**ADDIS ABABA UNIVERSITY**

**ADDIS ABABA INSTITUTE OF TECHNOLOGY**

**SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING**


# Developing a bidirectional smart charging station for the benefit of Electric utility and electric vehicle owners in Addis Ababa.

A thesis Submitted to Addis Ababa Institute of Technology, School of Graduate Studies, Addis Ababa University

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ELECTRICAL POWER ENGINEERING

By


Habtamu Beyene Bewnetu

Advisor: Dawit Habtu (PhD)


October 2024

Addis Ababa, Ethiopia

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APPROVAL BY BOARD OF EXAMINERS

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## DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree at this or other universities. I have fully acknowledged all the sources for the materials used in this thesis work.

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Date of submission: ___________________________

This thesis has been submitted for examination with my approval as a university advisor.

Dawit Habtu (PhD) ______________________

Advisor's Name Signature

## AKNOWLEDMENT

First of all, I would like to say thanks to the almighty God, without whom the completion of this work would have been impossible. Next, I would like to express my sincere gratitude to my advisor, Dawit Habtu (PhD), for his guidance, constructive comments, suggestions, and support for the successful completion of this thesis. I would not pass without extending my heartfelt gratitude to my beloved friends for their valued comments and support during the whole work.

## Abstract

Bidirectional electric vehicle charging systems have emerged as a revolutionary technology. This innovative solution allows two-way power flow. Currently, the use of electric vehicles has been increasing daily in Addis Ababa. This popularity of electric vehicles in Addis Ababa is expected to have a negative impact on existing electricity networks due to the increased energy demand from these vehicles on the the utility of the city. Moreover, there is a shortage of fast electric vehicles charging stations for electric vehicles owners in Addis Ababa. Consequently, this thesis aims to create a two-way smart charging station in Addis Ababa to provide advantages for both the electric utility company and owners of electric vehicles.

The quadratic programming optimization technique is the method adopted to develop an intelligent charging plan in order to lower the cost of charging for both, electric utility and electric vehicles users. With this method, the utility load can be significantly leveled all day, because the electric vehicle owners can charge the electric vehicle at scheduled least loaded hours and the utility can obtain power from electric vehicle batteries for highest load balancing during smartly scheduled peak load hours. An algorithm is developed to regulate the energy flow between vehicle-to-grid and grid-to-vehicle operational modes.

The validity of the proposed bidirectional charging station model and design was verified by MATLAB/Simulink. From the simulation result, it has been observed that electric vehicle can be charged at off-peak hours during the grid-to-vehicle scenario and also electric vehicles can provide active and reactive power support to the utility at peak load hours during the vehicle to grid scenario. As a result, with these two scenarios, load leveling can be realized. The purpose of reducing charging costs is realized by the adopted optimization techniques. With this optimization technique, electric vehicle users can benefit from supporting the grid during peak load hours and can charge the battery at a minimum of 15 minutes. The utility of a city can reduce about 50 MW of power in a day and can reduce large investment costs for upgrading the existing distribution network to meet new power demand due to the addition of electric vehicles to the grid system.



**Keywords: Addis Ababa, Smart charging, Bi-directional DC-DC converter; Vehicle-to-grid, Grid-to-vehicle.**

**List of figures**

**List of Tables**

## List of Abbreviations/NOMENCLATURE

| | |
|---|---|
| **AC** | Alternating Current |
| **AC-DC** | Alternating Current to Direct Current |
| **BEV** | Battery Electric Vehicle |
| **$CO_2$** | Carbon dioxide |
| **DC** | Direct Current |
| **DES** | Distributed Energy Source |
| **DER** | Distributed Energy Resource |
| **DR** | Demand Response |
| **EMI** | Electromagnetic Interference |
| **ESS** | Energy Storage System |
| **EV** | Electric Vehicle |
| **GHG** | Greenhouse Gas |
| **G2V** | Grid-to-Vehicle |
| **GSC** | Grid Side Controller |
| **HEV** | Hybrid Electric Vehicle |
| **ICEV** | Internal Combustion Engine Vehicle |
| **ILP** | Integer Linear Programing |
| **IPM** | Interior Permanent Magnet |
| **PEV** | Plug-in Electric Vehicle |
| **PHEV** | Plug-in Hybrid Electric Vehicle |
| **PI** | Proportional Integrator |
| **PLL** | Phase lock loop |
| **PWM** | Pulse Width Modulation |
| **PV** | Photovoltaic |
| **R&D** | Research and Development |
| **SOC** | State of Charge |
| **THD** | Total Harmonic Distortion |
| **V2H** | Vehicle-to-House |
| **V2G** | Vehicle-to-Grid |
| **VSC** | Voltage Source Converter |

**Variables**

| | |
|---|---|
| **A** | Identity matrix |
| **B** | Battery capacity vector |
| $\mathbf{V_q}$ | Voltage quadrature axis |
| **f** | Weight vector |
| **H** | Weight matrix |
| **I** | Current |
| $\mathbf{l_b}$ | Lower bound vector |
| $\mathbf{I_d}$ | Direct axis current |
| $\mathbf{i_{d*}}$ | reference current of direct axis |
| $\mathbf{i_q}$ | axis current of quadrature |
| $\mathbf{i_{q*}}$ | reference current of quadrature axis |
| $\mathbf{K_{ip}}$ | Controller gain |
| $\mathbf{K_{iq}}$ | Controller gain |
| $\mathbf{K_{pq}}$ | Proportional constant |
| **P** | Active power |
| $\mathbf{P_{charging}}$ | Charging/Discharging power |
| $\mathbf{P_{demand}}$ | Active power demand |
| $\mathbf{P_{grid}}$ | Grid power |
| $\mathbf{P_{load\ profile}}$ | power demand profile |
| $\mathbf{P_{ref}}$ | Active power reference |
| **Q** | Reactive power |
| $\mathbf{Q_{demand}}$ | Reactive power demand |
| $\mathbf{Q_{reference}}$ | Reactive power reference |
| $\mathbf{Q_{required}}$ | Reactive power required |
| **U** | User input |
| $\mathbf{U_b}$ | Upper bound vector |
| **X** | State vector |
| $\mathbf{X^T}$ | State vector transpose |
| $\mathbf{V_d}$ | Voltage of direct axis |
| $\mathbf{V_{DC}}$ | Voltage of direct Current |

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background

In the field of electric vehicles (EVs), bidirectional charging systems have become a transformative technology. This advancement allows EVs to both draw electricity from the grid and supply power back to it. This thesis explores into the principles, advantages, and potential uses of bidirectional EV charging systems. Smart grid technology could introduce methods to efficiently manage and schedule EV charging loads, ensuring smooth integration and operation of renewable energy sources within the power system, thereby minimizing stress on the grid. During peak load hours, Vehicle-to-grid (V2G) concept enables EVs to support the grid by injecting power.

Electric power can move in two directions with a bidirectional electric vehicle charging system: from the grid to the EV and from the EV to the grid. It essentially transforms EV batteries into advanced energy storage systems that can contribute to the stability and dependability of the grid system. A bidirectional electric vehicle charging system uses a bi-directional charger. This charger enables the EV to draw power for charging and supports the grid by injecting power back when needed.

Benefits of bidirectional electric vehicle charging systems

1. **Grid resiliency and stability:** By incorporating EVs as charging station units, bidirectional charging systems enhance the total resilience and grid stability. During periods of high energy demand or grid instability, EVs can supply power back to the grid, helping to stabilize electricity supply and mitigate power outages.
2. **Renewable energy integration:** Bidirectional charging systems enable better integration of EVs into the grid. EVs can store excess renewable energy generated during off-peak hours and inject it back to during peak demand hours. This promotes the utilization of clean energy and reduces reliance on conventional power plants.
3. **Reduced charging costs:** Bidirectional charging allows EV users to take advantage of time-of-use pricing schemes. They can charge their vehicles during off-peak hours when electricity rates are lower and then sell back electricity during peak hours when rates are

higher. This makes potential cost savings for EV users and optimizes the utilization of grid resources.

Potential applications of bidirectional electric vehicle charging systems

1. **Vehicle-to-grid (V2G) services:** Bidirectional charging systems can enable V2G services, where EVs act as distributed energy resources. For example, during peak load hours, EVs can provide additional power to the grid, serving to balance the electricity load and support the overall stability of the grid.
2. **Emergency backup power:** Bidirectional charging systems allow EVs to function as emergency backup power sources. During power outages or natural disasters, EVs can supply electricity to homes, businesses, or even critical infrastructure facilities like hospitals. This enhances community resilience and reduces reliance on traditional backup generators.
3. **Demand response programs:** Bidirectional charging systems facilitate the participation of EV owners in demand response plans. These plans motivate users to adjust their electricity practice in response to grid situations. In order to help maintain grid stability, EVs can actively react to these signals by charging or draining their batteries.

Bidirectional electric vehicle charging systems offer a unique opportunity to integrate electric vehicles into the electricity grid as active participants. By enabling two-way electricity flow, these systems enhance grid stability, support renewable energy integration, and provide various applications, including V2G services, emergency backup power, and participation in demand response programs. As the EV market continues to grow, bidirectional charging systems hold immense potential for shaping a more sustainable and resilient energy future.

## 1.2 Problem of the statement

While the adoption of electric vehicles in Addis Ababa is still in its early stages, there is growing recognition of their potential benefits such as the potential to reduce air pollution, improve energy security, and create new job opportunities in the clean energy sector. However, challenges such as limited charging infrastructure, traffic jamming/congestion, absence of convenient transport facilities, frequent power outages, and high upfront costs remain barriers to widespread adoption.

Currently, due to price escalation for fuel and government attention towards encouraging the import of electric vehicles, EVs become one means of transportation in a city. The vehicles that commonly operate in Addis Ababa city by electrical means are public services, taxis and private cars. For these electrically operating cars there are no public charging stations in Addis Ababa that can benefit both EV owners and the grid. As a result, EV owners are suffering due to a shortage of fast charging stations for their electric vehicles and, they are forced to stop their vehicles at unwanted places for a long time if the battery's state of charge is low. Moreover, the growing popularity of electric vehicles can poses a substantial risk to the current electric grids because of the extra demand they place on the grid system.

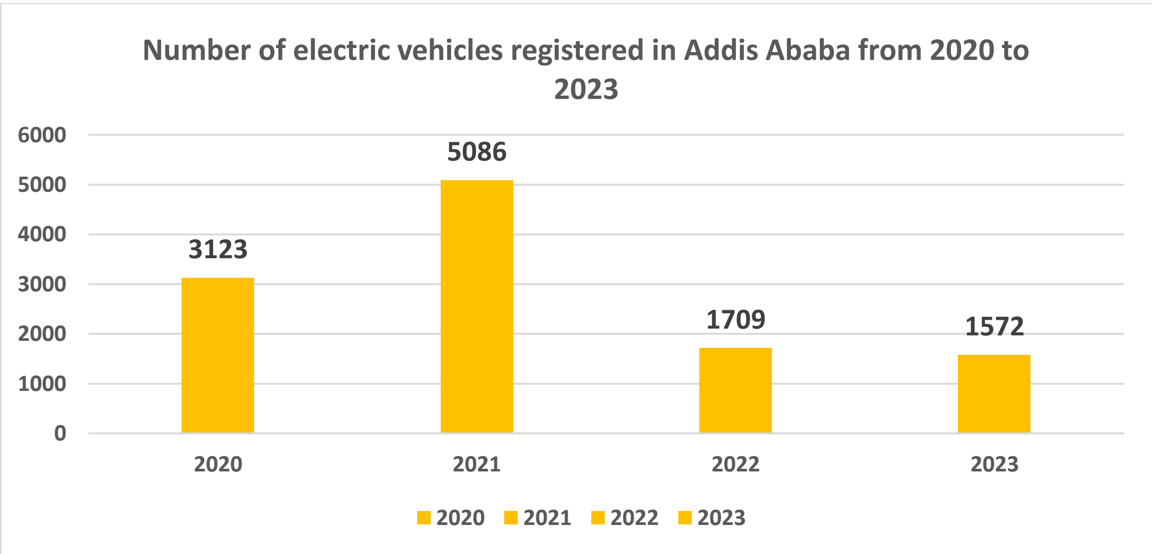


Figure 1.1 Number of Electric Vehicles Registered in Addis Ababa from 2020 to 2023

**(Source: Ministry of Water and Energy)**

Even if the imported vehicles number is not uniformly increasing from year to year, as we can see from the graph data, currently about 11,500 EVs are available in Addis Ababa, which is considered to be adversely affecting the grid. According to the Ministry of Energy currently, more than 30,000 EVs are available in Ethiopia, including both commercial and passenger vehicles. By 2032, the Transport Minister expects to import about 500,000 passenger EVs. From which about 60% share of the future Electric vehicles will be accessible in Addis Ababa.

## 1.3 Objective of the thesis

1.3.1 General Objective of the thesis: The general objective of the thesis is

- To develop a bidirectional smart charging station for the benefit of electric utility and EV owners in Addis Ababa.

1.3.2. Specific Objective of the thesis: The specific objective of the thesis is

- To develop a model for a bidirectional charging station in Addis Ababa for electrically operating vehicles including public transportation, Bajajs, and Taxis.
- To develop an algorithm for aggregator or EV side controller that determines the best charging schedule to profits EV users.
- To simulate grid-to-vehicle and vehicle-to-grid three phase charging/discharging model of a bidirectional charging system.
- To frame a centralized optimization model based on quadratic programming which can minimize whole grid strain and manage intelligent charging/discharging schedules for the collector.
- To alleviate the opposing effect of integrating a large number of EVs in Addis Ababa's electric network.

## 1.4 Significance of the thesis

Since they produce no emissions when in use, electric vehicles (EVs) have become more and more popular as alternatives to conventional fuel-powered vehicles in recent decades. Numerous studies have been conducted on G2V technology, including multiplexing of

EVSE (Electric Vehicle Supply Equipment) and smart and safe charging. These research help answer questions about how EV charging might be better controlled to reduce charging costs or lessen the impact on the electrical system.

However, EVs are now regarded as distributed storage and generating systems in addition to being a load on the grid thanks to V2G technology, which allows bidirectional power transfer. The integration of EVs into the electrical grid has presented both new technical and financial obstacles as well as opportunities, given the many advantages of EVs and the supplementary services offered by V2G technology. We wish to expand on the potential that EVs provide because they may be employed as both active and reactive power generating units. Therefore, establishment of fast charging station for EV users can make a more sustainable option than traditional power sources and also EV owners can save money on energy use. Thus, the integration of bidirectional charging system in addition to avoidance of customer suffering, it can also reduce the dependence on the power grid, making the charging network more resilient and reliable in case of power outages.

Generally, this thesis aims to show the contribution of establishing a bidirectional charging station in Addis Ababa city in a dedicated place or public parking place. The result not only brings relief to the shortage of charging stations but also can shows how EV owners and the grid benefited from this modeled and designed charging station.

## 1.5 Thesis outline

There are five chapters in the study. The thesis introduction, the study’s background, the problem statement, the thesis objective and the significance of the study are all included in the first chapter. Review of literature including the current research, is examined in the second chapter. The third chapter deals with simulation model design, algorithm development, optimization model and methodology of implementation. The fourth chapter deal with Simulation parameters and MATLAB Simulation. Finally, the fifth chapter deals with discussion, results, conclusions and the remaining work for the future.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Electric vehicle technology

The transportation sector, heavily reliant on combustion engines, significantly contributes to the accumulation of $CO_2$ in the atmosphere [1]. In recent times, there has been a global attention in interest towards electrifying the transportation sector as a gifted solution to these environmental challenges. Consequently, the demand for Electric Vehicles (EVs) has witnessed a rapid rise during the previous several years, and this trend is expected to continue in the predictable future [2]. Plug-in HEVs (PHEVs), Range Extended EVs (REEVs), and EVs are examples of alternative vehicle technologies that have become more popular due to their benefits, which include being more efficient, less noisy, and environmentally friendly [3] [4].

As the EV market expands, there is an increasing need for ongoing research and development to facilitate the widespread acceptance of EVs in the future [5]. Various kinds of EVs are currently obtainable in the market. Nevertheless, for the purposes of this thesis, the focus is on plug-in electric vehicles (PEVs), particularly battery electric vehicles (BEVs), which operate solely on battery power. Key parts of EV development include power trains, systems of energy storage, and charging infrastructure, all crucial for upcoming V2G setups [6].

Among the various types of EVs, hybrid electric vehicles (HEVs) utilize a combination of electric motors and Internal Combustion Engines (ICE) [7]. Typically, the electric motor provides assistance during low-speed acceleration, drawing power from a battery pack, while the ICE, fueled by gasoline, diesel, or natural gases, takes over for higher speeds. During regenerative braking, the electric motor charges the battery packs, while the ICE charges it during motoring. Unlike plug-in electric vehicles (PEVs), HEVs cannot be charged via an electric outlet. Similarly, plug-in hybrid electric vehicles (PHEVs) also combine electric motors and ICE. However, unlike HEVs, PHEVs can charge their battery packs through an electric outlet when parked. Range-Extended EVs (REEVs) also incorporate both ICE and electric motors [8], but unlike HEVs and PHEVs, they predominantly rely on electric motors for driving cycles, with the ICE serving to charge the battery during low-charge states. In contrast, battery electric vehicles (BEVs) solely use electric motors for traction, powered entirely by battery packs [9]. These motors typically exhibit greater power compared to those found in HEVs or PHEVs. Another variant of battery-operated EVs is hydrogen-powered EVs, known as Fuel Cell Electric Vehicles (FCEVs) [10]. FCEVs generate electric power by utilizing oxygen from the air and compressed hydrogen to drive electric motors. While FCEVs offer environmental benefits, they tend to be significantly more expensive than conventional gasoline-powered vehicles. Notably, major automobile manufacturers such as Renault, Peugeot, Nissan, Mitsubishi, Tesla, Hyundai, BMW, Volkswagen, Volvo, and Mercedes have developed and commercialized modern electric models, underscoring the technical viability, eco-friendliness, and increasing affordability of electric vehicles.


**Figure 2.1 Different models of EVs [10]**

### 2.1.1 System of energy storage

The central and vital section of an electric vehicle battery is its system of energy storage, namely the battery. Serving as the exclusive source of propulsion in BEVs, the battery currently stands as one of the most costly components in BEV technology. However, limitations persist in battery technology, posing a significant barrier to broader EV adoption within the transportation sector. Crucially, the appeal of EVs to users hinges on factors such as range, acceleration, and cost [19], all of which are directly or indirectly influenced by the state of battery technology.

Energy density (measured in Whr/L) and specific energy (measured in Whr/kg), as well as the volume of the battery, play crucial roles in determining the range and acceleration capabilities of Electric Vehicles (EVs) [18]. Particularly, low energy density is a prominent element influencing all-electrically operating vehicles. Moreover, the capacity of battery packs is significant due to the small space available within EVs for such packs. Hence, maximizing the capacity of battery packs within the same space holds considerable importance in EV technology advancement. Safety features and lifespan are also pertinent concerns. Battery technology is still in its early developing stage, it remains in its promising phases of growth, with the potential to evolve in the future towards advanced energy sizes, reduced costs, and compact sizes [19].

