

# **Single Phase Bidirectional Charger for Electric Vehicles to Support Reactive Power Compensation to Grid**

*A dissertation report submitted in fulfillment for award of degree*  
of

**Master of Engineering**  
in  
**Power Electronics and Drives**

*Submitted By*

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## DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled, “**Single Phase Bidirectional Charger for Electric Vehicles to Support Reactive Power Compensation to Grid**” in the partial fulfilment of the requirement for the award of the Degree of Master of Engineering in Power Electronics & Drives, submitted to **Electrical & Instrumentation Engineering Department of Thapar University, Patiala**, is an authentic record of my own work carried under the supervision of **Dr. Mukesh Singh**. It refers others researcher’s work which are duly listed in the 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.

Place: *Patiala*  
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This is to certify that the above statement made by the candidate is correct and true to best of my knowledge.

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# ABBREVIATIONS

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SG	Smart Grid
EV	Electric Vehicle
SOC	State of Charge
Ah	amp-hour
PEV	Plug-in Electric Vehicle
CC	Constant Current
CV	Constant Voltage
dc	Direct Current
Li-ion	Lithium-ion.
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
P-R	Proportional Resonant
SOC	State of Charge
THD	Total Harmonic Distortion
V2G	Vehicle to Grid
$V_{dc}$	DC-link voltage across capacitor
$I_{batt}$	Battery charging current
$V_{ac}$	Source voltage at the input side
$I_s$	Source current
$L_{dc}$	Inductor at the dc-dc converter.
$C_{batt}$	Capacitor of the dc-dc converter
$P_{cmd}$	Active power command giver by the user
$Q_{cmd}$	Reactive power command given by the utility
$P_{ref}$	Reference active power taken by the controller
$Q_{ref}$	Reference reactive power taken by the controller
P-I	Proportional and Integral
PWM	Pulse Width Modulation
D	Duty cycle
C-1	Controller-1 for ac-dc converter
C-2	Controller-2 for dc-dc converter
PFC	Power factor corrected
$\Delta$	The angle between source voltage and dc side voltage

# ABSTRACT

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This dissertation presents a single phase bidirectional plug-in electric vehicle (PEV) charger. The charger proposed here controls the charging rate of the battery and additionally provides reactive power support to the grid. The battery charger circuit consists of two converters i.e ac-dc boost converter (120V ac to 400V dc) and the dc-dc buck converter. A separate controller is used for each converter i.e Controller-1 (C-1) and Controller-2 (C-2). C-1 is for ac-dc boost converter and C-2 is for the dc-dc buck converter. The C-1 is used to support the reactive power to the grid to maintain the Power Factor (pf) and voltage regulation. However, the control action of C-1 is done through the dc-link capacitor. The change in controllable commands (P-Q commands) adjust the parameters of the dc side. Whereas C-2 has been designed to control the charging rate of the battery. The battery charging current can vary as per the status of grid. The P-Q commands are the reference active power and reactive power commands given by the user at the input side. In this dissertation, the proposed charger is used to charge the plug-in electric vehicle battery in different charging modes. This dissertation proposes a simulation model and mathematical analysis of the charger. The comparison of the improved results concludes the successful implementation of charger.

**Keywords:** Boost rectifier, Controller, Electric vehicle, Reactive power compensation.

# Chapter 1

## INTRODUCTION

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As per the international energy report, the energy usage of the the world transportation is going to increase upto 49% by year 2040 [1]. Therefore, a technology needs to be developed, which uses alternative resources to reduce oil consumption. Plug in Electric Vehicles (PEV's) and Plug in Hybrid Electric Vehicles (PHEV's) are used as an alternative technology, which consume lesser amount of oil [2]. PEV's sales are increasing now a days as an alternative to the conventional energy vehicles and do not produces emissions. Consequently increased usage of PEV reduces green house gas emission. PEVs depend on electric power, which is more efficient and increase fuel cost savings. In PEV, to cover the same distance, the cost of electricity used to charge the PEV battery is much cheaper than the fuel consumed by conventional vehicles. On annual basis fuel of \$710 can be saved as compared to Combustion Engine (CE) vehicles [3].

PEV demand is increasing now a days, because it is alternative to the conventional energy vehicles. PEV's present a more efficient operation, so that fuel cost can be saved. However, large number of electricity networks are being developed for PEV's. Due to increase in the peak loads grid is designed at low voltage distribution networks. The PEVs also used as energy storage by utilizing them as a readily available charger. A charger first converts a.c power in to d.c and they can send the power in unidirectional manner here. The charger performs various functions, which include voltage regulation, filtering of harmonics, Improvement of power factor and reactive power compensation also. Traditionally, capacitor bank, VAR supply and synchronous compensators are used for reactive power compensation. The battery life and state of charge does not affect by reactive power support. The losses of rectifier during compensation are supplied by grid. However, reactive power compensation affects only to the capacitors because more charging and discharging cycles are used.

In future, utilities would communicate between PEVs power and customer requirement and will control it. The ac-dc and dc-dc converters has 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. In this work, we have used two controllers are for ac-dc converter and dc-dc converter. Unique control strategy is formulated for each converter. The controller communicates for active and reactive power between EV and grid.

