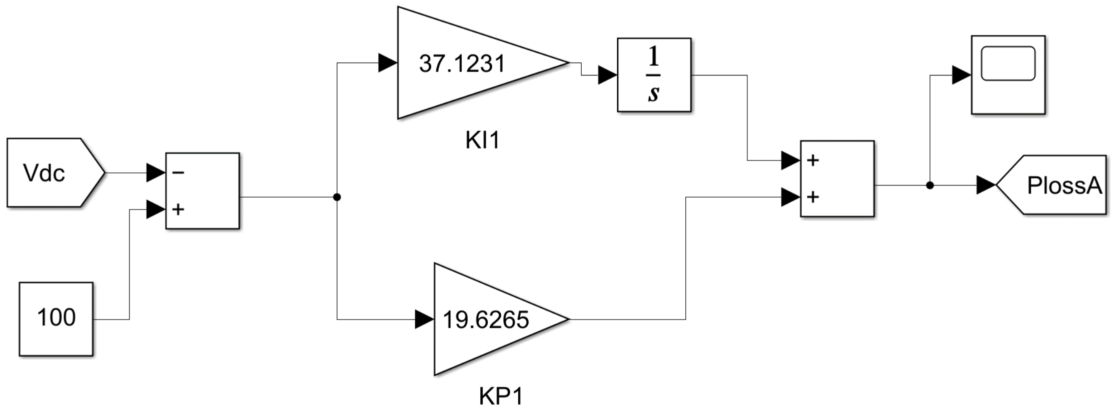

Figure 24. DC link voltage regulation control diagram

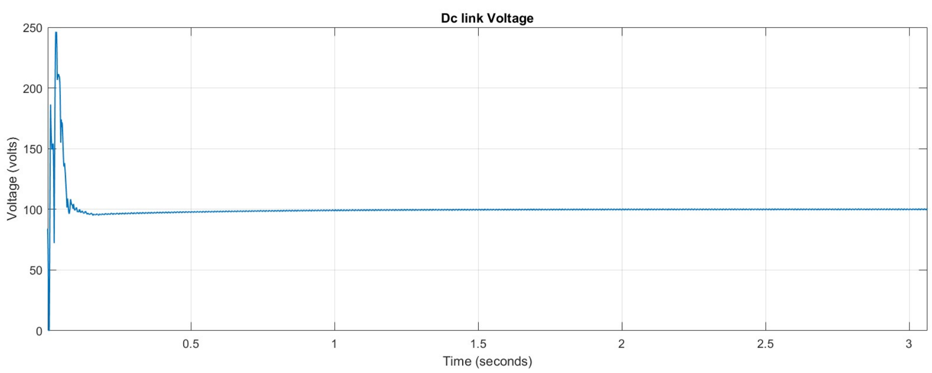

Figure 25. DC link voltage during G2V and V2G and V4G modes

the figure 25 shows that the DC link voltage after 0.6 seconds is stable around the reference value 100V.

3.3.3 Inverter current (I_{inv}) and Reference current ($I_{ref.inv}$):

In order to generates the reference current to drive the inverter the PQ theory is modeled below using MATLAB function see figure Next By employing hysteresis current control in figure 27, the inverter current can accurately track the reference current waveform,swiftly adjusting the switch states to maintain the output current within the desired range .This control technique offers excellent dynamic response, enabling precise and stable current regulation in single-phase inverters.

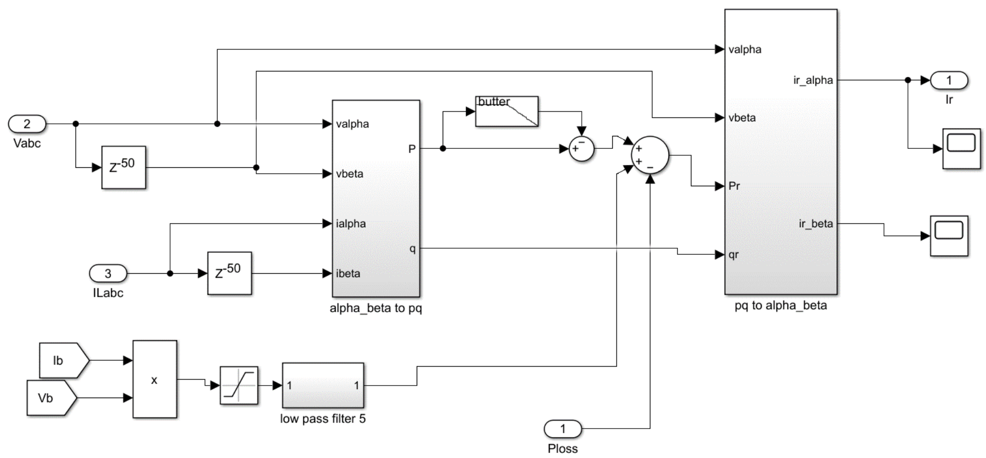

Figure 26. Proposed PQ model

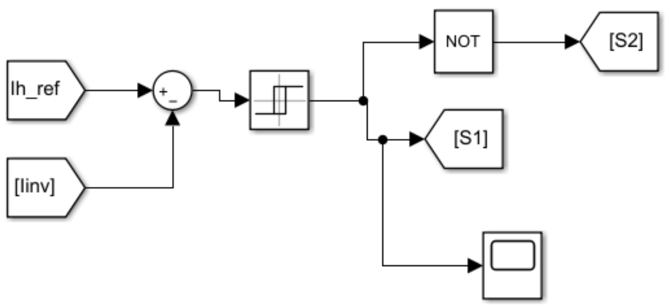

Figure 27. Hysteresis current control diagram HCC

The results of the inverter current and the reference current are shown in the graphs below

G2V mode (charging)

The inverter current and its reference waveform results in the G2V mode is shown in figure28

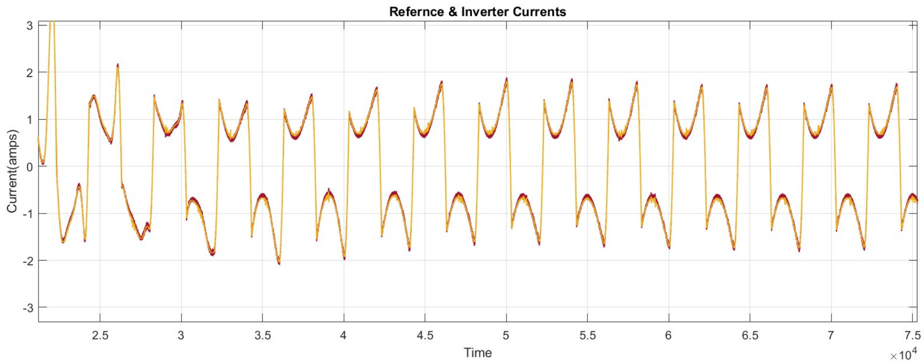

Figure 28. Inverter current and the reference current in G2V mode

V2H mode (Discharging to the load)

The inverter current tracking the reference inverter current in the V2H mode is shown in figure 29

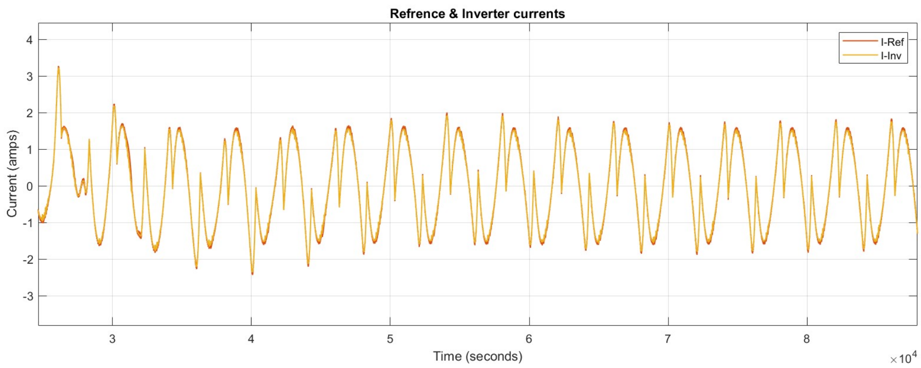

Figure 29. Inverter current and the reference current in V2H mode

V2G mode (Discharging to grid)

The graph in Figure 30 clearly demonstrates the successful tracking of the inverter current with the reference current during the V2G mode.

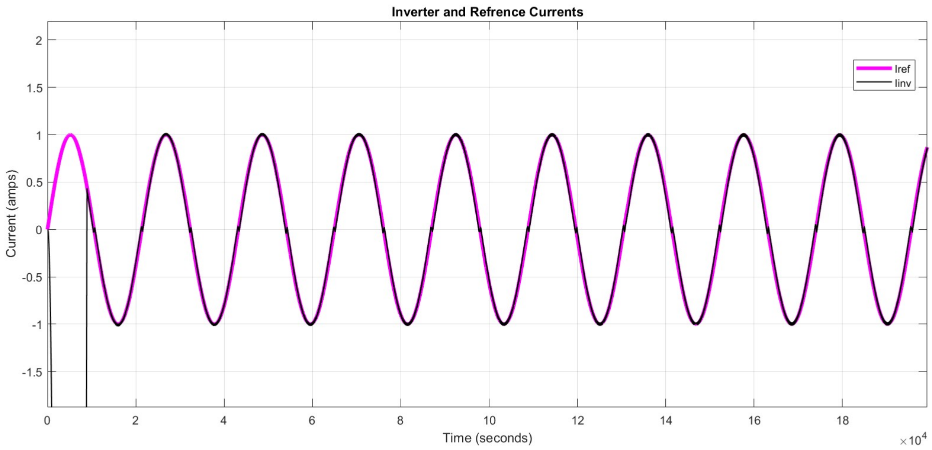

Figure 30. Inverter current tracking reference current in the V2G mode

3.3.4 Load current I_L

The figure 31 below show the behavior of the load current

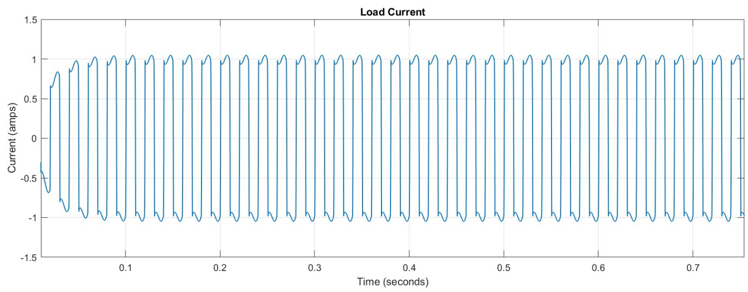

Figure 31. Load current I_l

3.3.5 Total harmonics distortion THD

In order to assess the harmonic content of the signals, a comprehensive analysis using the fast Fourier transform (FFT) is conducted throughout the entire simulation under various stages filtering,charging,discharging. This analysis enables the visualization of the frequency representation and determination of the total harmonic distortion (THD) value associated with the grid current. the simulation results obtained in the three different modes are shown below