Many improvements over the past few decades have led to the current generation of long-lasting, secure, affordable, and high-energy batteries. As of the following figure battery technology has gone through wonderful growth.

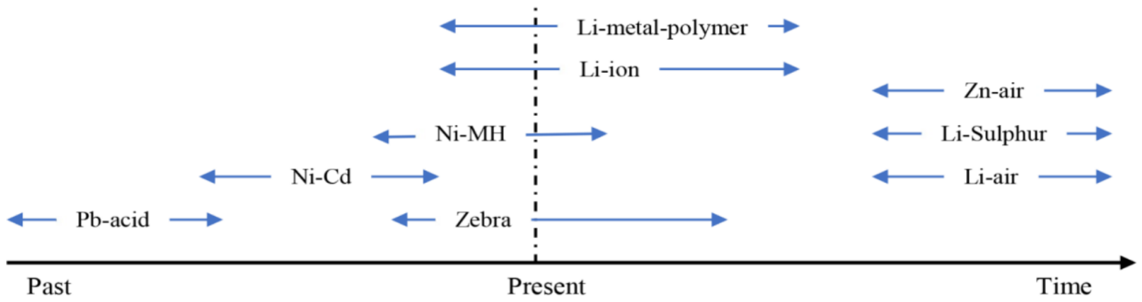


**Figure 2.2 Battery technology timeline progress [19]**

Li-ion batteries are currently used by the majority of main EV manufacturers because of its benefits, which include an extended range of operation, a higher energy density, cost-effectiveness, and non-toxicity. One of the most crucial advantages of Li-ion batteries is their ability to accept fast charging, a feature highly valued by consumers as it alleviates concerns regarding prolonged charging times. Prominent EV models like the Nissan Leaf, Mitsubishi i-MiEV, Tesla Model S, and Chevrolet Volt are favored choices among EV users, all uses Li-ion batteries as their main energy storage systems. Despite advantageous nature of Li-ion batteries, risk fire and explosion are the known drawbacks of Li-ion batteries [20].

### 2.1.2 EV chargers

Off-board, on-board and wireless are the three dominant EV charging system.[11].

a. **Off-board EV battery charger**: This systems use sophisticated Battery Management System (BMS) to deliver high power to EVs for charging. Additionally, the incorporation of AC/DC conversion hardware into external components can reduce the weight and volume of EVs, thereby enhancing overall efficiency [12]. However, the implementation of off-board EV battery chargers entails additional costs associated with developing charging station infrastructure. CHAdeMO is the prominent off-board charger which is used all over the world [13].

b. On-board EV battery charger: EVs have both AC/DC and DC/DC converters. Consequently, the cars' weight and volume rise [14]. On-board chargers, however, offer greater versatility. In addition to many other places with an AC power source, EVs can be charged in residential settings.

c. **Wireless EV battery charger:** this often referred as recharging EVs without the need for wire connections, as illustrated in Figure 2.3. This innovation also offers the potential for charging while the vehicle is in motion, although it comes with significant infrastructure costs. The system operates through two induction coils: one for transmitting and the other for receiving. However, despite its potential benefits, wireless charging has not gained widespread adoption compared to conductive chargers due to its lower efficiency and higher cost [17].

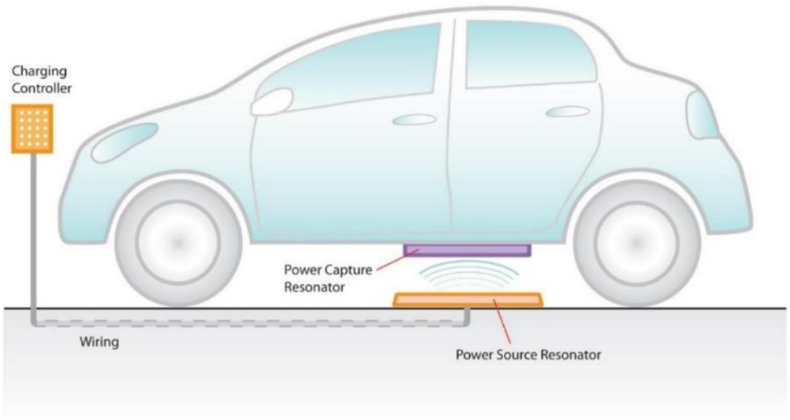


**Figure 2.3 Wireless EV charging**

### 2.1.3 Infrastructure of charging

The electric grid serves as the external source of charging for BEVs. A charger is used to charge the BEV battery from the grid. Since the grid provides alternating current (AC) and the battery is in direct current (DC) form, a charger is vital to charge a BEV battery.
To provide the necessary conversion process, a standard EV charger includes an AC-DC converter, sometimes referred to as a rectifier. To improve energy conversion efficiency, a second DC-DC converter is integrated into the design of fast-charging stations. Based on their configuration and the necessary charging level, EV charging mechanism can be classified as either on-board or off-board.

Certain specifications are incorporated into the design of on-board chargers. For the EV to be driven efficiently, they need to be small and light. On-board chargers are appropriate for slower charging levels, nevertheless, because they usually have a power rating constraint. Off-board chargers, on the other hand, are situated in certain areas. Because a DC-DC converter is built into the charger to enable quick charging, they are often bigger [21].

Internationally recognized standards for EV charging exist in addition to charger design. These consist of CHAdeMO EV standards, the International Electromechanical Commission (IEC), and the Society of Automotive Engineers (SAE) [22]. Standard of SAE charging level are shown in Table 2.2 [22].

It is critical to reduce charging time as much as possible in order to alleviate consumer worries about charging times and encourage wider EV adoption. The most practical and efficient option in this respect is the use of DC fast charging equipment for charging stations. In contrast to AC charging topologies DC fast charging drastically cuts charging periods to a matter of minutes. The unit gets bulky due to this design. At the same time, weight has a significant impact on EV performance. As a result, these charging outlets should be off-board and in dedicated areas.

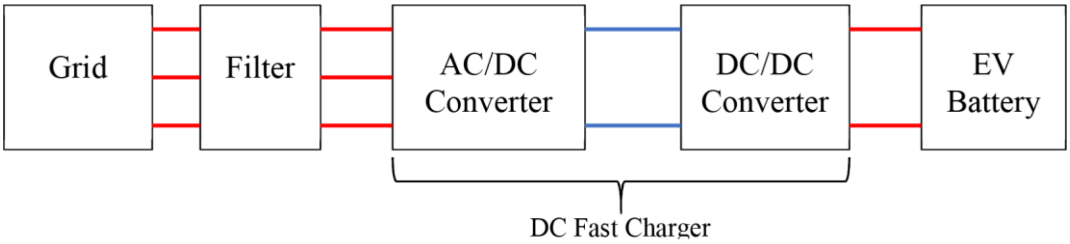


**Figure 2.4 Block diagram of DC fast charging station**

Based on the direction of power flow—from the grid to the car and vice versa—two designs for DC rapid charging systems are currently being considered. Table 2.2 shows that DC rapid charging systems enable users to pay for their purchases in less than an hour or roughly ten minutes.

This configuration offers the benefit of preserving life of battery since the number of charging cycles is limited [24]. However, it lacks the capability to engage in Vehicle-to-Grid (V2G) systems, meaning power cannot flow from the EV battery back to the grid. In contrast, Two-way DC fast chargers permit power flow in both in charge and discharge modes of operation. This feature is advantageous for applying V2G systems and benefits from a broader deployment of EVs. Nevertheless, this bidirectional setup can impact battery longevity due to a higher amount of charging cycles [24].

**Table 2.1 SAE charging standards [21]**

| Charging Level | Charge rating | Charging time | Remark |
|---|---|---|---|
| AC level 1 | 120V,1.4kW(12A)120V, 1.9kW(16A) | PHEV:7h(SOC-0%tofull) BEV:17h(SOC-20% to full) | On-board charger |
| AC level 2 | 240,up to 19.2kW(80A) | **For 3.3kW charger:** PHEV:3h(SOC-0%tofull) BEV:7h(SOC-20% to full) **For 7kW charger:** PHEV:1.5h(SOC-0%tofull) BEV:3.5h(SOC-20% to full) **For 20kW charger:** PHEV:22min(SOC-0%tofull) BEV:1.2h(SOC-20% to full) | On-board charger |
| AC level 3 | >20kW, single phase and three-phase | To be determined | To be determined |
| DC level 1 | 200-450$V_{DC}$ up to 36kW (80A) | **For 20kW charger:** PHEV: 22 min (SOC-0% to 80%) BEV:1.2h (SOC-20% to full) | Off-board charger |
| DC level 2 | 200-450$V_{DC}$ up to 90 kW (200A) | **For 45kW charger:** PHEV: 10 min (SOC-0% to 80%) BEV: 20 min (SOC-20% to 80%) | Off-board charger |

## 2.2 Ancillary services of V2G technology

"Ancillary services" encompass a variety of processes essential for maintaining the continuous flow of power within the grid, thereby ensuring its stability and security. Energy storage systems are anticipated to assume a critical role in bringing vital grid services in the future. Notably, the majority of EVs spend only about 4-5% of the day actively on the road, with the remainder of their time spent parked. This idle time presents an opportunity to leverage Electric Vehicles (EVs) to facilitate ancillary services within Vehicle-to-Grid (V2G) systems [25]. V2G technology provide the following ancillary services.

a. **Peak load shaving and load leveling:** involve managing the fluctuating power demand observed across industrial, commercial, and residential loads within the distribution network. It's commonly observed that these loads exhibit short periods of peak power demand. By using the energy stored in EV batteries to power the grid during periods of high demand and charge the batteries during off-peak hours, V2G technology provides a solution. This strategy produces desired results by successfully reducing the electric grid's peak load and achieving a more balanced load profile [26].
b. **Voltage regulation:** Frequency and voltage of the grid can be regulated by V2G system. It's crucial that the generation of electricity on the grid precisely matches the energy consumption from various sources such as households, factories, buildings, and EVs at any given moment. Failure to maintain this balance could result in the grid frequency exceeding its designated threshold, potentially leading to a blackout. In instances where there's an abrupt increase in frequency due to excess power generation, EVs can contribute by charging their batteries. Conversely, if the frequency drops to lowest level, it can easily be adjusted by either detaching EVs from the grid or discharging a portion of the EVs allied to the grid.

A significant fleet of EVs can assist the power grid in regulating voltage by modulating (injecting or consuming) reactive power throughout the grid. The power electronic configuration of EV battery chargers enables them to modify their reactive and active power load, without significant repercussions on their battery longevity. Consequently, reactive power compensation emerges as a highly promising ancillary service within future V2G systems [27].

c. **Supporting renewable energy integration:** EVs can serve as storage units during periods of higher renewable energy generation [28]. By combining EVs with renewable energy sources, the grid stability can be enhanced.
d. **Income generation:** EV users can make money by charging their batteries during off-peak hours at lower electricity prices and discharging them during peak-load hours at higher electricity prices, depending on national restrictions.
e. **Spinning reserve:** Spinning reserve refers to the surplus power capacity readily available to augment the output of power generation units during times of heightened demand. This excess power is seamlessly injected into the electric grid when required. In this context, V2G technology serves as a spinning reserve service by utilizing the energy stored in grid-connected EVs to provide supplementary generation capacity, thus mitigating the impact of generation outages [29]. Traditional generating units usually keep backup power in case of faults or outages. V2G technology could help utilities by enabling failure recovery procedures and reducing the need for extra backup generation capacity [29].
f. **Harmonics:** Harmonics pose a challenge in modern electric grids due to the presence of numerous non-linear power loads. Non-linear loads are causes for loss of power quality. Electric vehicle chargers are one of these loads that adds harmonics to the grid. However, EV chargers can act as active filters to reduce the harmonics produced by EV chargers coupled to the grid if they have efficient control mechanisms in place [30].

## 2.3 Effect of EVs on power system network

While the development of Electric Vehicles (EVs) offers numerous advantages, concerns have been raised regarding the potential impact on electric grid conditions as the EV market expands in the future. There will inevitably be adverse consequences on the electric grid and utilities when a higher adoption of EVs is integrated into the power system network for battery charging. Vehicle-to-Grid (V2G) systems must be designed and implemented with these effects in mind. Phase imbalance, power consumption, harmonics, overloading, voltage drop, and power system network stability are some of the effects on the electric grid caused by a large amount of EVs in the distribution network [19]. The possible difficulties that utilities and the electrical grid might encounter as a result of the extensive integration of EVs into the grid are highlighted in this section of the literature.

### 2.3.1 Profile of the load

The electric grid is subject to an increased load as a result of the integration of electric vehicles (EVs) into the power distribution network. Usually, the power supply is controlled according to predetermined demand criteria. Electric utilities must meet an additional demand from customers when EVs are connected to the grid for battery charging. Uncontrolled charging, which happens when EV charging is done without enough planning, gives EV owners the freedom to charge their cars whenever they want, which could make peak load hours worse. This could possibly increase load during peak load hours. Electric utilities may have difficulties as a result of increased peak power, which necessitates more generation to meet demand.

Numerous studies have examined the repercussions of uncontrolled Electric Vehicle (EV) charging on peak loads, both in current and future scenarios. One such study by Claire Weiller, titled "Plug-in hybrid electric vehicle impacts on hourly electricity demand in the United States," delves into the effects of EV charging on the hourly load profile of the United States [31]. According to this research, if EV charging remains uncontrolled, the load on the grid could double. These findings show that the importance of managing and planning charging schedules to maintain grid reliability within the integration of a large EV fleet with the electric grid.

### 2.3.2 Components of the system

A power distribution network's system components are carefully planned and executed according to preset standards that are derived from the equilibrium between the supply and demand for electric power. However, the introduction of a significant number of Electric Vehicles (EVs) into the distribution network necessitates additional power from the generation side to meet the increased demand. The same system components in the distribution network are used to provide this extra power. Since the current system components were not built to handle the extra power needed for EV charging, there is a risk that they will be overloaded. The effects of EV charging on overhead distribution networks have been studied by a number of subject-matter specialists [19]. For instance, an investigation of the effects of EV charging on the distribution network was carried out in a study by [33], which came to the conclusion that the rising penetration of EVs has a detrimental impact on transformer longevity.

In the event that EVs become more widely distributed in the future, overloading of distribution network components is inevitable if suitable network planning and load management techniques are not implemented.

### 2.3.3 Phase imbalance and profile of the voltage

Phase imbalance in the electrical system may result from single-phase AC charging [19]. Furthermore, there is a suspicion that the growing integration of EVs into the electrical grid could lead to voltage variation and decrease at EV charger connecting sites [19]. But according to a research by Csaba Farkas, Gergely Szűcs, and László Prikler, the voltage drop caused by EV charging throughout the network is still within tolerable bounds [34]. Likewise, another study [35] found that EV charging does not surpass voltage restrictions and has little effect on component loading.

Since the beginning of EV technology, a great deal of research has been done on voltage drop and deviation. Others argue that the effects are rather minimal, while others expect considerable impacts. Due to differences in system configuration and operational factors that can affect the results, such discrepancies in findings are to be expected. Charging doesn't go beyond voltage restrictions and has little effect on component loading.

## 2.4 V2G and Utilities

Numerous encouraging advantages of vehicle-to-grid (V2G) technology have the potential to greatly improve power quality and the general health of the electric grid. As was previously mentioned, effective charging and discharging schedules are crucial to achieving these advantages. Electric utilities are essential in this respect. By effectively managing Electric Vehicle (EV) loads through rate incentives or direct signals, utilities can ensure that EVs contribute to a smoother load curve, thereby enhancing grid reliability and enabling frequency regulation [39]. However, the success of this approach is contingent upon the implementation of smart charging strategies by utilities.

With the rapid growth of the Electric Vehicle (EV) market in recent years, the feasibility of implementing Vehicle-to-Grid (V2G) technology has significantly increased. However, the problem of providing electricity to charge EV batteries without negatively impacting the electric grid and creating problems for electric utilities has attracted a lot of attention because of EVs on the road keeps growing. While numerous strategies have been proposed to address this challenge, there remains a focus on refining smart charging schedules to further improve the efficiency and effectiveness of EV charging while minimizing its impact on the grid.

Vehicle-to-Grid (V2G) technology implementation requires the creation of an smart charging schedule. Although many research have suggested different methods, some might not fit the parameters and technique used in this specific investigation. Surveying the many methods used by researchers to tackle the scheduling problem is the goal of this section of the literature study. The results of this survey have been used to develop a mathematical model and problem formulation for the scheduling problem, which will be covered in more detail later in this study.

Out of all the approaches, optimization models are the one that is most frequently used globally to address (dis)charging problems. In order to create a better solution that meets the needs of both utility companies and EV owners, this study also employs optimization techniques. Utilizing optimization techniques has the benefit of employing mathematical problem formulation, which yields the most economical answer for the ideal charging schedule [40].

## 2.5 Techniques of optimization

To confirm a successful and economical method for charging and discharging electric vehicles (EVs), a variety of optimization strategies have been used. Some studies focus on the user's perspective, some on the electric grid's perspective. Currently, the most effective approach is a model that benefits EV owners, related utilities, and the electric grid.

In their paper "Towards an optimal EV charging scheduling arrangement with V2G and V2V energy transfer," Alexandros-Michail Koufakis, Emmanouil S. Rigas, and Nick Bassiliades offer a novel approach to EV charging regulation [41].Their approach, which uses real-world data, effectively uses energy resources and satisfies customer requests. The model utilizes mixed-integer programming to schedule EV charging in the best possible way for three different scenarios: (i) using only grid energy, (ii) using additional grid energy, and (iii) combining additional battery storage and energy from grid[41].

A study on the best ways to charge and discharge electric vehicles (EVs) using flexible scheduling strategies is introduced in Reference [43]. The charging/feedback system for EVs based on parking mode and mobility mode is presented in this study. While the parking mode seeks to lower charging prices, the mobility mode places a higher priority on minimizing charging delays. Data from a Chinese city's electric load profile is used to validate the model's validity.

According to a predefined building load profile, a recent study showed that deploying Vehicle-to-Grid (V2G) technology in a midsize building scenario might result in a notable 14.3% reduction in energy costs [44]. This model incorporates a battery energy storage system and photovoltaic generating inside a medium-sized building's charging station. The study formulates the optimization problem as an Integer Linear Programming (ILP) task using known data about the number of electric vehicles (EVs) that visit the charging station.

A dynamic optimal scheduling technique for electric vehicle (EV) charging and discharging in conjunction with a wind-thermal system is examined and analyzed by Dongqi Liu, Yaonan Wang, and Yongpeng Shen [45]. To determine the best charging and discharging schedule for EVs, this system uses a fuzzy decision-making algorithm with multi-objective particle swarm optimization. The algorithm's main goal is to reduce $CO_2$ emissions, wind power constraints, overall grid operating costs, and EV customers' annoyance. The model also seeks to balance active power supply and demand based on grid circumstances.

Additionally, using Vehicle-to-Grid (V2G) technology, [46] explores a charging plan that uses heuristic algorithms to support both active and reactive power. [47] and [48] outline other pertinent research that use comparable approaches and tactics. These works focus on using a quadratic optimization strategy to achieve a goal curve.