## 1.1 Literature Review

A PEV uses electric motor or traction motor for propulsion and motor is powered through batteries. The PEV battery charging is the most important concern in the smart grid. The increasing number of PEVs increases the burden at load side, which affects the generation, transmission and distribution. A large number of PEV loads increases the rating of the charger used for PEV. This consequently increases the size of the battery and harmonic content present in the line current. Due to this the rating of the Distribution Transformer (DT) is increased, which reduces the lifetime of DT upto 30% of its regular life [4]. The increased number of PEV loads increases the consumption of reactive power, which results in low power factor and increased voltage regulation. Hence, there is urgent need of compensation to improve the voltage profile and power factor [5], [6].

PEVs batteries act as energy storage devices, so that energy can be stored for a period and can be used when required. A large number of PEV stations are being developed for charging purposes and to store the power in the batteries [7]. EVs have been considered to be of a few benefits and hence effective in the long life operation of grid, because the power stored in the PEV batteries can be used back at the time of peak loads on the grid. The PEV battery provides support of the reactive power to the grid, which results in an increase in efficiency of the power transformer and will decrease in the loading of the DT [8]. In the future, the customers will be given incentives in return of the amount of energy given by PEV batteries to the grid [9–12]. The power is transferred from Vehicle to Grid (V2G) with help of different charger topologies.

There are two types of topologies used for this purpose i.e unidirectional charging topology and bidirectional charging topology. 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 converter, which is used for V2G applications [15–17]. A bidirectional topology is implemented in this dissertation, where

charger can send the reactive power in bidirectionally and active power unidirectionally [18], which obtains the commands from user and the utility and adjust the line current and battery charging current accordingly. In [19], battery life and State Of Charge (SOC) is not affected by reactive power support. However, reactive power compensation affects the dc-link capacitors because charging and discharging cycles are used. Generally, capacitor bank, VAR supply and synchronous compensators are used for reactive power compensation. These options can be eliminated by using PEVs in five different operating modes which are i) charging only operation, ii) charging and capacitive, iii) capacitive only, iv) inductive only and v) charging and inductive mode. The losses of the a.c to d.c rectifier used in bidirectional converter during compensation are supplied by the grid.

The bidirectional charger has two stages i.e ac-dc boost converter and dc-dc buck converter. In first stage a.c voltage is rectified to obtain d.c voltage i.e 120V ac to 400V dc. In second stage, dc-dc buck converter used to controls the battery charging current. Two types of bidirectional chargers are there, these include on-board and off-board chargers, on-board chargers can charge the batteries at any outlet which is available at either home garage 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 [20]. The off-board chargers on the other side 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 [21].

The charger proposed in [2] requires large size of the dc-link capacitor, which results in limited reactive power output. The size of the dc-link capacitor depends on the topology used in the converter, size of the charger and the coupling inductor at the input side. The dual-buck and half bridge converters require the large size of the dc-link capacitor, which makes them less suitable for reactive power support. In dual-buck and half bridge converters output power exceeds its rated power, which increases the stress on dc-link capacitor. 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 hence forth produces an error. The charger proposed in [24] has slow response for the commands given at the input side. The battery state of charge is spared during reactive power compensation in this type of charger, which affects the performance of the charger.

## 1.2 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 various researchers have proposed the PEV chargers with reactive power compensation. However, limited work has been done related to voltage regulation with reduced harmonics in the source current [23, 25]. Therefore, the work proposed in this dissertation focuses to maintain the voltage profile and to reduce the harmonic components in the source current by providing reactive power compensation. The various chargers proposed in [17–19, 26] can be used to support the reactive power. The problem existing with these chargers is that, when PEV demands reactive power compensation during the charging and discharging of the battery, the battery state of charge is spared and the PEV increases the demand from dc-link capacitor ( $C_{dc}$ ). This results in more charging and discharging cycles and increased second harmonic ripples in the dc-link voltage ( $V_{dc}$ ). Therefore, the charger used here has full bridge converter which uses the reduced size of dc-link capacitor. The full bridge converter uses optimized value of the capacitor to overcome the problem of ripples in dc-link voltage. The full bridge converter output power does not exceed its rated power to have less stress on dc-link capacitor. The mathematical analysis of the converter is also done in this dissertation to determine the optimized size of the dc-link capacitor. However, the problem with the charger in [24] is its slow response on input commands. Therefore, the proposed charger can be used to improve the response time of the controller also under various input conditions.

## 1.3 Objective of the work

The objectives of the dissertation are summarized as follows.

- The charger used in this dissertation is transformerless, which reduces the size, cost and losses of the charger.
- The converter used here is of full bridge type, which uses the reduced size of dc-link capacitor.
- The ripple content in dc-link voltage is reduced by selecting proper size of the dc-link capacitor. Therefore, analysis is performed for proper selection of the dc-link capacitor.

- The proposed scheme for reactive power compensation to the grid, increases the dynamic response of the charger with respect to input commands given from the user side.
- The proposed charger in this dissertation is shown by simulink model and the verification of simulink results has been done with mathematical analysis.
- The dynamic performance of the proposed controller has been improved using different input commands and the source current contains less harmonics which results in reduced Total Harmonic Distortion (THD).

## 1.4 Organization

The work carried out in the dissertation has been organized in 5 chapters. Chapter 1 deals with introduction and literature review. Chapter 2 deals with the schematic block diagram, complete system diagram and circuit diagram explanation of PEV charger and its modelling with explanation of need of reactive power support and study of battery technology. Chapter 3 deals with the design of controllers and complete mathematical analysis for ac-dc boost converter and dc-dc buck converters. Chapter 4 deals with the simulation results for ac-dc, dc-dc and combined system with following P-Q commands and its discussion. Chapter 5 deals with conclusion, future scope of the work and references.