G2V mode (charging)

The Grid current THD obtained in the charging mode simulation is about 4.45 % ,which is less than 5 % according to IEEE 519-1992 (figure 32)

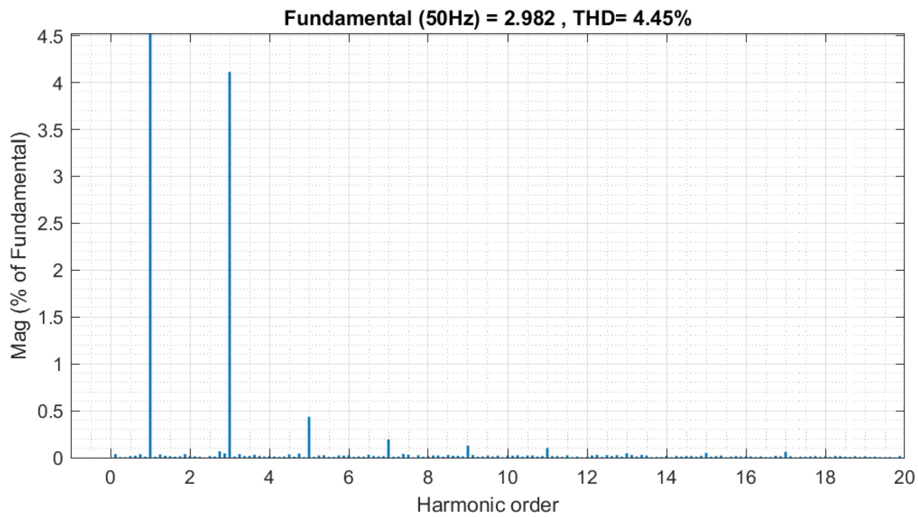

Figure 32. Grid current THD during G2V mode

V2H mode (Discharging to the load)

The Grid current THD obtained in the discharging mode simulation is about 4.06 % ,which is less than 5 % according to IEEE 519-1992 (figure 49)

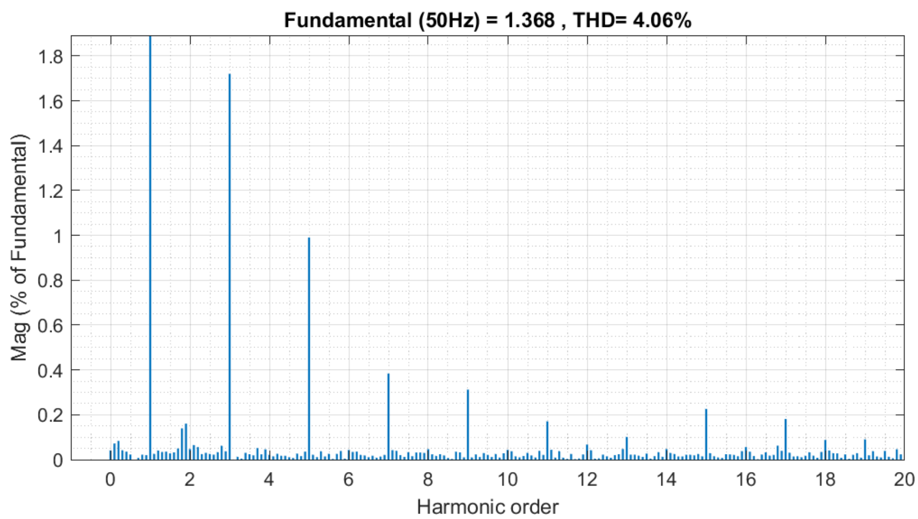

Figure 33. Grid current THD during V2H mode

V4G mode (Filtering)

The Grid current THD obtained in the charging mode simulation is about 3.86 % ,which is less than 5 % according to IEEE 519-1992 (figure 34)

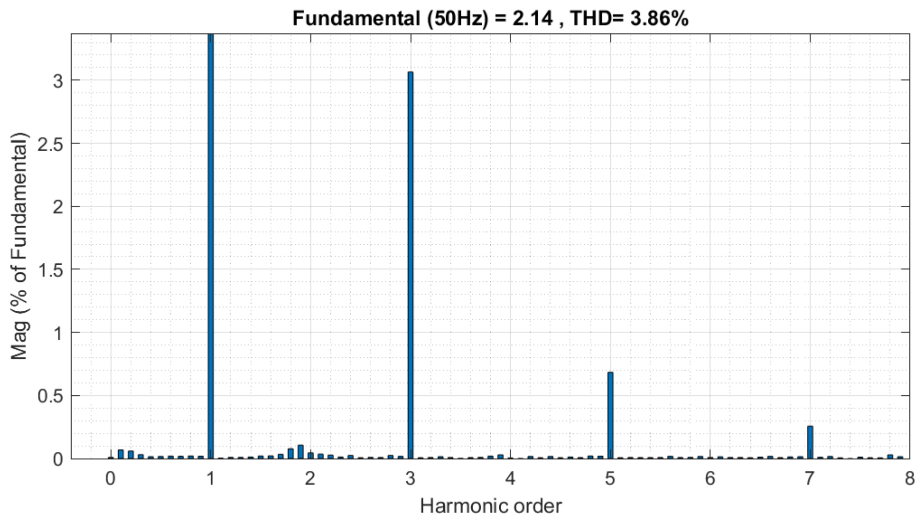

Figure 34. Grid current THD during filtering mode

V2G mode (Discharging to grid)

The Grid current THD obtained in the V2G mode simulation is about 6.22 % (35),which will be improved in future work.

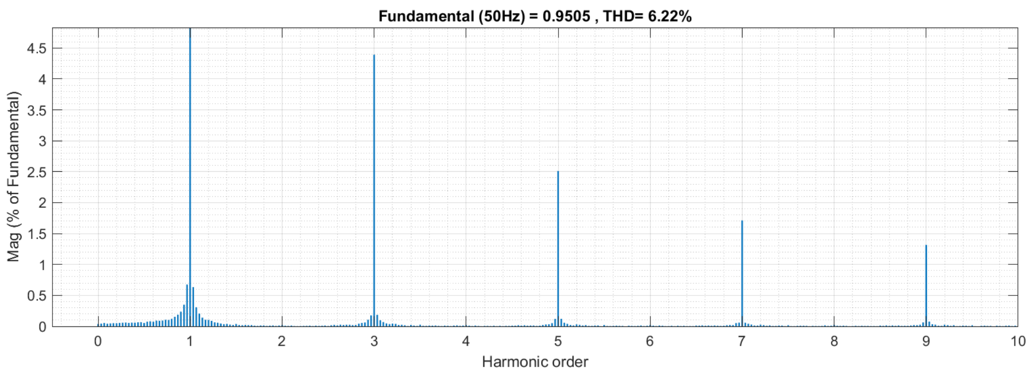

Figure 35. Grid current THD during V2G mode

3.4 Predictive control simulation results

This section shows the simulation result obtained using the predictive control methods (figure:36

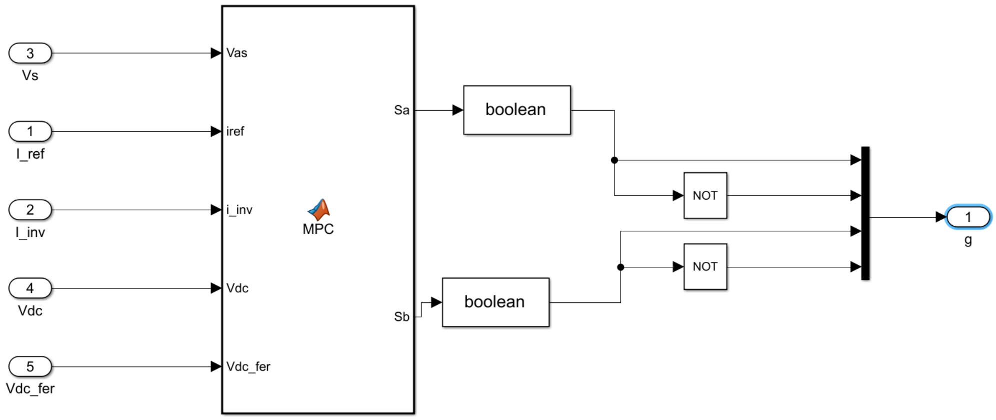

Figure 36. Model predective control modeling

3.4.1 Grid voltage (V_s) and Grid current (I_s):

G2V mode (charging)

The graphs provided bellow figure 37 represents the behavior and characteristics of the Grid voltage and the grid current in the G2V operation mode (charging mode) .

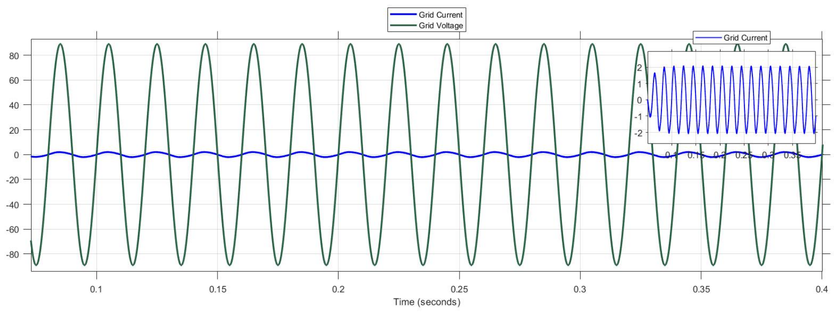

Figure 37. Grid voltage and Grid current during G2V mode

we can deduce that the grid voltage and the grid current are in phase.

V2G mode (Discharging to grid)

The graphs provided bellow figure 38 represents the behavior and characteristics of the Grid voltage and the grid current the V2G mode :

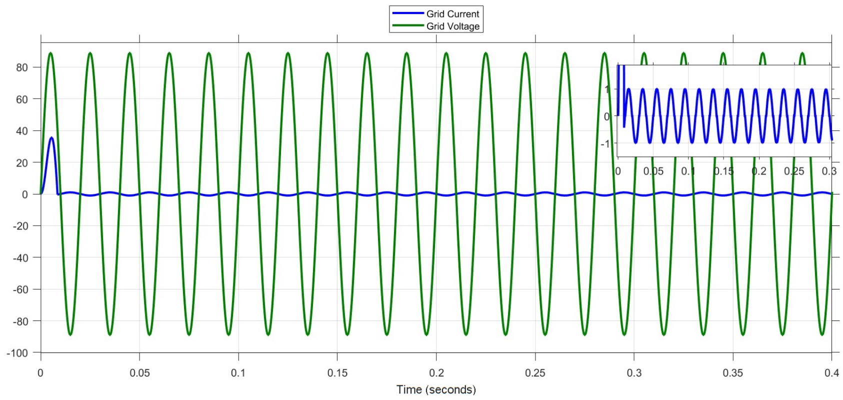

Figure 38. Grid voltage and Grid current during V2G mode

we can deduce from the graph38 that the grid voltage and the grid current are out of phase, which means power is being injected to the grid .

