Single Phase Low Voltage On-board Charger for Plug-in Electric Vehicle (PEV) Charging applications

A Dissertation submitted in fulfillment of the requirements for the Degree
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in

Power Systems

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DECLARATION

I hereby declare that the work which I have presented in dissertation entitled, ***"Single Phase Low Voltage On-Board Charger for Plug-in Electric Vehicle (PEV) Charging applications"***, in fulfillment of the requirements for the award of degree of Master in Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department of Thapar Institute of Engineering & Technology, Patiala is an authentic record of my own work carried under the supervision of **Dr. Surya Prakash**. It refers to other researcher's work which is duly listed in reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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ABSTRACT

This dissertation mainly emphasis on charging of electric batteries through single phase on board bidirectional charger for charging of Electric Vehicles. The charger resides of following components: i) AC-DC full bridge bidirectional boost converter (120V AC to 400V DC); and ii) a half bridge DC-DC buck converter. The motive of AC-DC converter controller is to supervene the Power (P-Q) commands provided by grid or utility. With the change in controllable commands the parameters of DC side can be adjusted. The DC-DC converter is used to control dc voltage and hence thereby controlling the charging current. For each converter a separate controller is provided that maintains the balance between input power and output power. The controller for AC-DC converter is used to boost up the input grid voltage upto 400V dc. The charger must have to supervene the instructions/commands provided by grid or utility. The DC-DC converter is used to proselyte fixed voltage into variable voltage so that current required for charging the battery can be restrained. This dissertation mainly focuses on Level-1 and Level-2 On Board charging system. The three types of chargers are used for the purpose of charging which are: i) 1.44kVA charger ii) 3.3kVA charger iii) 6.6kVA charger. The 1.44kVA type charger falls under the category of Level-1 charging system and 3.3kVA and 6.6kVA type chargers fall under the category of Level-2 charging system. The 6.6kVA charger is fast as compared to 3.3kVA charger and 1.44kVA charger. The parameters that are shown in tables in Chapter 3 are used to obtain desired results as shown in Chapter 4. In this dissertation the proposed charger is used to charge the plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) in charging only operation. The block diagram of Simulink Model and results of different charging levels are represented in this dissertation work.

Keywords: *AC-DC converter, DC-DC converter, Battery Charger, Plug-in Electric Vehicles, Unified Controller.*

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

EV	Electric Vehicle
CC	Constant Current
CV	Constant Voltage
SOC	State of Charge
Li-ion	Lithium ion
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PR	Proportional Resonant
PI	Proportional Integral
THD	Total Harmonic Distortion
V_{dc}	DC link Voltage
V2G	Vehicle to grid
G2V	Grid to Vehicle
C_{bt}	dc-dc converter side capacitor
L_{dc}	dc-dc converter side inductor
L_c	Coupling Inductor
L_f	Inductance at dc side
C_f	Capacitance at dc side
V_a	Source Voltage
C_c	Coupling Capacitor
P_{cmd}	Active power command
Q_{cmd}	Reactive power command
I_{bt}	Battery Charging Current
I_c	Charging Current
P_r	Reference active power
Q_r	Reference reactive power
PWM	Pulse Width Modulation
d	Duty cycle
Δ	Angle between grid voltage and dc side voltage

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Electric Vehicles and Plug-in Electric Vehicles are growing very fast in today's environment and will remain in upcoming years. These are the best alternative to conventional Internal Combustion Engine (ICE) vehicles [1]. The electric vehicles are powered by an electric motor rather than petrol/diesel engine. So electric vehicles do not have a tailpipe and hence do not cause pollution. Large numbers of electric vehicles produce the congestion problem in distribution grid during peak load hours. So, to overcome this problem, coordinated charging will be must to decrease the bad impact on the grid [2], [3].

The Battery charger proposes of two converters that share a DC link. The DC link is used to connect these two converters. DC link plays a vital role in charging of the battery from the grid to vehicle. AC to DC transformation of power is carried out with the help of charger. The electric vehicle charger is power linkage device that links the grid to the vehicle. The only purpose of the charger is to follow Power commands that are provided by grid or utility. These commands are of various types which will be explained further. The single phase On-Board charger can also fulfill power quality functions such as support of reactive power, regulation of voltage, filtering of harmonics and power factor improvement [4]. The profit of plug-inan electric vehicle is the capability to keep up the steady and secure operation of the grid by making cooperation between utility and vehicle.V2G (Vehicle to Grid) operation can also take place by using PEV charger. There is a necessity of providing reactive power back to the grid during peak load times. During peak load times the voltage profile of grid decreases which results in an increase in voltage regulation and hence increase in line current. The increased line current helps to create a huge amount of copper losses. So, to maintain and reduce copper losses reactive power supply to the grid is a must. According to studies that shows reliance on a large number of PEV connected, charger ratings in those PEVs, distribution transformer rating (25-100kVA), charging current harmonics and geographical location, the lifetime of distribution transformer can be reduced down to 26% of normal working life expectancy [5],[6]. However the increased number of PEV connections makes the on-site generation of reactive power an important add-on value. The design of battery charger is of utmost importance to regulate the power flow, and, as a result, maintains reliable service of electric power.

Electric mobility requires modern, reliable and efficient infrastructures in order to finally reach a wide diffusion. At the same time, these infrastructures have to be integrated with existing, and often aging, electric networks: this matching must face several technical challenges, mostly on urban scenarios, where many technical and operational constraints are present. Moreover, electric vehicles charging operations require very accurate control devices in order, not only to avoid causing further troubles to the low voltage distribution systems but also to help to ensure network security and power quality.

In future, utilities would communicate between PEVs power and customer requirement and will control it. The ac-dc and dc-dc converters have been used in this dissertation for charging operations because of these reasons are: to implement the isolation and reduce the harmonics present in dc battery charging current to increase battery lifetime [7]. In this work, we have used two controllers are for the ac-dc converter and dc-dc converter. The unique control strategy is formulated for each converter. The controller communicates for active power and reactive power between Electric Vehicle and grid.

The following are some terms that are related to the battery.

Cell, Module, and Pack**:** A single cell comprises of two current leads and separate space which holds electrodes, separator, and an electrolyte. A module is crafted of certain few cells either by doing welding or by attached physically in between cells. Electric Vehicles have more than one pack of battery cells which are located at different locations in the car. The energy stored in the battery, which is present in PEV, is used by dc motors to propel the car.

Ampere-hour Capability**:** It is the aggregate charge that can be released from a fully charged battery under determined conditions. The Appraised *Ah* limit is the ostensible limit of a completely charged battery. The states of the battery are predefined by the producer. Generally, *Wh* capacity is used to represent the battery capacity [8]. The rated *Wh* capacity can be defined as

$$\text{Rated Wh Capacity} = \text{Rated Ah Capability} \times \text{Rated Battery Voltage}$$

C-rate**:** The purpose of C-rate is used to portray the rate of charge or discharge which is equal to the capacity of a battery in 1 hr. For a one Ah battery, C-rate is equal to charge or discharge of the battery at 1A and 0.2C corresponds to 0.2A.

State of Charge (SOC)**:** SOC is a measure that is utilized to extrapolate the measure of the charge which relates to the measure of electric vitality that can pull the EV with just electric power. It is undifferentiated from the fuel measure that is utilized to demonstrate how much fuel is left in the tank in an ICE vehicle.

$$SOC = \frac{Remaining\ Capacity}{Rated\ Capacity}$$

State of discharge**:** It is a complement to SOC, which means that it shows how much amount of electric power has been withdrawn from Electric Vehicle battery [8]. Therefore, the sum of SOC and SOD is always equal to 1. Mathematically, it can be written as:

$$SOD = 1 - SOC$$

1.2 LITERATURE SURVEY

The Plug-in Electric Vehicles (PEVs) are also known as Battery Electric Vehicles (BEVs). According to survey, the use of energy is going to elevate the transportation of world by 45% till 2030. The enhancement in the use of electric vehicles (EVs) is must to curb the climate change and to alleviate the oil fuel consumption. However, there are certain constraints regarding the acceptability of electric vehicles (EVs) because of capital cost, operating costs and deficient infrastructure for charging systems. The research work on PEVs is still on the way to bring major advancement in near future.

Electric Vehicles (EV) are propelled by traction motors present in it and use the electric energy stored in it. The motor present in EVs gets power from batteries present in it. In a smart grid environment, the electric vehicle charging is a major concern. A large number of electric vehicles also cause a problem of congestion in charging station. Due to congestion of electric vehicles, the charger must have to provide power to a large number of vehicles. This elevates the rating of the charger and hence produces the harmonics in current waveform and distorts the output. The life of distribution transformer is decreased by 26% of its regular lifetime due to overloading on distribution transformer [5]. The overloading occurs due to increase (congestion) of Electric Vehicles in charging station. Due to congestion of electric vehicles in charging station, the reactive power consumption elevated which yields in a decrement of the voltage profile of distribution transformer. This will lead to demote the power factor and hence, therefore, voltage regulation is elevated [5], [6].

Electric Vehicle batteries act as power storage devices to store the power in batteries for a particular interval of time and the stored power can be used when needed [9]. Charger plays an importunate role to the integration of EVs in the grid so as to demote the negative impact of congestion network of electric vehicles in charging station. The prime cons of EVs are its storage capability. The Electric Vehicle provides the stored power in batteries back to the grid during peak load times and hence increases the efficiency of the distribution transformer and also alleviate the overloading of distribution transformer [6]. The costumers will be given a bonus for that [2], [10-12].

The two kinds of topologies are used for this purpose i.e. unidirectional charging and bidirectional charging. The unidirectional topology is Power Factor Corrected (PFC) topology used for unidirectional charging operation of the battery [13], [14]. The bidirectional topology uses single-phase ac-dc boost converter, which is also used for V2G purposes [15–17]. However, the bidirectional charger used in this dissertation is helpful to meet the reactive power requested by the grid and to fulfill the active power demand provided by the user [18]. The change in active and reactive power demands will make changes in dc link voltage and further changes the battery charging current. In this way, the battery charging is controlled. Reactive power assistance to the grid does not affect to the SOC of the battery but it does make changes in dc-link capacitors because more charging and discharging cycles are used [19]. Synchronous condensers, Capacitor banks are used to provide reactive power assistance to the grid but the use of above items are replaced by certain operations which are i) charging only operation, ii) charging and capacitive mode, iii) capacitive only mode, iv) inductive only and v) charging and inductive operation. The losses occurred in bidirectional charger during ac to dc rectification is fulfilled by the utility.

The charger proposed in this dissertation has two stages which are AC-DC boost rectifier and the DC-DC buck converter. The ac-dc converter is helpful to transform low ac voltage (120V) into high dc voltage (400V) without using a transformer. The dc-dc buck converter is used to convert cloud nine dc link voltage into low battery voltage and dc-dc controller is also used to control the battery charging current [20]. Two types of bidirectional chargers may be utilized, these include On-board and Off-board chargers. On-board chargers can charge the batteries at any outlet which is available at either home or any workplace. The on-board chargers have limited power rating because of their limited size and dimensions; therefore, they take more time to charge the batteries [21]. The off-board chargers on the other hand are used for fast charging and take lesser time to charge a vehicle. The on board chargers have drawn more attention because of their low cost, easy availability, good efficiency and ease of use [7].

The charger proposed in [2] requires large size of the DC-link capacitor, which results in limited reactive power output. The reactive power compensation depends upon the size of the size of the dc-link capacitor which further depends on the configuration used in the converter, size of the charger and the coupling inductor at the source side. In [22] the proposed charger contains more harmonics in charging current, which increases the losses and reduces the life of the battery. Likewise, in [23] the actual power taken from the supply and the power taken from the reference at the Point of Common Coupling (PCC) in the proposed controller does not match and henceforth produces an error. The charger represented in [24] has very slow response for the commands given at, the source side. The battery state of charge (SOC) is skipped during reactive power compensation in this type of charger, which affects the performance of the charger.

1.3 RESEARCH MOTIVATION

The future looks quite promising with PEVs, which increasing the PEV sales. Therefore, more number of PEVs charging stations need to be developed. The number of electric PEVs circulating on our city streets grows faster everyday [1-4]. EVs offer a significant advantage contrasted with self-contained hybrid electric vehicles (HEV) and traditional internal combustion engine vehicles: as their association with the electric power grid makes them proficient to act both as grid-to-vehicle (G2V) devices, when they are in charging mode, and vehicle-to-grid (V2G) devices, when at the contrary they are in discharge mode. G2V (Grid-to-vehicle) comprises mainly conventional and swift battery charging systems, but fast charging, in particular, can really pressurize the grid/utility distribution network because of high power demand. Other effects on the quantity of power withdrawn from the electric utility can also be originated by the charging practices in different locations of a fleet of EVs. This means that EVs can be represented alternatively as dispatchable loads or generators. Various types of chargers have been represented in [17–19] that can be used to assist the reactive power. The work done on reactive power till now by researchers is very less [23, 25]. Also, the work done on low voltage supply to electric vehicles is very rare. Therefore, the authors are motivated to develop the pace in this work area so that low voltage applications can be applicable in rural and urban areas at rapid rate. The work on high voltage part has been done in large amount; therefore, there is a need to focus on low voltage side for charging the electric vehicles especially in domestic areas.