# Chapter 2

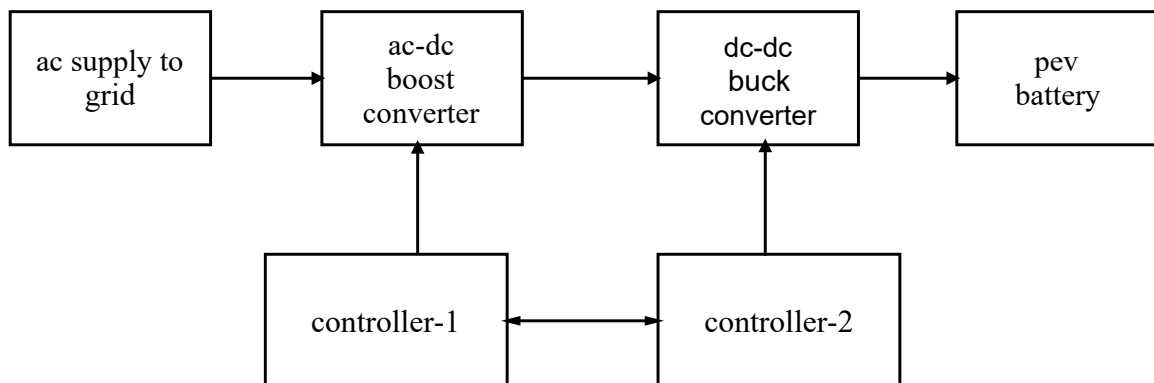
## DESIGN OF CHARGER

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### 2.1 General Concept

The schematic block diagram shown in Fig 2.1 represents the purpose of each block in diagram. The ac supply is taken from the grid, which is available at 230V/50Hz or 110V/60Hz. The purpose of charger is to charge the PEV battery, which requires dc supply at required voltage. Therefore, ac-dc converter is used. The ac-dc converter converts low ac voltage to high dc voltage. The PEV battery requires controlled charging current, so to control the dc voltage dc-dc converter is used. The controlled voltage of dc-dc converter results in controlled charging current. The controller-1 (C-1) is used to control the active and reactive power demand given at by the input references. The controller-2 (C-2) is used to control the charging rate of the battery, C-2 communicates with C-1 and results in controlled charging current according to given references.

The charger proposed in Fig 2.2 has been modified by replacing two converters instead



**Figure 2.1:** Schematic block diagram.

of using transformer in the charger. The charger proposed in dissertation [22] uses a transformer in charger, which increases the weight, size and losses of the charger. Therefore, a transformerless charger is proposed in this dissertation. The transformerless charger consist of two converters i.e ac-dc boost converter and dc-dc buck converter. In ac-dc boost converter, the voltage of the ac side 230V, 50Hz /120V, 60Hz is converted in to 400V dc because, battery taken has nominal voltage of 363V. Hence voltage needs to boost up with the help of boost converter. In boost converter, inductor is used in series with the source to boost the input ac voltage, which converts 120V ac input voltage to 400V dc voltage at the output of converter across dc-link capacitor ( $V_{dc}$ ). In ac-dc boost converter Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) switches are used. In the dc-dc converter, fixed voltage across the dc-link capacitor is converted into variable voltage at the output of the converter, so that, the battery charging current can be controlled. The focus of the dissertation is to provide controlled charging to the battery as well as support the reactive power compensation to the grid also.