V2H mode (Discharging to the load)

The graphs provided bellow figure 39 represents the behavior and characteristics of the Grid voltage and the grid current in the V2H mode.

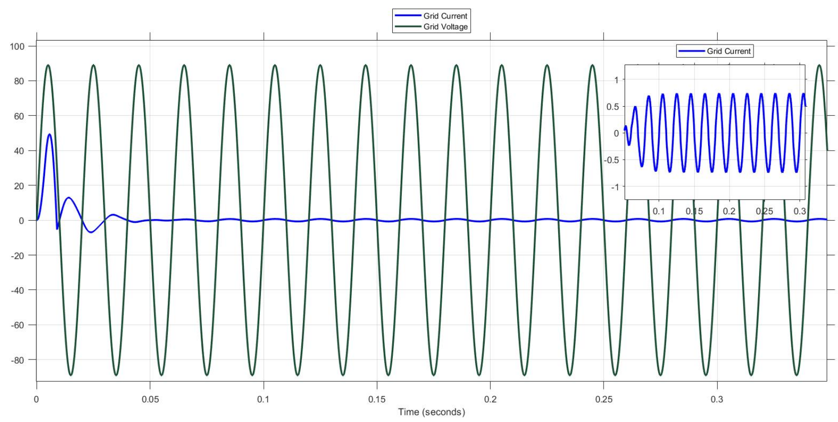

Figure 39. Grid voltage and Grid current during V2H mode

V4G mode (Filtering)

The graphs provided bellow figure 40 represents the behavior and characteristics of the Grid voltage and the grid current the filtering mode :

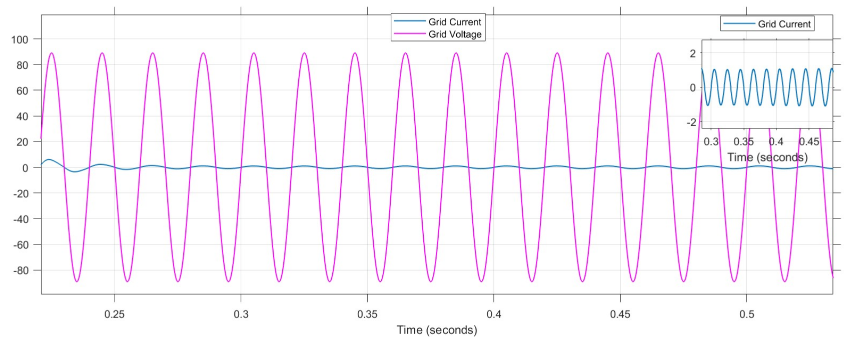

Figure 40. Grid voltage and Grid current during V4G mode

3.4.2 DC link voltage V_{dc}

The DC link voltage is calculated by equation (2.15) the output of the V_{dc} for the three operation modes is shown in the figure below 41.the figure shows the effectiveness of the MPC strategy to regulate the DC voltage to desired value 100V .

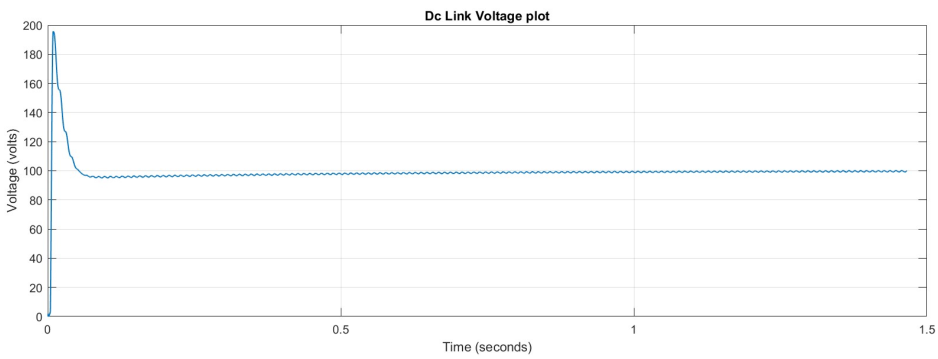

Figure 41. DC link voltage using MPC

3.4.3 Inverter current (I_{inv}) and Reference current ($I_{ref.inv}$):

The reference inverter current is calculated in equation (2.16) the figures below demonstrate the output inverter current tracking the reference current in the three operations modes

G2V mode (Charging)

The figure 42 below shows the successful control of the output inverter current during the charging mode.

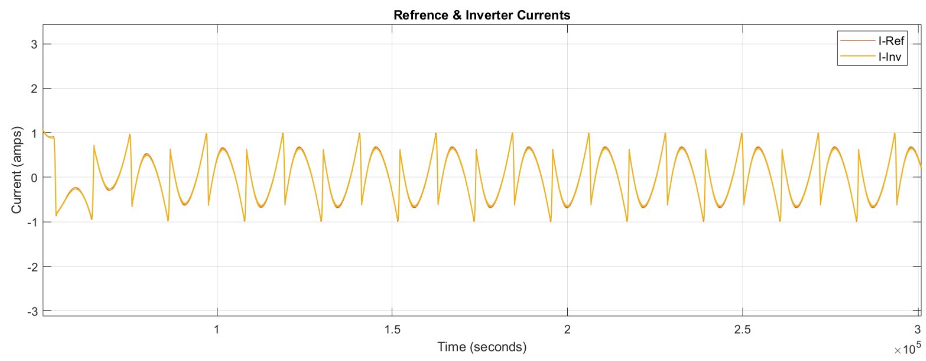

Figure 42. Inverter current tracking references current in the charging mode

V2H mode (Discharging to the load)

The graph in Figure 43 clearly demonstrates the successful tracking of the inverter current with the reference current during the discharging mode.

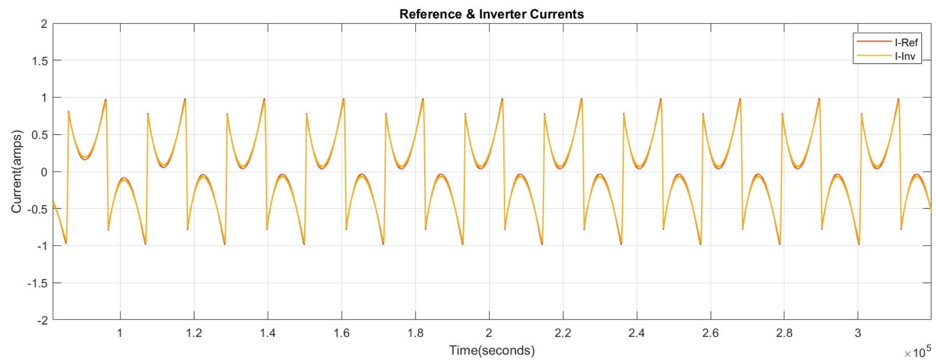

Figure 43. Inverter current tracking reference current in the discharging mode

V2G mode (Discharging to grid)

The graph in Figure 44 clearly demonstrates the successful tracking of the inverter current with the reference current during the V2G mode.

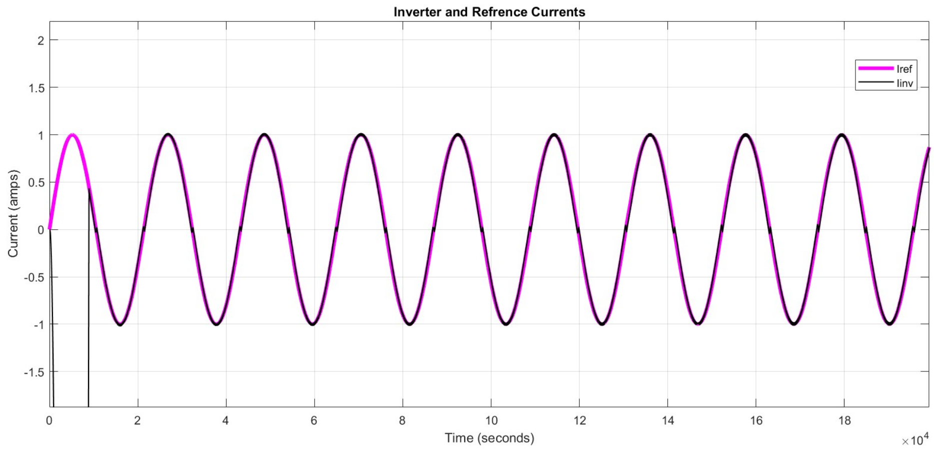

Figure 44. Inverter current tracking reference current in the V2G mode

3.4.4 Load current I_L

The figure 45 shows the results obtained for the load current I_L using predictive control

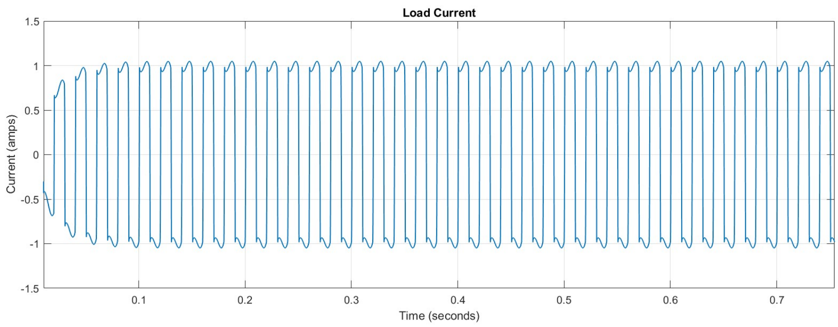

Figure 45. Load current I_L

3.4.5 Total harmonics distortion THD

To evaluate the harmonic content of the signals, a comprehensive analysis employing the fast Fourier transform (FFT) is performed throughout the entire simulation across different stages, namely filtering, charging, and discharging as we have done with HCC control method section. This analysis facilitates the visualization of the frequency representation and allows for the determination of the total harmonic distortion (THD) value associated with the grid current. The simulation results for the three distinct modes are presented using MPC control method below.

Grid to vehicle mode (Charging)

The simulation in the charging mode yielded a grid current THD of approximately 2.34%, which falls below the 5% limit specified by IEEE 519-1992 (see Figure 46).

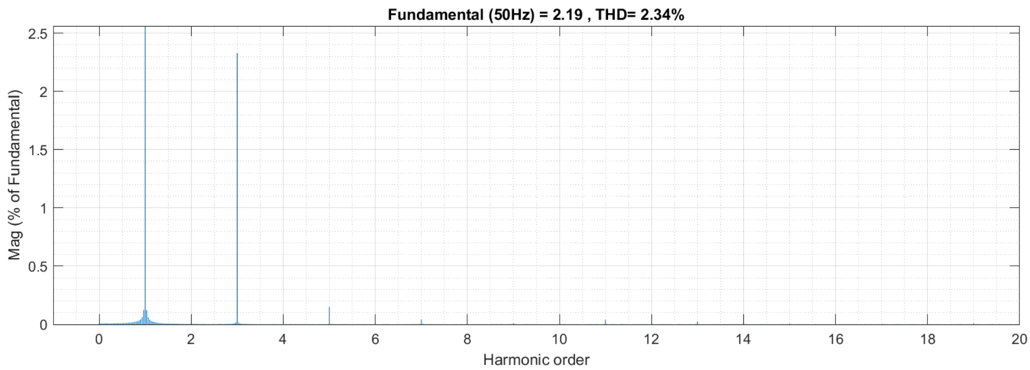

Figure 46. Grid current THD during G2V mode

V2H mode (Discharging to the load)

The simulation results in the discharging mode indicate that the grid current THD is approximately 3.66%, which falls below the threshold of 5% as specified by IEEE 519-1992 (see Figure 47).