The main disadvantage associated with these chargers is that when Electric Vehicle demands reactive power during the charging and discharging of the battery, the battery state of charge is skipped and the Electric Vehicle demand from dc link capacitor (C_{dc}) increases. This yields in more charging and discharging cycles and increased second harmonic ripples in the dc-link voltage (V_{dc}). Therefore, full bridge ac-dc converter is used to alleviate the size of dc link capacitor [26]. The upsides of full bridge converter are that it doesn't put weight on dc interface capacitor because its yield power does not cross its rated power. To conquer the problem of second harmonic ripples, the full bridge converter uses the optimized value of the capacitor. In this dissertation, the mathematical analysis is done to obtain the optimized value dc link capacitor. However, the problem with the charger in [23] is its lagging response on active and reactive power commands.

1.4 OBJECTIVE OF THE DISSERTATION

The objectives of the dissertation are summarized as follows.

i. To develop the charger which is transformerless and hence alleviates the size, cost and losses of the charger.

ii. To develop the ac-dc full bridge boost converter, which reduces the size of DC-link capacitor.

iii. To develop the dc-dc buck converter that controls the battery charging current.

iv. To develop the proposed charger as shown by Simulink model and the verification of Simulink results has been done with mathematical analysis.

1.5 ORGANISATION OF THE DISSERTATION

The thesis work has been illustrated in five chapters.

Chapter 1 includes Introduction and Literature review.

Chapter 2 deals with the schematic block diagram of the proposed charger, a block diagram of controller operation and complete block diagram of PEV charger and its modeling with an explanation of need of reactive power support and study of battery technology.

Chapter 3 includes the design of controllers and completes mathematical analysis for ac-dc full bridge boost converter and dc-dc buck converters.

Chapter 4 deals with the simulation results for 1.4kVA, 3.3kVA, 6.6kVA chargers with following P-Q commands and its comparison and discussion.

Chapter 5 deals with the conclusion of the thesis, future scope of the dissertation and references.

CHAPTER 2

DESIGN OF CHARGER

2.1 GENERAL CONCEPT

Since the origin of Electric Vehicles, there are many different charging strategies took place that is used to charge the PEV battery. With the time many different circuit charger topologies take place i.e. dedicated or integrated. However, the charger can be classified on the basis of location (either on board or off board the vehicle), waveform type (either AC or DC), the direction of power flow (either unidirectional or bidirectional) as listed in Table 2.1.

Table 2.1 Classification of Charger

Types of Classification	Options
Topology	Dedicated or Integrated
Location	On board or Off board
Connection	Mechanical, Conductive or Inductive
Waveform Type	AC or DC
Power flow direction	Unidirectional or Bidirectional

Fig 2.1 shown below represents the schematic block diagram of proposed charger. In this there are total six blocks and each block represents its own function. The supply carried from the grid is of alternating type i.e. ac supply. The supply carried away from grid utility is available at 110V or 230V. The ac supply passes through ac-dc converter and dc-dc converter and further to PEV battery. The PEV battery is a dc type battery which requires dc voltage and dc current. The ac-dc converter boosts up low voltage ac into high voltage dc and this dc voltage further goes to dc-dc buck converter. The dc-dc converter lowers down the high dc link voltage to low battery voltage. Here two controllers are used which are ac-dc controller and dc-dc controller [27]. The ac-dc controller is used to follow power commands provided by utility or client. The ac-dc controller is used to regulate active power demand and reactive power demand. After that, reference charging current is produced which is further equated with sensed charging current. The resultant of that helps to control dc link voltage. The second controller is dc-dc controller. This controller helps to control battery charging current. In this controller reference dc link voltage is equated with actual dc link voltage. The

difference between these two helps to control charging current of battery. However controlled dc link voltage helps to control dc battery charging current.

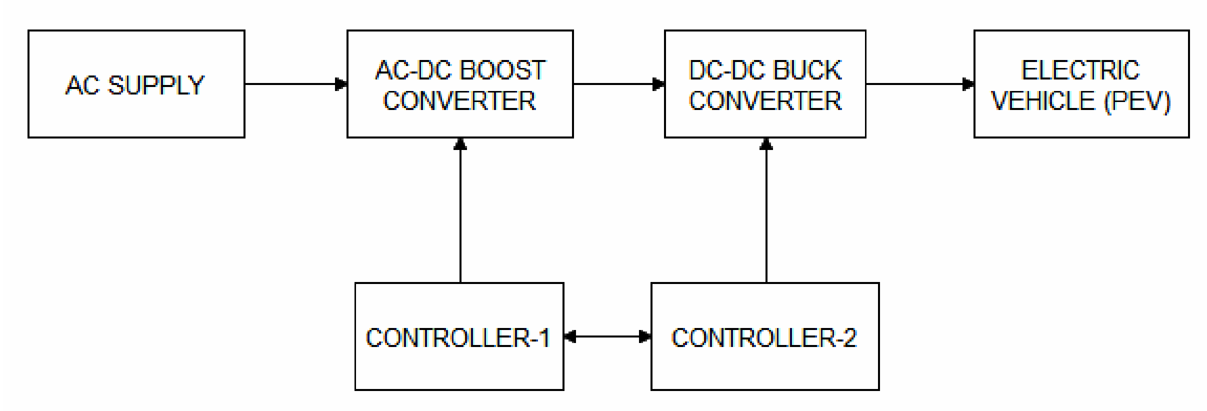

Figure 2.1 Schematic Block Diagram of Proposed Charger

The main function of the charger is to charge the Plug-in electric vehicle (PEV) battery. The operation of controller is shown in Fig 2.2.

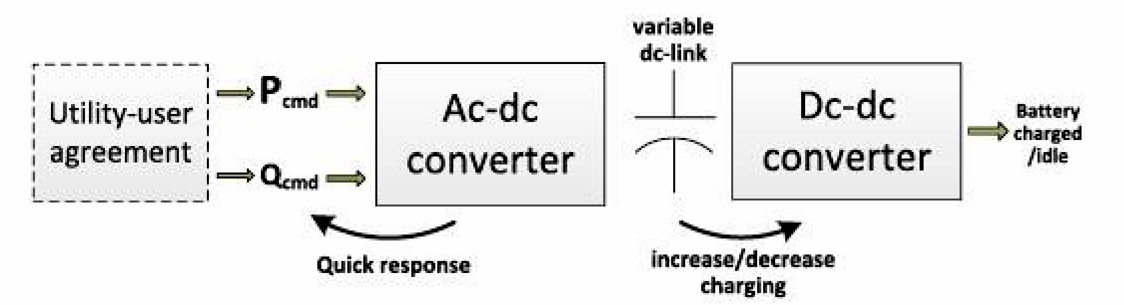

Figure 2.2 Block Diagram of Controller Operation [27]

The charger proposed in Fig 2.3consists of two converters instead of using transformer. The biggest advantage of using these two converters is that it makes the charging operation transformerless. Usage of transformer makes the system bulky and lot of wear and tear takes place by using transformer. The usage of transformer increases the size and weight of transformer. This dissertation consists of transformerless charger. The transformerless charger has ac-dc and dc-dc converters. The function of ac-dc converter is to boost up supply voltage, which is available at 120V or 230V, up to 400V dc link voltage [28]. The nominal battery taken is 365V. Hence the dc link voltage is kept up to 400V. In ac-dc boost converter, the inductor is connected in series with the supply to boost the supply ac voltage, which converts 120V ac supply voltage to 400V dc voltage at converter output across dc-link capacitor (V_{dc}). MOSFET (Metal Oxide Semiconductor Field Effect Transistor) switches are utilized in ac-dc boost converter. MOSFET switches are used in low power and high frequency applications. The advantage of using MOSFET switches is that they are cheap. In the DC-DC buck converter, fixed voltage across the dc-link capacitor is transformed into variable voltage at the output of the converter, so that, the battery charging current can be regulated. The prime motive of this dissertation is to charge the battery in fully controllable way.

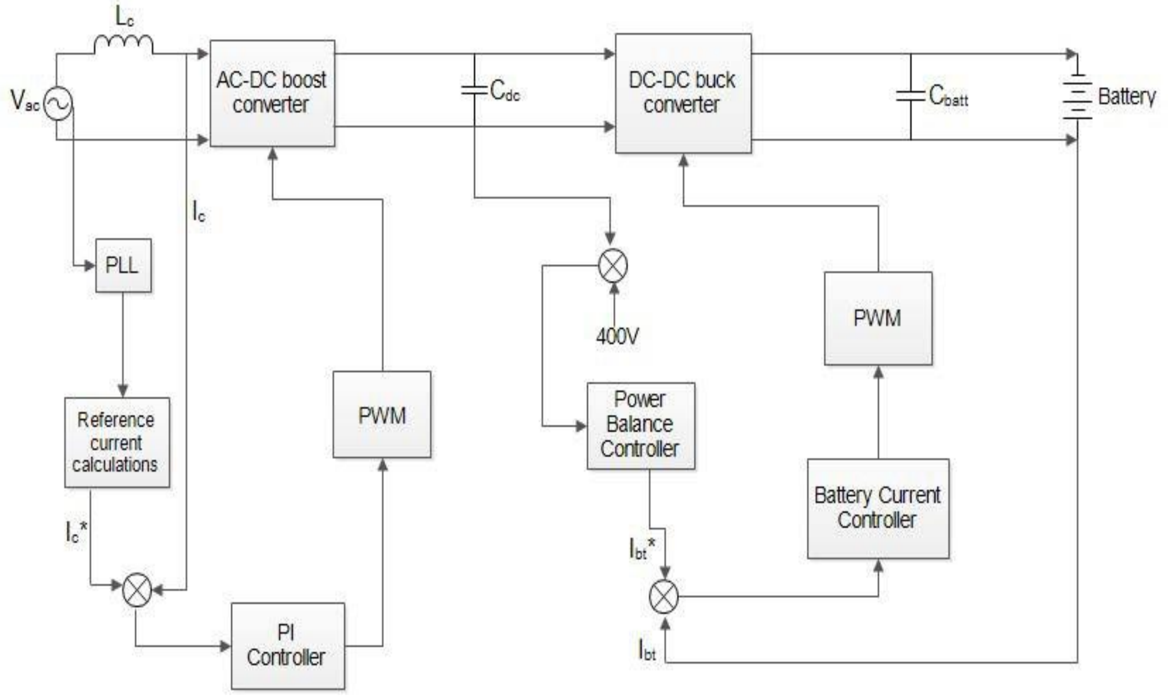

Figure 2.3 Complete Block Diagram of Proposed Charger

2.2 WORKING OF CHARGER

The topology used in this dissertation is used to probe battery grid intercourse. Electric Vehicles consists of onboard charger that comprises of two stages: i) ac-dc converter ii) dc-dc converter. The ac-dc converter is a boost rectifier that boosts up low ac supply voltage to high dc link voltage. The regulator for AC-DC boost converter only regulates dc interface voltage and tracks reactive power command (Q_{cmd}). The dc-dc converter is a buck converter that lowers the dc link voltage to battery voltage. The dc-dc converter regulates battery

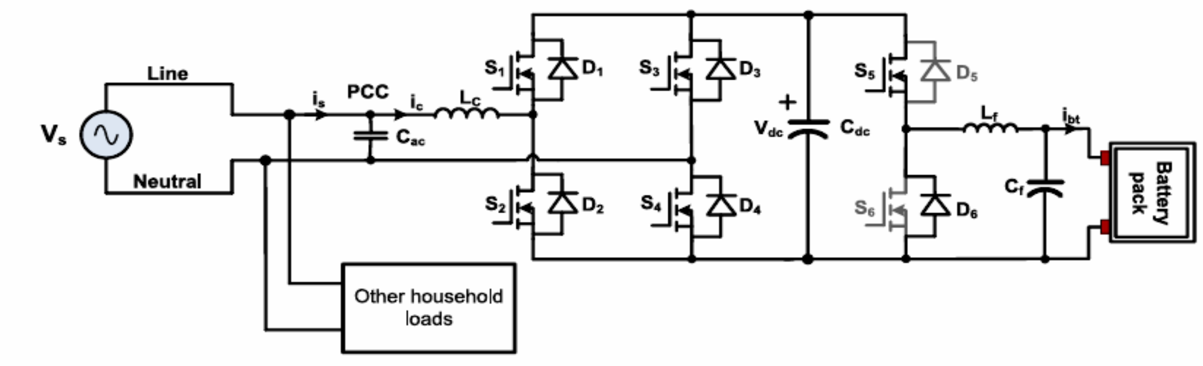

Figure 2.4 Battery Charger Circuit Diagram [27]

charging current. The main motive of charger is to charge the battery along with reactive power compensation to grid. Fig 2.4 represents circuit diagram of the battery charger. The ac-dc converter is experienced with bipolar modulation which means converter output is either $+V_{dc}$ or $-V_{dc}$. During the turn-on interval of switches S_1 and S_4, switches S_2 and S_3 remains switched off and vice-versa. MOSFET switches carry peak current equal to $\sqrt{2}I_c$ where I_c is RMS charging current. DC link voltage (V_{dc}) takes part in both ac-dc and dc-dc controllers and hence V_{dc} can be taken as a reference to control the battery charging current (i_{bt}). To obtain dc-dc buck operation switches S_5 and D_6 are switched on as shown in Fig. 2.4. When switch$S_5$is switched on, the battery charging current (i_{bt}) will pass through S_5 and L_f, and further charges the C_f and battery. During turn off period of switch S_5, diode D_6 freewheels the inductor current that passes via inductor L_f and PEV battery while C_f is discharged into battery. In this dissertation the charger operates in charging only mode. However, the inductor at grid side (L_{ac}) is also used to boost up low ac grid voltage to high dc link voltage (V_{dc}) across dc link capacitor.