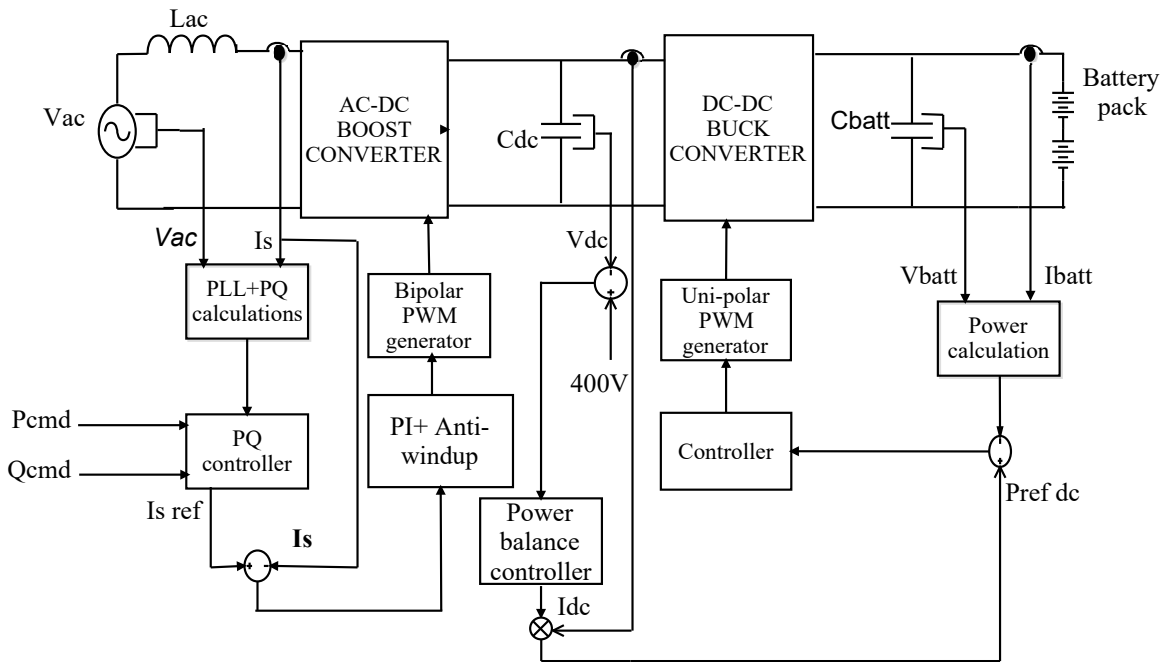
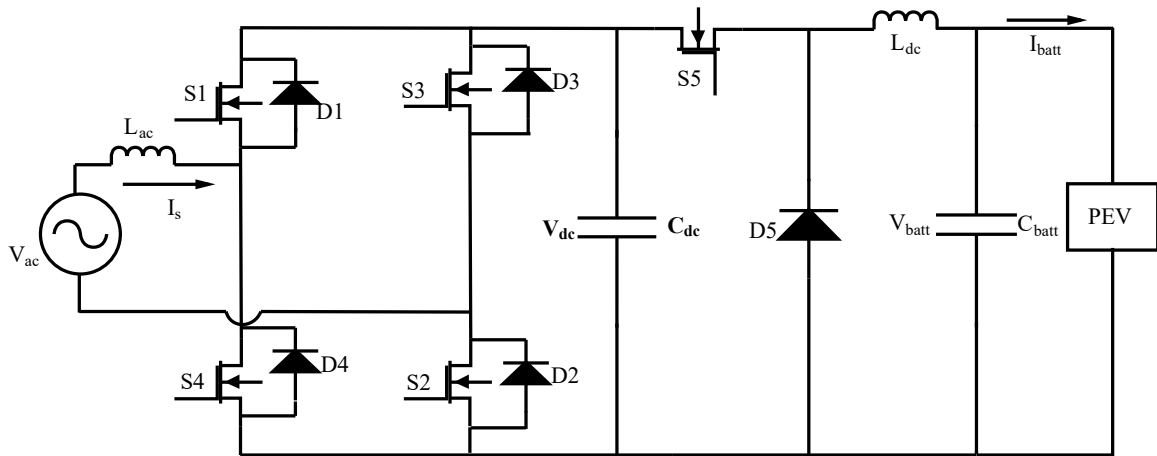


Figure 2.2: Block diagram of complete system.

## 2.2 Working of the charger

In Fig 2.2 the controller for ac-dc boost converter uses bipolar modulation, it means that the rectifier output voltage is either ( $V_{dc}$ ) or  $-(V_{dc})$ . The circuit diagram of the charger is shown in Fig 2.3, when switches  $S_1$  and  $S_2$  are on, switches  $S_3$  and  $S_4$  are off, and vice

versa. Taking reference to the ( $V_{dc}$ ), battery reference current ( $i_{bt}$ ) is derived. The buck converter is used to control battery charging current by varying the output voltage of the buck converter with the help of duty cycle given at the gate of MOSFET switch used in this converter. Buck converter operation is achieved by using switches  $S_5$  and  $D_5$ . When switch  $S_5$  is on, current will pass through  $S_5$  and  $L_{dc}$  and charges the battery and capacitor ( $C_{batt}$ ). When  $S_5$  is off, current will freewheel through  $D_5$ ,  $L_{dc}$ ,  $C_{batt}$  and battery. Here we are using the charger only for charging purpose. The inductor at the input side ( $L_{ac}$ ) is used as filter at the input to prevent input side current from the grid to have Total Harmonics Distortions (THD) not more than 5%. The ( $L_{ac}$ ) also used to boost the input ac voltage to the dc voltage (output) side. An appropriate value of the inductor and capacitor at the output side is used, which minimize the ripples present in the waveforms. The battery taken in this dissertation is lithium-ion with Constant Current (cc) and Constant Voltage (cv) charging mode. The lithium-ion battery has fast charging rate and has light weight compared to lead acid batteries. The battery is in cc mode, when it starts charging from zero State Of Charge (SOC) and charges upto 20% SOC. In this mode voltage changes from zero volts to 95% of the nominal voltage of the battery and current remains constant. In cv mode, current of the battery changes and voltage of the battery remains constant.



**Figure 2.3:** Circuit diagram of charger.

The charging and discharging mode of the battery depends on the active Power ( $P_{cmd}$ ) command given by the user of vehicle at the input side. The charging rate of the battery can be controlled according to ( $P_{cmd}$ ) is given by user. The reactive power command ( $Q_{cmd}$ ) is given by the utility side to act the PEV in different modes. If positive value of ( $Q_{cmd}$ ) given by the utility and positive value of ( $P_{cmd}$ ) given by user, PEV acts in charging mode and dc-link capacitor also acts in charging mode. If ( $P_{cmd}$ ) is positive and ( $Q_{cmd}$ ) is negative, then PEV acts in charging mode and dc-link capacitor acts in discharging mode and provides

reactive power to the supply. In reactive power mode of operation, battery SOC is not affected here but in dc-link capacitor more charging discharging cycles take place, which reduces the life of dc-link capacitor.