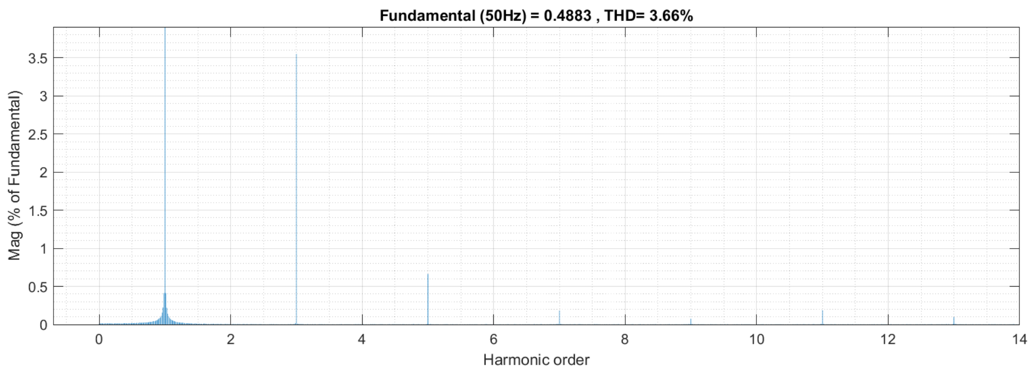

Figure 47. Grid current THD during V2H mode

V4G mode (Filtering)

The Grid current THD obtained in the charging mode simulation is about 1.70 % ,which is less than 5 % according to IEEE 519-1992 (figure 48)

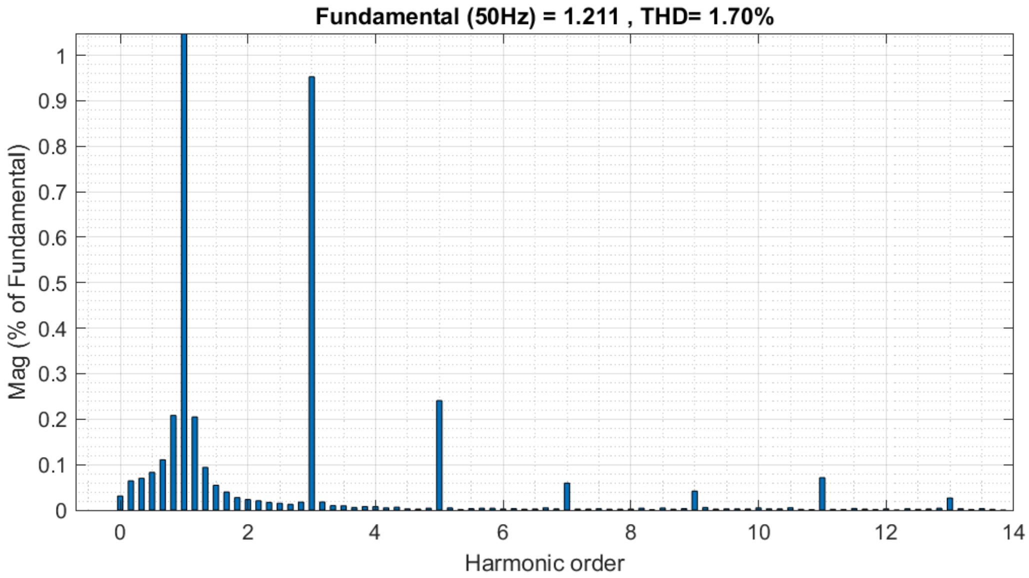

Figure 48. Grid current THD during V4G mode

V2G mode (Discharging to grid)

The Grid current THD obtained in the V2G mode simulation is about 6.22 % (49),which will be improved in future work.

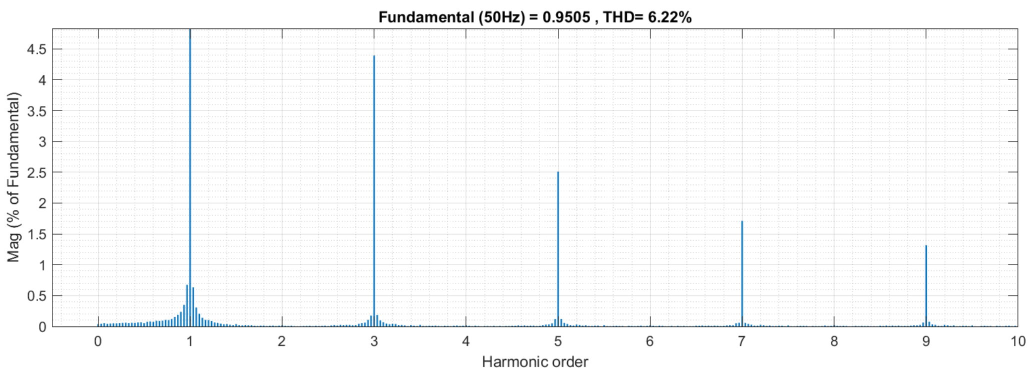

Figure 49. Grid current THD during V2G mode

3.5 Battery simulation results

In flowchart (17, the suggested battery management system functions based on grid availability, power demand, and battery state of charge (SOC). This enables the bidirectional charger to transition between various modes, as depicted in the aforementioned simulation results. Within this section, battery simulation results are presented.

3.6 G2V mode

3.6.1 Battery voltage and current

The figure below shows the characteristics of the battery voltage during the G2V mode (from 0s to 2.8s) is CC charging mode, then in CV charging mode the battery voltage increases to its corresponding reference voltage 12.8 V.

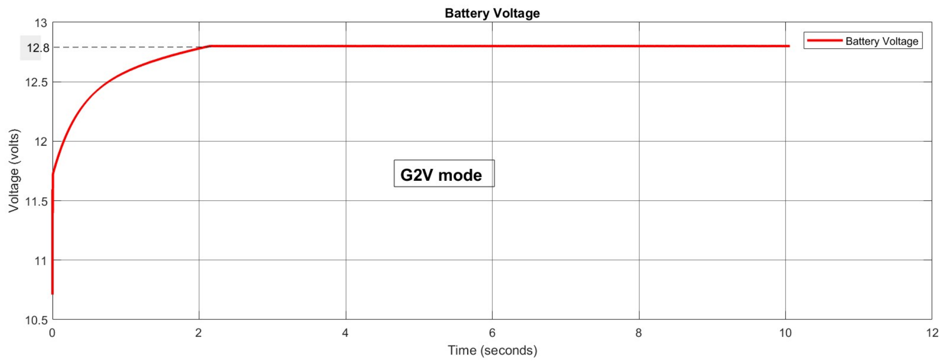

Figure 50. Battery voltage during G2V

The figure 51 below shows the characteristics of the battery current during G2V mode, current is constant in CC mode and it decreases in CV mode.

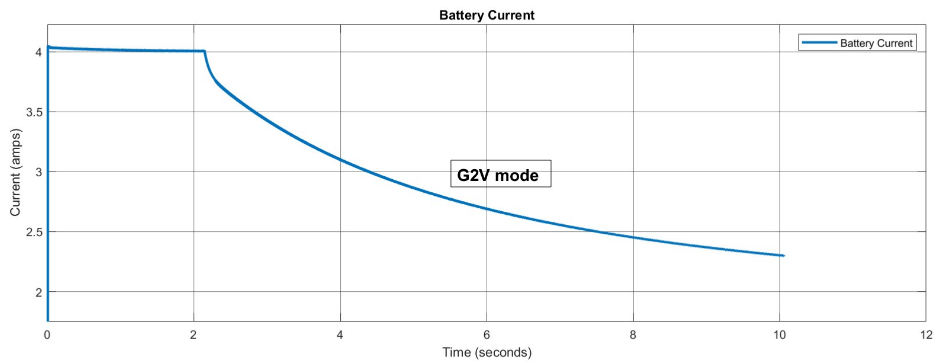

Figure 51. Battery current during G2V mode

3.6.2 Battery SOC in G2V mode

The figure below illustrate the battery state (SOC) during the charging mode (G2V) the

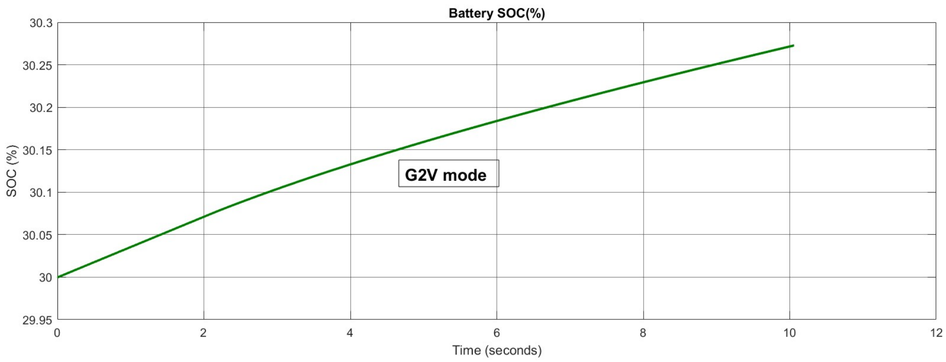

Figure 52. SOC during G2V mode

graph clearly shows that during the charging mode the SOC increases with the time

3.6.3 Active power in G2V mode

For the G2V mode, the active power results illustrate the system's capability to receive power from the grid and charge the EV battery. The measurements offer valuable information about the efficiency and effectiveness of the charging process, including any losses or deviations from the desired power transfer.
The figure 53 shows the obtained results for the active power during discharging mode (G2V)

$$P_{grid} = P_{Demand} - P_{Injected} \tag{3.1}$$

where:
Pgrid is the grid power.
Pdemand is the load power.
Pabsorbed is the power absorbed by the EV battery.