## 2.6 Smart Charging

In order to benefit consumers, the grid, or the economy, smart charging entails managing the charging profiles of electric cars (EVs). Algorithms used for this purpose can be set to achieve a number of goals, including minimizing losses, lowering greenhouse gas (GHG) emissions, preventing transformer and line overloading, lowering overall operational costs, lowering generation expenses, and maximizing user profit. In order to accomplish these objectives, smart charging essentially balances the EV loads by using Demand Side Management (often referred to as Grid to Vehicle (G2V) mode), which necessitates unidirectional power flow, during the charging process. The Vehicle to Grid (V2G) mode, which involves injecting power into the grid, is an extension of smart charging. Considering that they are parked 96% of the time, EVs serve as dispersed generators and reserves in this mode. They participate in auxiliary services markets and help with load balancing, frequency regulation, and spinning reserve. They can also help with peak shaving and valley filling. The main disadvantage of V2G is that its implementation requires an interface electrical converter that permits bidirectional power flow, which might cause rapid battery degradation.

## 2.7 Conclusion

This chapter's review of the literature has helped to create a thorough grasp of the most recent technological developments that have resulted from years of research and development in the electric vehicle (EV) sector. In order to address the needs of EV customers and promote broader use of EVs for the benefit of utilities, it provides insights into the present and future requirements for fast charging infrastructure. Additionally, it clarifies the difficulties and barriers that arise when EVs are integrated into the distribution network without a suitable management system and outlines the steps that utilities must take to lessen these difficulties and turn them into advantages, particularly by implementing smart charging schedules.

# CHAPTER THREE

# DESIGNING AND MODELLING OF A BIDIRECTIONAL CHARGING STATION

## Introduction

In this chapter, a bidirectional charging station design and model is developed which brings a two-way power flow between electric vehicles and Addis Ababa city utility. The developed model creates a chance for applying a two-way smart charging stations[53].

## 3.1 V2G/G2V a bidirectional charging mechanism

The concept of a bidirectional charging system offers a solution to various power system issues, benefiting both electric vehicle (EV) owners and utility. Essentially, this technology utilizes the EV batteries as an intermediate power source. Extensive statistical analysis and literature studies indicate that most EVs remain idle during peak hours. By tapping into the stored energy of these idle vehicles, the grid receives active and reactive power from V2G system, effectively helping manage the load demand through an AC-DC converter. At the time of low load demand, EV users can then recharge their vehicle batteries. By adopting V2G, consumers can save money on charging costs while also receiving compensation for supplying power back to the grid. Moreover, successful implementation of V2G technology would eliminate the need for power grid operators to invest in supplementary operational expenses associated with running additional power plants to meet high demand hours.

To implement this model, the establishment of charging stations is crucial, whether they are located in residential areas or public spaces. These stations serve the purpose of delivering power to EVs from the grid as needed, aligning with the requirements of EV owners. By using these chargers in the stations power can be provided back to the grid during periods of high load demand, this two-way power flow model is essential for maximizing the benefits for both the grid and EV users. This thesis suggests a strategy for charging stations to minimize the charging time interval, aiming for a time frame below 15 minutes by utilizing DC fast charging technology. A long side the charging station's topology, the charging and discharging process of EVs must be controlled. The grid-side controller (GSC) and the EV-side controller are the two control mechanisms that have been examined and used in this work to accomplish this. While the EV-side controller serves as the aggregator in the V2G configuration, the GSC controls the operation of the AC-DC converter that is connected to the electrical grid. Based on signals from the electric utility and EV customers, the EV-side controller controls how the DC-DC converter operates. By allowing EV owners to charge their batteries according to their desired schedule, the EV-side controller also takes signals from utility to correct the charging plan in order to load levelling and smooth operation of the electric utility.

Generally, a bidirectional charging system applied in this thesis embrace conversion of AC to DC, Filtering, conversion of DC to DC, controlling source of current, GSC, EV side aggregator and utility signals.

- **Grid:** is the source of three phase electricity.
- **Filter:** LCL filter plays a vital role in purifying the output current of the inverter, provides a filtered current empty of harmonics to the grid, and incorporate considerable attenuation of unwanted frequencies. As the result, the system performance and cost efficiency would be enhanced.
- **Bidirectional AC-DC power converter:** Since V2G mode of operation needs two-way movement of power for charging and discharging EVs a three phase bidirectional AC-DC converter is used.
- **Bidirectional DC-DC power converter:** It is the link next to AC-DC converter and it performs buck and boost conversion based on EVs battery state of charge and availability of grid power.
- **Grid side controller (GSC):** is used for providing extra power for charging EVs and for supporting the utility with reactive power. The following figure shows an overview of a bidirectional charging system model.
- **EV side controller (EVSC):** Providing active power for charging EV batteries and providing reactive power support for utility is its main purpose.
- **State of charge of battery (SOC):** State of charge (SOC) is another important tool for the vehicle side controller. The state of charge of EV battery determines the need of charging current.
- **User/Owner signal:** based on the charging demand to charge battery (G2V mode) and the readiness of battery to provide active power to the grid (V2G mode), EV side controller receives signal from EV user.

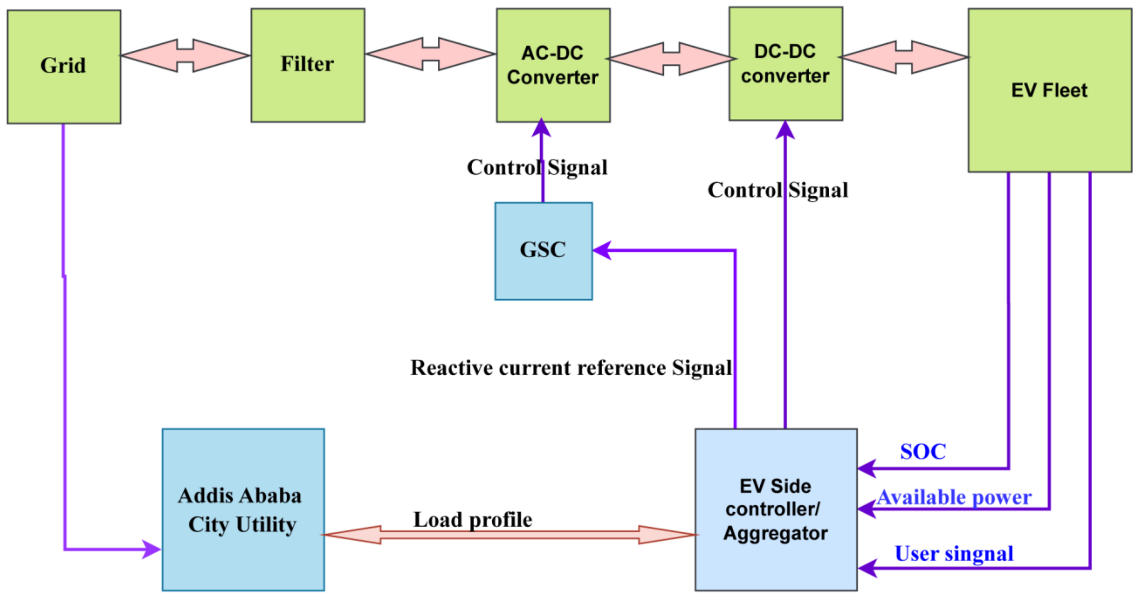


**Figure 3.1 a model of a bidirectional charging station**

A bidirectional charging system was simulated using Matlab/Simulink with rated power of 500kW. The system uses MOSFET for buck boost conversion operation and IGBT for based inverter bridge. The 600Vdc bus voltage is maintained by converter controller block and battery charging /discharging current is controlled by buck boost converter controller block. The aim of this model is to charge the EV battery from grid during off-peak hours and discharge the EV battery to the grid during peak load hours. Lithium ion battery is taken for with capacity of 300Ah.

The EV charging station model consists of the following main portions:

- Three-phase AC/DC PWM converter
- Control system for AC/DC converter
- Synchronous DC/DC converter
- Control system for DC/DC converter
- Circuit protection system

The three phase AC voltage from the grid converted to DC by using AC/DC PWM converter, the circuit consists of six IGBT/Diode components and LCL filter is modeled for conversion. For regulation of the EV charger the DC bus capacitor is inserted between the models of AC/DC and DC/DC converters. Because of its higher efficiency and a larger specific power value Li-ion type battery is selected. To show the change in the operation mode of the charger a manually operating switch is used in the model. When the switch is "1", the flow of power is from grid-to- vehicle or charging mode. When the switch is "0" the flow power is from vehicle-to-Grid (V2G) or discharging mode of operation. The Simulink model for the bidirectional DC/DC converter, it includes two MOSFET/Diode components for the operation of buck or boost mode depending on the pattern of the gate signals.

The PLL algorithm would be implemented with the corresponding design parameters in the Simulink environment. The model of the PLL system, for which the imaginary (d) component of the phase voltages in the rotating reference frame is used as a reference, is shown in Figure 3.15. It can be noticed that the value of angular line frequency is added as a feed forward into the loop as well.

The closed-loop control of the DC/DC part of the three-phase bidirectional EV charger model is managed by a two-loop control system, having an outer voltage loop that regulates the battery voltage or DC bus voltage depending on the mode of operation for the synchronous DC/DC converter and inner current loop that is responsible for tracking the reference value for inductor current. The control algorithm for the DC/DC converter would be implemented in Simulink as shown in Fig. 3.2. For activating buck mode or boost mode operation current and voltage controller is added into the model. For the rectifier mode of operation; G2V of the EV charger model, the bidirectional DC/DC converter acts as a buck type so the output voltage can be considered as the battery voltage, which is desired to be sensed and regulated in the two-loop control system. On the other hand, the synchronous DC/DC converter would operate in boost mode, for which the power flow becomes from the battery side to the DC link, when the three-phase charger system is in the inverter mode of operation. Therefore, the output voltage could be regarded as the DC bus voltage, which is regulated in the control system for the DC/DC part of the EV charger model for this mode of operation. Furthermore, the sensed voltage for the inductor current (vs) is used as a measured value for the current controller.

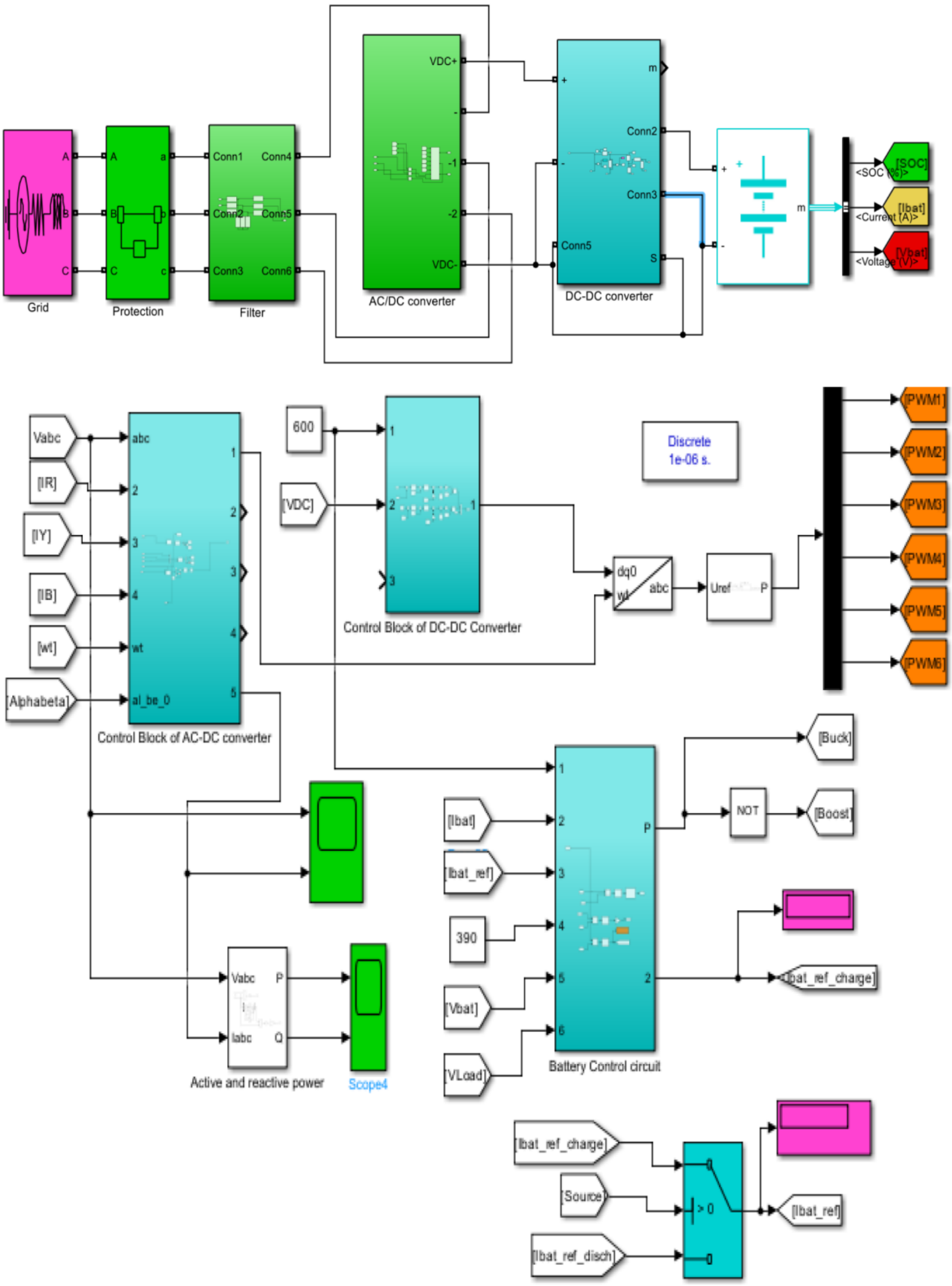


**Figure 3.2 Complete Simulink model of the proposed bidirectional EV charging station.**

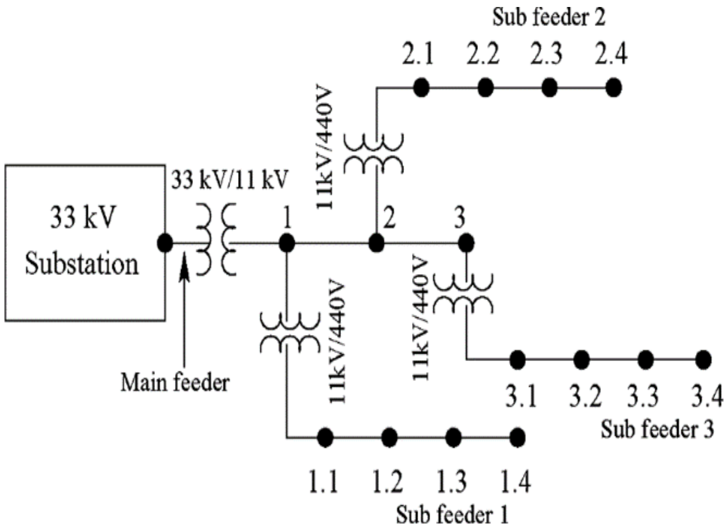


**Figure 3.3 a simple substation model of Addis Ababa city.**

A distribution network of a substation in Addis Ababa city is modeled with all the necessary parameters. The model helps to determine active and reactive power values at peak load hours at different nodes by using proper calculations. From the determined active and reactive power the node which is more susceptible to voltage instability can be identified. Therefore, a charging station can be connected to that node. As per different research findings most of the off-peak hour load is approximated to be 60% of the peak hour load. The impedance of the entire section is assumed to be constant with a specified resistance and reactance value. The system is assumed to be a balanced three-phase system.

## 3.2 Direct current fast charging station

In practice, On-board and Off-board charging approaches are the two known EV charging approaches. This thesis specifically emphases on charging EV battery in an off-board charging arrangement, where the conversion of current takes place in the station of charging and charger. Unlike the on-board charging method, the off-board charging approach enables fast charging battery and saving costs. The growing popularity of electric vehicles is largely due to the availability of off-board fast charging stations. These chargers spread the time and miles that an EV can operate on battery power, addressing users' concerns about range anxiety for plug-in electric vehicles [54].

Improvements in battery technology have made it possible for them to receive fast charging, succeeding in reduced charging times. The conversion of AC to DC voltage takes place outside the vehicle at the fast charging stations via DC coupling. The charging station determines the conversion of currents and the direction of power flow. Two types of power converters are used in charging stations. These converters are responsible for flow of power in forward and reverse direction. Nevertheless, this thesis takes a different method for the next conversion phase. It uses a regulated current source instead of using a DC-DC converter. This alternative provides the same results while also offering the additional capability to integrate the EV-side controller into the system.

### 3.2.1 Battery Charger Configuration

DC fast charging uses off- board charging mechanism. The main element of an off-board charger with V2G functionality is a two-way DC-DC converter as it is depicted in Figure 3.4, it consists of two MOSFET switches controlled by control signals. It is used to connect the electric vehicle battery system to the DC distribution grid.

In case of V2G mode or discharging mode of the battery, boost switch operates; then converter increases the battery voltage $V_{batt}$ and current $I_{batt}$ in the battery inductor $L_{batt}$ and flows towards capacitor voltage Vdc. In the case of the battery charging process, the buck converter works actively. As a result buck switch is ON, and battery current $I_{batt}$ flows from Vdc to the inductor for charging the EV battery. On the other hand, the control of the battery charger depends on the state of charge SOC of the battery; for charging and discharging mode of operation constant voltage and current control techniques are used.

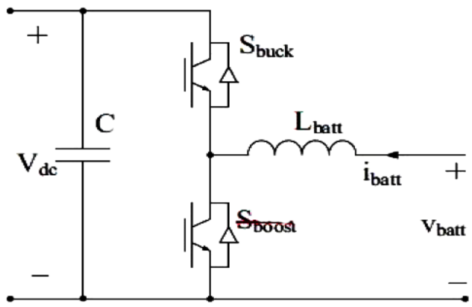


**Figure 3.4 Battery charger configuration**

In case of constant voltage control technique, the battery is acted as a voltage source, then the duty ratio dv describes the battery is in charging mode and the converter is buck mode or the system is in G2V mode as shown in figure 3.5.

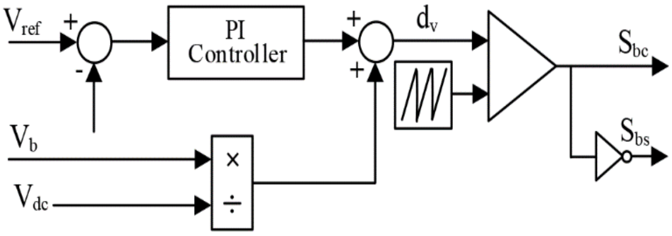


**Figure 3.5 Simulink model of current control during buck mode of operation**

In case of constant current control technique the battery is acted as a current source, then the duty ratio di describes the battery is in discharging mode and the converter is boost mode or the system is in V2G mode as shown in figure below.