During charging of battery, the presence of MOSFET switches causes large amount of switching losses. Due to this, the charger must have to follow P_{cmd} and Q_{cmd}, so that the input power must be equal to output power without any loss. The values of inductor and capacitor components at battery side must be taken appropriately so as to reduce ripples in output waveforms. In this dissertation the lithium-ion battery is considered that operates in both constant current (CC) and constant voltage (CV) charging modes. The quality of Lithium-ion (Li-ion) battery is established over other types of batteries in case of fast large density and fast discharging rate during fast acceleration. The lithium-ion battery is highly efficient and has less weight as compared to other batteries. During constant current charging, the charging current is constant and voltage varies. One observation is that about 50 minutes are necessary to charge the Electric Vehicle battery up to 70% SOC in CC mode and then the mode is switched into CV mode. The CV mode takes about 2.5 hours to charge the battery from 70% SOC to full charge (100% SOC). Hence total time taken to charge the battery with 1.4kVA charger is approximately 3.5 hours. In CC mode the voltage changes at sharp rate and current remains constant. In CV mode, battery current changes and voltage remains same. It depends on user or utility active and reactive power commands (P_{cmd} and Q_{cmd}) whether to charge or discharge the battery as per necessity. Rate of charging of battery is controlled by user or client active power commands as per needs. During peak load hours there is a need of reactive power demand to the grid and during this time period the utility provides reactive power command (Q_{cmd}) to battery so that PEV battery acts in different modes according to the need. If active power command is positive and reactive power command is zero then charger works in charging only mode i.e. Grid-to-Vehicle mode. If active power command (P_{cmd}) is positive and reactive power command (Q_{cmd}) is negative, then PEV operates in charging mode and dc-link capacitor operates in discharging mode and provides reactive power to the supply. Fig 2.5 illustrates diagram of reactive power compensation. However reactive power operation does not influence the battery state of charge (SOC) but its operation does effect on dc link capacitor due to more charge-discharge cycles. During charging also, the charger can supply reactive power to grid. During extreme conditions the charger can take back reactive power from the grid. The reactive power is provided by dc link capacitor not by battery. In this dissertation Level-1 and Level-2 chargers are used. These are low voltage chargers that are used to charge the battery. Level-1charger is of 1.44kVA rating and Level-2 charger is of two types i.e. 3.3kVA and 6.6kVA ratings.

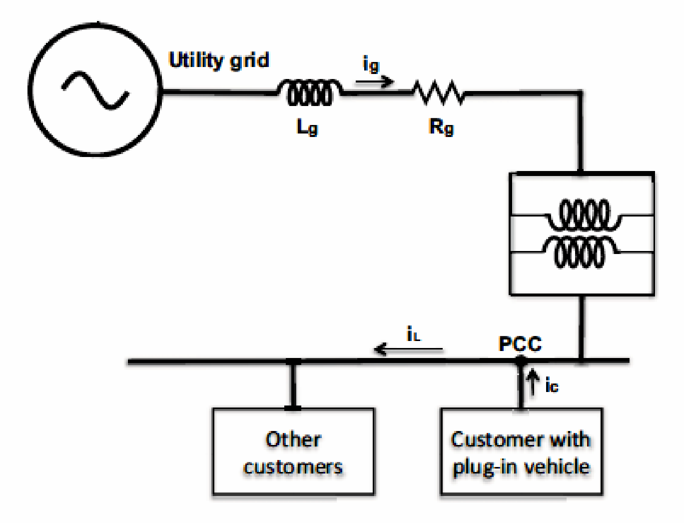

Figure 2.5 Proposed reactive power support diagram [28]

2.3 TYPES OF CHARGING MODES

There are different charging modes of PEV battery as shown in Table 2.2. This dissertation consists of charging only mode of operation i.e. charger operates in charging only mode. The table shown below represents the active and reactive power commands provided by client or utility. The first row of table shows that active power command (P_{cmd}) is positive and reactive power command (Q_{cmd}) is zero, which means that charger works in charging only mode. The second row of the table shows that both active and reactive power is positive, which means that charger works in charging and inductive mode. The inductive mode of operation means that the reactive power is taken from grid. The third row of table shows that active power command is positive and reactive power command is negative, which means that charger operates in charging and capacitive mode of operation. By capacitive mode of operation means that reactive power is supplied to grid. The fourth row shows that active power command is negative and reactive power command is positive, which means that charger operates in discharging and inductive mode of operation. The fifth row shows that both active power command (P_{cmd}) and reactive power command (Q_{cmd}) are negative i.e. charger operates in discharging and capacitive mode. The sixth row of table shows that active power is zero and reactive power is positive i.e. charger operates in inductive mode. The seventh row shows that active power command is zero and reactive power command is negative i.e. charger operates in capacitive mode.

Table 2.2 Charging Modes

Active Power Commands (P_{cmd})	Reactive Power Commands (Q_{cmd})	Charging Modes
P_{cmd} = positive	Q_{cmd} = zero	Charging only mode
P_{cmd} = positive	Q_{cmd} = positive	Charging and Inductive Mode
P_{cmd} = positive	Q_{cmd} = negative	Charging and Capacitive Mode
P_{cmd} = negative	Q_{cmd} = positive	Discharging and Inductive Mode
P_{cmd} = negative	Q_{cmd} = negative	Discharging and Capacitive Mode
P_{cmd} = zero	Q_{cmd} = positive	Inductive mode
P_{cmd} = zero	Q_{cmd} = negative	Capacitive mode

2.4 NECESSITY OF SUPPORT OF REACTIVE POWER

As we know there is a must need of reactive power compensation during the charging PEV or PHEV. The advantages of reactive power compensation are that it helps to maintain the voltage profile of distribution grid. The Electric Vehicle charger consists of ac-dc converter full bridge bidirectional converter that must supply to battery from the grid but also provide supply reactive power back to grid. The dc link voltage helps to provide reactive power back to grid for V2G operation. In earlier days the main problem with the electric vehicles is its storage of battery. The delay in arrival of electric vehicles in market is due to less storage of electric vehicle battery. Now a day's battery storage problem has been resolved. The battery can provide its stored power to grid as per its needs. This helps in improvement of voltage profile of grid at distribution level. However Electric vehicle congestion in charging station causes a lot of trouble for utility/grid. The electric vehicle congestion causes a lot of power generation that ultimately affects the distribution grid voltage. The Electric Vehicle charging is one of the main concerns of smart grid applications because of its influence on generation, distribution and transmission [5]. The grid can make its benefit by using stored energy in electric vehicle battery. This helps to improve the operation of the system and increases the efficiency of system. The transmission of reactive power from source to load causes a lot of transmission and distribution losses and reactive power at supply end is not equal to reactive power at load end. This leads to decrease in efficiency of system. The more amount of reactive power must be supplied from source end to load end so as to overcome transmission and distribution losses [6]. It is favorable to generate reactive power near to the load end to reduce the transmission and distribution losses and to improve the voltage profile at distribution side end. However large number of electric vehicles causes congestion in charging station and affects the distribution system. The large number of EV's decreases the voltage profile at distribution end which leads to losses and hence reduces the efficiency. According to survey which shows that depending upon number of Electric Vehicles connected, size of battery storage, rating of charger, charging current harmonics, distribution transformer rating etc, the life of distribution transformer decreases up to 26% of its regular life [8]. Grid must maintain Smart meters, grid communication, distributed energy management to prevent above problems.

The reactive power compensation is done to reduce harmonics present in waveform. The reactive power compensation by V2G (Vehicle to Grid) helps to improve the efficiency of distribution transformer. A microwave expends up to 0.6kVAR of reactive power and a clothes washer utilizes around 0.9kVAR. The other loads at the residential side comprise AC (Air Conditioner), dishwasher, refrigerators etc. The customers never pay bill for reactive power consumption instead utility pays bill for the residential users. The increasing number of Electric Vehicles and distribution transformer issues marks the benefits of onsite generation of reactive power. Therefore, generation of reactive power from V2G (Vehicle to Grid) increases the efficiency of charger and improves the power transfer via transmission lines. The reactive power compensation also decreases overloading of distribution transformer. Therefore, charger design is of utmost importance to regulate the power flow between grid and vehicle.

2.5 ALREADY UTILISED INNOVATIONS IN BATTERIES

2.5.1 Lead-Acid Batteries:

The lead-corrosive battery was the most favored alternative to control early EVs; hence, it is promptly accessible at a sensible cost inferable from the development of the innovation also, producing. In earlier days the lead corrosive batteries are easily available at sensible price owing to advancement in technology. The advancement in technologies makes the lead-acid batteries a favorable choice for application in Electric Vehicles [29]. The lead-acid battery responds quickly to load changes because of good discharge rate. However, the biggest drawback of these batteries is that these are heavy and have low energy density also have short life expectancy. However, the lead–acid battery is not preferable for more than 20% of its rated capacity discharges.

2.5.2 Nickel Metal Hydride (Ni-MH) Batteries:

The electrolyte used for these kinds of batteries is an alkaline solution. The Ni-MH battery is made up of nickel hydroxide on the positive electrode, and the negative electrode consists of alloy of vanadium, titanium, nickel, and other metals. Ni-MH battery has twice the energy density as compared to that of the lead–corrosive battery and hence the range of PEV is doubled for the same size [30]. The materials used in Ni-MH are harmless to the environment; moreover, the batteries can be recycled. The Nickel Metal Hydride batteries have large lifespan expectancy. The Nickel metal hydride batteries are expensive as compared to lead acid.

2.5.3 Lithium-ion (Li-ion) Batteries:

The lithium-ion battery is much superior as compared to lead acid and Ni-MH batteries because of large discharge rate for faster acceleration all over the electric range. The Li-ion battery has great energy density and has good elevated temperature execution, and furthermore recyclable. The positive electrode is built of an oxidized cobalt material, and the negative electrode is made up of a carbon (C) material [29]. The blend of lithium salt in an organic solvent is utilized as an electrolyte. The Li-ion batteries are favored over lead acid and nickel hydride batteries due to less weight and greater efficiency. The big advantage of these kinds of batteries is that these are expensive and in case of safety they need improvement [31]. The Li-ion battery still needs to improve in equalization of charging of individual battery cell to offset the aggregate charge among the cells in a delicate way. Table 2.3 represents comparison between different energy storage technologies.

Table 2.3 Features of some energy storage technologies

Storage Technologies	Advantages	Disadvantages
Lead-Acid Batteries	High capacity, low volume energy density, low capital cost, long life time	Low efficiency, potential adverse environmental impacts
Metal-Air Batteries	Very high energy density	Few rechargeable batteries available
Li-Ion batteries	Very high efficiency and energy density	Low number of life Cycles
Super capacitors	High efficiency	Low energy density, few power systems applications

From above we can conclude that Li-ion batteries are very much preferred over other types of batteries for Electric Vehicle applications.

CHAPTER 3

CONTROLLER DESIGN

3.1 INTRODUCTION

In this chapter the working and operation of controller is explained. In this dissertation the charger consists of two controllers as shown in Fig 3.1 and 3.2. First is used for Ac-Dc rectifier and Second one is used for DC-DC converter. The controller is designed in such a way that the charger must operate in quadrant I and IV of the P-Q power plane. So indirectly we can say that active power acts as unidirectional here and reactive power.