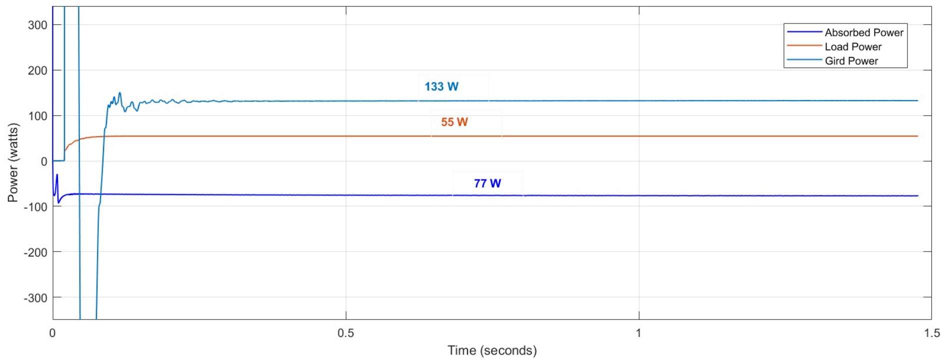

Figure 53. Active power during G2V mode

3.7 V2H and V4G modes

3.7.1 Battery voltage and current

The figure 54 below shows the characteristics of the battery voltage during the filtering mode (from 0s to 2.8s) and the V2H mode(from 2.8s to 8s), during the filtering mode the battery voltage is constant at open circuit voltage, then when it is switched to the discharging mode (V2H) at t=2.8s the battery voltage decrease with the time.

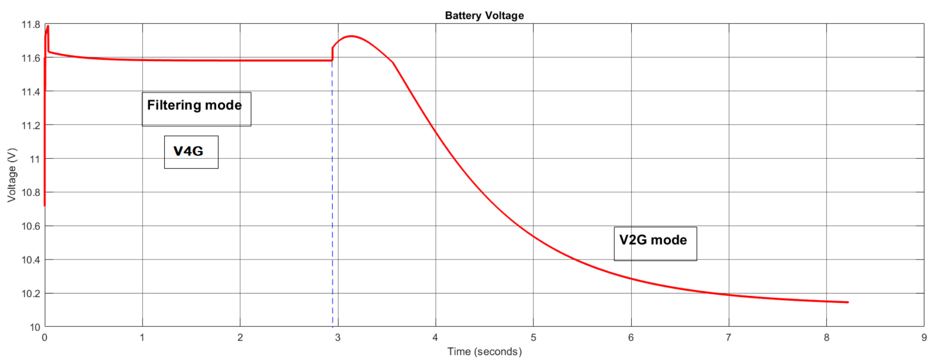

Figure 54. Battery voltage during filtering (V4G) and V2H mode

The graph depicted in Figure 55 illustrates that while operating in the filtering mode, the current remains steady at 0 A. However, upon switching to the (V2H) discharging mode at t=2.8s, the battery current gradually drop over time until it reaches its reference discharging value.

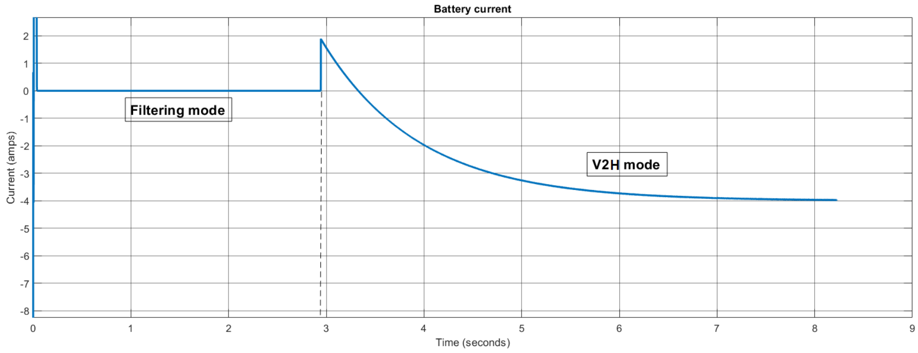

Figure 55. Battery current during V4G and V2H

3.7.2 SOC in V2H and V4G modes

The graph shown in figure 56 shows the SOC behaviour in V2H and V4G modes.

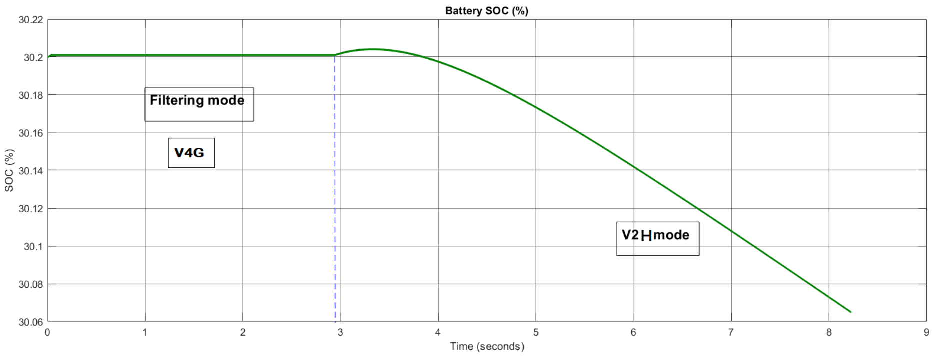

Figure 56. SOC during V2H and V4G mode

The figure 56 shows clearly that the battery SOC remains constant at 30.22% during filtering mode until it switches to the V2H mode at t=2.8s where it drops down due to the discharging of the battery.

3.7.3 Active power in V2H and V4G mode

In the V2H mode, the results demonstrate the ability of the system to extract power from the electric vehicle (EV) battery and supply it back to the grid. The active power measurements provide insights into the efficiency and accuracy of the bidirectional power flow control algorithm during V2H operation where

$$P_{grid} = P_{demand} + P_{absorbed} \tag{3.2}$$

Furthermore, the results for the Filtering mode showcase the system's performance in mitigating power quality issues and reducing harmonics. The active power measurements provide an understanding of the system's ability to filter out unwanted frequencies and maintain a stable and high-quality power supply. The figure 57 shows the obtained results for the active power during V2H mode.

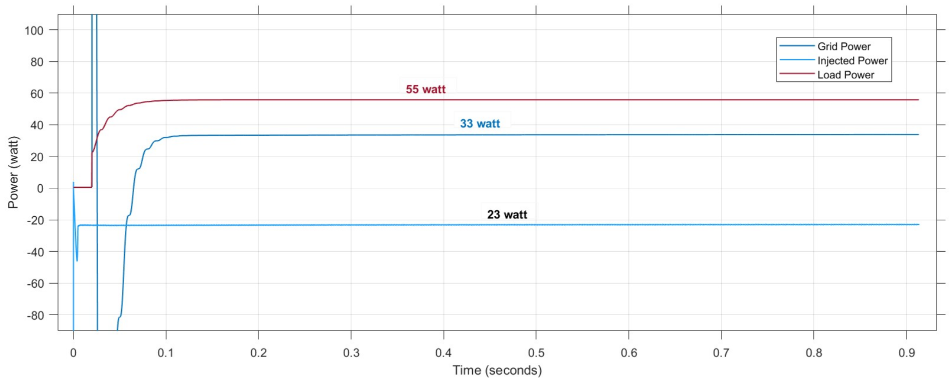

Figure 57. Active power during V2H mode

3.8 V2G mode

3.8.1 Battery voltage and current

the figure 58 demonstrate the behaviour of the battery voltage during the discharging V2G mode.

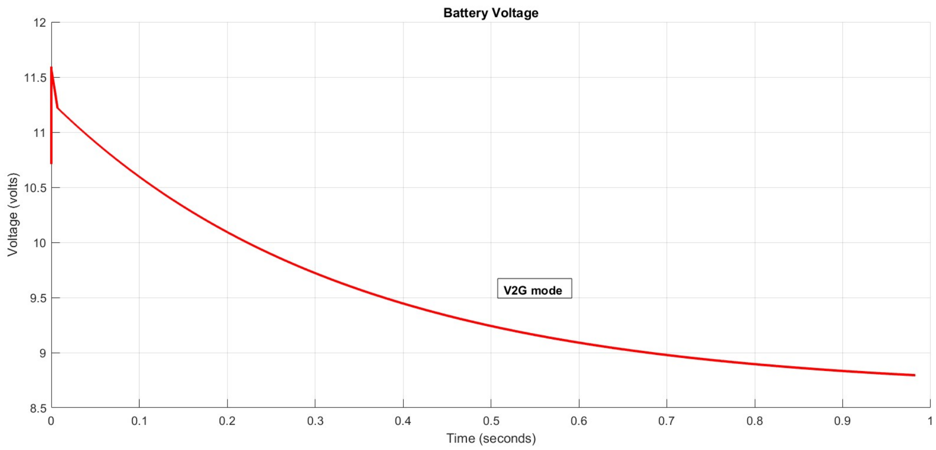

Figure 58. Battery voltage during V2G

The graph depicted in Figure 59 shows the battery current behavior during the V2G discharging mode where current is constant at its reference discharging value.

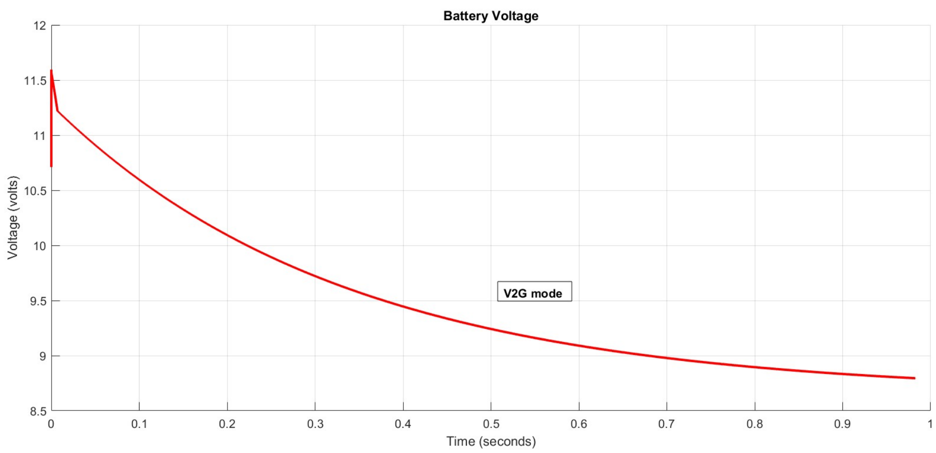

Figure 59. Battery current during V2G

3.8.2 SOC in V2G mode

The figure bellow shows the battery SOC during the V2G mode In this operation mode the