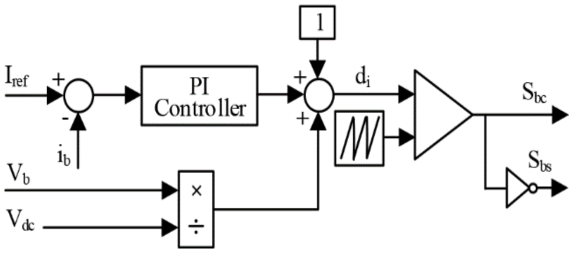


**Figure 3.6 Simulink model of current control during boost mode of operation**

The polarity of the current signal and mode of operation (charging or discharging) is determined by PI controller. PI controller is again used to compare the reference current to zero. After the mode is identified PI compares the reference and measured current errors are sent to PI controller. Based on the signal from the PI, the buck/boost switching pulses will be generated.

### 3.2.6. Individual EV charging and discharging EVs battery calculations.

The required charging and discharging rate of EV's battery can be controlled by using the following method.

$$C_{rate} = \frac{Pb_{ij}}{V_j Ahr_j} \quad \text{……………………. (3.6)}$$

Where, $C_{rate}$ - is charging rate.

$Pb_{ij}$ - is the power required/available to charge/discharge the $j^{th}$ battery of $i^{th}$ charging station, $V_j$ is voltage of the $j^{th}$ battery of $i^{th}$ charging station, $Ahr_j$ is Ampere hour of the $j^{th}$ battery of $i^{th}$ charging station.

During calculation of $C_{rate}$ value should not exceed preferred rate of EV owners.

Current Ampere hour is calculated as

$Ahr_j = Ahr_{rating} (\frac{SOC_{rate}}{100})$ …………………. (3.7)

Where, $Ahr_{rating}$ is the rated Ahr of the battery

In case of discharging (V2G mode)

$SOC_{rem} = SOC_{Curr} - SOC_{limit}$ …………….. (3.8)

Where, $SOC_{Curr}$ - is current state of charge.

$SOC_{limit}$ - is the limit of state of charge.

$SOC_{rem}$ - is the remaining state of charge.

In case of charging (G2V mode)

$SOC_{rem} = 100 - SOC_{Curr}$ ………………… (3.9)

The battery current calculated as

$Ahrb_{ij} = Ahr_{ij}C_{rate}$ ………………… (3.10)

Where, $Ahrb_{ij}$ - is the current which flows between the grid and the battery. $Ahrb_{ij}$- is positive, during charging or G2V mode and negative during discharging or V2G mode.

Parameter of the flow chart is

$C_{rate}^{limit}$ - is the preferred maximum set by the EV owners.

CS - is charging station.

$V_{bat}$ - is battery voltage. The rest are mentioned above.

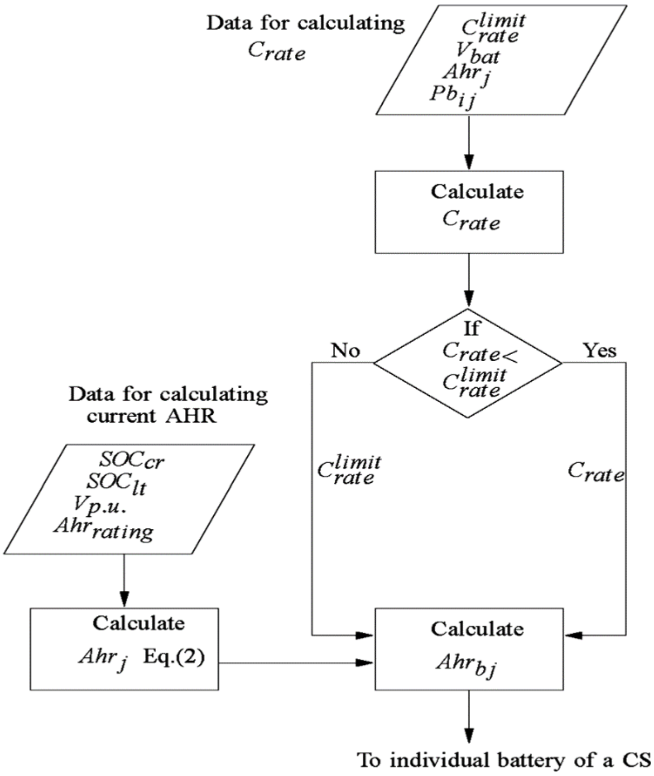


**Figure 3.7 Flow chart for charging and discharging of individual EV battery.**

### 1.2.3 Distribution of power among charging stations (CS) and EVs.

The transformer rating is the key factor for the division of power among the CSs [67]. However, there are a situation in which one of the CS has the highest available energy with a lower transformer rating. Different charging stations different energies at different time period and hence, the division of the charging and discharging power among different charging station can be calculated as follows.

$$P_i = (P\frac{E_i}{E}) \times \eta \quad \text{(charging)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.11$$

$$P_i = (P\frac{E_i}{E}) \times \frac{1}{\eta} \quad \text{(discharging)} \ldots\ldots\ldots\ldots\ldots\ldots 3.12$$

Where P is the power which should be drawn/supplied from/to the node, $P_i$ is the net power exchanged at the i$^{th}$ CS, $E_i$ is the available/required batteries energy of the i$^{th}$ CS and E is the total energy available/required by the CS. $\eta$ is the charging/ discharging efficiency of the system.

Available/required energy can be calculated as follows

$$E_i = \sum_{j=1}^{m} E_{bij} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.13$$

Where is the energy available/required by the j[th] battery of the i[th] CS and is calculated as follows:

$$E_{bij} = \frac{SOC_{rem}}{100} V_{bat} Ahr_{rating} \text{ ……………………. } 3.14$$

Where $E_{bij}$ is the energy available in the battery during discharging or energy required by the battery during charging. Total energy of the CS can be calculated as follows.

$$E = \sum_{i=1}^{n} E_i \text{ ……………………………………… } 3.\ 15$$

## 3.3 Comparison of power switches

Most commonly used controllable switches for the design of the power electronic converters are shown below in Table 3.1 [55].

**Table 3.1 controllable switches comparison**

| Device | Power capability | Switching speed |
|---|---|---|
| MOSFET | low | fast |
| IGBT | medium | medium |
| IGCT | high | slow |

As shown above the IGBT tends to be the best option for the design of the charging station is power electronic interfaces. An IGBT converter has an efficiency of typically 90% [56].

## 3.4. Bidirectional power converter

### 3.4.1. Two-way rectifier operation

Conversion of high voltage AC to DC for battery charging is the first step in off-board EV charging. It is possible to use AC-DC converters for both unidirectional and bidirectional flow. This work explores and implements a bidirectional three-phase AC-DC converter for EV charging and discharging due to the V2G requirements and two-way power flow.

The primary link between EVs and the electrical grid is the bidirectional AC-DC power converter. This converter functions as a rectifier during charging, converting high-voltage AC from the utility to DC bus voltage. In V2G mode, this converter functions as an inverter, converting DC voltage back into AC for retransmission into the power system.

The circuit diagram for the three-phase AC-DC converter that was modelled for this investigation is displayed in Figure 3.2. Grid-connected filters can eliminate current harmonics introduced by switching. In addition to positive and negative DC bus voltages, the neutral point in three phases permits the generation of other voltages. Because of this, losses in power switching are reduced by around a factor of two because all power semiconductor switching devices only encounter half of the line voltage [56].

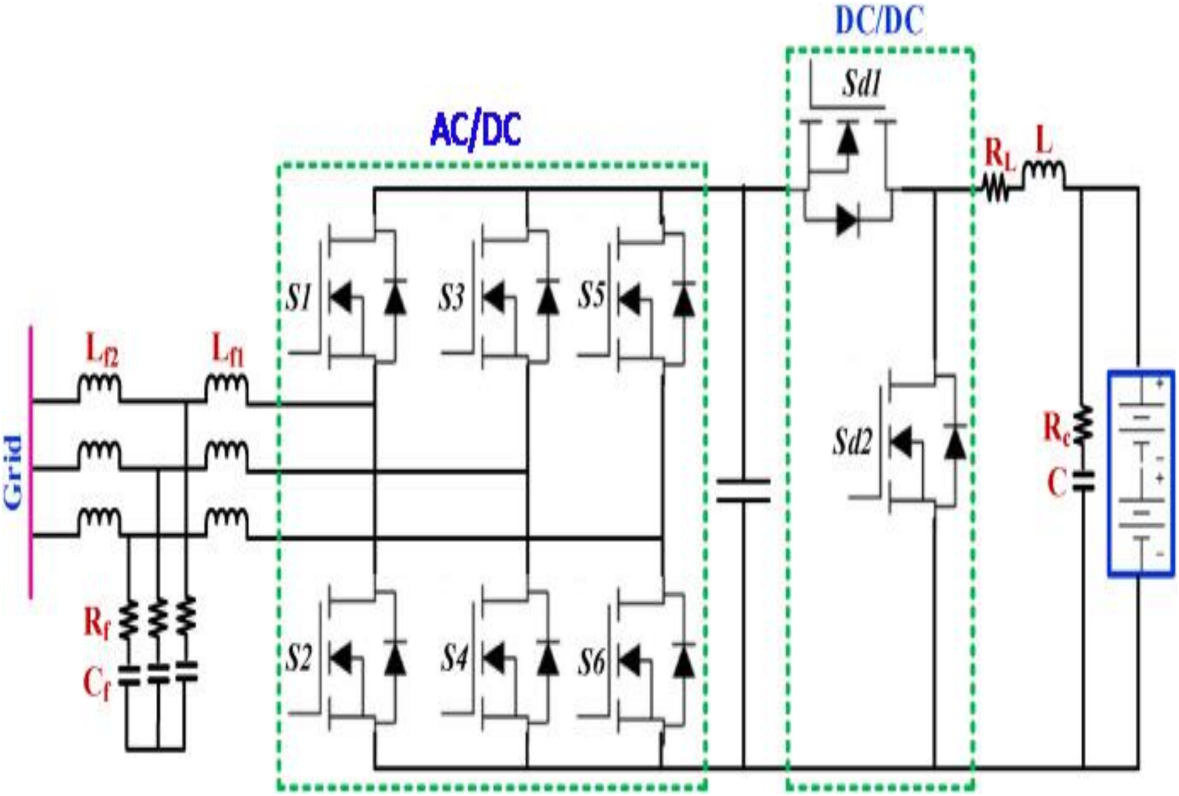


**Figure 3.8 Three-phase AC-DC/DC-DC converter [57]**

### 3.4.1.1 Specification of a bidirectional AC-DC converter

In this thesis to convert three phase input AC voltage to DC a three phase rectifier is used. This device comprises six IGBT switches arranged in a bridge configuration to convert the AC voltage to pulsating DC voltage. The rectifier connected to the grid side smoothens the pulsating DC voltage using a filter or capacitor bank to obtain a more constant DC voltage. As labelled in table 2.4, according to SAE charging standards and The AC/DC converter uses DC level 3 standard and therefore this thesis assumes the output DC power to be 450 kW and the inverter efficiency.

$$ή = \frac{P_{DC}}{P_{AC}} = 0.9 \approx P_{AC} = \frac{P_{DC}}{0.9} = \frac{450}{0.9} \approx 500\text{kw} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \; 3.16$$

The IGBT anti-parallel diodes must be kept reversed-biased in order to not conduct in the wrong direction during the charging mode of operation (power transfer from AC to DC side). This can be achieved if the output DC voltage is kept above the line-to-line grid peak voltage value. The design also assumes a DC bus voltage of 600 V so that the previous restriction translates to:

$$V_{DC} > \sqrt{2}V_{Grid,RMS} = \sqrt{2}.\sqrt{3}V_{Grid,RMS} \approx V_{Grid,RMS} < \frac{600}{\sqrt{6}} V_{Grid,RMS} < 245 \text{ ......... } 3.17$$

According to the above (3.16,3.17) condition, the SAE J1772 Standard and the fact that the grid voltage varies typically between 0.95 and 1.05 pu [58], choosing the grid voltage on the AC side to be 380 V is an acceptable option to remain within the constraint imposed by equation (3.17). Assuming a power factor of typically 0.95 and with equation (3.16), the grid current can be found as follows:

$$P_{AC} = V_{grid,rms}.I_{grid,rms}.p_f \text{ ........................ } 3.18$$

$$I_{grid,rms} \approx 1200A$$

**Table 3.2 Grid Converter Electrical Specifications**

| | Input side(Rms) | Output side(DC value) |
|---|---|---|
| Grid voltage(v) | 380 | 600 |
| Grid current(A) | 1200 | 830 |
| Real power(kW) | 450 | 500 |

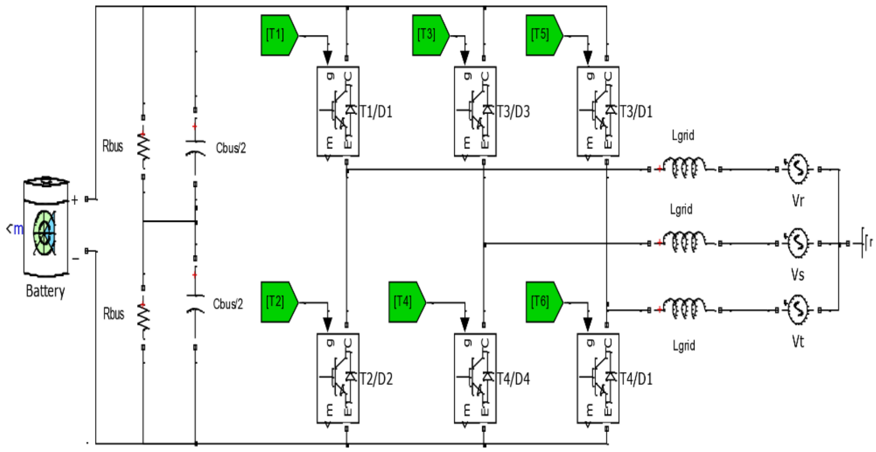


**Figure 3.9 Simulink model of AC/DC converter [55]**

### 3.4.2 Two-way chopper

As the second link between EVs and the power grid, the bidirectional DC-DC converter carries out both boost and buck conversion tasks. Between the AC-DC converter and the EV battery, a bidirectional DC-DC converter must be included. This is because a conversion to a lower value is usually necessary because the DC voltage generated from the AC-DC converter's output is usually higher than what is needed to charge the EV battery.

#### 3.4.2.1 Specification of a bidirectional DC-DC converter

In order to adapt to various battery car voltages, the charging station dc bus must be interfaced with the battery via a generic DC/DC converter that must also be bidirectional to allow both of the battery charging and V2G modes. Since the dc bus voltage is always higher than the battery voltage, the converter acts as a buck configuration in battery charging mode, and as a boost configuration in V2G mode.

$I_{Grid,DC}$ = 830A, $P_{total,input} = V_{DC} \cdot I_{Grid,DC}$ = 600Vx830A= 500kW ………. 3.19

The converter output power is calculated as follows:

$$ή = \frac{P_{out}}{P_{in}} = 0.9 \approx \; P_{out} = 0.9\text{x}500\text{kW} = 450\text{kW}$$

The maximum EV battery voltage 360V is considered to be the converter output voltage. Therefore, the converter output current is calculated as:

$$I_{output} = \frac{P_{out}}{V_{out}} = \frac{450kw}{360} = 1250\text{A} \quad \text{……………..}\ 3.20$$

**Table 3.3 Charging Station Output Converter Electrical Specifications**

| | Input side(DC) | Output side(DC value) |
|---|---|---|
| voltage(v) | 600 | 360 |
| current(A) | 830 | 1250 |
| power(kW) | 500 | 450 |

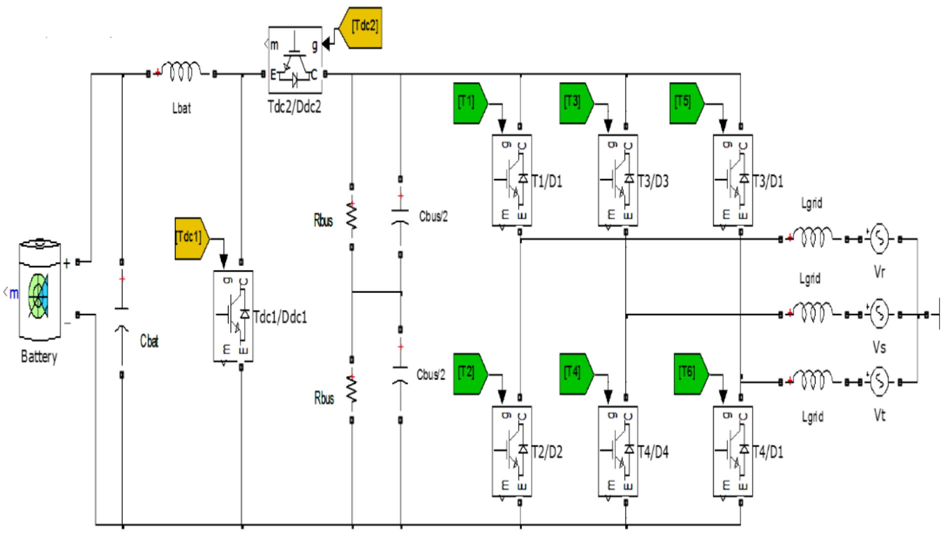


**Figure 3.10 Simulink model for DC/DC converter**

## 3.5 Control strategy of converter

To implement a bidirectional charging system, this thesis used two control system to manage power movement between EV batteries and the electric grid. In order to give reactive power to the grid and generate active power for EV charging, the grid-side controller is responsible for switching control of the AC-DC converter. The vehicle-side controller regulates the local flow of power between the grid and EV batteries.

### 3.5.1 Grid side controller (GSC)

The grid side controller aims to do two things. Primarily, to supply extra energy for EV battery charging. The second is to support reactive power whenever utilities ask for it. Figure 3.4 displays the Simulink GSC block diagram utilized in this investigation. The diagram shows that the GSC is made up of measurements, a phase lock loop (PLL), a Vdc regulator, and a current regulator [51]. The regulator calculates and sets the voltage reference using the reference currents Id and Iq (reactive current). Iq reference current is always set to zero for power flow from the grid to the EV battery [57].

Grid side controller can provide reactive power support to the grid by injecting reactive power at the common coupling point. The reference q-axis current is generated by the reactive power controller. Nevertheless, reference q-axis current is produced via a common coupling point voltage controller [57].

The method used for the GSC control scheme in this investigation was taken from the study in [57]. This method maintains synchronization of utility voltage by using the PLL algorithm, calculations of active and reactive power, and direct-quadrature-zero transformation equations. Phase currents and utility voltages are transformed from the a-b-c coordinate system to the d-q coordinate system using the Park transformation technique. Furthermore, ωt is obtained from PLL. Transformation equation of d-q is as follow.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\omega t) & \sin\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{2\pi}{3}\right) \\ \cos(\omega t) & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \times \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \quad \text{……………3.15}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\omega t) & \sin\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{2\pi}{3}\right) \\ \cos(\omega t) & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \times \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \quad \text{……………..3.16}$$

The following equations are used to determine three-phase active and reactive power using the values derived from the aforementioned formula:

$$P = \frac{3}{2}(v_{dxi_d} + v_q \text{x} i_q) \quad \text{…………………………..… 3.17}$$

$$Q = \frac{3}{2}(v_{dxi_d} \text{-} \ v_d \text{x} i_q) \quad \text{…………………………..3.18}$$

There are oscillations and average components in the immediate active and reactive power that is obtained. Both powers are obtained from low pass power in order to calculate average components. The control depends on tracking reference orders for active and reactive power [57]. This is accomplished by implementing two PI control loops that use the following equations [57].

$$i_d^* = k_{pp}\left(P_{ref} - P\right) + k_{ip} \int \left(P_{ref} - P\right) dt \quad \text{……………………………..3.19}$$

$$i_q^* = k_{pq}\left(Q_{ref} - Q\right) + k_{iq} \int \left(Q_{ref} - Q\right) dt \quad \text{……………………………..3.20}$$

Kpp and kpq are proportional constants, while Kip and Kiq are integral constants for the PI controller. Pref is the active power for charging, while Qref is the reference value of reactive power obtained from the power grid.