## 2.3 Modes of the charger

Table 2.1 shows the represents the charging modes of the PEV battery. In this dissertation, the charger is used only in charging mode. In Table 2.1, power commands given by the user i.e  $P_{cmd} = +ve$  and  $Q_{cmd} = 0$  value means that the charger is in only charging mode. The second row of the table shows the positive value of both the commands means that the charger is in charging mode as well as Inductive mode. The Inductive mode means that, the charger takes reactive power from the supply.

**Table 2.1:** Modes of charging

Charging Modes		
Active power command ( $P_{cmd}$ )	Reactive power command ( $Q_{cmd}$ )	Charging modes
$P_{cmd} = +ve$	$Q_{cmd} = 0$	Charging mode
$P_{cmd} = +ve$	$Q_{cmd} = +ve$	Charging and Inductive mode
$P_{cmd} = +ve$	$Q_{cmd} = -ve$	Charging and Capacitive mode
$P_{cmd} = -ve$	$Q_{cmd} = +ve$	Discharging and Inductive mode
$P_{cmd} = -ve$	$Q_{cmd} = -ve$	Discharging and Capacitive mode
$P_{cmd} = 0$	$Q_{cmd} = +ve$	Inductive mode
$P_{cmd} = 0$	$Q_{cmd} = -ve$	Capacitive mode

Similarly, the  $P_{cmd} = +ve$  and  $Q_{cmd} = -ve$  means that the charger is in charging mode as

well as acts as capacitor and support the reactive power to the grid.

## 2.4 Need of reactive power support

A advantage of the PEV is to keep up the operation of the grid by co-ordination of the PEV and utility. The various services that the PEV can provide to the grid. The PEV charger has ac-dc converter to convert the ac power from the grid to the dc power to the PEV battery. The proposed charger also provides ac power back to the grid by PEV battery. The power from the dc side is transferred for V2G reactive power operation. The utility has benefit by using considerable amount of power stored in a battery based on the services provided by PEV to the grid. The utility is concerned with the problems occurred because of integration of PEV's. Therefore, the charger is designed to alleviate these problems are shown below.

The reactive power at the load side is taken by the supply through the transmission and distribution system. This causes the increased losses and decreased efficiency. Therefore, the generation of reactive power decreases the amount of reactive power supplied from the source side, which needs to be sent from source to the load. The PEV charging is primary concern of the smart grid due to its affect on generation, transmission and distribution. When, there are large number of PEV's connected to the grid, the distribution system produces more issues when there is requirement of power generation because of large PEV's are connected to the grid.

The study shows that the more number of PEV connected to the grid, size of the charger, the rating of the charger, size of the distribution transformer, size of the batteries and harmonic content in the charger current get affected. The life of the transformer may reduce upto 30% of its life if any charging management is available [8]. To prevent these problems, the utilities must build smart grid like variable rates, grid communication, smart meters, and distributed energy management.

A normal microwave oven uses upto 0.5 kVAR of reactive and a washing machine consumes upto 0.8 kVAR of reactive power. The few other loads at the residential side include air conditioner, dish washer, refridgerator and so on. The customares never billed for reactive power consumption but utility pays for the reactive power for the private clients. However, with increasing the number of PEV connections to the grid and issues related to the system and transformer makes important to the on side generation of reactive power. Therefore, generation of reactive power by V2G will help in increased efficiency of power transferred through transmission lines and decreases overloading of transformers. Hence, the proposed charger will be advantageous in effort to control the power flow, which results in maintaining the continuous service of efficient electrical supply.

## 2.5 Previous Battery Technologies:

### 2.5.1 Lead Acid and Nickel Metal Hydride (NiMH) Batteries:

Earlier electric vehicles were powered by the most energetic batteries that are lead acid. Because of this reason, the battery price is cheapest now days. The battery can be owned by the customares. The emerging technology and manufacturing also leads the lead corrosive battery was the most favoured choice to control early EV's. Consequently it is promptly accessible at a sensible cost inferable from the development of the innovation and assembling. Its great release control limit makes it less demanding to react quick to load changes. Conversely, it has a low vitality thickness and is overwhelming. Likewise, lead corrosive batteries have short life expectancies as a result of the decay from the profound releases.

The disadvantage of NiMH battery is its high self discharging rate as compared to lead acid batteries. This causes the loss of charge from battery when not in use. The battery discharges 6 – 11% on the first day and 0.6-1.1% per day at room temperature [28]. The NiMH batteries are costlier than lead acid. In. The NiMH batteries have poor charge acceptance capability at high temperature reduces the charging efficiency. Most of the EV's present now days in market has NiMH battery.

### 2.5.2 Li-ion battery technology for vehicles:

According to experts, the Lithium-ion (Li-ion) batteries are going to be viable sources in the future generations of PEV [29]. The advantages of Li-ion batteries compare to other types of batteries are these batteries supply more supplying power for better discharge for faster acceleration and higher energy density for better electric range. The Li-ion batteries are preferred in vehicle applications for high efficiency and low weight. However, some issues in the Li-ion batteries still need to be improved for widely use in PEV's are life of the battery (more charge and discharge cycles), cost of the battery and safety [29]. A important issue with the Li-ion battery is to charge each cell of the battery to balance out the total charge among the cells in a precise way compared to NiMH and lead acid batteries. The lithium is more chemically react on the several conditions, which require battery management system for protection by overheating and overcharging. The poor cold temperature operation is major drawback of the Li-ion battery.