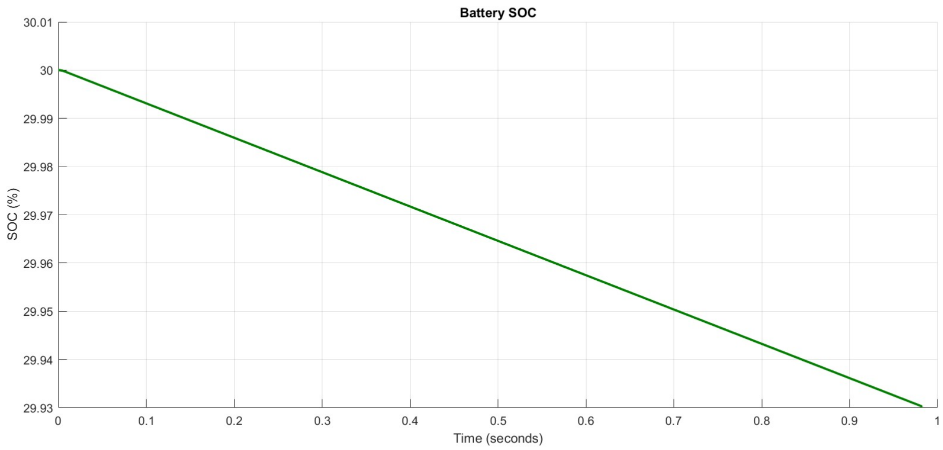

Figure 60. SOC during V2G mode

SOC decreases since the power flow is from the battery to the grid

3.8.3 Active power in V2G mode

In the V2G mode, the results demonstrate the ability of the system to inject power from the electric vehicle (EV) battery to the grid. The active power measurements provide insights into the efficiency and accuracy of the bidirectional power flow control algorithm during V2G operation where

$$P_{grid} = P_{injected} - P_{loss} \tag{3.3}$$

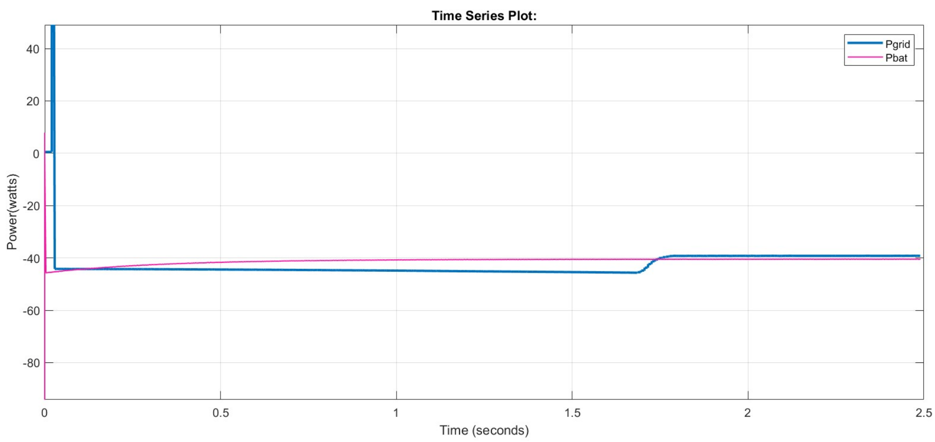

Figure 61. Active power during V2G mode

By analyzing the active power results in these different operation modes, a comprehensive assessment of the system's performance and its suitability for various applications can be made. These results contribute to the understanding of the system's capabilities and form a basis for further improvements and optimizations in future implementations.

3.9 Conclusion

In this chapter, we have presented the results obtained from two control techniques: HCC and MPC. The presentation begins with an overview of the outcomes achieved using the first control technique, HCC, followed by a discussion of the results obtained with the second technique, MPC. The analysis encompasses various parameters, including Grid voltage, Grid current, DC-link voltage, and Inverter current, for the four operations modes: V2G, G2V,V2H and V4G. Additionally, performance evaluation is conducted by calculating the total harmonic distortion (THD). In addition, This chapter has extensively examined and presented the results of active power flow for all operation modes: Vehicle-to-Grid (V2G), Grid-to-Vehicle (G2V),Vehicle-to-Home and Filtering (V4G). The analysis of these results provides valuable insights into the performance and effectiveness of the system in each mode. In the upcoming chapter, we will further explore the results obtained from real-world scenarios, following the same methodology as the simulation phase.

Hardware implementation results

4. Hardware implementation results

the hardware implementation results shed light on the charger's performance as a shunt active filter in terms of harmonic content, power factor, and voltage regulation. These factors are critical in ensuring compatibility with the grid, minimizing power quality issues, and complying with relevant standards and regulations. By examining the harmonic distortion, power factor, and voltage regulation achieved by the bidirectional charger, we gain valuable insights into its compliance with grid codes and its impact on the overall power quality. In this section, we present the results obtained from the hardware implementation of a bidirectional charger using two control methods HCC and MPC, focusing on its performance and effectiveness in real-world scenarios. The hardware implementation serves as a validation platform for assessing the charger's capabilities and evaluating its efficiency and reliability. for that we have used Real Time Unit (Utech) that is compatible with Matlab/Simulink for computation, and control signals generating. for data acquisition we have used two voltage sensors and three current sensors, Oscilloscope for signal visualisation, single phase AC power source, smoothing inductor and power converter.

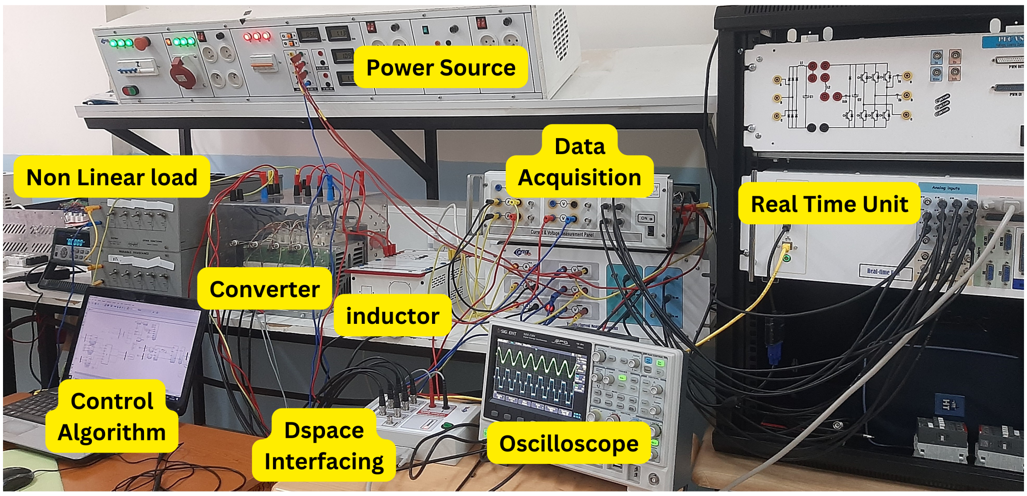

Figure 62. HARDWARE IMPLEMENTATION

4.1 Hysteresis current control (HCC) implementation results:

This section shows the implementation results obtained when the charger is used as a shunt active power filter (SAPF)

4.1.1 Grid voltage (V_s):

The graph provided bellow fig: 63 represents the behavior and characteristics of the Grid voltage

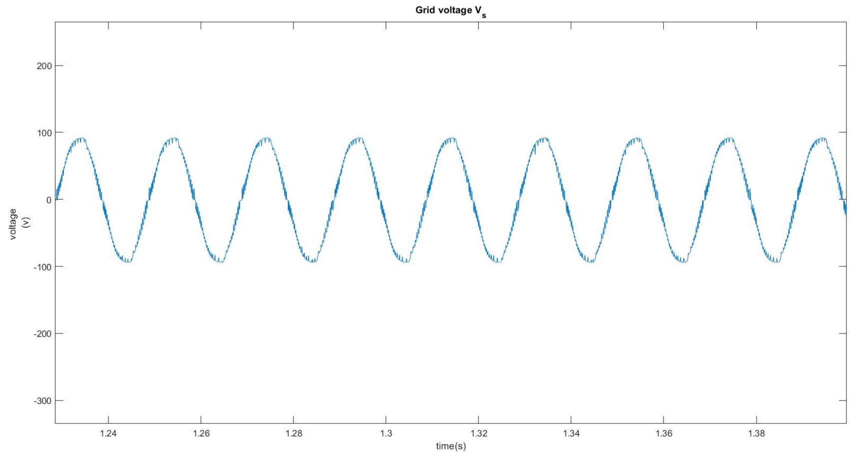

Figure 63. Grid Voltage (Vs)

4.1.2 Grid current (I_s):

The graph provided below fig: 64 illustrates the behavior and characteristics of the grid current during the filtering

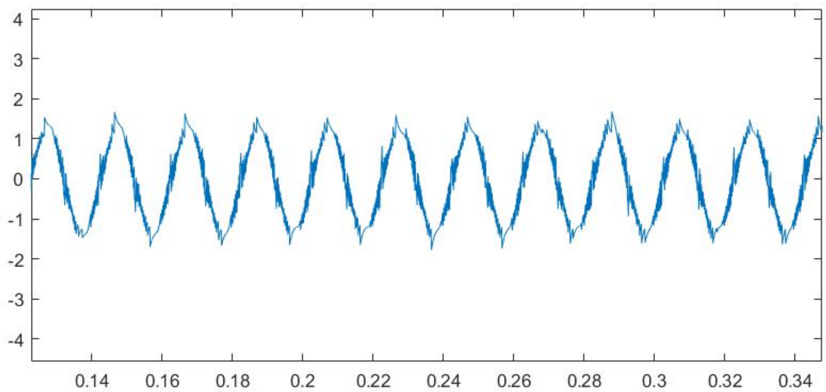

Figure 64. Grid current (Is)

4.1.3 DC link voltage (V_{dc})

The results of the dc link voltage V_{dc} is shown in fig 65 during the Filtering

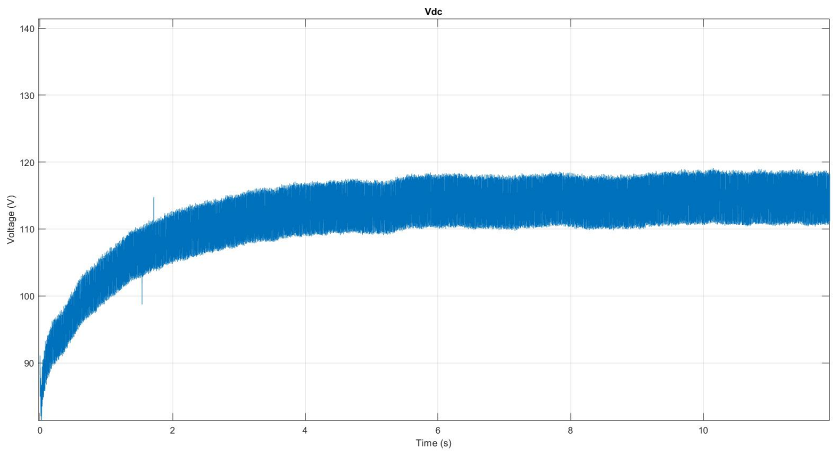

Figure 65. DC link Voltage V_{dc}

the figure 65 shows that the DC link voltage after is stable around the value 110V near to the reference value; Now after finding the regulated dc link voltage (V_{dc}) we can use its value to determine the hysteresis reference current in order to control the AC-DC converter.