The GSC controller is designed with two loops. Inner current loop and outer voltage loop. In order to manage the inner current loop, the voltage reference and the actual voltage on the outer loop are compared to determine the current reference [57]. Inner loop control is achieved by using equations (3.19) and (3.20) with the currents found by park transformation. The following equations [57] summarize the duty ratios in d–q coordinates by first adding the findings (ed and eq) with the decoupling terms, and then normalizing them by DC-link voltage.

$$\begin{bmatrix} d_d \\ d_q \end{bmatrix} = \frac{1}{V_{dc}} \begin{bmatrix} e_d + v_d + 3\omega L \times i_q \\ e_q + v_q - 3\omega L \times i_d \end{bmatrix} \quad \text{……………….. 3.21}$$

However, as demonstrated below [57], the inverse matrix transformation technique is used to produce duty ratios in the a-b-c frame of reference:

$$\begin{bmatrix} D_a \\ D_b \\ D_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin(\omega t) & \cos(\omega t) \\ \sin\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t - \frac{2\pi}{3}\right) \\ \sin\left(\omega t + \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \times \begin{bmatrix} d_d \\ d_q \end{bmatrix} \quad \text{…………..3.22}$$

### 3.5.1.1 Phase locked loop (PLL):

An essential component for effective control of a grid-connected converter is the phase-locked loop (PLL) [59] [60]. It quickly and precisely tracks the frequency variation of the grid voltage. In order for the grid-connected converter's control loops to all be correctly synchronized with the grid system.

The main characteristics of this conversion are [62]:

- Two orthogonal axis variables can be obtained from any rotating space vector that is produced by an arbitrary number of phases (balanced/unbalanced, symmetrical/unsymmetrical). As a result, there won't be any reciprocal elements influencing these variables.
- In terms of the converter's control point, this transformation is good. Because all of the balanced AC variables are converted to DC by the simultaneously revolving reference frame, dq0. The PI controller makes it simple to manage these DC quantities. Because PI controllers have the following benefits:

a. Zero steady state error

b. Reduced effect of disturbance input or noise signals [63].

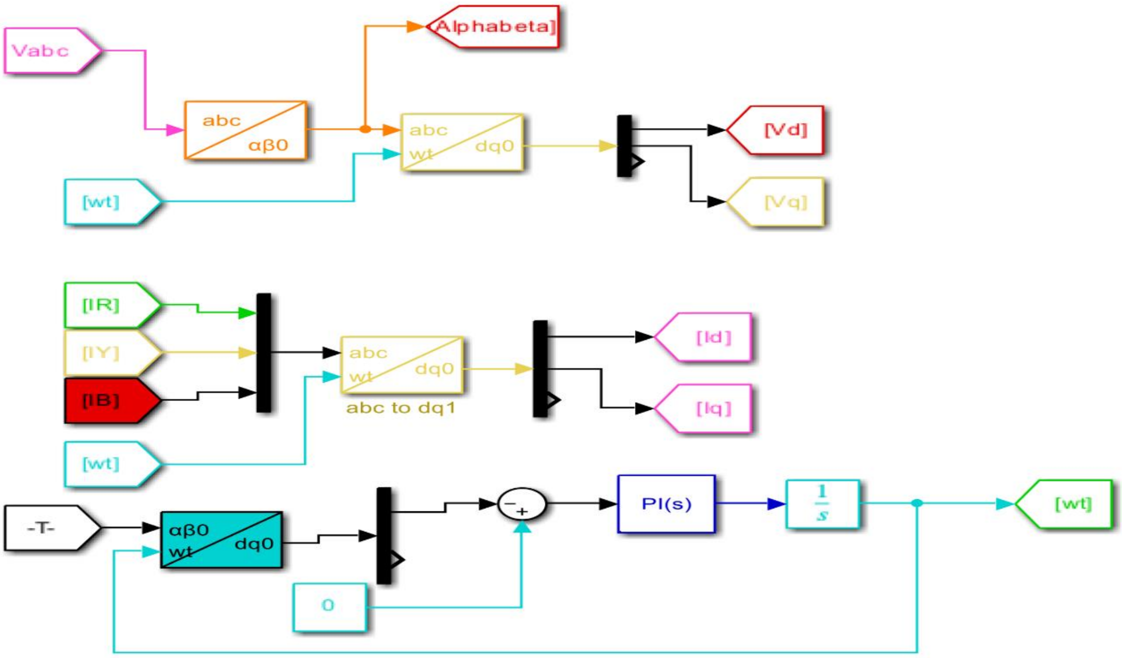


**Figure 3.11 Control strategy of grid side converter**

### 3.5.2 Vehicle side controller (Aggregator)

In addition to providing the utility with reactive power for the electric grid, the GSC controller plays a crucial role in providing excess active power for EV battery charging. It does not, however, regulate the currents used for EV battery charging and discharging. The vehicle side controller is crucial to the charging and discharging operation. In this V2G system concept, the vehicle-side controller serves as an aggregator. It communicates with the utility to determine when to charge and discharge EV batteries and is directly connected to a controlled current supply. Furthermore, due to the fact the vehicle side controller communicates with the utility, it receives requests for reactive power from utility and sends a signal to the GSC to deliver the grid with reactive power.

The EV side controller communicates with the utility to get the anticipated power demand in order to determine the dis/charge schedule. Additionally, in order to establish a timetable based on the electricity needed to charge EV batteries and allow V2G operation, the EV side controller communicates with the utility and the EV fleet. The EV side controller employs an algorithm to regulate its three primary input signals in order to perform G2V or V2G operations in compliance with preset criteria depending on the utility power profile and available EV. The state of charge (SOC) of the EV batteries, the owner and load profile signals are the three input signals of the EV side controller.

a. **User/Owner signal:** based on the charging demand to charge battery (G2V mode) and the readiness of battery to provide active power to the grid (V2G mode), EV side controller receives signal from user. According to this study model, a user input of "0" means that charging has to begin. Unless charging battery to the fullest, charging shouldn't be halted until the user input is "0."
b. **Utility load profile signal:** The daily load profile is received by the vehicle side controller's utility input. The amount of active power that is available in EV batteries to support utility is determined by the EV side controller after analyzing the load profile. Next, the EV side controller ascertains the time of day that EVs can supply active power while they are in an idle state. In order to balance the overall utility load and save money for both EV owners and the utility, it also determines the times of day with the lowest utility load and provides EV owners with a charging plan to charge during those hours.
c. **State of charge:** is another important tool for the vehicle side controller for the two mode of operation. The need of charging current determined by SOC of an EV battery. SOC creates the necessary charging current within a battery's SOC range. For example, if the SOC is 20%, then the battery needed to be charged in the shortest of time.

If the battery's state of charge (SOC) is 80%, then charging current should be at lower rate in order to fully charge the battery. Unless the state of charge is at higher state, there is no vehicle –to-grid operation.

For example, In order to use the EV battery for V2G charging operation the state of charge should be above 40%, if the state of charge is below 40% the EV side controller does not allow the EV battery to operate in V2G mode. The appropriate mode of operation is determined by an algorithm for the need of both utility and EV owners by analyzing signals from EV side controller.

### 3.5.2.1 Vehicle side controller algorithm

The EV side controller uses the flow chart shown in Figure 3.15 below. In this thesis, the user input maximum value defined by ‘1’ and the minimum value is ‘0’ denoted by U. The number "1" indicate the readiness of EV battery to provide active power to the grid based on utility request and if the SOC is greater than 40%. In order to reduce the peak load demand, the EV side controller uses the active power stored in the EV battery during idle hours and it sends the active power to the utility based on the signal from EV side controller. Furthermore, the utility request was promptly responded by the EV side controller for reactive power support.

At the time of cars are charging and the required amount of reactive power is not met, the demand for reactive power is paused until sufficient power is available.
Coordination of conditional statements and the necessary power is computed to meet algorithmic requirements.

$$P_{demand} = P_{load} - P_{threshold} \quad \text{3.23}$$

Where, $P_{demand}$ = utilities’ demanding active power;

$P_{load}$ = utilities’ load profile;

$P_{threshold}$ = threshold power demanded by EV side controller.

$$Q_{required} = Q_{reference} - q_{demand} \quad \text{3.24}$$

Where, $Q_{required}$ = reactive power required by utilities;

$Q_{reference}$ = reactive power reference to determine$Q_{required}$;

$Q_{demand}$ = utilities’ reactive power demand.

- If the user input =1, $P_{demand}$> 0 and SOC >40%, the EV battery can send discharge current signal to a controlled current source to supply active power.
  The source of discharge current is calculated as:

$$\frac{P_{required}}{Vdc} \quad \text{3.25}$$

- If user input is set to '0', EV batteries are at the need of charge regardless of utility power demand.
- The following factors affect charging currents:

**Table 3.4 Battery state of charge**

| Level | Voltage | Remark |
|---|---|---|
| 100% | 13V | No charging current is needed |
| 90% | 12.75 | Charge significantly slow rate |
| 80% | 12.50 | |
| 70% | 12.30 | Charge slowly |
| 60% | 12.15 | |
| 50% | 12.05 | Charge more quickly |
| 40% | 11.95 | |
| 30% | 11.81 | |
| 20% | 11.66 | |
| 10% | 11.51 | Worst zone |

1. An EV battery charging is needed more quickly if $20\% \leq SOC \leq 60\%$, then the controlled current source receives charging signal.
2. An EV battery charging is needed at a slightly slower rate if $60\% \leq SOC \leq 80\%$, As a result, the controlled current source receives a signal with a slightly lower charging current.
3. An EV battery charging is needed at a significantly slower rate if $80\% \leq SOC < 100\%$, As a result, the controlled current source receives the minimum charging current signal.
4. Charging is completed if SOC reaches 100%.

- By using equation (3.20) reactive power demand can be monitored. This allows utility to receive the reactive power they need.

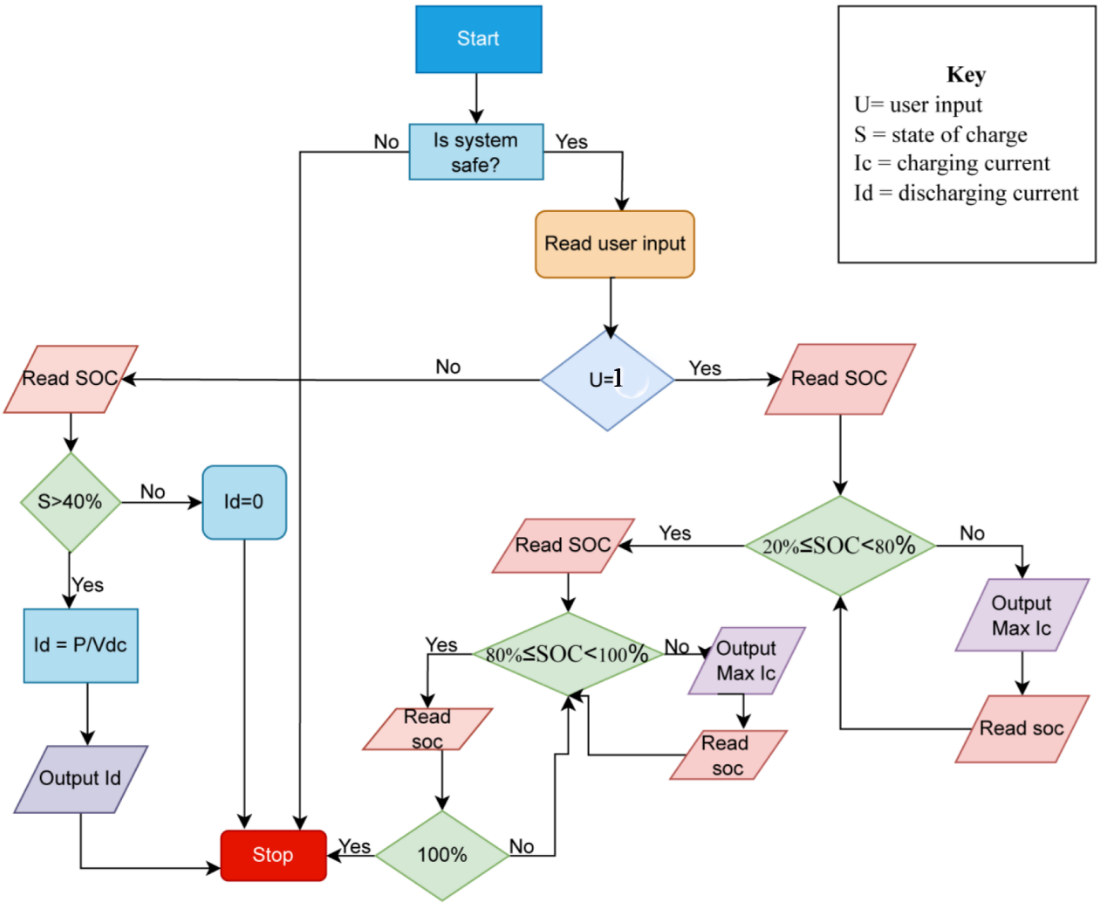


**Figure 3.12 Algorithm for vehicle side controller**

## 3.6. Optimization Method

### 3.6.1 System description

Developing optimization techniques is one way to reduce the cost of EV charging. EV owners will receive financial incentives based on the amount of electricity they send to the grid in the case of V2G operations to deliver ancillary services like load leveling and peak load shaving. The cost of charging will be decreased in this way.

The first stage in optimizing an electric car for usage in the charging and discharging process is to develop a mathematical model. The formula of a model is represented as follows:

$$SOC = \mathbf{A}.\ SOC + \mathbf{B.I} \text{ ………………….3.26}$$

where A is the identity matrix, I is the control variable that represents the EV battery's (dis)charging current, B is a vector that represents battery capacity, and SOC is the state variable. The general concept of an EV taking part in a V2G scenario is represented in discrete temporal state space as follows:

$$SOC_{\boldsymbol{k+1}} = A.\ SOC_k + B.I_k \text{ ………….. 3.27}$$

Where, k is time step of current. Total electric vehicles joining in vehicle-to-grid scenario, the equation (3.27) rewritten as in the following format:

$$\begin{bmatrix} SOC_{k+1}^{1} \\ \vdots \\ SOC_{k+1}^{U} \\ \vdots \\ \vdots \\ SOC_{N}^{1} \\ \vdots \\ SOC_{N}^{U} \end{bmatrix} = A \begin{bmatrix} SOC_{k}^{1} \\ \vdots \\ SOC_{k}^{U} \\ \vdots \\ \vdots \\ SOC_{N-1}^{1} \\ \vdots \\ SOC_{N-1}^{U} \end{bmatrix} + B \begin{bmatrix} I_{k}^{1} \\ \vdots \\ I_{k}^{U} \\ \vdots \\ \vdots \\ I_{N-1}^{1} \\ \vdots \\ I_{N-1}^{U} \end{bmatrix} \text{…………………3.28}$$

Where, k goes zero to N;

N = The whole step of time;

U = EVs participated in optimization.

EV battery model can be applied for optimization technique limitation. In order to transform equation (3.28) into standard form we should able to change it from equation to equality constraint as the following.

$$A_{eq}.\ Z = b_{eq} \text{…………………..3.29}$$

Where, Z is each EVs' control variable and the vector including all state variables and each time step. Equation (3.29) takes the following form in standard form:

$$-\mathbf{A}.\ SOC_k + SOC_{\boldsymbol{k+1}} - B.I_k = 0 \text{ ……………. 3.30}$$

And the standard form of equation (3.29) and equation (3.30) written as following:

$$
\underbrace{\begin{bmatrix} I & 0 & \dots & \dots & 0 & -\boldsymbol{B} & 0 & \dots & \dots & 0 \\ -\boldsymbol{A} & I & \ddots & & \vdots & 0 & \ddots & \ddots & & \vdots \\ 0 & \ddots & \ddots & \ddots & \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\ \vdots & & \ddots & \ddots & 0 & \vdots & & \ddots & \ddots & 0 \\ 0 & \dots & 0 & -\boldsymbol{A} & I & 0 & \dots & \dots & 0 & -\boldsymbol{B} \end{bmatrix}}_{A_{eq}} \underbrace{\begin{bmatrix} SOC_{k+1}^{1} \\ \vdots \\ SOC_{k+1}^{U} \\ \vdots \\ \vdots \\ SOC_{N}^{1} \\ \vdots \\ SOC_{N}^{U} \\ I_{k}^{1} \\ \vdots \\ I_{k}^{U} \\ \vdots \\ \vdots \\ I_{N-1}^{1} \\ \vdots \\ I_{N-1}^{U} \end{bmatrix}}_{z} = \underbrace{\begin{bmatrix} \boldsymbol{A}_0 SOC_{k}^{1} \\ \vdots \\ \boldsymbol{A}_0 SOC_{k}^{U} \\ 0 \\ \vdots \\ 0 \end{bmatrix}}_{b_{eq}} \quad \dots\dots\dots\dots\dots\dots \; 3.31
$$

Where, A = U×U identity matrix;

B = EV’s capacity vector;

k = goes from zero to N

The right-hand side vector of (3.31), which is identical to the beq of equation (3.29). The second vector in (3.31) represents z of equation (3.29). from the matrix the equation (3.29) is equivalent to the equation (3.29). HThe system model for optimization created from the above-mentioned equations will be utilized in the following sections of this chapter.

### 3.6.2 Problem statement

It is anticipated that the optimization strategies employed in this thesis to develop an intelligent charging strategy will lower overall charging costs for both utility companies and EV users. When EVs participate in an aggregated vehicle-to-grid scenario, this is feasible. Stated differently, EVs charge batteries during off-peak hours and supply electricity to utilities during peak load hours. Generally speaking, it entails lowering grid power for load levelling and peak shaving throughout a 24-hour period. Using EV batteries to provide power during peak hours reduces the demand profile of a specific area or region when grid electricity is restricted. Supplying electricity to EV batteries simultaneously, when power consumption is at its lowest, throughout the day. This can be stated in standard mathematical terms.

$$\text{Min } ({P^2}_{grid}) \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \; 3.32$$

Where

$$\boldsymbol{P}_{grid} = \boldsymbol{P}_{load\,profile} + \boldsymbol{P}_{charging} \quad \dots\dots\dots\dots\dots \; 3.33$$

$\boldsymbol{P_{grid}}$ is power of the grid, = $\boldsymbol{P_{load\ profile}}$ is the daily demanded power of a Addis Ababa city idle time power for EVs, and $\boldsymbol{P_{charging}}$ is the power demanded to charge EVs.