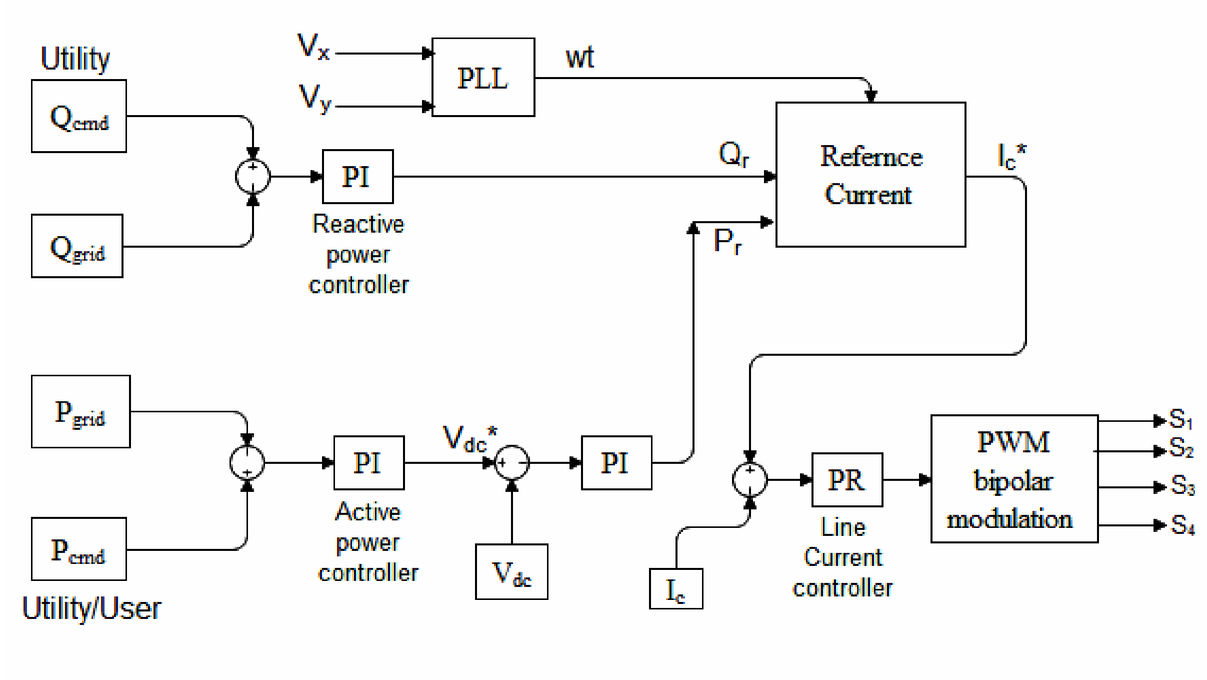

Figure 3.1 Block Diagram of Controller for AC-DC converter

Fig 3.1 represents the proposed controller section for AC-DC boost converter. The conversion of signals is done through p-q theory. In this theory two voltage and current orthogonal signals are obtained by delay function. After that the output of instantaneous p-q block passes through low pass filters. The function of low pass filters is to demote the ripples inherit in it. After that the output active and reactive power (*P* and *Q*) are equated with active and reactive power commands (P_{cmd} and Q_{cmd}) provided by user/utility. The delayed (Orthogonal) signals are used for PLL algorithm (Phase locked loop) algorithm that tracks the phase angle of line voltage and induce the reference phase signal for charging current. The sensed signals are holded up for atleast one quarter to generate orthogonal signals. The ac-dc boost converter controls the dc link voltage (V_{dc}). The active power command (P_{cmd}) is used as reference power for purpose of battery charging. The difference between output powers and command powers further passes through two different PI controllers i.e. active and reactive power controllers. The main function of PI controllers is to demote the steady state error. Further there are two loops which acts as feedback loop i.e. P loop and Q loop. The output of P loop (V_{dc}*) is compared with dc link voltage (V_{dc}). The difference between actual and reference signals further passes through dc voltage controller (PI Controller) which produce power called P_r. Q_r in Q loop is produced as same as in case of P loop. The main function of these two signals is to produce reference charging current (i_c*). The reference charging current is further compared with actual charging current (i_c). The difference between these two parameters results in an error and this is further sent to PR controller to control the charging current [32]. After this the charging current passes through bipolar modulation. The yield of bipolar modulation results in gate pulses for switches. Hence in this way AC –DC converter controller controls the charging current by applying gate pulses to the switches.

Fig 3.2 represents the controller for dc-dc converter. The second converter is DC-DC buck converter which is used to reduce the dc link voltage to battery voltage so that charging current must flow from high voltage to low voltage i.e. from dc link capacitor to PEV battery. The DC-DC converter must have a controller that controls the above process. In this controller the sensed dc link voltage must proceed through low pass filter that helps to reduce ripples in it. The reference dc link voltage (V_{dc}*) is equated with sensed dc link voltage (V_{dc}).

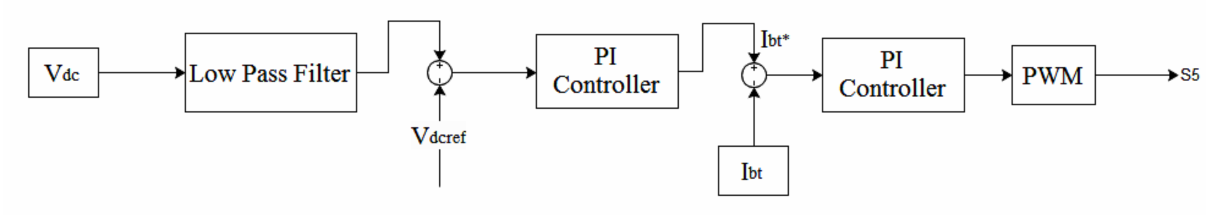

Figure 3.2 Block Diagram of Controller for DC-DC converter

The difference between sensed and reference signals passes through power balance controller (PI controller). The PI controller outputs a reference charging battery current (i_{bt}*). The sensed battery charging current (i_{bt}) is equated with reference charging current of battery (i_c*) [33]. The obtained result is regulated with battery current controller (PI Controller). Pulse Width Modulation (PWM) block recieves the output signal of battery current controller (PI Controller) and generates duty cycle (S_5) consequently.

3.2 PROBLEM FORMULATION

The active power (P) and reactive power (Q) equations are as follows.

$$P = V_a I_s \cos\Delta \tag{3.1}$$

$$Q = V_a I_s \sin\Delta \tag{3.2}$$

The apparent power is given by:

$$S = V_a I_s \tag{3.3}$$

The reactive power can also be defined as:

$$Q = \sqrt{S^2 - P^2} \tag{3.4}$$

Here the direction of current flow is taken positive from grid to vehicle (G2V) since the prime motive of the charger is to charge the battery. Hence positive sign of Active power (P), Reactive power (Q) and Apparent power (S) indicates the power sent from grid-to-vehicle (G2V).

The active power is also written as:

$$P = \frac{V_a V_{dc}}{X_s} \sin\Delta \tag{3.5}$$

The reactive power can also be written as:

$$Q = \frac{V_a V_{dc}}{X_s} (V_a - V_{dc} \cos\Delta) \tag{3.6}$$

$$S = \frac{V_a}{X_s} \sqrt{V_a^2 + V_{dc}^2 - 2V_{dc} V_a \cos\Delta} \tag{3.7}$$

where X_s is ωL_s.

V_a and V_{dc} are the source and battery side RMS voltages respectively.

The p-q theory is used to calculate single phase P and Q. The ‘x’ components are indicators of sensed signals. The ‘y’ signals are produced by delay function. The orthogonal signals (y) are delayed by one-quarter of grid period which is equal to (1/240) corresponds to 100 samples with 24 kHz sampling frequency [34]. The signals are delayed for utilization in PLL algorithm which tracks phase angle of line voltage and produces a reference signal for charging current. The single-phase active is given by:

$$P = \frac{1}{2}\left(V_x * I_x + V_y * I_y\right) \tag{3.8}$$

The single phase reactive power is given by:

$$Q = -\frac{1}{2}\left(V_x * I_y + V_y * I_x\right) \quad (3.9)$$

However number of low pass filters used for both P and Q are two.

The active power command (P_{cmd}) is given by the client and reactive power command (Q_{cmd}) is provided by utility/grid. The charger must have to follow these power commands for efficient operation. During peak load hours grid can regulate P_{cmd} to harmonize charging power [35]. If any client or costumer provides reactive power to the grid then grid must provide an incentive to the costumer. However, P_{cmd} and Q_{cmd} must be examined before being sent to the charger.

The active power (P) must be matched with active power command (P_{cmd}) to fulfill the desired operation. This can be done by changing dc link voltage (V_{dc}*). The loop equation for this is as follows:

$$V_{dc}^{*} = \left(K_p^a + \frac{K_i^a}{s}\right) \times (P_{cmd} - P) \quad (3.10)$$

The dc voltage loop (v-loop) follows dc link voltage (V_{dc}*). The difference of actual dc link voltage and reference dc link voltage passes through PI controller. The constants of the controller are changed accordingly to match the actual and reference value. This loop's output produces reference tracking active power (P_r). The equation for this is as follows:

$$P_r = (K_p^b + \frac{K_i^b}{s}) \times (V_{dc}^{*} - V_{dc}) \quad (3.11)$$

The output reactive power is matched with reactive power command from the grid with the help of reactive power loop (Q-loop). The mismatch between actual reactive power and reactive power command is passed through PI controller whose constants have to be modified to match the sensed and reference reactive power (Q_r). The equation for Q-loop is as follows:

$$Q_r = \left(K_p^c + \frac{K_i^c}{s}\right) \times (Q_{cmd} - Q) \quad (3.12)$$

Q-loop tells whether the charger can supply or sink the reactive power.

The reference charging current is induced by yields of v-loop and Q-loop. The following equations are also used to calculate reference charging current (i_c*).

$$\emptyset = \tan^{-1}\frac{Q_r}{P_r} \quad (3.13)$$

$$I_c = \frac{P_r}{V_a \cos \emptyset} \tag{3.14}$$

$$i_c^* = \sqrt{2} I_c \sin(\omega t - \emptyset) \tag{3.15}$$

Where I_c is the RMS value of charging current.

PR (Proportional Resonant) controller is used to regulate the mismatch between reference charging current (i_c*) and sensed charging current (i_c) [36]. The difference between two charging currents are fed to PR controller whose constants are changed to match the sensed and reference charging current. The PR controller yield is used to produce duty cycle (d) for an ac-dc converter [37]. The equation for i-loop is as follows:

$$d = (K_p^d + \frac{2K_i^d \omega_c s}{s^2 + 2\omega_c s + \omega^2}) \times (i_c^* - i_c) \tag{3.16}$$

For dc-dc converter, the reference dc link voltage (V_{dc}*) is equated with V_{dc}. The resultant error passes through power balance controller (PI) controller. The constants of PI controller are modified to remove the mismatch between sensed and reference dc link voltage. The output of PI controller yields reference battery current (i_{bt}*). The equation for this is as follows:

$$i_{bt}^* = \left(K_p^e + \frac{K_i^e}{s}\right) \times \left(V_{dc} - V_{dcref}\right) \tag{3.17}$$

This loop is used to maintain the input-output balance of power. The main purpose of this loop is to fulfill P_{cmd} so as to charge the battery without any loss. The equation for this loop is as follows:

$$d_\circ = \left(K_p^f + K_i^f\right) \times (i_{bt}^* - i_{bt}) \tag{3.18}$$

Where d_0 is duty cycle for the dc-dc converter.

3.3 CHARGER PARAMETERS

The charger parameters are shown in Table 3.1. The first row of the Table shown below represents apparent charging power (S). Actually, there are three types of chargers used in this dissertation: i) 1.44kVA charger ii) 3.3kVA charger iii) 6.6kVA charger. To charge the battery efficiently input power must be equal to output power. The prime motive of the charger is to charge the Electric Vehicle battery. The second and third row of Table shown below represents source voltage and grid frequency that has value 120V and 60Hz respectively. The grid side inductor (L_f) and capacitor (C_f) values are taken in an appropriate manner so as to reduce the harmonics in charging current [38]. The parameters of the ac-dc converter are taken so that it controls the dc link voltage across dc link capacitance. The dc-dc converter parameters are taken in such a way that it controls battery charging current efficiently. Parameters for 1.44kVA charger are shown below in Table 3.1. However, the parameters for 3.3kVA charger are same as that of 1.44kVA charger.

Table 3.1 Parameters of 1.44kVA charger

Parameters	Symbol	Values
Apparent power of the charger	S	1.44×10^3 VA
Supply Voltage	V_a	120 V RMS
Frequency	F	60 Hz
Supply-side inductance	L_c	1.0mH
Switching frequency for ac-dc converter	F_{sw1}	$24 * 10^3$ Hz
DC link voltage	V_{dc}	385 V
DC link capacitance	C_{dc}	440×10^{-6} F
Switching frequency for dc-dc converter	F_{sw2}	42×10^3 Hz
Filter capacitor (battery side)	C_f	190 µF
Filter inductance (battery side)	L_f	390 µH

Table 3.2 represents parameters for 6.6kVA Charger. The parameters of 6.6kVA are different from that of 1.44kVA and 3.3kVA charger.

Table 3.2 Parameters of 6.6kVA charger

Parameters	Symbol	Values
Apparent power of the charger	S	6.6×10^3 VA
Supply Voltage	V_a	230 V RMS
Frequency	F	60 Hz
Supply-side inductance	L_c	1.5mH
Switching frequency for ac-dc converter	F_{sw1}	$24 * 10^3$ Hz
DC link voltage	V_{dc}	390 V
DC link capacitance	C_{dc}	860×10^{-6} F

Switching frequency for dc-dc converter	F_{sw2}	42×10^3 Hz
Filter capacitor (vehicle side)	C_f	200 µF
Filter inductance (vehicle side)	L_f	690 µH

3.4 CHARGER PARAMETERS FOR AC-DC CONVERTER

The 1.44kVA ac-dc converter charger parameters are shown in Table 3.3. The parameters are selected in such a way that ac–dc converter boosts up low ac supply voltage to high dc link voltage efficiently.