Each kind of Li-ion cell has a few points of interest, LFP cathode is another and promising cathode for PEV applications with expanded security and soundness highlights [30]. In any case, it brings down cell voltages contrasted with different cathodes, also, henceforth a large portion of these must be associated in arrangement requiring all the more adjusting

issues. To take care of the low cell voltage issue, nanostructures are being utilized. This new nanotechnology offers preferable power and longer life over prior eras [31]. A Li-ion cell with lithium titanate spinel anode is moreover beneficial instead of graphite for a EV because of its charging and discharging quickly. What's more, it has moved forward cycle and timetable lifetime. For this situation, vitality thickness is traded off to the detriment of getting a considerably more extensive operation temperature go and also a more secure voltage run [32]. Thus, scientists concur that out of all the batteries, the Li-ion batteries emerge for the points of interest of greater vitality thickness and light weight, life cycle, mishandle resistance and cost are the following hindrances to overcome for this innovation. The greater part of the vehicle makers that made openly accessible PEV models in the market is they utilize Li-ion batteries.

# Chapter 3

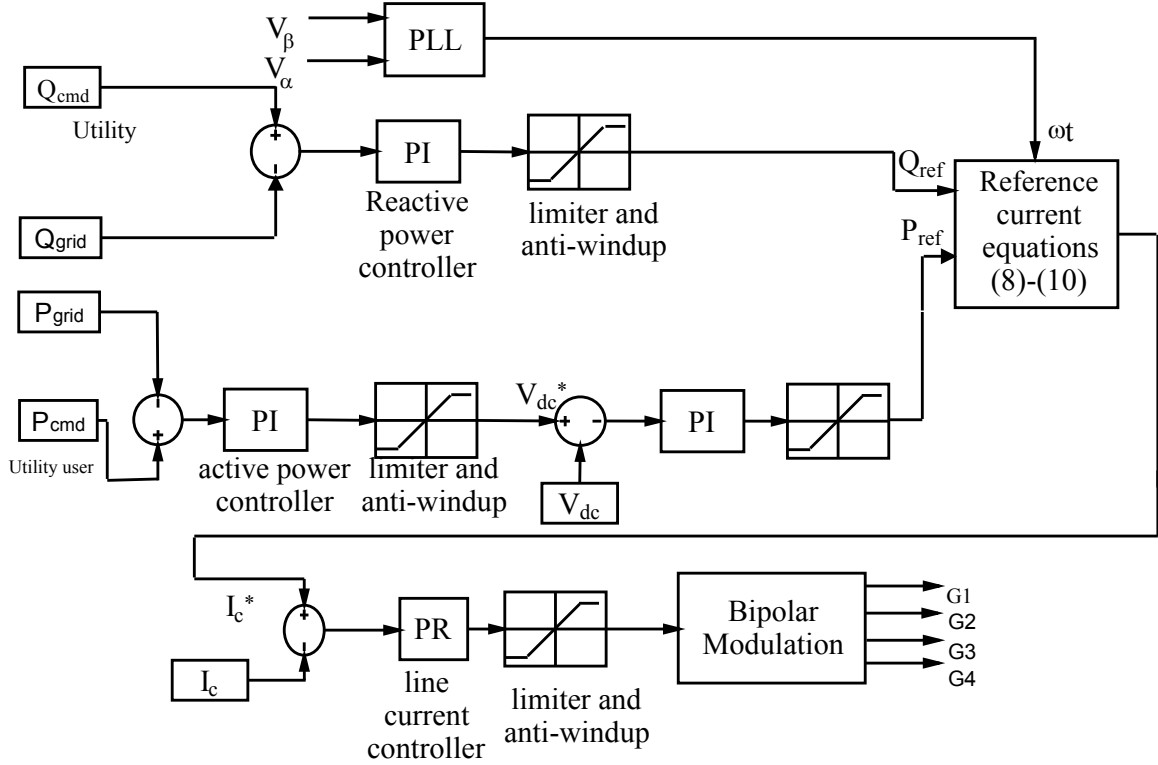
## DESIGN OF CONTROLLER

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### 3.1 Introduction

This chapter describes the controller operation and its working. The charger in this dissertation uses two controllers ( C-1 and C-2) shown in Fig 3.1 and Fig 3.2, one for the ac-dc boost converter (C-1) and another for dc-dc converter (C-2). The designing purpose of the controller is to operate the charger in quadrant I and IV of the active and reactive power plane. It means active power is unidirectional here, and reactive power is bidirectional.