Then simplified problem helps to determine time to charge and discharge.

As the result, average peak power consumption and its changeability within 24 hours can be minimized. It uses the load profile of Addis Ababa city to optimize the charging schedule. The model developed in this thesis practices the load profile data of Addis Ababa city to optimize charging schedule and to lower cost of charging by minimizing grid power.

### 3.6.3. Optimization Technique (quadratic programming)

Quadratic programming was used as the optimization method for optimization techniques. Desired state of charge for EV users is capable of minimizing the grid load. Equation (3.34) provides overall form of quadratic programing.

$$\text{Minimize } (1/2.X^{T}\cdot Hx+f^{T}\cdot X) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots..3.34$$

Subject to;

$$A_x \leq b \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots...\ 3.35$$

$$A_{eq}X = b_{eq} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.3.36$$

$$I_b \leq X \leq U_b \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots3.37$$

Where, x = equivalent state vector;

$X^T$ = transpose of x;

H = The quadratic term is designed using weight matrix;

$f^T$ = The quadratic term is designed using weight vector;

Constraints representing the quadratic optimization process to minimize the objective function are given by equations 3.35 to 3.37. Equation (3.35) constrains inequality, equation (3.36) constrains equality, and equation (3.37) represents boundary conditions, where $U_b$ and $I_b$ are upper and lower boundary respectively.

### 3.6.4 Utility Load profile data of Addis Ababa city

Smart charging schedule designed for Addis Ababa city that takes into account the combined power demands of a commercial, residential, and industrial region. With this control method, the utility uses a single load profile curve to create a smart timetable for the entire region.

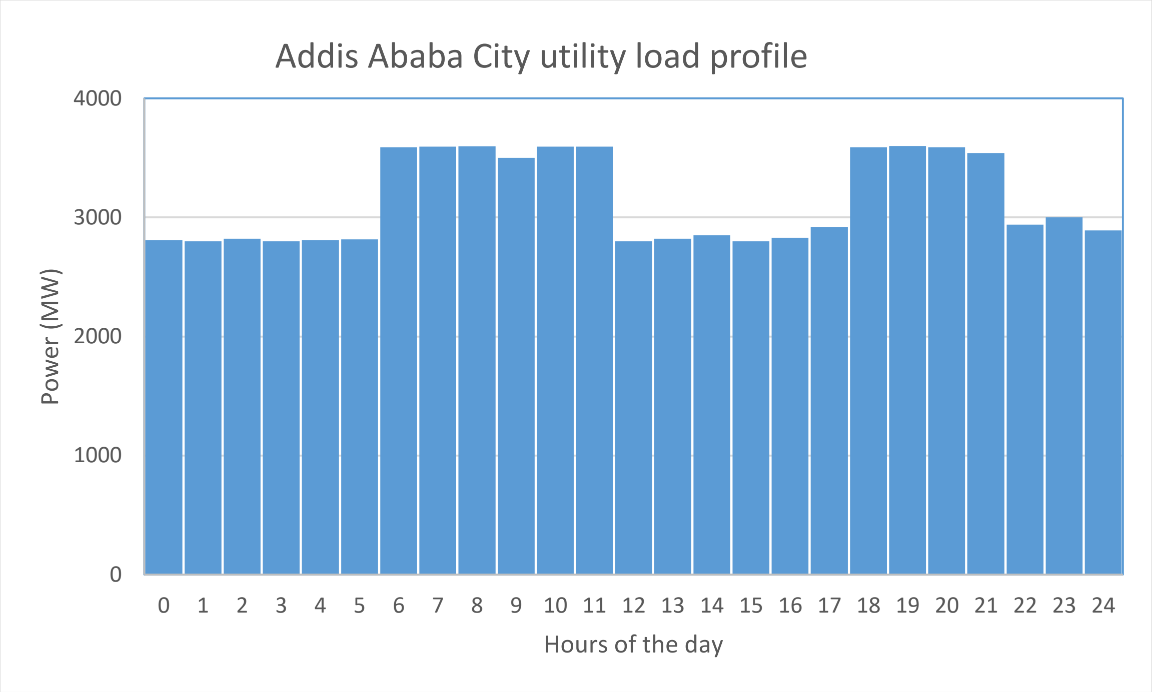


**Figure 3.13 Addis Ababa city average load profile (Source: Gerji LDC)**

According to the utility average load profile diagram, power demand peaks between 6:00 and 11:00 in the morning and between 18:00 and 21:00 at night. The power flow from EV batteries to the grid can flatten the load curve during these peak load demand hours, and optimization techniques can be used to reduce the peak load. Similarly, the EV batteries can draw electricity from the utility during the planned hours of 12 a.m. to 17:00 p.m. and 22:00 p.m. to 5:00 a.m.

### 3.6.5 Charging and discharging scheduling

Figure 3.18 illustrates the development of a basic EV charging and discharging optimization schedule model in this thesis. The utility load profile, electric cars, and charging equipment are the three main parts of the model. In particular, the utility is in charge of supplying electricity. In accordance with the demands of EVs, the charging apparatus purchases electricity from the grid and subsequently distributes it to the vehicles. Additionally, it transmits price data to EVs and the vehicles' present state to the grid system. Electric vehicles give feedback to the charging equipment about their current condition and are controlled to charge or discharge depending on real-time price information.

Three steps make up the scheduling process: transmitting commands, gathering data, and making decisions in real time. The decision-making unit first gathers demand data, EV battery state of charge, and energy price data from the utility or the grid. The decision-making unit then produces the charging and discharging plans for every EV after entering the gathered status data into the decision network. The grid then completes the energy scheduling for that period by sending the appropriate electricity to different charging devices after receiving the directives.

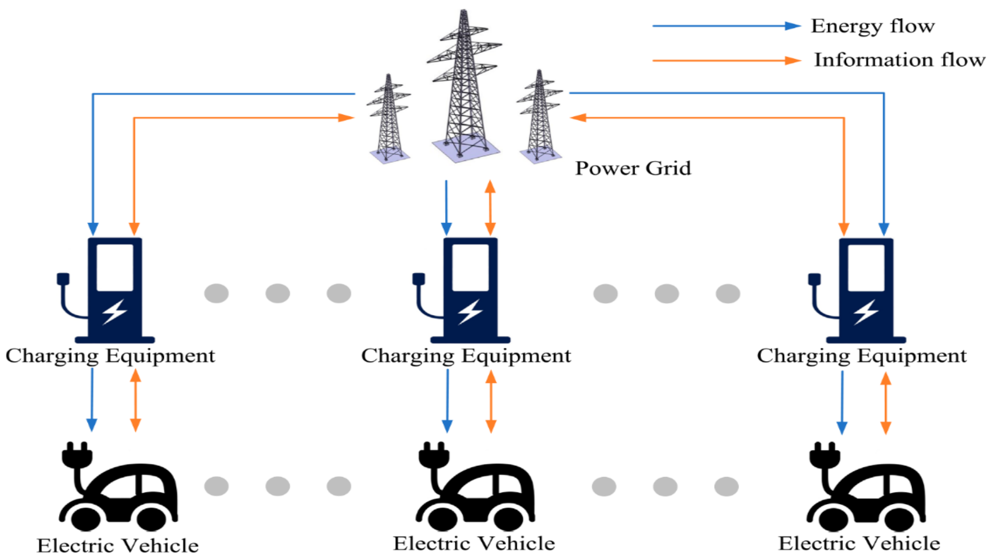


**Figure 3.14 Charging and discharging Scheduling for EVs**

### 3.6.5.1 Basic assumptions for scheduling

In the community, there are a total of N EVs. The set of EVs is designated as

B = {1,…,i,…,N}. It is assumed that EVs start charging and discharging immediately after being connected to the charging equipment. The scheduling process only considers EVs in the state of charging and discharging. A scheduling period is set as 24 h, with a scheduling step of 1 h. The set of time slots is designated as H = {1,…,t,…,24}.

In each scheduling step, EVs are divided into online and offline states. The set of online time slots for EV i is denoted as $T_i^{online}$ = {$T_i^{start}$… t…$T_i^{end}$ }, 0 ≤ $T_i^{start}$≤ t ≤ $T_i^{end}$ ≤ 23. $T_i^{start}$ is the time slot when the EV connects to the charging equipment to start charging. $T_i^{end}$ is the time slot when the EV finishes charging and leaves. Assuming that all EVs arrive at off- peak hours to be charged, the online time slots should be a continuous set of natural numbers. In other time slots, if EV i is not connected to the charging equipment, it is considered as not participating in the current scheduling.

#### 3.6.5.2 Cost of charging and discharging $C_{i,t}^{charge}$

The primary objective of the optimized scheduling for EV charging and discharging is to minimize the cost associated with EV charging and discharging. Based on the previous assumptions, this paper considers the following cost factors. The cost of charging and discharging $C_{i,t}^{charge}$ depends on the current electricity price and the amount of charging and discharging. Thus, the cost generated by charging and discharging behavior can be represented as:

$$C_{i,t}^{charge} = \lambda i.\ I_{i,t} \quad \text{………………………………………} \quad 3.38$$

Where, λi is the current electricity price during time slot t. $I_{i,t}$ is the total charging and discharging quantity of EV i in time slot t. It can be specifically expressed as follows:

$$I_{i,t} = \begin{cases} P_{i,t}\,, t \in T_i^{online} \\ 0, t \notin T_i^{online} \end{cases} \quad \text{…………………… ……… } 3.39$$

Where $P_{i,t}$ is the average charging and discharging power of EV i during time slot t. It is positive during charging and negative during discharging. $T_i^{online}$ is the set of online time slots.

### 3.6.6 Objective function

We can formulate objective function for optimization using problem description.

Let $P_t$ Demand for utility power at interval t,

$C_{i,t}$ Assuming constant charging and discharging power for every EVs across interval of time.

Further $P_t$ is a total power demand of the city as of the following equation (3.40).

$$P_t = P_t^{residential} + P_t^{indestrial} + P_t^{commercial} \text{ ……………………3.40}$$

Where, = $P_t^{residential}$ is power demanded by residential at interval t.

$P_t^{indestrial}$ = is power demanded by industry.

$P_t^{commercial}$ = is power demanded by commercial sector.

One way to express the objective function is as;

$$\text{Min} \sum_{t=1}^{T} \sum_{i=1}^{U} (P_t + C_{i,t}) \text{ …………………………………3.41}$$

Where, $P_t$ is the power demanded by utility before charging and power discharged by EVs during the time period t.

$C_{i,t}$ - is the EV's power for charging and discharging over time t.

-U is total number of EVs.

- T is total time step

### 3.6.7 Constraints

In order to minimize utility power the charging and discharging constraints are explained as follow:

- For each EVi, charging current $I_{i,t}^{c}$, at each interval t, then the constraint of charging current with in the limit is expressed as:

$$I^{c,min} \leq I_{i,t}^{c} \leq I^{c,max} \quad \forall_{t,i} \text{ ……………………………………..3.42}$$

Where $I^{c,min}$ is minimum charging current and it is negative.

Note that: Minimum charging current = Maximum discharging current.

- For state of charge of each EV i after each time step t, needs to be updated in the following way:

$$S_{i,t} = S_{i,t-1} + b_i I_{i,t-1}^{c} \quad \forall_{t,i} \text{………………………………………3.43}$$

Where, $S_{i,t}$ is state of charge for each EV at present time interval and

$S_{i,t-1}$ is each EV's state of charge at a specific point in time.

Each EV battery i capacity represented as ‘bi’

Charging and/or discharging current of each EV battery at previous interval (t-1) represented as $I_{i,t-1}^{c}$ .

- The interval for SOC $S_{i,t}$ state of charge of battery has minimum and maximum limit.
- In order to keep battery life safe for each EV state of charge $S_{i,t}$ should be constrained between minimum state of charge($Si^{min}$)and Maximum state of charge($Si^{max}$)

$$Si^{min} \le S_{i,t} \le Si^{max} \qquad \forall_{i,t} \text{ ..................................... 3.44}$$

- At the time of discharging EV battery is supporting utility with active power, therefore,

$$Si^{min} \le Si, t^{desired} \qquad \forall_{t,i} = t^{desired} \text{ ........................ . 3.45}$$

- The equality constraint can be used to determine the charging and discharging power of each EV battery i at each interval t. Expressed as:

$$P_{i,t} = I_{i,t}^{c} V_{DC} \qquad \forall_{t,i} \text{ ..................................................3.46}$$

Where, $P_{i,t}$ is charging power if $P_{i,t} > 0$,

$P_{i,t}$ is discharging power if $P_{i,t} < 0$,

$V_{DC}$ is the DC-DC converter's voltage.

- EV batteries have a charging and discharging power constraint, P(i,t), that is limited. Expressed as:

$$P_i^{b-} \le P_{i,t} \le P_i^{b+} \qquad \forall_{t,i} \text{ ...................................... 3.47}$$

Where, $P_{i,t}$ is charging power,

$P^{b-}$ is maximum battery discharge power,

$P^{b+}$ is maximum battery charging power

- Utility power (P) is limited as follow. and

$$0 \le P_t \le P_t + \sum_i P_i^{+} \qquad \forall_{t,i} \text{ ..................................... 3.48}$$

- The minimum and maximum utility power($P_t$) constrained as :

$$0 \le P_t \le P_t + \sum_i P_i^{+} \quad \forall_{t,i} \text{ ................................................... 3.49}$$

Where, '0' is the definition of minimum utility power.

$P_t + \sum_i P_i^{max} = P_t$ is positive power demand and $\sum_i P_i^{max}$ is maximum charging and discharging power of EVs.

### 3.6.8 Optimization results

Developing smart charging plans for the best possible charging and discharging of EV batteries is the second objective of this thesis. For the sake of performing optimization the overall utility load profile of Addis Ababa city is considered over a period of 24 hours.
All available EVs are assumed to be taken in V2G charging scenario. A fleet consisting of 30 EVs are selected from different load area to achieve optimization and all are assumed to be plugged in. EV charging and discharging patterns are examined over a 24-hour period, with an hourly time delay between each analysis. Data from the most recent and current charging systems was collected. The current and latest charging system data was taken. The parameters used for analysis is listed as follow:

- Different battery energy capacity $b_i$ is selected to represent different EVs available in the market. Additionally, from Bajaj taxi to higher end EV types are considered.
- As we can see from the above graph low power demand or off-peak hour is from 12:00 to 17:00 and from 22:00 to 5:00 hours, therefore, in this time the initial state of charge is taken as 80% of total charge, because off-peak hours are the time for charging EVs at fast charging rate.
- Fast charging is expected for both charging and discharging in order to charge EVs in the shortest amount of time possible for SOC, which is between 20% and 80%. Slow charging is used from 80% to 100% to ensure that the battery is fully charged (this can be seen between 24:00 and 07:00, based on assumptions).
- For the next day's usage the EVs need to be ready, they were constrained to be fully charged before 6.00.
- In state of charge between 20%-80% charging EVs are carried out in minimum time and in state of charge (SOC) between 80%-100% charging is undergoing at slow rate.
- The average battery state of charge is assumed to be between 50% and 57% because EVs in various locations have varying travel needs.
- Each EV is considered to have a minimum state of charge of 20% and a maximum permitted state of charge of 90%. This assumption was made by considering the battery healthy operation.
- The battery's healthy operation was taken into consideration when making this assumption.

- As of CHAdeMO standard maximum charging current is assumed to be 125A and the minimum charging current or maximum discharging current is set at -125. 600V is the selected DC voltage for optimization based on DC fast charging levels and to create a fast charging plan.
- The following assumption are made: the number of charger in a single charging station is to be 5. Each charger is rated 500kW charging and discharging power. A city can have 20 charging station. Therefore, the total power for optimization becomes 5x500kW = 2500kW or 2.5MW.

**Table 3.5 Parameters and values used in optimization**

| Parameter | Value |
|---|---|
| Max. charging current: $I_i^{c,max}$ | 1250A |
| Max. discharging current: $I_i^{c,min}$ | -1250A |
| State of charge: $S_i^{min}$ | 20% |
| State of charge: $S_i^{max}$ | 90% |
| State of charge threshold: $S_{desired}$ | 80% for all EVs |
| Desired time for $S_{desired}$: $t_{desired}$ | 00:00 |
| Max. discharging power: $P^{min}$ | 500kWx5x20 = 50MW |
| Max. charging power: $P^{max}$ | -500kWx5x20 = -50MW |
| Total time steps | 24 |
| Base power of the Addis Ababa city utility. | 3500 MW |

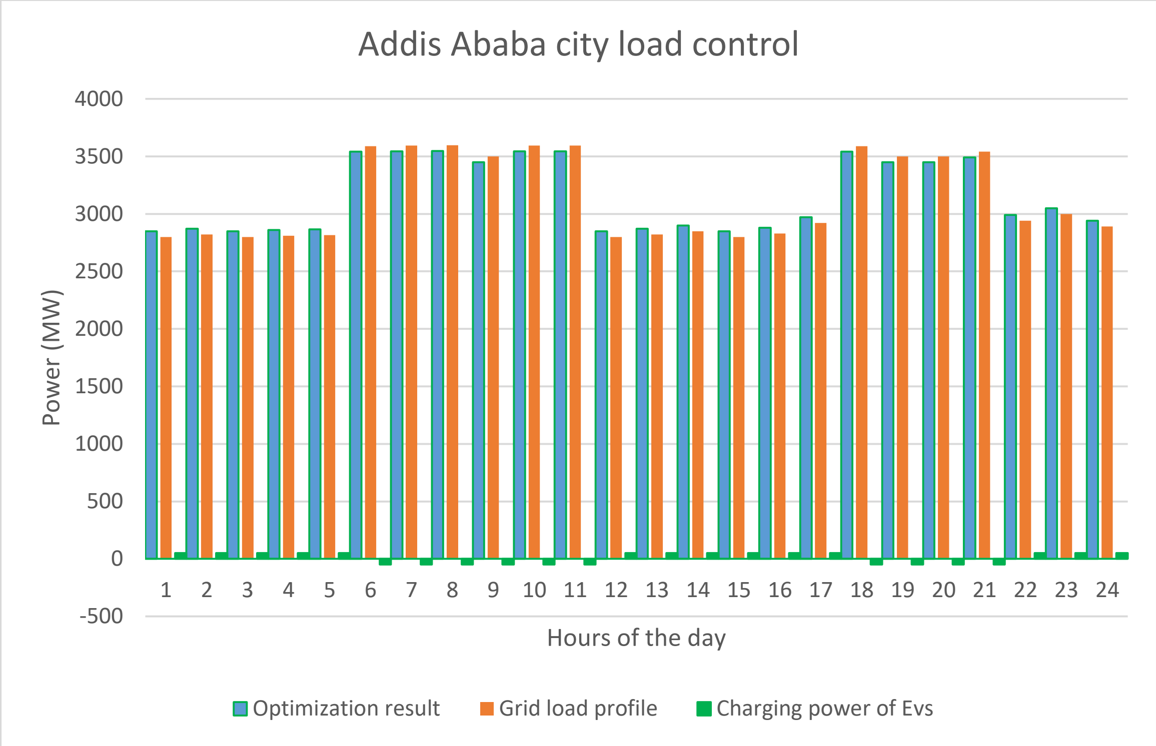


**Figure 3.15 Result of optimization**

As we can see from figure 3.19 charging time of EVs are from 12:00 to 17:00 and from 22:00 to 5:00 hours. Similarly, even if the graph of charging power of EVs are not visible due to small power magnitude (50MW) compared to grid load profile and optimization result, Similarly, active power support is given from 6:00 to 11:00 and 18:00 to 21:00 hours. As observed in the above picture, peak power is decreased from 3500 MW to roughly 3450 MW, or a drop of roughly 3500-3450=50 MW. The approximate average power after optimization is 3450 MW.