Table 3.3 Parameters of 1.44kVA charger for ac-dc converter

Parameters	Symbol	Value
Angular frequency	ω	377 rad/s
Crossover angular frequency	ω_c	3.0 rad/s
Proportional constant for current loop (i-loop) controller (P-R)	K_p^d	1.2
Integral constant for current loop (i-loop) controller (P-R)	K_i^d	1000
Proportional constant for dc voltage loop (v-loop) controller (PI)	K_p^b	1.5
Integral constant for dc voltage loop (v-loop) controller (PI)	K_i^b	100
Proportional constant for reactive power loop (Q-loop) controller (PI)	K_p^c	0.2
Integral constant for reactive power loop (Q-loop) controller (PI)	K_i^c	30
Proportional constant for active power loop (P-loop) controller (PI)	K_p^a	1
Integral constant for active power loop (P-loop) PI contr.	K_i^a	20

Table 3.4 illustrates the parameters of 6.6kVA charger for ac-dc converter.

Table 3.4 Parameters of 6.6kVA charger for ac-dc converter

Parameters	Symbol	Value
Angular frequency	ω	377 rad/s
Crossover angular frequency	ω_c	3.0 rad/s
Proportional constant for current loop (i-loop) controller (P-R)	K_p^d	1.2
Integral constant for current loop (i-loop) controller (P-R)	K_i^d	1000
Proportional constant for dc voltage loop (v-loop) controller (PI)	K_p^b	1.5
Integral constant for dc voltage loop (v-loop) controller (PI)	K_i^b	100
Proportional constant for reactive power loop (Q-loop) controller (PI)	K_p^c	0.1
Integral constant for reactive power loop (Q-loop) controller (PI)	K_i^c	30
Proportional constant for active power loop (P-loop) controller (PI)	K_p^a	1
Integral constant for active power loop (P-loop) PI controller.	K_i^a	20

3.5 CHARGER PARAMETERS FOR DC-DC CONVERTER

The parameter for the dc-dc converter is shown in Table 3.5. The parameters shown below are used in the dc-dc controller so that it may control the battery charging current efficiently. The dc-dc buck converter is used to step down high dc link voltage to low battery voltage. Here the battery voltage taken is 365 V.

Table 3.5 Parameters of 1.44kVA charger for dc-dc converter

Parameters	Symbol	Value
Proportional constant for balance loop controller (PI)	K_p^e	0.045
Integral constant for balance loop controller (PI)	K_i^e	0.5
Proportional constant for battery current (i_{bt}) loop controller (PI)	K_p^f	0.15
Integral constant for battery current (i_{bt}) loop controller (PI)	K_i^f	10

Table 3.6 represents the parameters for 6.6kVA dc-dc converter. The parameters for 6.6kVA charger are different from 1.44kVA and 3.3kVA charger.

Table 3.6 Parameters of 6.6kVA charger for dc-dc converter

Parameters	Symbol	Value
Proportional constant for balance loop controller (PI)	K_p^e	0.045
Integral constant for balance loop controller (PI)	K_i^e	0.5
Derivative constant for balance loop controller (PID)	K_d^e	50
Proportional constant for battery current (i_{bt}) loop controller (PI)	K_p^f	0.05
Integral constant for battery current (i_{bt}) loop controller (PI)	K_i^f	20

A low pass filter is used to filter second harmonic components of dc link voltage for dc-dc converter when producing battery charging current (i_{bt}*). The transfer function of low pass filter is as follows:

$$H(s) = \frac{k\omega_{c1}^2}{s^2+2\varepsilon\omega_{c1}s+\omega_{c1}^2} \tag{3.19}$$

where ω_{c1}=2πf$_c$, f$_c$=20Hz and ε=√2.

CHAPTER 4

RESULTS AND DISCUSSIONS

For performing simulations of single phase PEV charger, three different types of chargers have been considered i.e. i) 1.44kVA charger ii) 3.3kVA charger iii) 6.6kVA charger. 1.44kVA charger comes under the category of the Level-1 charging system. While 3.3kVA and 6.6kVA chargers fall under the category of Level-2 type charging system. The main target of the charger is to follow charging power and reactive power commands given by utility operator. The model is represented by simulating it in MATLAB/SIMULINK software. The battery charger is supposed to be made to redeem the commands provided by grid or utility, to degrade the total harmonic distortion (THD) in output waveforms.

Onboard chargers are those in which firstly AC is converted into DC and then it is supplied to EV battery. While off board chargers are those in which DC supply is directly fed to the battery. On board chargers are less advantageous as compared to off-board chargers as they make the vehicle heavy and hence results in size, space, cost and weight issues. On boardcharging systems can be inductive or conductive. The conductive charging system makes the direct contact between conductor and charger inlet. The inductive charging system transfers the power magnetically. An off-board charger is less constrained by size and weight issues. During peak hours the PEV charger acts in charging only mode of operation. However, power increases during peak hours because of increased grid supply but this process will lead to decreased voltage profile of transformer at distribution side. To overcome this problem the grid send a reactive power command to any of PEV present in charging station and hence earn the reactive power from Electric Vehicle. Therefore, the coordination of active and reactive power is must between grid and vehicle for efficient operation.

The results of charger are shown here is for Level-1 and Level-2 type charging. Level-1 consists of 1.44kVA charger and Level-2 consists of 3.3kVA and 6.6kVA charger. In first case the charger that is to be taken is of 1.44kVA rating i.e. the input given to the charger is 1.44kVA and charger must have to follow these commands. In second case the charger that is to be taken is of 3.3kVA and 6.6kVA ratings. The charger used in this dissertation is applicable for low voltage applications. The charger must have to supervene the input commands given by the user/utility. The V_{dc}* voltage changes firstly during the change of active and reactive power command. After that P_r and Q_r changes correspondingly which results in change of reference charging current and then produce changes in battery charging current. In this dissertation the results are represented in three cases.

4.1 RESULTS OF CHARGER

4.1.1 1.44kVA Charger:

The system variables that are investigated in this configuration are:

- Source Voltage
- Line current
- Battery Charging Current (I_{bt})
- DC link Voltage (V_{dc})
- State of Charge (SOC)

As explained above the charger in this dissertation works in charging only mode i.e. active power command is positive and reactive power command is zero. The direction of power flow is from grid-to-vehicle and sign convention is taken positive. Normally the battery voltage taken is between 320V-390V. Initially the battery SOC is 20%. The battery voltage is 365V and battery current is 3.8A which makes the charging power equals to 365V * 3.8A = 1440VA. The RMS value of source voltage is 120V and its peak value is 170V as shown in Fig 4.1. Two grid side inductance values are used here i.e. 0.5mH and 1.0mH for Level-1 charger. The nominal capacity of the battery is 12Ah.

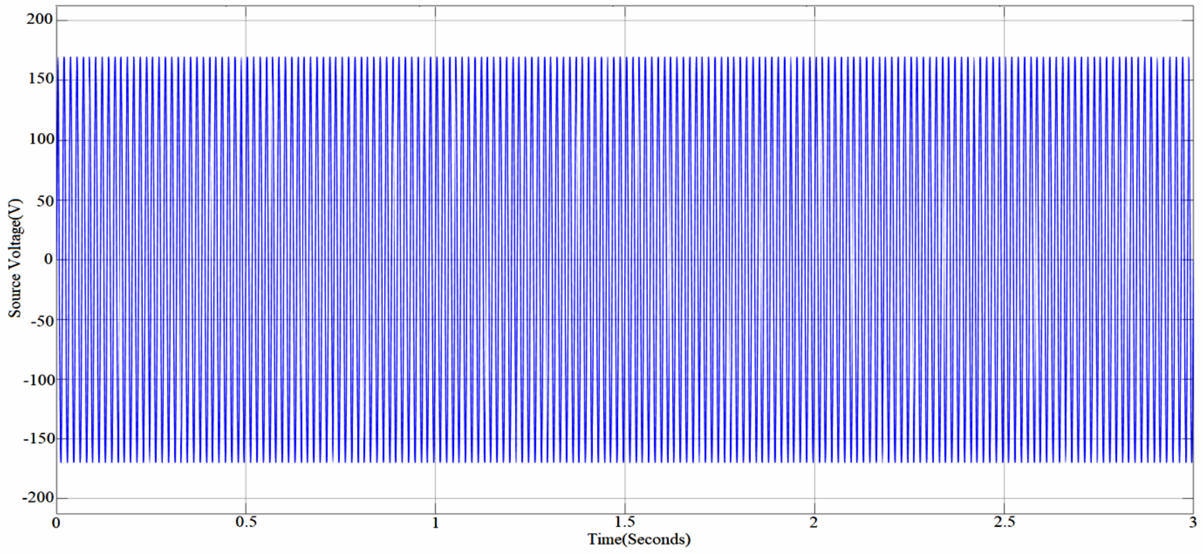

Figure 4.1 Source Voltage for P = 1.44kVA

Fig 4.2 shows line current or supply current. The line current (I_c) RMS value is 12 A and its peak value is 17A. The line current will change during any of the changes occur in active power and reactive power commands. The change in line current will make a change in battery charging current (I_{bt}) so as to keep the total power constant.

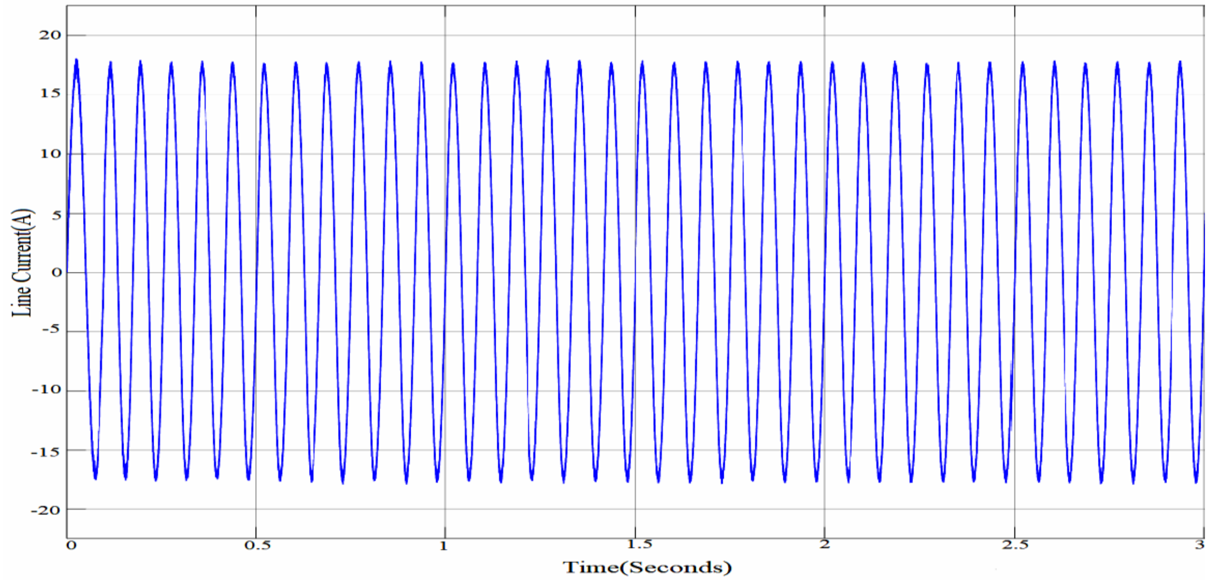

Figure 4.2 Line Current for P = 1.44kVA

The value of DC link voltage is approximate 385V. The DC link voltage is kept at 385 V because battery voltage is adjusted at 365V as shown in Fig 4.3. To step down the voltage without transformer, a dc-dc buck converter is used. DC link capacitor connects ac-dc converter with the dc-dc converter. If dc link capacitor exhibits more 2nd harmonic components then it leads to battery damage. Hence THD must be within the limits.

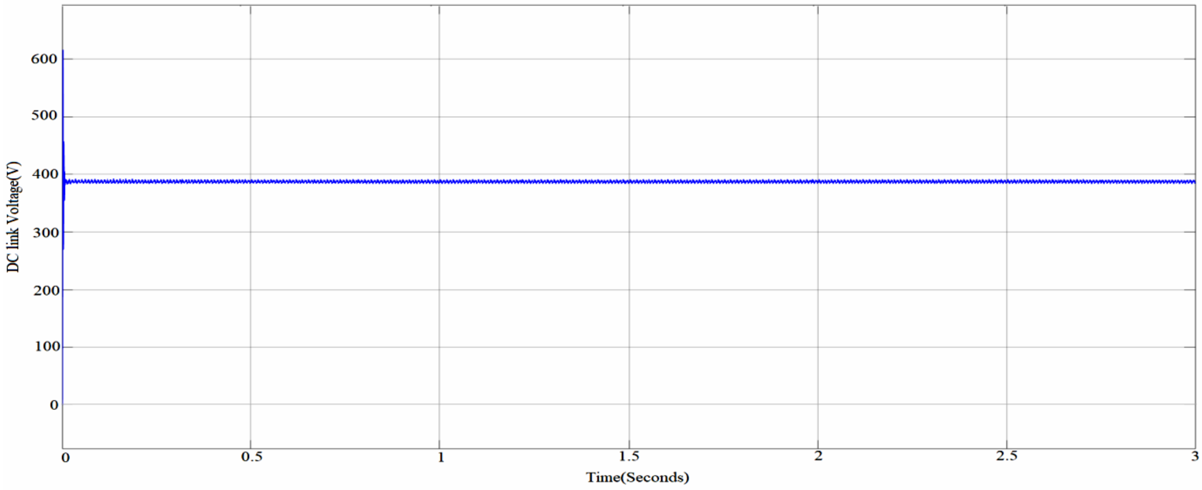

Figure 4.3 DC link Voltage for P = 1.44kVA

Fig 4.4 represents the waveform of Battery Charging Current (I_{bt}). The RMS value of battery charging current is 3.8A. The battery charging current harmonic content must be within limits otherwise it will lead to damage of the battery. However, the nominal capacity of the battery is 12Ah.