4.1.4 Inverter current (I_{inv}) and Reference current ($I_{ref.inv}$):

We can clearly observe that the inverter current precisely tracks the reference current, providing strong evidence of the effective functioning of the control algorithm.67

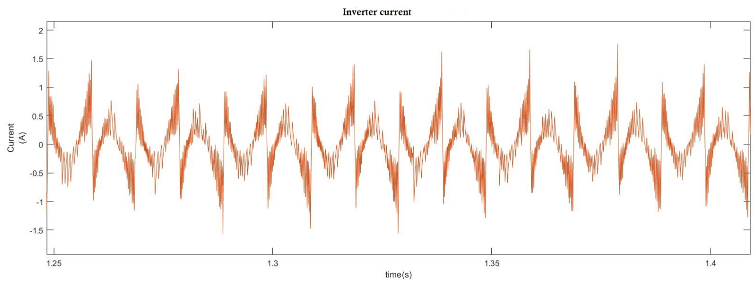

Figure 66. Inverter current waveform

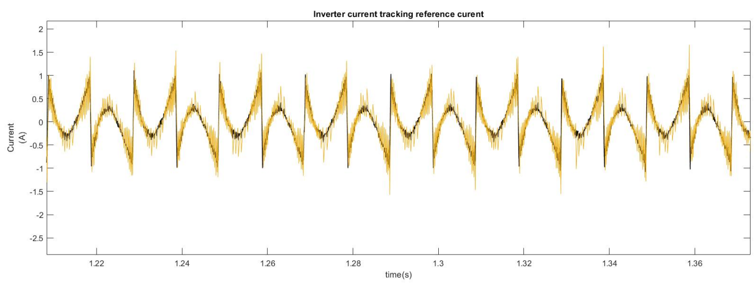

Figure 67. Inverter current tracking reference current I_{ref}

4.1.5 Load current

The figure 75 shows the load current obtained using the HCC control strategy in the filtering mode

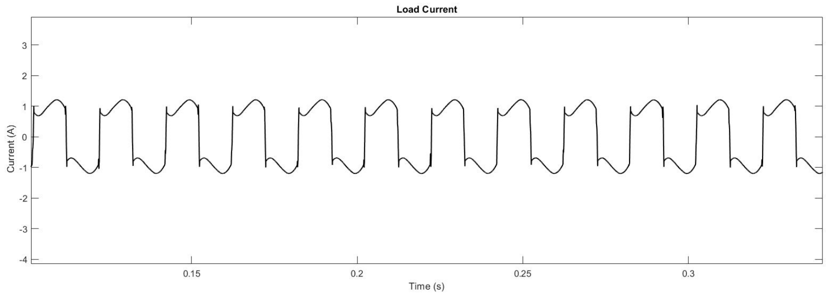

Figure 68. Load current

4.1.6 Total harmonics distortion

The Grid current THD obtained in the hardware implementation in the filtering stage is about 4.43 % ,which is less than 5 % according to IEEE 519-1992 (Figure69)

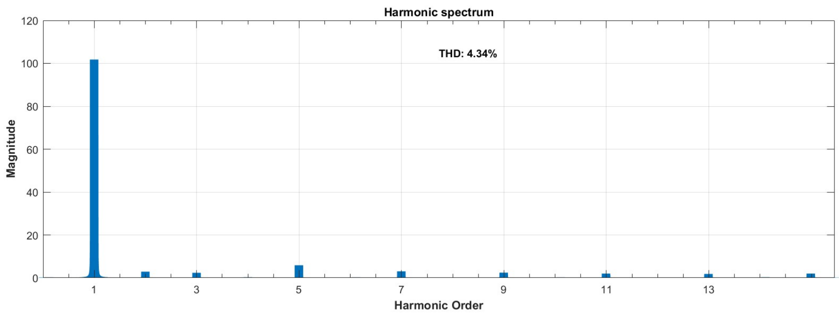

Figure 69. Grid current THD during the filtering mode

4.2 Predictive control hardware implementation results

After showing the implementation results for the HCC control methods now in this section we will present the results obtained from using the predictive control method (MPC)

4.2.1 Grid voltage (V_s):

The graph provided bellow fig: 70 represents the behavior and characteristics of the Grid voltage

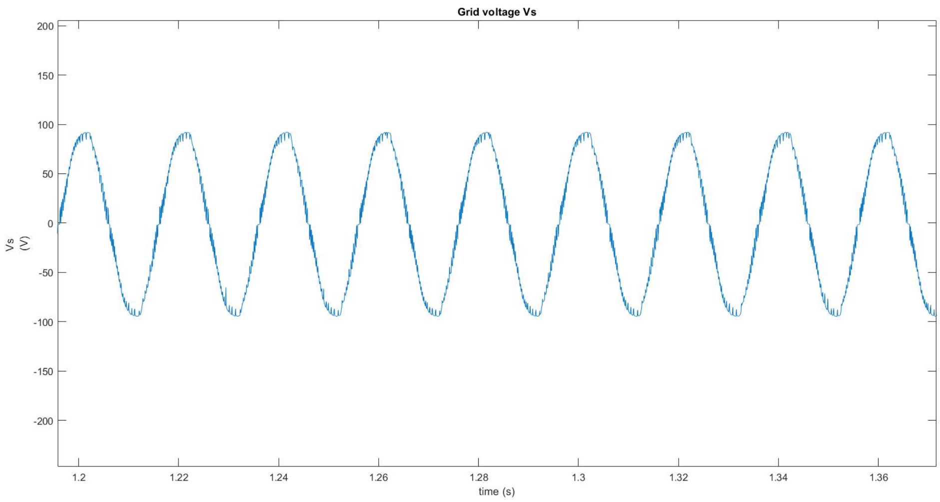

Figure 70. Grid Voltage (Vs)

4.2.2 Grid current (I_s):

The graph provided below fig: 64 illustrates the behavior and characteristics of the grid current during the filtering

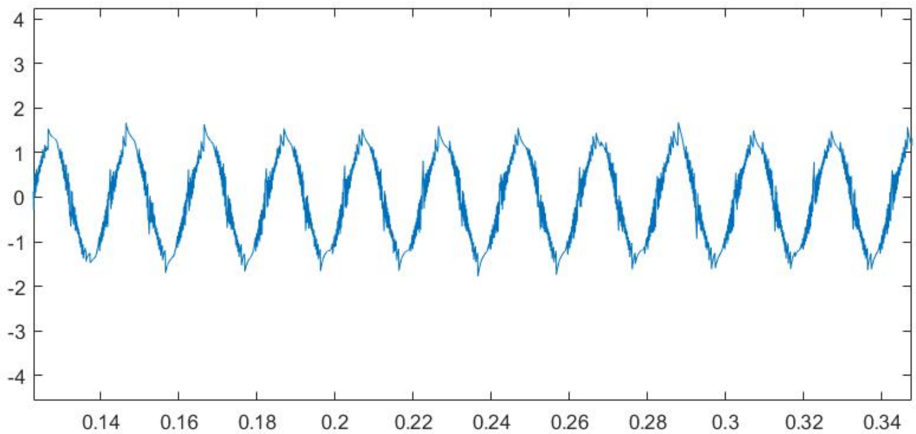

Figure 71. Grid current (Is)

4.2.3 DC link voltage (V_{dc})

The results of the dc link voltage V_{dc} is shown in fig 65 during the Filtering

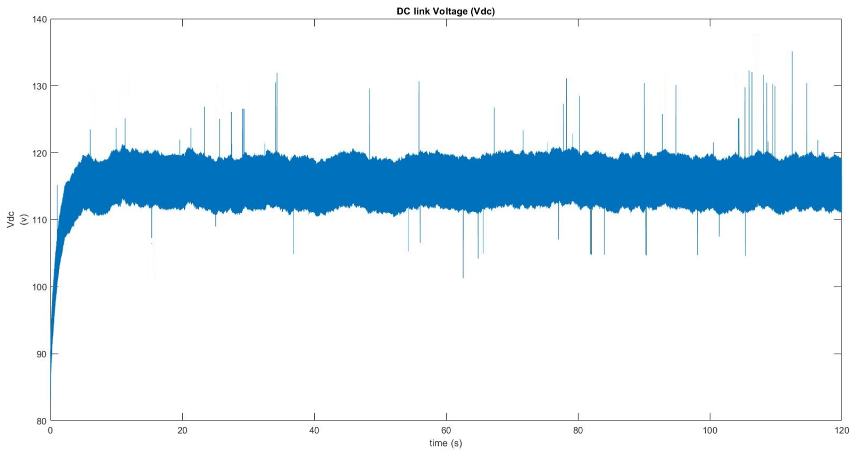

Figure 72. DC link Voltage V_{dc}

the figure 72 shows that the DC link voltage after is stable around the value 110V near to the reference value this results validate the effectiveness of our control method.

4.2.4 Inverter current (I_{inv}) and Reference current ($I_{ref.inv}$):

The output wave forms for the current inverter and its reference when the charger works as a filter are presented below it can be seen clearly in graph 74 that the inverter current is well tracking the reference current this result validates the selected control system.

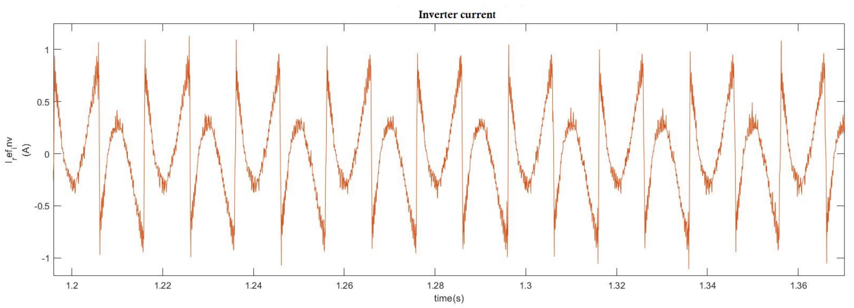

Figure 73. Inverter current waveform

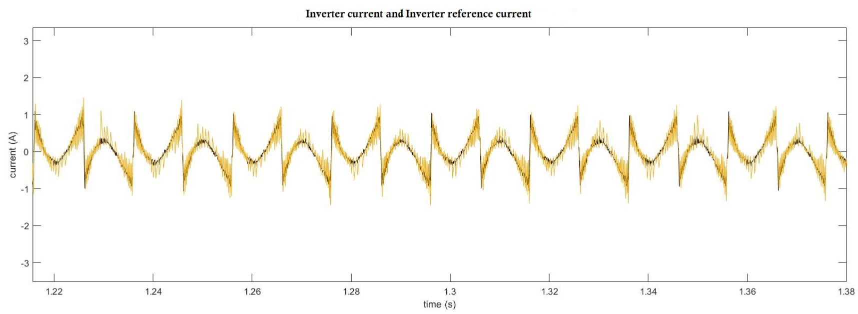

Figure 74. Inverter current tracking reference current I_{ref}

4.2.5 Load current

The figure 75 shows the load current obtained using the HCC control strategy in the filtering mode.