### 3.6.9 Cost analysis

Cost analysis is done in this section of the study to support the argument that EV owners and utilities can save money by using the results of the optimization techniques used in this study. Ethiopian electric utility data is taken as the basis for the cost analysis in this study. Over the course of the year, Addis Ababa's power load profile remains relatively close to the data presented in this chapter. Therefore, load profiles for a city with and without optimization are used in cost analysis to find the least amount of money. Data from Ethiopian electric utility tariffs shows that in addition to energy prices, Addis Ababa city must pay money for power consumption per kilowatts (kW). For the sake of calculating the reduced cost due the support made by EVs, let's assume the minimized power tariff to be **2.48 ETB/kWh**. With this assumed value it becomes possible to save about 1**90,500 ETB/kWh** cost of charging. Which is about **4,572,000 ETB/day.**

**Table 3.6 Smart scheduling strategy for cost minimization**

| | |
|---|---|
| Consumed power before optimization (kW) | 3,500,000 |
| Consumed power after optimization (kW) | 3,450,000 |
| Power reduced (kW) | 50,000 |
| Tariff before optimization (ETB/kWh) | 6.29 |
| The minimized power tariff for EVs for supporting the grid (ETB/kWh). | 2.48 |
| Reduced Cost (ETB/kWh) | 3.81 ( 190,500) |

# CHAPTER 4

# SIMULATION AND VERIFICATION OF DESIGNED MODEL

## 4.1 Simulation of V2G mode of operation

Simulating the model developed in the previous chapter figure 3.1 is the first objective of the thesis. In this setup, a three-phase AC-DC converter is connected to a three-phase grid voltage to enable a two-way power flow between EV batteries and the grid. Table 4.1[65] provides the simulation settings needed to simulate a desired bidirectional charging station. Additionally, as an alternative to bidirectional DC-DC converters, utility-controlled current sources and grid-connected AC-DC converters are utilized to connect EV batteries.

**Table 4.1 Three phase voltage source specification [65]**

| Component | Parameter | value |
|---|---|---|
| Grid | voltage | 380V |
| | Phase | Three phase |
| | Frequency | 50Hz |
| | Filter capacitance | 30$\mu F$ |
| | Filter inductance | 5mH |
| Converter ratings | Voltage | 500Vdc |
| | Charger Power | 500kW |
| Voltage source converter (VSC) | switching frequency | 10,000Hz |
| | Bus capacitance | 5600 $\mu F$ |
| | Output capacitance | 0.625 $\mu F$ |
| | Back filter inductance | 20mH |
| $V_{dc}$ | DC link voltage | 600V |

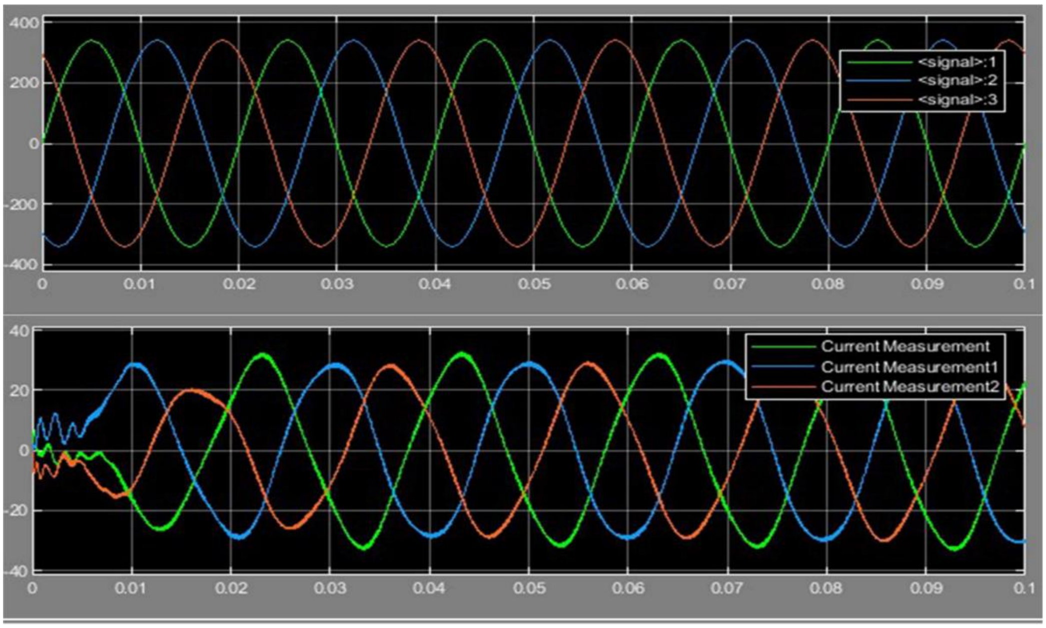


**Figure 4.1 V2G mode three phase voltage and current wave form simulation**

As we can see from figure 4.1 when vehicles are operating in the V2G mode (discharging), three-phase grid voltage and currents are in phase, which means grid is receiving power from vehicles. Because the vehicle's power electronics regulate the power flow, voltage and current are in phase. In order to achieve a power factor of one or nearly one, the converters transform the battery's voltage and current into usable AC power that is synchronized with the grid.

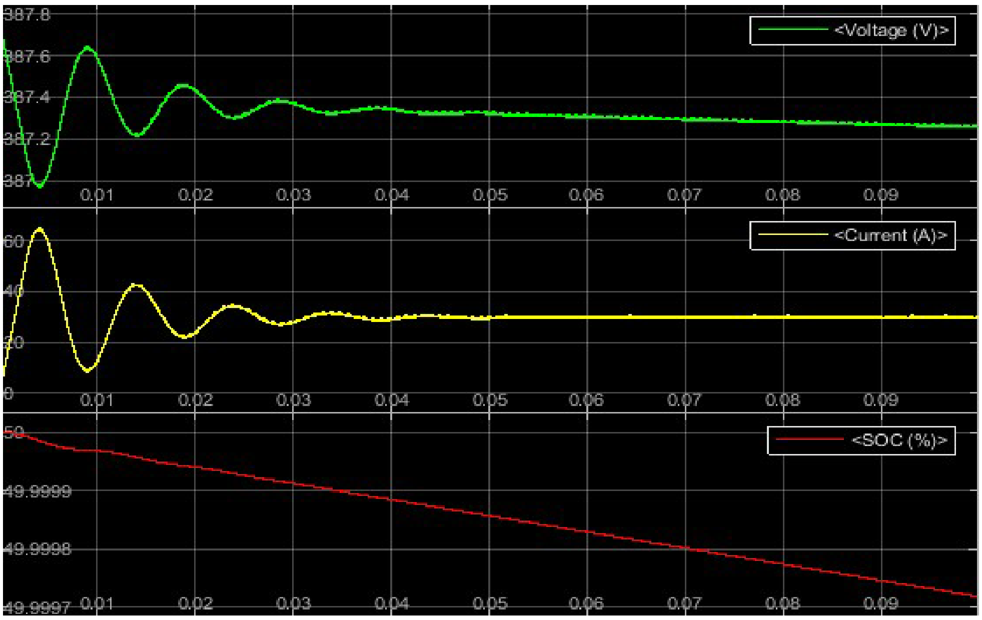


**Figure 4.2 simulation of battery state of charge in case of V2G mode**

As we can see from the above as the discharging current of the battery increase the voltage and state of charge of battery decrease.

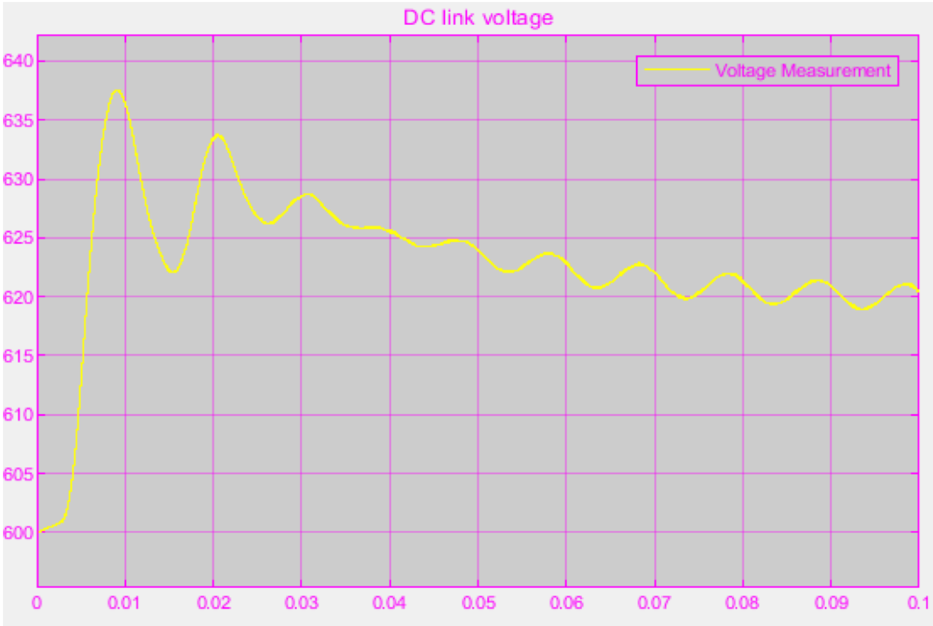


**Figure 4.3 simulation of DC link voltage in case of V2G (discharging) mode**

Figure 4.3 shows the DC link capacitor voltage is positively rising in case of discharging mode of operation.

## 4.2 G2V mode of operation simulation

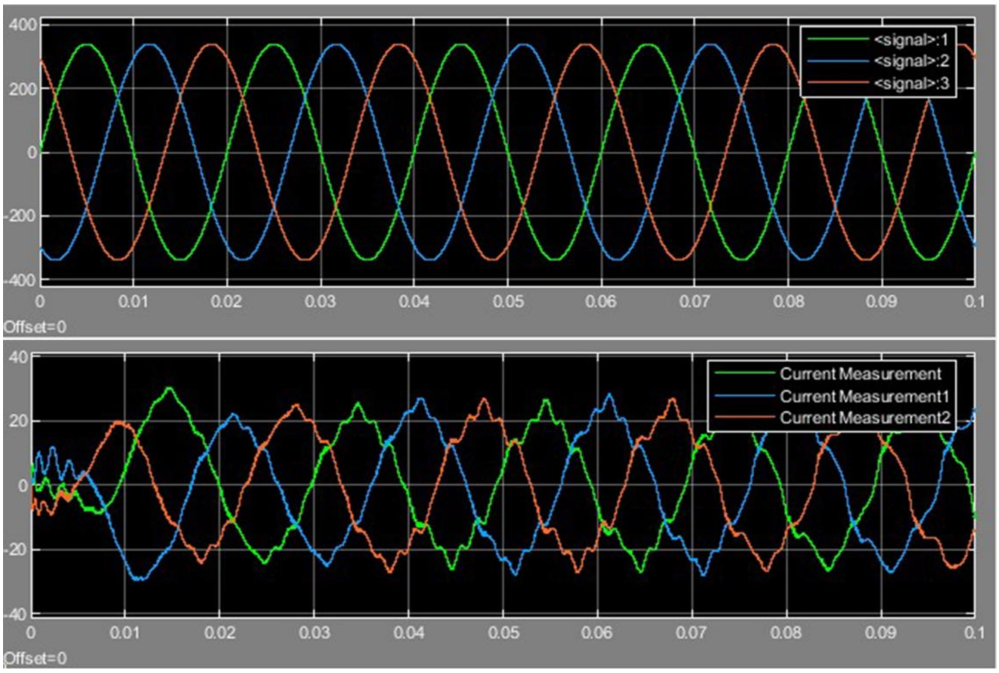


**Figure 4.4 G2V mode three phase voltage and current wave form simulation**

As we can see from figure 4.4, in case of G2V mode of operation (charging) voltage and currents are out of phase which means vehicles are receiving power from the grid. The voltage and current are out of phase because of different factors.

1: Power electronic components: During the conversion of AC power to DC power includes converters can introduce delays and phase shift in voltage and current wave form.

2. Impedance effects: The impedance of the charging station and the vehicle itself can influence the phase relationship between voltage and current. The impedance brings lag between the voltage and current waveforms, leading to a phase difference.

3. Grid conditions: fluctuations in the grid voltage and frequency can affect the phase difference between voltage and current.

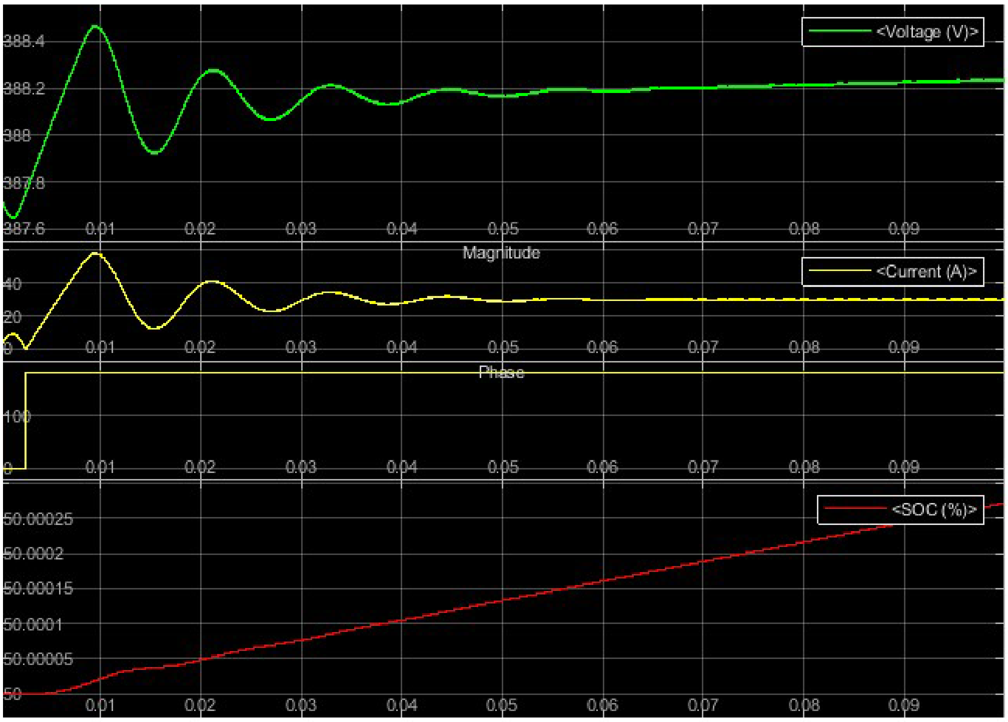


**Figure 4.5 simulation of battery state of charge in case of G2V mode of operation**

As we can see from the above as the charging current of the battery increase the voltage and state of charge of battery increase.

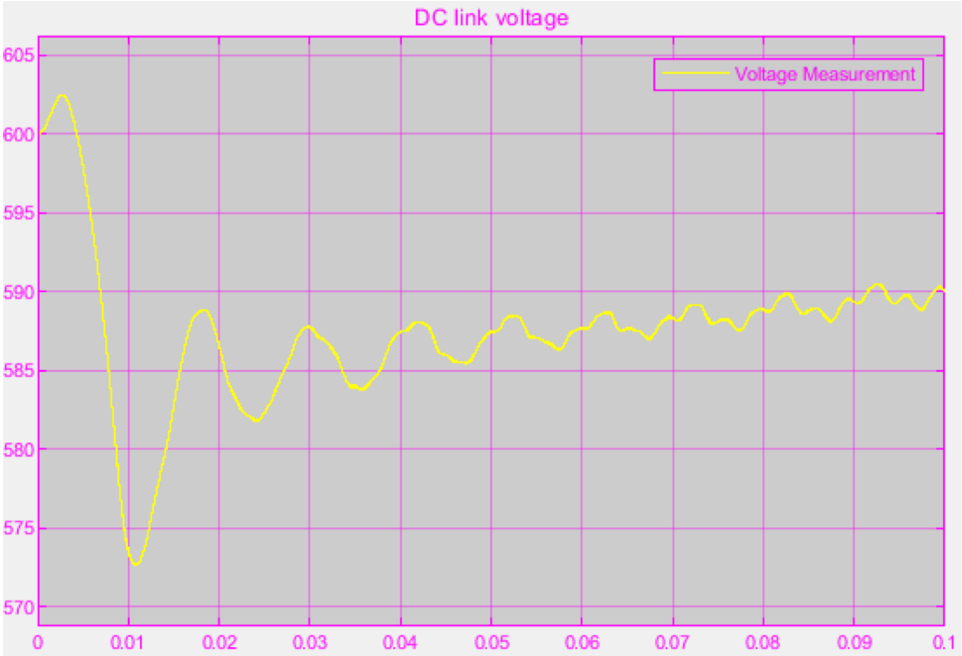


**Figure 4.6 simulation of grid voltage in case of G2V mode of operation**

- As we can see from figure 4.6 shows the voltage across DC link capacitor is negatively declining in case of G2V mode of operation. Due to voltage drop in distribution line, increase in power demand, and voltage regulation issues.

## 4.3 Verification of working of V2G mode of operation

Case I: based on some predefined signals

a. **EV owner signal:** In the first case study, the owner/user signal is a two-valued time-based signal. The number "0" indicates that charging is needed by EVs. "1" denotes idle time of EVs, during which the discharge procedure may be initiated in accordance with the SOC threshold that the EV owner has established. The figure below displays the owner signal. According to the figure, EV is idle for 5-15 seconds and then again for 25-35 seconds. Consequently, these idle hours are the time in which the EVs can support the grid with active power if its state of charge (SOC) is higher than the user-defined threshold.

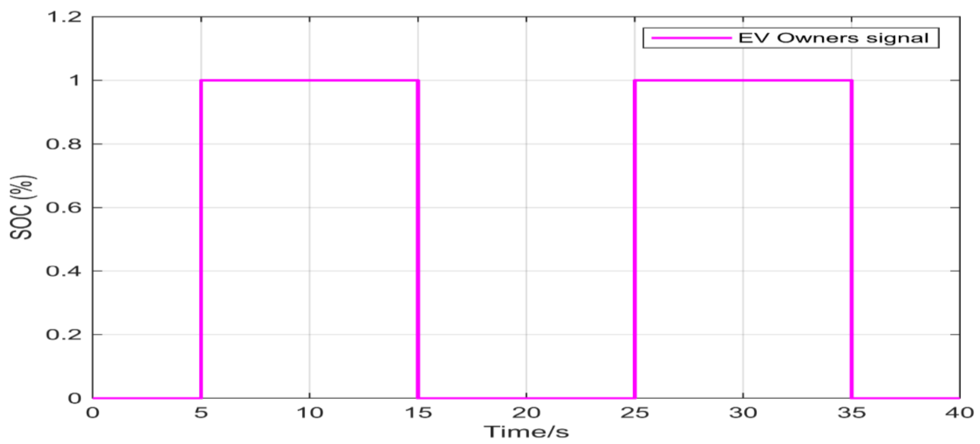


**Figure 4.7 EV owner signal**

**b. Utility demand signal:** The utility signal is supposed to be a continuous signal with both active and reactive power shortages. Let's use the average load in Addis Ababa, which is 3000MW, as a benchmark for comparison. Power demand of a city is full filled by these reference signals. The power demanded by the DC-link and an AC-DC converter is determined by comparing the utility demand signal, which indicates a shortage in the required power, with reference signals.