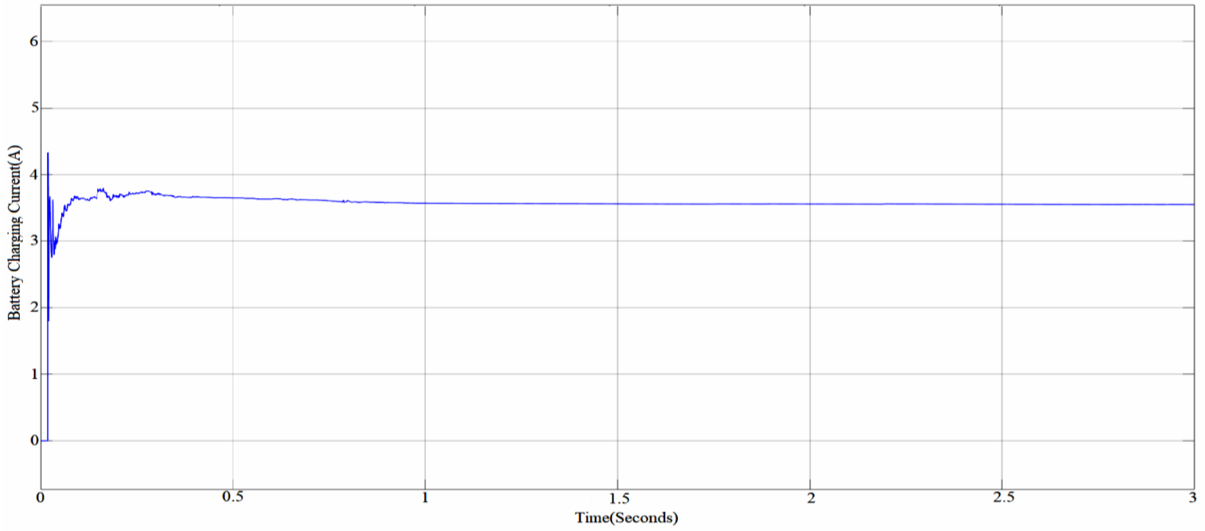

Figure 4.4 Battery Charging Current for P = 1.44kVA

Fig 4.5 represents graph for State of Charge (SOC). The state of charge represents how much amount the battery is charged. The initial SOC of the battery is 20% and if battery operates in constant current mode then it takes about 3.2 hours to fully charge the battery.

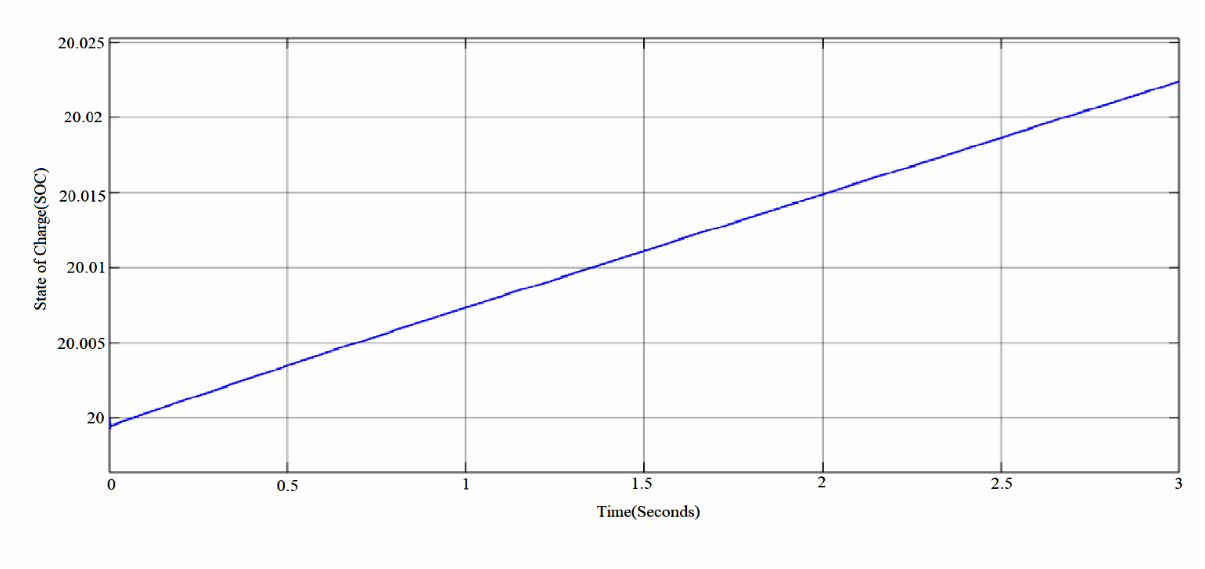

Figure 4.5 State of Charge (SOC) for P = 1.44kVA

4.1.2 3.3kVA Charger:

The system variables shown in this configuration is:

- Source Voltage
- Line Current
- DC link Voltage (V_{dc})

- Battery Charging Current (I_{bt})
- State of Charge (SOC)

Fig 4.6 represents source voltage for 3.3kVA charger. The RMS value of source voltage is 230V and its peak value is 310V.

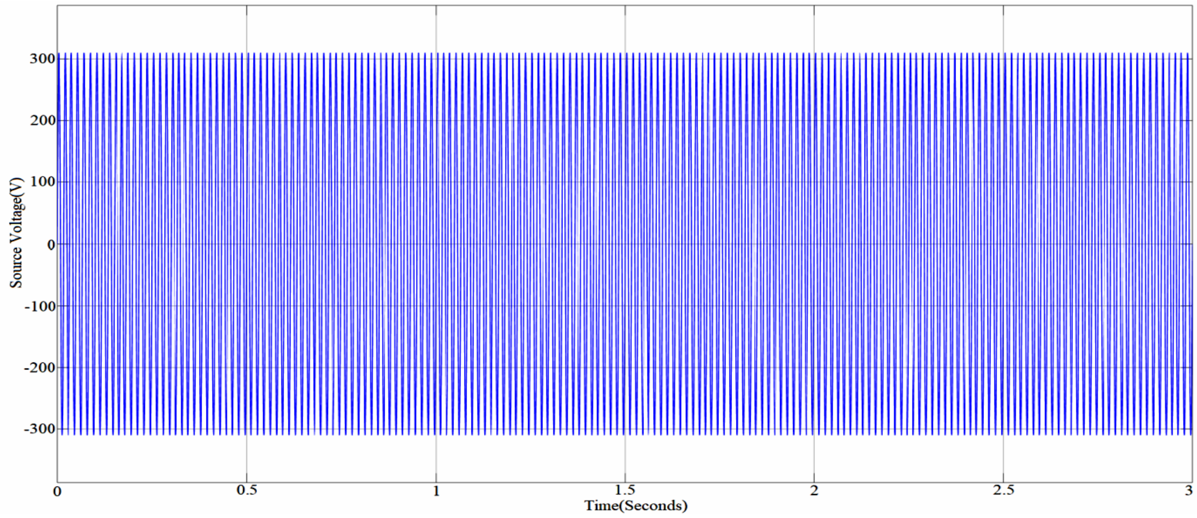

Figure 4.6 Source Voltage for P = 3.3kVA

Fig 4.7 represents waveform of Line current. The DC link voltage for this charging mode is shown in Fig 4.8. The dc link voltage harmonics must be within the limits to provide efficient operation of charging.

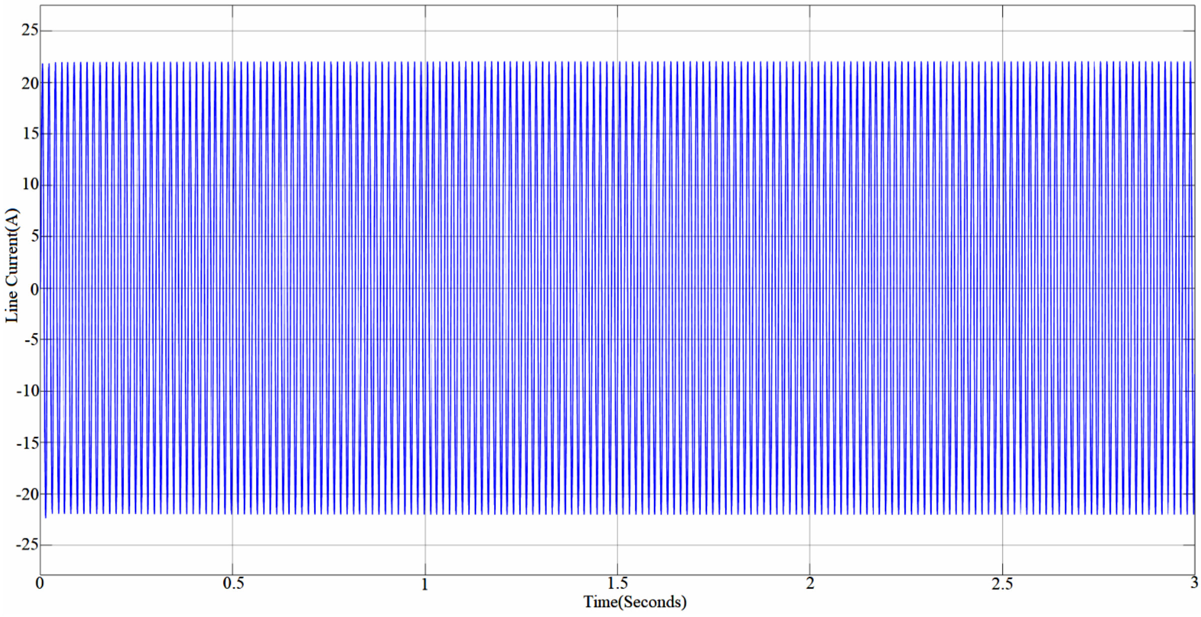

Figure 4.7 Line Current for P = 3.3kVA

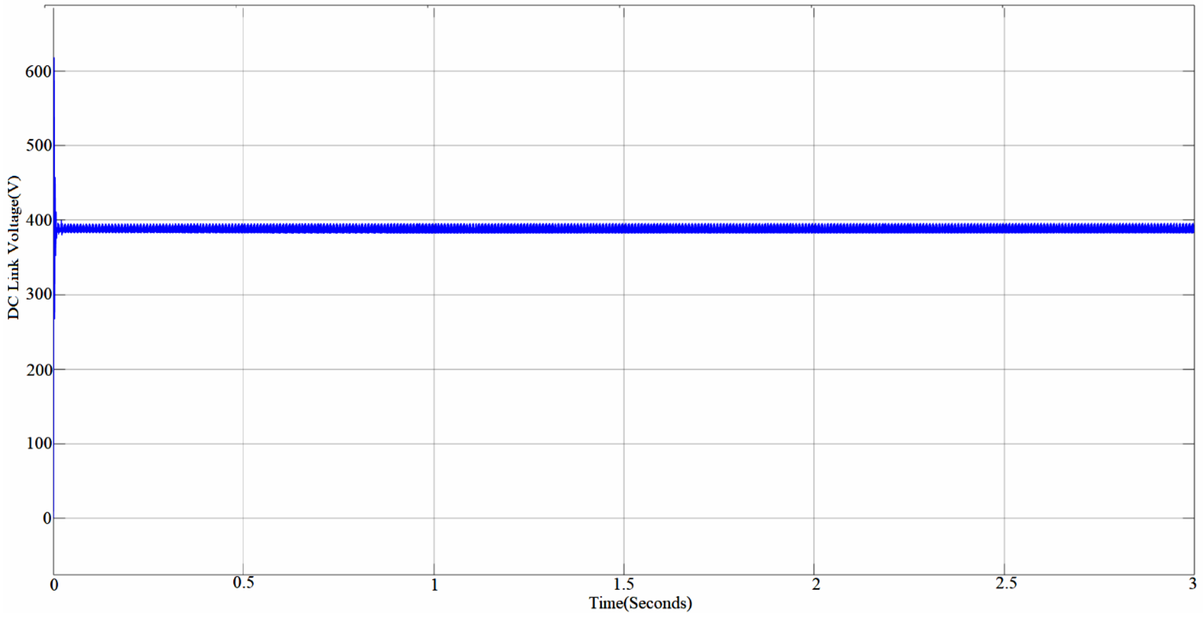

Figure 4.8 DC link Voltage for P = 3.3kVA

The battery charging current for 3.3 kVA charger is shown in Fig 4.9. The RMS value of this mode of battery charging current is approximately 9A. The total (apparent) power for this mode of the charger is equal to 365V * 9.04A = 3300kVA. The input commands given by utility or user to the charger must be pursued by the charger. The value used for grid side inductance is 1.0mH for 3.3kVA charger.