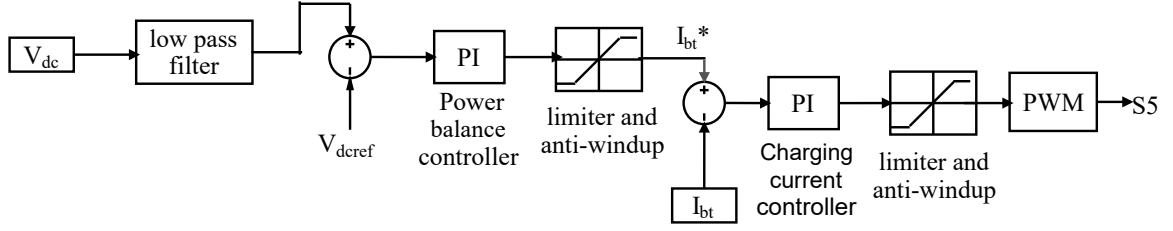
In the C-1, as shown in Fig 3.1, p-q theory is used for conversion of signals. In the p-q theory, two orthogonal signals of voltage and current are obtained by delay function. The output power obtained at p-q theory block is passed through low pass filters to reduce the ripples present in it. The output powers  $P$  and  $Q$  are compared with the  $P_{cmd}$  and  $Q_{cmd}$  given by the user and by the utility respectively. ( $P_{cmd}$ ) used as reference power for battery charging purpose, and boost rectifier regulates the dc-link voltage ( $V_{dc}$ ). The error present after the comparison passes through two separate P-I controllers, which is used to minimize the steady state error. Two feedback loops are formed called P-loop and Q-loop. The output of the P-loop is  $V_{dc}^*$ , which is compared with the sensed voltage of dc-link capacitor  $V_{dc}$  at dc-link capacitor. The error after comparison of voltage is passed



**Figure 3.1:** Controller for ac-dc converter (C-1).

through P-I controller, which results to in a power called  $P_{ref}$ . Similarly, in the Q-loop,  $Q_{ref}$  is generated. The two signals of  $P_{ref}$  and  $Q_{ref}$  are used to obtain the reference value of charger current ( $I_c^*$ ). The phase angle of the line voltage is obtained by Phase Locked Loop (PLL). The PLL utilizes the delay signals and tracks the line voltage phase angle and generate the reference phase angle for the reference charger current ( $I_c^*$ ). The  $I_c^*$  is further compared with sensed line current  $I_c$  and error signal is sent to the Proportional and Resonant (PR) controller [33], [34]. The controlled output is sent as refernce signal for bipolar modulation technique. The output of the bipolar modulation block produces gate pulses for the switches.

C-2 is for dc-dc buck converter shown in Fig 3.2. In C-2, sensed voltage of dc-link capacitor  $V_{dc}$  is passed through a low pass filter to reduce ripples present in it. The  $V_{dc}$  is compared with the reference voltage  $V_{dcref}$  and is passed to a P-I controller block. The output of P-I controller generates a reference battery charging current ( $I_{bt}^*$ ). The current is



**Figure 3.2:** Controller for dc-dc converter (C-2).

compared with sensed charging current of battery  $I_c^*$  and error is again controlled with P-I controller. The output signal of P-I controller is used as reference signal for Pulse Width Modulation (PWM) block and generates the duty cycle ( $S_5$ ) accordingly.

## 3.2 Problem Formulation

The formula of active and reactive power from the supply can be defined as:

$$P_{ac} = V_{ac} I_s \cos \delta \quad (3.1)$$

$$Q_{ac} = V_{ac} I_s \sin \delta \quad (3.2)$$

The combination of active and reactive power results in apparant power, which is given as:

$$S = V_{ac} I_s \quad (3.3)$$

power definitions are:

$$P_{ac} = \frac{V_{ac} V_{dc}}{\omega L_{ac}} \sin \Delta \quad (3.4)$$

$$Q_{ac} = \frac{V_{ac}}{\omega L_{ac}} (V_{ac} - V_{dc} \cos \Delta) \quad (3.5)$$

$$S = \frac{V_{ac}}{\omega L_{ac}} \sqrt{V_{ac}^2 + V_{dc}^2 - 2V_{dc} V_{ac} \cos \Delta} \quad (3.6)$$

where  $V_{ac}$  and  $V_{dc}$  are rms values of the source and dc side voltages respectively.

The three phase supply from the grid is converted to single phase with the help of instantaneous p-q theory [35]. In p-q theory, the sensed signals are  $\alpha$  components, so  $\alpha$  components are delayed by quarter cycle to generate  $\beta$  components. Therefore, the single phase powers obtained by p-q theory are:

$$P_{ac} = \frac{V_{\alpha}}{\sqrt{2}} \frac{I_{\alpha}}{\sqrt{2}} + \frac{V_{\beta}}{\sqrt{2}} \frac{I_{\beta}}{\sqrt{2}} \quad (3.7)$$

$$Q_{ac} = \frac{V_{\alpha}}{\sqrt{2}} \frac{I_{\beta}}{\sqrt{2}} + \frac{V_{\beta}}{\sqrt{2}} \frac{I_{\alpha}}{\sqrt{2}} \quad (3.8)$$

The bidirectional modes of the charger affect the charging current value. Therefore, the proper selection of dc-link capacitor becomes necessary to prevent the ripples in its voltage. The ripple current rating of the capacitor depends on the supply frequency [36], so the parameters which define the capacitor selection are capacitor voltage and its current rating. The Root Mean Square (RMS) value of the low frequency ripple current is:

$$I_{cap,low} = \frac{\sqrt{P_{ac}^2 X_{ac}^2 + (V_{ac}^2 - X_{ac} Q_{ac})^2 (P_{ac}^2 + Q_{ac}^2)}}{\sqrt{2} V_{ac} V_{dc}} \quad (3.9)$$

where  $X_{ac}$  is the reactance of the source side inductor,  $V_{ac}$  is rms value of the supply voltage,  $P_{ac}$  is active power which is drawn by the charger,  $Q_{ac}$  is the reactive power consumed by the charger and  $V_{dc}$  is the voltage across the dc-link capacitor ( $C_{dc}$ ). It is important to note that low frequency ripple current does not depend on the capacitance value but depends on the dc-link voltage. Therefore, the low and high frequency ripple current decides the type and size of the dc-link capacitor [36]. The equation of the ripple voltage in the dc-link capacitor is:

$$\Delta V_{dc} = \frac{\sqrt{P_{ac}^2 X_{ac}^2 + (V_{ac}^2 - X_{ac} Q_{ac})^2 (P_{ac}^2 + Q_{ac}^2)}}{\omega V_{ac}^2 C_{dc} V_{dc}} \quad (3.10)$$