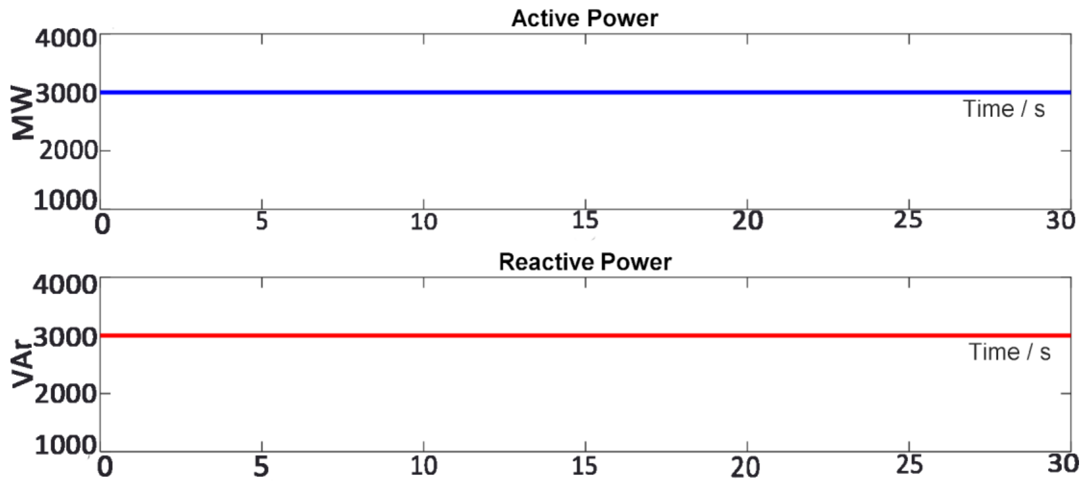


**Figure 4.8 Reference utility signal**

The utility demand signal is shown in Figure 4.9, and the reference signals used by the EV side controller are shown in Figure 4.8. There is an active power loss of 1000MW between 5 and 10 seconds and another active power deficit of 500MW between 20 and 25 seconds, as can be seen by comparing Figures 4.2 and 4.3. Additionally, Figure 4.9's second demand signal, which is displayed in red, indicates a 300MVAr reactive power shortfall between 5 and 10 seconds and another 500MVAr reactive power deficit between 17 and 25 seconds.

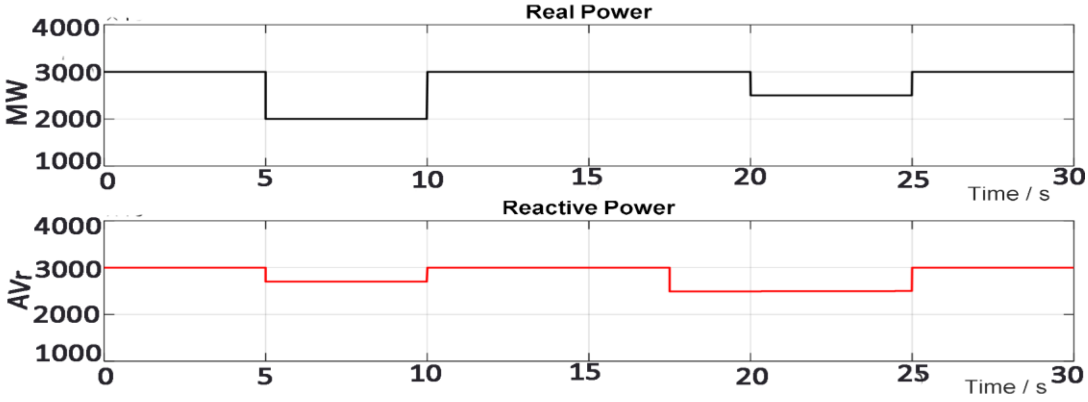


**Figure 4.9 Signal demanded by utility**

**Table 4.2 Battery parameters and specifications**

| Component | Specification |
|---|---|
| Nominal voltage | 365V |
| Battery capacity | 300Ah |
| Initial state of charge(SOC) | 52% |
| Response of battery time | 1s |
| Cut-off voltage | 265V |
| Voltage at full charge | 429.0252 |
| Internal resistance | 0.016921 ohms |

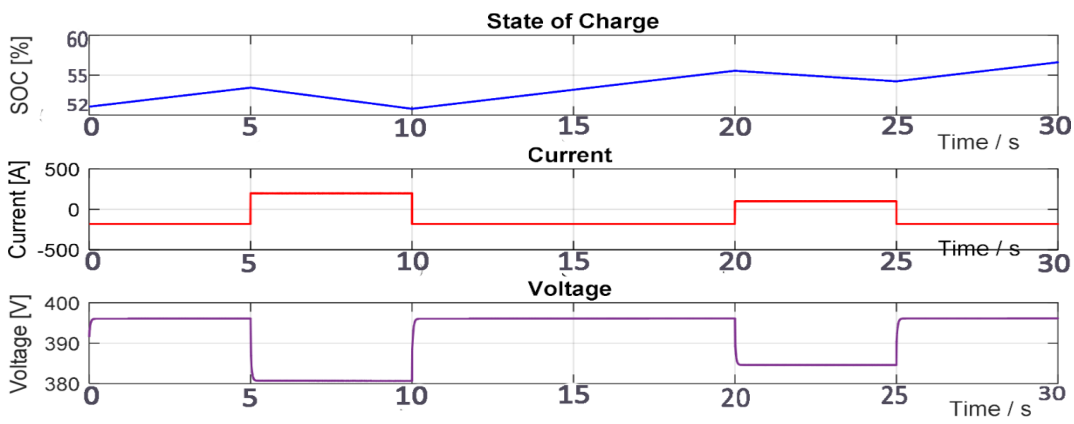


**Figure 4.10 Simulation of EV battery status based on owner defined signal**

EV battery state is displayed in Figure 4.10 following the development of a V2G system simulation. 0–5 seconds, 10–20 seconds, and 20–25 seconds are user-defined time, in this time interval the battery draws power from the grid to charge. Additionally, it maintains the active and reactive power support during when the time interval is from 5–10 seconds and from 20–25 seconds.

**Case study II: Based on peak shaving hours**

The purpose of the model is to illustrate the possible contribution of EV batteries for load leveling service that can be offered to utilities. In this concept, over the course of a day, EV batteries actively supply electricity to the grid during off-peak hours and return power to the battery during peak demand hours. Using a developed algorithm, the EV side controller regulates the charging and discharging process. For EV batteries, the previously mentioned specifications are applied. Simulation settings for case II verification are displayed in Table 4.3.

**Table 4.3 Parameter of simulation**

| Parameter | Values |
|---|---|
| Time of simulation | 24 hours |
| EV number/Batteries | 1 |
| Maximum current to charge | 125A |
| voltage from converter | 600V |
| Capacity | 85 kWh |

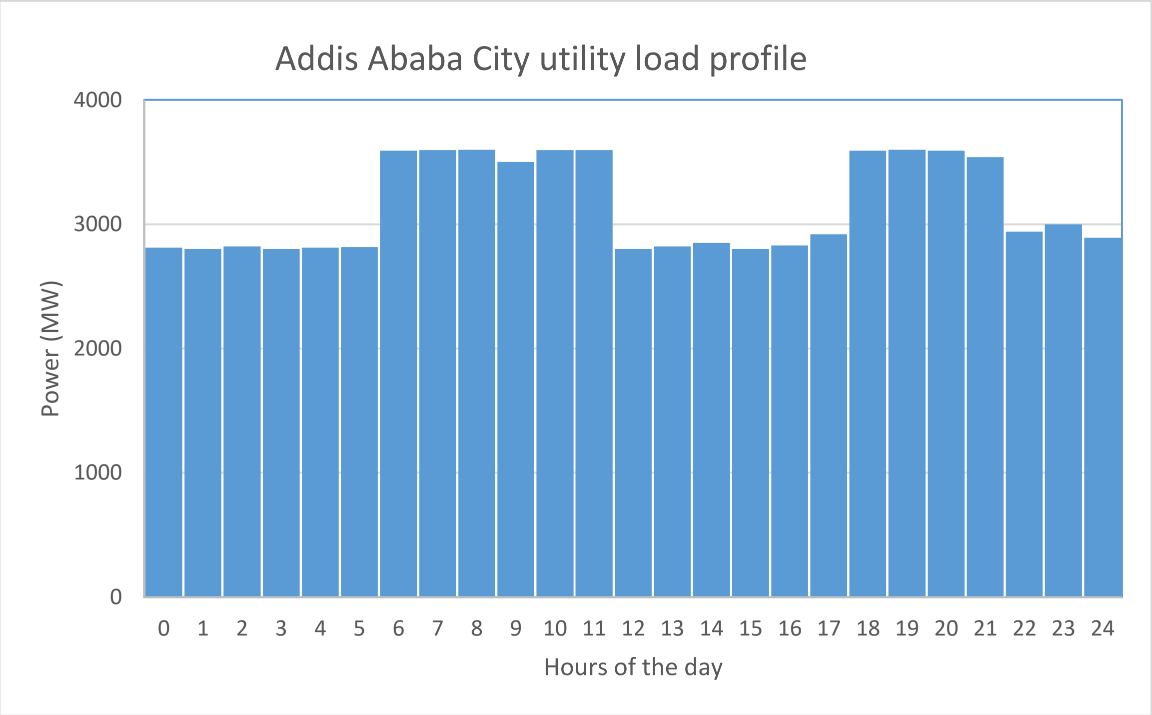


**Figure 4.11 Addis Ababa city utility load profile used for optimization**

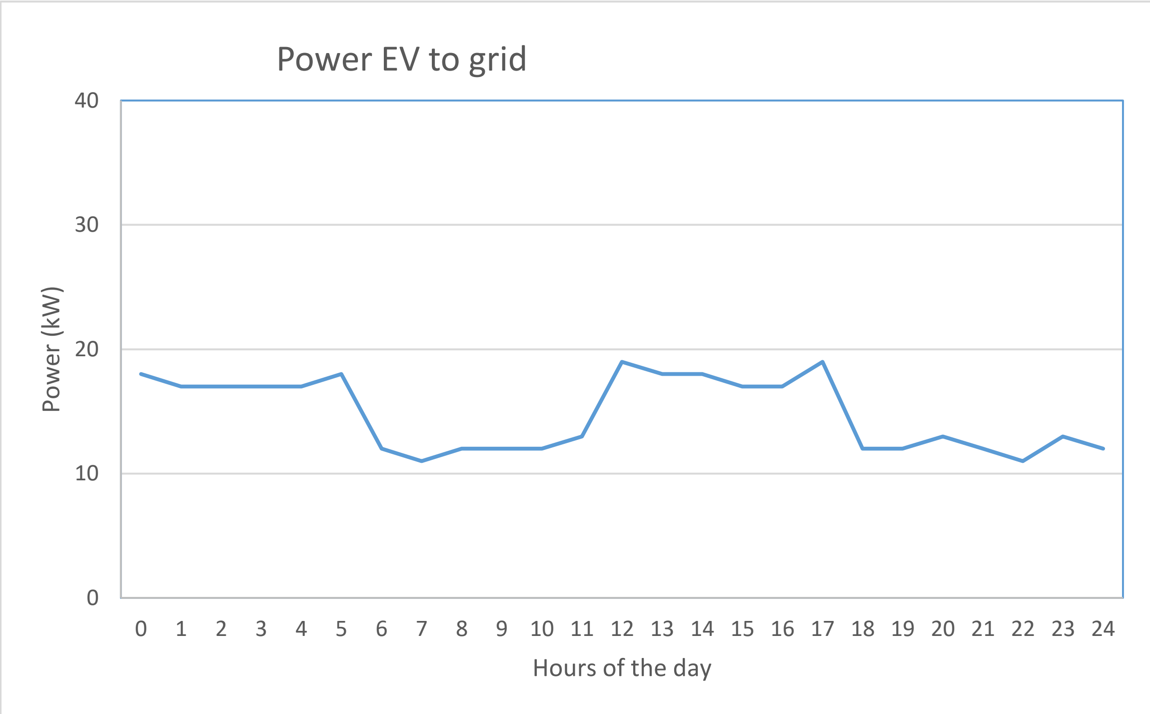


**Figure 4.12 Power delivered to grid from EV**

As demonstrated in Figure 4.11, EV batteries need to be charged between 22:00 and 5:00 and 12:00 and 17:00 in order for V2G to function successfully. Furthermore, for peak shaving purposes, EV batteries should supply electricity to the grid between 6:00 and 11:00 and 18:00 and 21:00 hours. Figure 4.12 displays the collective SOC of the EV batteries.

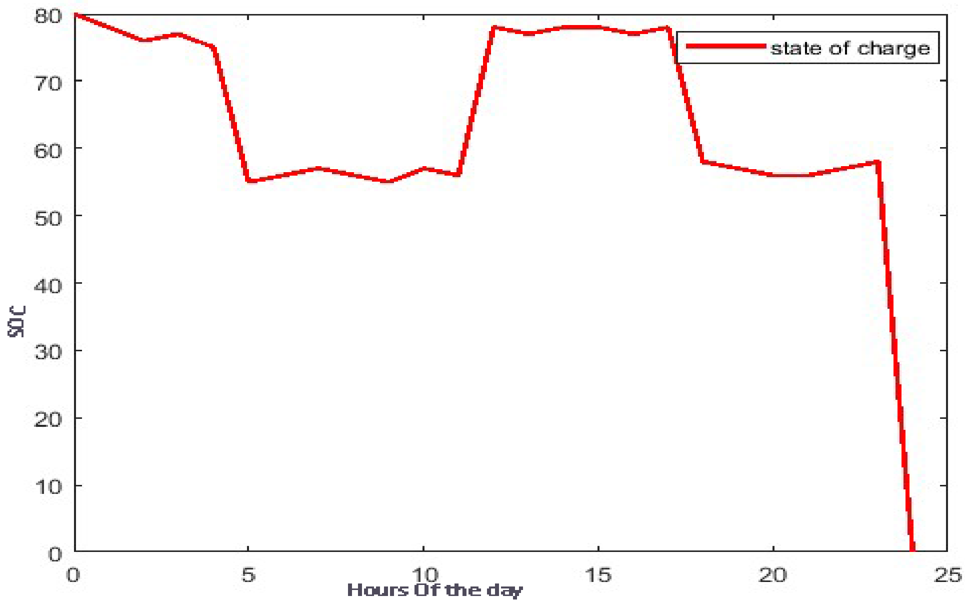


**Figure 4.13 Collective SOC of EV batteries**

# CHAPTER FIVE

# RESULT, DISCUSSION AND FUTURE WORK

## 5.1. Result and discussion

In the meantime, a large number of EV fleets in Addis Ababa are thought to put an additional stress on the utilities. In order to alleviate the lack of dependable charging stations and to mitigate the negative effects of integrating a larger number of EVs into the distribution network, this thesis contributes to the development of fast charging stations. Furthermore, in order to reduce the cost of charging for EV owners and electric utilities, the proper model for a smart charging schedule was created and simulated in MATLAB for this thesis.

Furthermore, in order to realize the second objective of this thesis optimization model was developed in a MATLAB Simulink to implement quadratic programming. Based on optimization developed model and parameters defined, it is becomes possible to achieve load leveling and peak power shaving by fully charging EV batteries during periods of low utility power demand. At the same time, active power support has been confirmed by model developed at hours of highest power demand.

Generally, the models developed in this thesis and the simulation result found from these models are one of the achievement to show effectiveness of a bidirectional charging station or V2G and G2V scenario. The charging cost will be reduced if EV owners are incentivized for supporting utilities with power needs. A bidirectional charging station also has the advantage of lowering electricity tariffs significantly. On the other side, the V2G situation offers a number of benefits for the utility. First, leveling the load maintains grid stability without requiring additional generation side investment. Grid health may be negatively impacted by the additional load of EVs, but by taking part in V2G and G2V, the effect of additional load of EVs do not bring any negative effect on the system. Furthermore, Participating in V2G also enables utilities to reduce consumer power use, which maintains optimal grid stability and dependability and spares the grid from extra strain. The main benefit for the utility is that, once a bidirectional charging station is set up, they won't need to alter their system to handle the additional EV load on the distribution network.

## 5.2. Conclusion

The three-phase vehicle-to-grid and grid-to-vehicle mode of operation is simulated using the chosen parameters and system specification in MATLAB/Simulink. In the simulation process, the behavior of three-phase voltage and current waveform is observed, how dc-link voltage is acting in both G2V and V2G scenarios is seen and how the state of charge of the battery is acting in both the charging and discharging process. Finally, the simulation result approves the practicability of a bidirectional charging system with the developed model.

The steady-state battery voltage and current with inductor current waveform are observed. The output battery voltage is measured as 350mV. The inductor current is measured as 3.5A. The waveform of the reference DC bus voltage value of 600V is successfully observed in both G2V mode and V2G mode of operation. Since the DC bus capacitance value of the determining factor for ripple value, the ripple value is minimized by using the appropriate capacitor value. By using the DC bus reference voltage, the system's overall performance is also evaluated for both the G2V and V2G modes of operations. In addition, the closed-loop performance of a bidirectional charging system model was analyzed the desired outcome of the charger was observed. Therefore, the result of the simulation confirms the effectiveness of employed control strategies in both vehicle-to-grid and grid-to-vehicle scenarios, along with the selected parameters and system specifications.

Charging EV batteries at fullest level helps to accomplish load leveling during times of low utility power demand, according to the optimization model that was designed and the parameters that were established. The cost analysis is conducted during the day's peak power hours. Finally, cost analysis is made based on the optimization technique adopted and it was confirmed that the charging cost of the utility and EV users is minimized by charging at a reduced power tariff by reducing peak power demand of a day from 3,500 MW to 3450 MW. As a result, the cost of charging is reduced to 4,572,000 ETB/day. Therefore, the establishment of a bidirectional EV charging station in a dedicated place or public parking place in Addis Ababa can bring a significant solution in mitigating EV owners suffering due to a shortage of charging stations, minimizing the cost of charging and supporting the utility.

## 5.3. Future work

For future the grid may not be the only source of power, instead renewable energy sources can be oriented towards integration of EVs and also for widespread acceptance of EVs economical aspect of implementation of a bidirectional charging stations can be explored.

For the best results, a hybrid algorithm can be created by combining various optimization strategies for smart scheduling EV battery charging. Bidirectional charging stations can be implemented by investigating alternative control mechanisms.

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