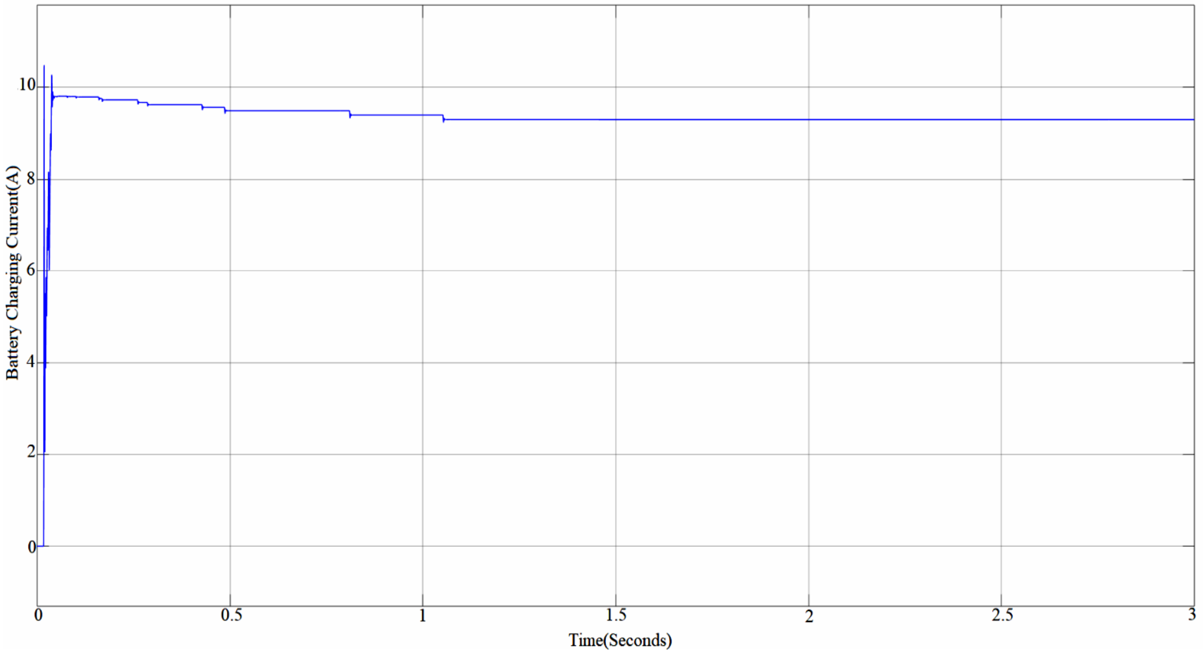

Figure 4.9 Battery Charging Current for P = 3.3kVA

Fig 4.10 illustrates battery SOC. The initial SOC of the battery is 20%. If charger continues to work in constant current (CC) mode then it may fully charge the battery within 1.6 hours.

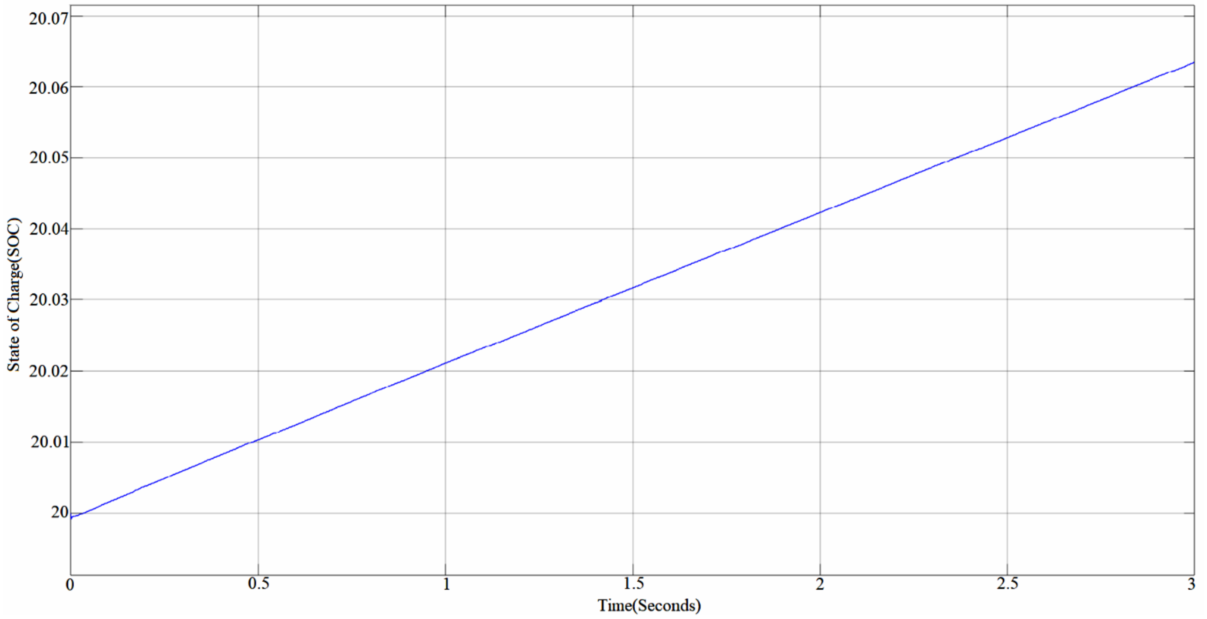

Figure 4.10 State of Charge (SOC) for P = 3.3kVA

4.1.3 6.6kVA Charger:

The graphs which are shown in this configuration are:

- Source Voltage
- Line Current
- DC link Voltage (V_{dc})
- Battery Charging Current (I_{bt})
- State of Charge (SOC)

The inductance value used for 6.6kVA charger is 1.5mH. The source voltage for 6.6kVA charger is 230V and its peak value is 310V as shown in Fig 4.11.

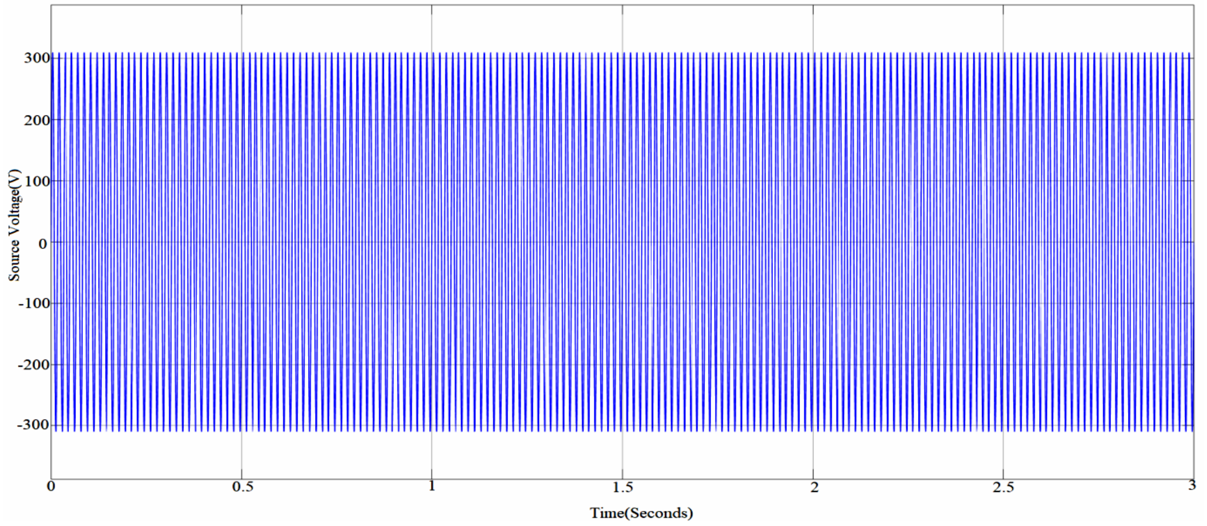

Figure 4.11 Source Voltage for P = 6.6kVA

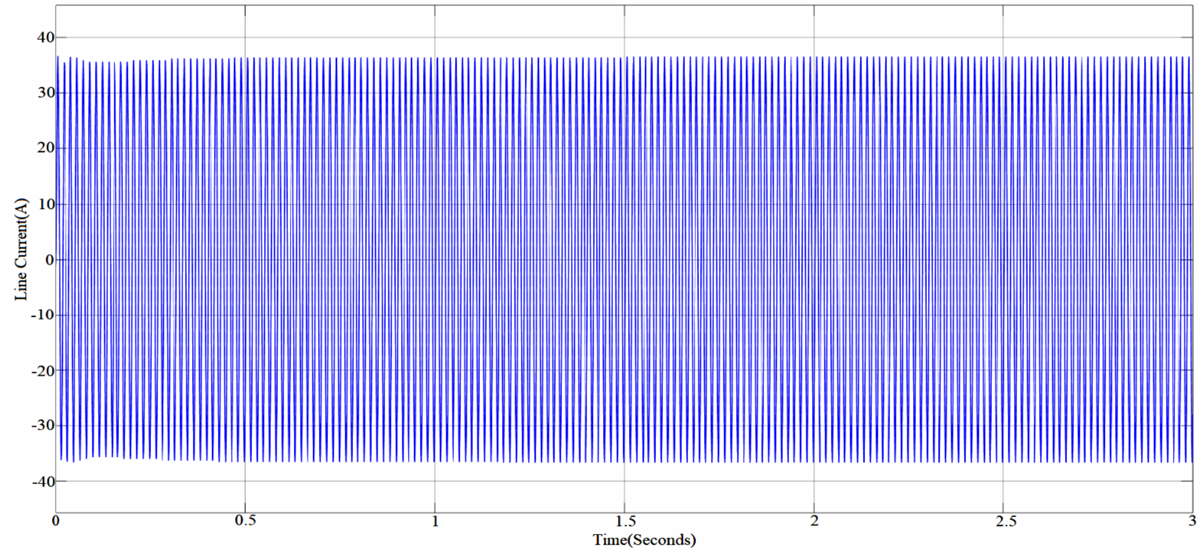

Figure 4.12 Line Current for P = 6.6kVA

The results shown below are produced by using the load side inductance which is equal to 650µH so as to downgrade harmonics of charging current of battery. Fig 4.12 represents line current for 6.6kVA charger whose RMS value is equal to 24A and its peak value is approximately 34.5A. The dc interface capacitance esteem utilized here is raised to 840µF. The capacitance value is elevated to reduce THD in battery charging current (i_{bt}) waveform. The THD must be within the limits for proper operation of charging of PEV (Electric Vehicle). Fig 4.13 represents DC link voltage waveform for 6.6kVA charger.

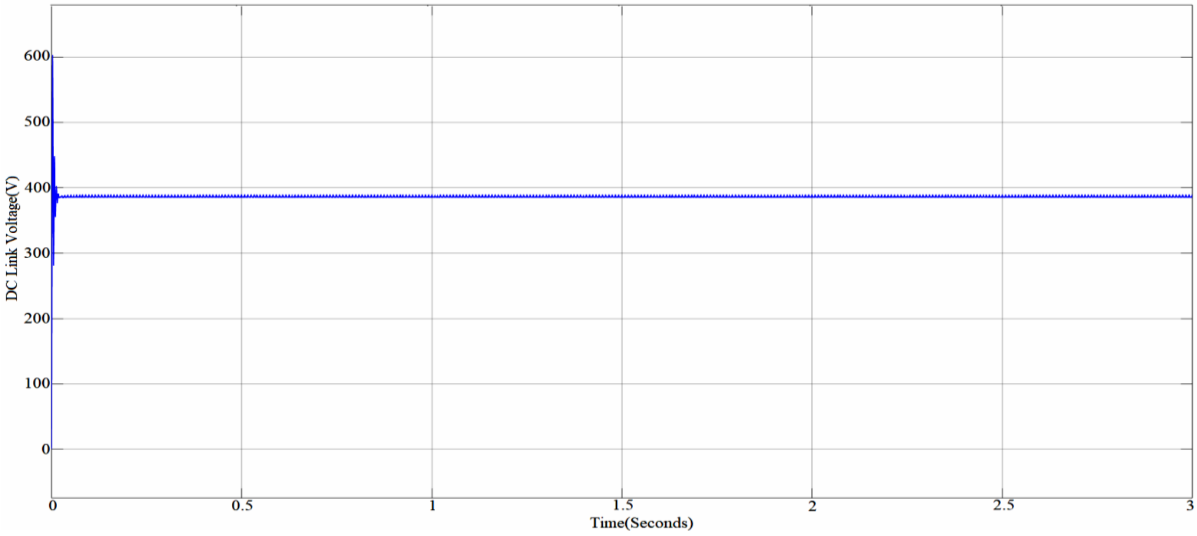

Figure 4.13 DC link Voltage for P = 6.6kVA

Fig 4.14 represents battery charging current (i_{bt}). The RMS value of charging current is approximately 18A. The dc-dc controller is helpful to control battery charging current. The change in power commands results in a change in battery charging current so as to preserve the apparent power constant.