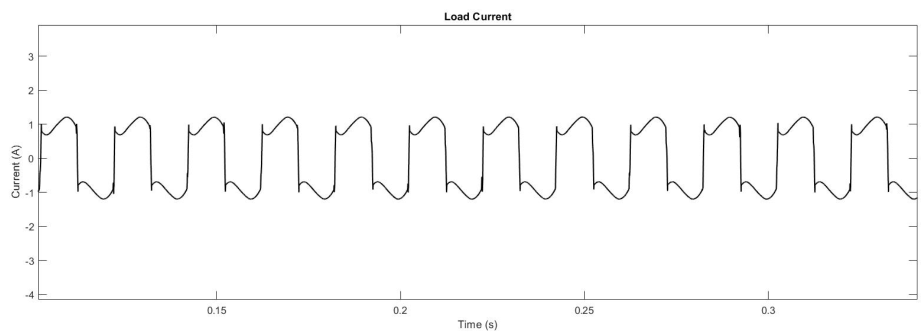

Figure 75. Load current

4.2.6 Total harmonics distortion

The Grid current THD obtained in the hardware implementation in the filtering stage is about 3.41 % ,which is less than 5 % according to IEEE 519-1992 (Figure69)

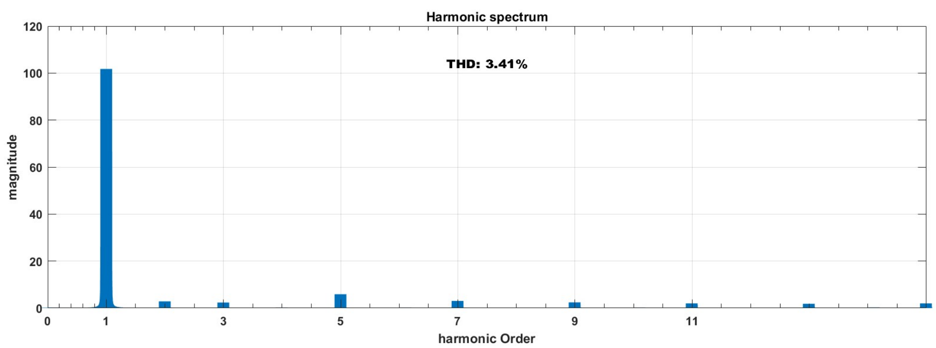

Figure 76. Grid current THD during the filtering mode

4.3 Comparison and Discussion

The table below compare the two control methods results in both simulation and implementation for different operation modes;

Table 4. Simulation and implementation results for THD

	Total harmonics distortion %				
	simulation				implementation
Operation modes / Control method	G2V	V2G	V4G	V2H	V4G
HCC	4.45%	6.22%	3.86%	4.06%	4.34%
MPC	2.34%	6.22%	1.70%	3.66%	3.41%

The table shows that the simulation and implementation results obtained using the predictive control (MPC) are better than the results obtained from using HCC control for the four operation modes.

4.4 Conclusion

this chapter has presented the hardware implementation of EV bidirectional charger in the V4G mode.the same control algorithms HCC and MPC has been utilized to control the inverter in real world scenarios.This hardware implementation has validated the effectiveness of the modeled control algorithms in terms of power quality improvement.

Conclusion

In conclusion, this master thesis has addressed the pressing global concerns surrounding greenhouse gas (GHG) emissions and environmental pollutants resulting from the use of internal combustion engine vehicles (ICEVs). The need for technological advancements to mitigate these detrimental environmental impacts has motivated nations worldwide to explore solutions, with electric vehicles (EVs) emerging as a promising alternative.

This study has focused on the design and implementation of an EV bidirectional charger, emphasizing its crucial role in enabling two-way power flow. By allowing EVs not only to draw power from the grid but also to feed excess energy back into it, the bidirectional charger contributes to optimized energy usage and reduced environmental impact. The architecture of the EV bidirectional charger comprises two stages: the AC-DC inverter and the DC-DC converter. The AC-DC inverter serves the dual purpose of converting AC power to DC power for battery charging and acting as a shunt active filter to generate compensating current. Two control methods, namely hysteresis current control (HCC) and model predictive control (MPC), have been utilized to regulate the operation of the AC-DC inverter effectively. The second stage, the DC-DC converter, enables bidirectional flow of active power. In this study, a control algorithm has been designed using MATLAB/Simulink to manage the operation of the DC-DC converter. During the charging mode, the DC-DC converter functions as a buck converter, while during the discharging mode, it operates as a boost converter. Simulation results obtained using HCC and MPC control methods have been extensively analyzed and compared. Through this evaluation, it has been determined that the MPC method consistently achieves superior performance in terms of efficiency and control accuracy the simulation results . Real-world implementations have further validated the efficacy of the proposed bidirectional charger design, supporting its practical feasibility . By demonstrating the benefits of bidirectional chargers and providing insights into their control strategies, this master thesis contributes to the existing body of knowledge in EV charging infrastructure. The findings presented herein offer valuable guidance for optimizing energy management and mitigating environmental impact. It is anticipated that the integration of bidirectional chargers into the EV ecosystem, encompassing both the AC-DC inverter and the DC-DC converter, will play a significant role in fostering sustainable transportation and a greener future.

For future work, several avenues can be explored.Further research can focus on the development and implementation of advanced control algorithms that enhance the efficiency and reliability of bidirectional chargers. Additionally, studies can be conducted to investigate the integration of renewable energy sources into the smart grid ecosystem, leveraging their potential for sustainable charging solutions. Moreover, exploring the optimization of charging infrastructure design and deployment strategies can contribute to seamless integration and operation of EVs in smart grids. This includes considering factors such as grid capacity, load balancing, and the development of intelligent charging scheduling algorithms. the study of vehicle-to-grid (V2G) technologies and their potential for bidirectional power flow between EVs and the grid holds promise for future research. V2G and V2H systems can enable EVs to act as distributed energy resources, supporting grid stability and offering opportunities for grid services.

References

[1] Vítor Monteiro, J. G. Pinto, and João Luiz Afonso. "Operation Modes for the Electric Vehicle in Smart Grids and Smart Homes: Present and Proposed Modes". In: *IEEE Transactions on Vehicular Technology* 65.3 (2016), pp. 1007–1020. DOI: 10.1109/TVT.2015.2481005.

[2] Vivian Sultan et al. "Integration of EVs into the smart grid: a systematic literature review". In: *Energy Informatics* 5.1 (2022), pp. 1–28.

[3] Bijan Bibak and Hatice Tekiner-Moğulkoç. "A comprehensive analysis of Vehicle to Grid (V2G) systems and scholarly literature on the application of such systems". In: *Renewable Energy Focus* 36 (2021), pp. 1–20.

[4] Mohamed E El-Hawary. "The smart grid—state-of-the-art and future trends". In: *Electric Power Components and Systems* 42.3-4 (2014), pp. 239–250.

[5] Narayan Bhusal et al. "Power system resilience: Current practices, challenges, and future directions". In: *Ieee Access* 8 (2020), pp. 18064–18086.

[6] BR Madhu, Dinesh Mn, and Ravitheja Bm. "Design of shunt hybrid active power filter (SHAPF) to reduce harmonics in AC side due to Non-linear loads". In: *International Journal of Power Electronics and Drive Systems* 9.4 (2018), pp. 19–26.

[7] KV Suslov, VS Stepanov, and NN Solonina. "Smart grid: effect of high harmonics on electricity consumers in distribution networks". In: *2013 International Symposium on Electromagnetic Compatibility*. IEEE. 2013, pp. 841–845.

[8] Colin Bayliss and Brian Hardy. *Transmission and distribution electrical engineering*. Elsevier, 2012.

[9] Yi Tang et al. "Generalized design of high performance shunt active power filter with output LCL filter". In: *IEEE Transactions on Industrial Electronics* 59.3 (2011), pp. 1443–1452.

[10] Sayed Saeed Hosseini, Ali Badri, and Masood Parvania. "The plug-in electric vehicles for power system applications: The vehicle to grid (V2G) concept". In: *2012 IEEE International Energy Conference and Exhibition (ENERGYCON)*. IEEE. 2012, pp. 1101–1106.

[11] Minho Kwon, Sehyung Jung, and Sewan Choi. "A high efficiency bi-directional EV charger with seamless mode transfer for V2G and V2H application". In: *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*. IEEE. 2015, pp. 5394–5399.

[12] Murat Yilmaz and Philip T Krein. “Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles”. In: *IEEE transactions on Power Electronics* 28.5 (2012), pp. 2151–2169.

[13] Salah Alatai et al. “A Review on State-of-the-Art Power Converters: Bidirectional, Resonant, Multilevel Converters and Their Derivatives”. In: *Applied Sciences* 11.21 (2021), p. 10172.

[14] Zhengming John Zhang and Premanand Ramadass. “Lithium-ion battery systems and technology”. In: *Batteries for Sustainability: Selected Entries from the Encyclopedia of Sustainability Science and Technology*. Springer, 2012, pp. 319–357.

[15] DAJ Rand and PT Moseley. “Lead–acid battery fundamentals”. In: *Lead-Acid Batteries for Future Automobiles*. Elsevier, 2017, pp. 97–132.

[16] Kazunori Ozawa. *Lithium ion rechargeable batteries: materials, technology, and new applications*. John Wiley & Sons, 2012.

[17] M.S. Alam, R.K. Pillai, and N. Murugesan. *Developing Charging Infrastructure and Technologies for Electric Vehicles*. Advances in Mechatronics and Mechanical Engineering. IGI Global, 2021. ISBN: 9781799868606. URL: https://books.google.dz/books?id=oG9bEAAAQBAJ.

[18] Jia Ying Yong et al. “A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects”. In: *Renewable and sustainable energy reviews* 49 (2015), pp. 365–385.

[19] Mithat C Kisacikoglu, Metin Kesler, and Leon M Tolbert. “Single-phase on-board bidirectional PEV charger for V2G reactive power operation”. In: *IEEE Transactions on Smart Grid* 6.2 (2014), pp. 767–775.

[20] Metin Kesler, Mithat C Kisacikoglu, and Leon M Tolbert. “Vehicle-to-grid reactive power operation using plug-in electric vehicle bidirectional offboard charger”. In: *IEEE Transactions on Industrial Electronics* 61.12 (2014), pp. 6778–6784.

[21] José M Maza-Ortega et al. “Ancillary services in hybrid AC/DC low voltage distribution networks”. In: *Energies* 12.19 (2019), p. 3591.

[22] Bhim Singh et al. “A review of single-phase improved power quality AC-DC converters”. In: *IEEE Transactions on industrial electronics* 50.5 (2003), pp. 962–981.

[23] Math HJ Bollen. “Understanding power quality problems”. In: *Voltage sags and Interruptions*. IEEE press Piscataway, NJ, USA, 2000.

[24] Jose Rodriguez et al. “State of the Art of Finite Control Set Model Predictive Control in Power Electronics”. In: *IEEE Transactions on Industrial Informatics* 9.2 (2013), pp. 1003–1016. DOI: 10.1109/TII.2012.2221469.