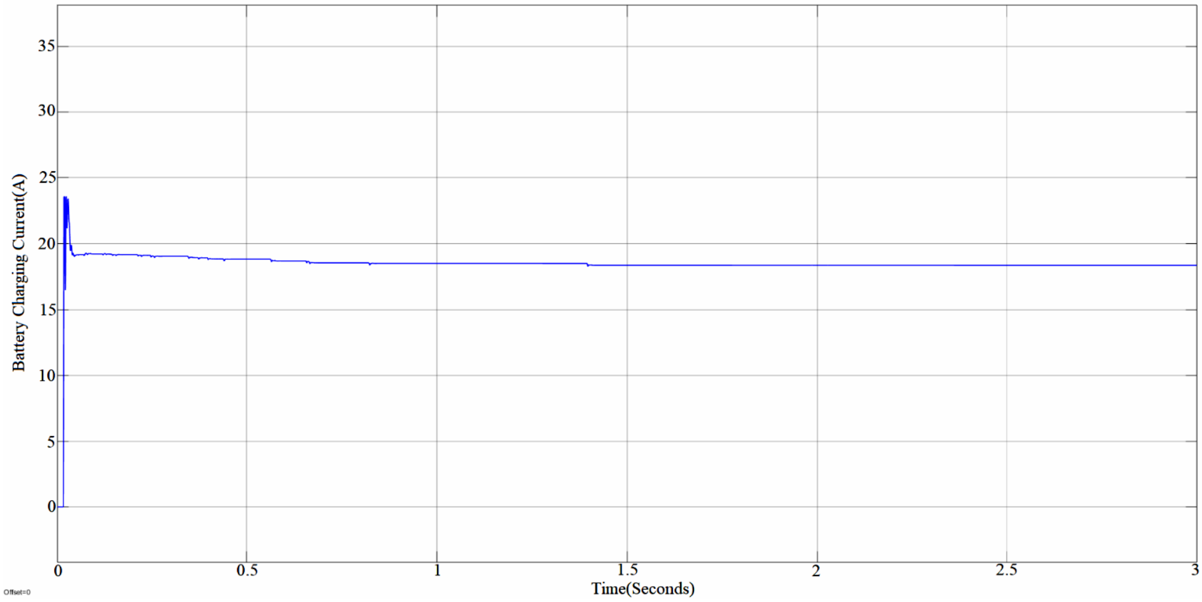

Figure 4.14 Battery Charging Current for P = 6.6kVA

Fig 4.15 represents battery state of charge (SOC). In case of 6.6kVA charger if battery continuous to operate in CC mode then it will charge the battery within 0.8 hours.

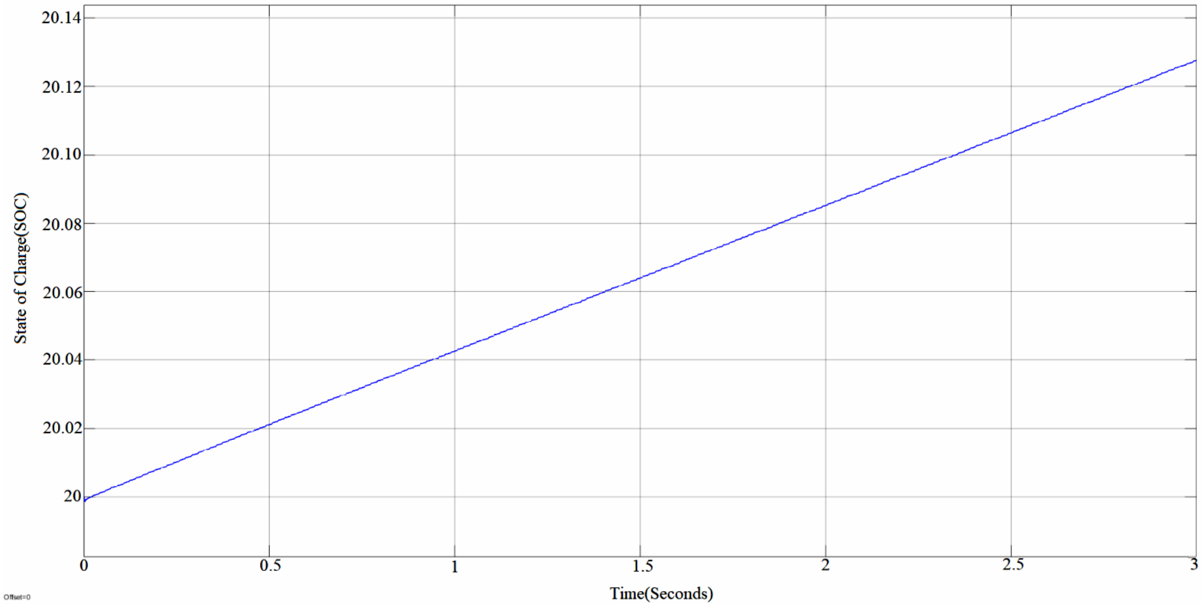

Figure 4.15 State of Charge (SOC) for P = 6.6kVA

Table 4.1 shows the different types of the charger. The Voltage, line current, DC link voltage, Battery charging current is represented in Table shown below.

Table 4.1 Types of Battery Charger

Level-1 charger (1.44kVA)	Voltage (RMS)	Line Current (RMS)	DC link Voltage (V)	Battery Charging Current (A)
	120V	12A	385V	3.8A
Level-2 charger (3.3kVA)	Voltage (RMS)	Line Current (RMS)	DC link Voltage (V)	Battery Charging Current (A)
	230V	17A	385V	9A
Level-2 charger (6.6kVA)	Voltage (RMS)	Line Current (RMS)	DC link Voltage (V)	Battery Charging Current (A)
	230V	24A	385V	18A

4.2 SUMMARY OF THE CHAPTER

Till now we have discussed three types of chargers which are i) 1.44kVA ii) 3.3kVA iii) 6.6kVA. The 1.4kVA charger falls under the category of Level-1 type charging system. The 3.3kVA and 6.6kVA chargers come under the category of Level-2 type charging system. The results shown above are simulated for all the three types of chargers in charging only mode. The difference between three types of chargers is represented. 1.44kVA charger takes more time to charge the battery as compared to 3.3kVA and 6.6kVA charger. The charging of the battery is free from all kinds of harmonics that means charging necessity is fulfilled.

CHAPTER 5

CONCLUSIONS AND SCOPE FOR FUTURE

5.1 CONCLUSION

In this dissertation, the bidirectional charger is acclimatized to charge the Electric Vehicle battery. Here the charger operates in charging only mode i.e. it only charges the battery instead of reactive power compensation to the grid. The charger constitutes two converters. First one is ac-dc converter and the second one is dc-dc converter. The charger consists of two controllers which are interlinked with each other. AC-DC and DC-DC controllers obey the input commands given by client or grid. With the change in input commands, the charging current, the battery current and dc link voltage changes as per their need so as to maintain the apparent power constant.

The results of all three modes of charger are represented in Chapter 4. The comparison between all three types of chargers has been made. The three chargers which are represented in this dissertation are of different ratings which are: i) 1.44kVA ii) 3.3kVA iii) 6.6kVA. Comparison of various types of chargers yields that the 6.6kVA charger is faster than 1.44kVA and 3.3kVA charger. Various tables are shown in Chapter 3 which represents the parameters used for making the charger. At the time of peak hours, it is the responsibility of PEV to provide the reactive power to the grid as per utility demands so as to preserve the voltage profile of distribution transformer. The parameters of the charger have been modified to optimize the results. The parameters used in above results conclude the better dynamic behavior of the charging system. The P_{cmd} and Q_{cmd} commands are followed by the charger by using above parameters.

5.2 FUTURE SCOPE

As we know fuel reserves are depleting at a faster rate, this emphasis the costumers for the switching of vehicles from conventional to an electric one.

- The concept of Electric Vehicle is still new in India but in near future, the population of electric vehicles will increase. Electric Vehicles are more advantageous as compared to conventional vehicles in case of emissions, dependency on fuels and energy storage from the grid.

- The use of intelligent controllers like Fuzzy Controller, ANFIS, may be feasible in near future for the purpose of controlling the battery current.
- There are certain constraints which need to be improved in future. PEVs research is going on from many decades. The fuel reserves are depleting day by day at a faster rate. This leads to the increase in the price of fuel. That is why Electric Vehicles are exercised as an alternative source of energy and also Electric vehicles can store power and can provide the utility in case of emergency. The single phase unidirectional charger can be transformed into bidirectional charger for making possible V2G operation of the charger.
- The single-phase charger can be transformed into 3-phase by using three single phase legs. The advantage of this is that the ac voltage may be transformed into dc voltage in a controlled manner directly.

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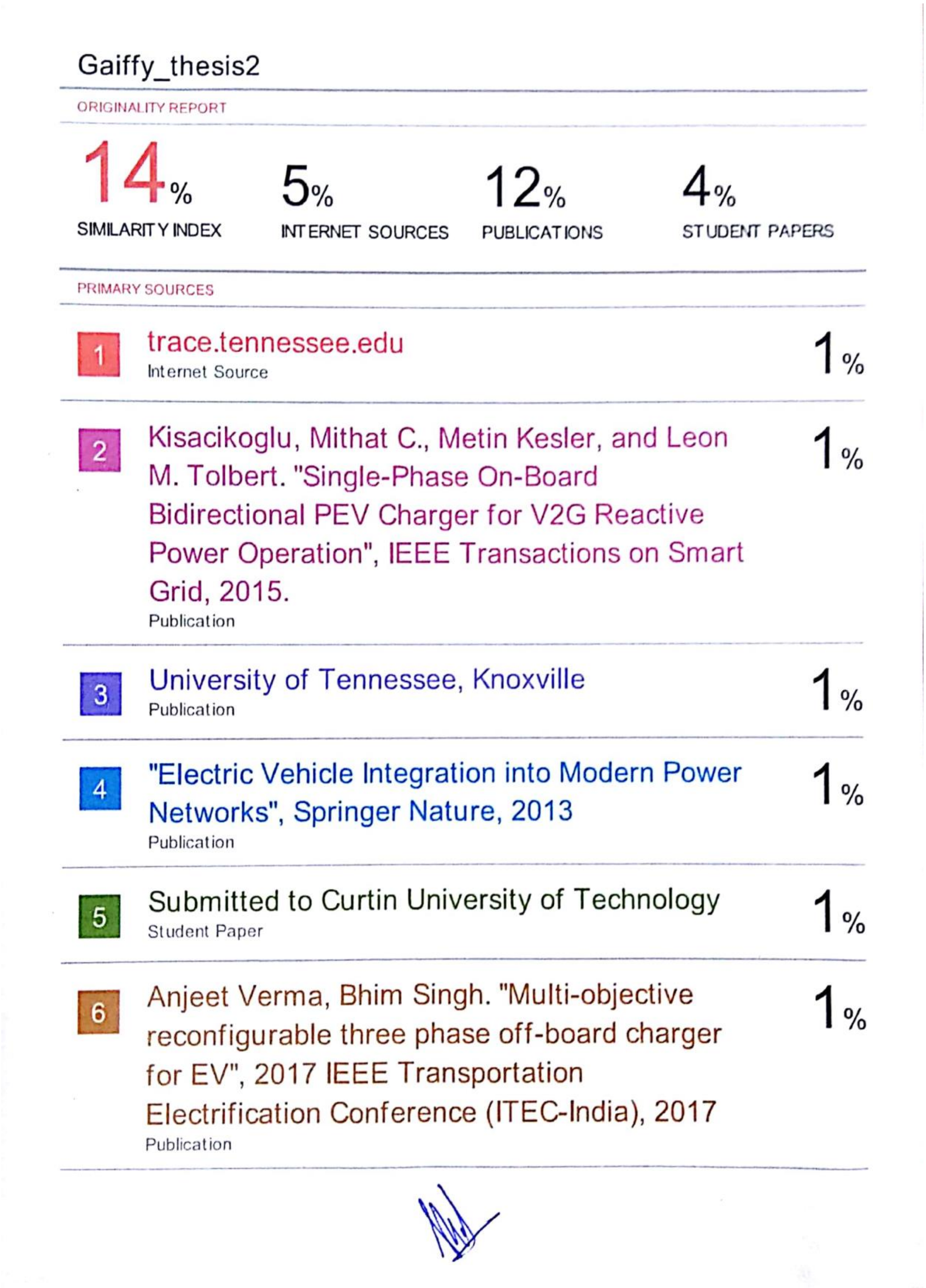

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