Where  $\omega=2\pi f$  and  $f$  is the value of supply frequency. The first loop used to match active power command ( $P_{cmd}$ ) by changing reference dc voltage ( $V_{dc}^*$ ) value. Here  $P_{cmd}$  and  $P_{ac}$  are compared through comparator and passes to the next loop. In this case controller constants are changed, so that reference value match with the desired value. In the C-1 analysis, the equation of the  $V_{dc}^*$  is calculated by:

$$V_{dc}^* = (K_p^1 + \frac{K_i^1}{s})(P_{cmd} - P_{ac}) \quad (3.11)$$

In inner loop, the output will be reference tracking power level for charger and  $V_{dc}$  is voltage of inner dc loop. The reference and desired value of the battery voltages are compared and constants of the controller varied. Here, voltage difference is the function of the power. Similarly, charger output power (reactive power) is matched with reactive power taken by grid in the outer  $Q$  loop via a P-I controller. The output taken from the reactive power loop is supplied to the charge so that the charger can supply or sink. Here reactive power command given by user and reactive power at the grid is compared, which is the function of reference value.

The value of  $V_{dc}^*$  is used to find the equations of  $P_{ref}$  and  $Q_{ref}$  as:

$$P_{ref} = (K_p^2 + \frac{K_i^2}{s})(V_{dc}^* - V_{dc}) \quad (3.12)$$

$$Q_{ref} = (K_p^3 + \frac{K_i^3}{s})(Q_{cmd} - Q_{ac}) \quad (3.13)$$

The phase angle ( $\delta$ ) of the line voltage is calculated by  $P_{ref}$  and  $Q_{ref}$ . The value of  $\delta$  is used to calculate the value of  $I_c^*$ . We can control the inner loop using P-R controller. The error between the source current ( $I_c$ ) and  $I_c^*$  is fed to the P-R controller. The output of P-R

controller used to generate the duty cycle ( $D$ ) for the ac-dc rectifier converter.

$$\delta = \tan^{-1} \frac{Q_{ref}}{P_{ref}} \quad (3.14)$$

$$I_c = \frac{P_{ref}}{V_{ac} \cos \delta} \quad (3.15)$$

$$I_c^* = \sqrt{2} I_c \sin(\omega t - \delta) \quad (3.16)$$

The change in input P-Q commands results in change in P-Q references and this results in change in charger current. The change in charger current results in change in gate pulses, so that the gate pulses to the switches act accordingly. Similarly, in the controller-2, the change in  $P_{cmd}$  changes set point for the dc-link capacitor, which results in change in the battery charging current shown in the equation:

$$I_{bt}^* = (K_p^4 + K_i^4/s)(V_{dc} - V_{dc,ref}). \quad (3.17)$$

### 3.3 Parameters used in the charger

Table 3.1 shows the parameters of the proposed charger. The proposed charger has been designed on two values are 1.44kVA and 3kVA. The results on both the powers are shown in chapter-4. The value of source voltage is 120 V rms and supply frequency as 60 Hz. The appropriate values of the inductor and capacitor are taken in table shown below to reduce the ripples on the dc side and improves the THD on source side.

**Table 3.1:** System parameters

Charging Modes		
Parameters	Symbol	Values
Apparant power	$S_{ac}$	1.40 kVA
Source voltage	$V_{ac}$	120 V rms
Supply frequency	$f_{ac}$	60 Hz
Source inductance	$L_{ac}$	1 mH
ac-dc switching frequency	$f_{sw}$	24 kHz
DC-link Voltage	$V_{dc}$	390 V
DC-link capacitance	$C_{dc}$	$330 \times 10^{-6}$ F
Battery side capacitance	$C_{batt}$	$220 \times 10^{-6}$ F
dc-dc converter side switching frequency	$f_{sw1}$	42 kHz
Battery side inductance	$L_{batt}$	$400 \times 10^{-6}$ H

### 3.4 Parameters used in the controller for ac-dc converter

The parameters shown in Table 3.2 are for ac-dc controller. The values used in this table have been used in the controller and taken as the reference from [19].

**Table 3.2:** System parameters of ac-dc controller.

<b>ac-dc controller parameters</b>		
<b>Parameters</b>	<b>Symbol</b>	<b>Values</b>
Angular frequency	$\omega$	377.14
Proportional constant for P-R controller (P-loop)	$K_p^1$	1
Integral constant for P-R controller (P-loop)	$K_i^1$	20
Proportional constant for P-I controller (V-loop)	$K_p^2$	1.5
Integral constant for P-I controller (V-loop)	$K_i^2$	100
Proportional constant for P-I controller (Q-loop)	$K_p^3$	0.1
Integral constant for P-I controller (Q-loop)	$K_i^3$	30
Proportional constant for P-I controller (i-loop)	$K_p^5$	0.6
Integral constant for P-I controller (i-loop)	$K_i^5$	500

### 3.5 Parameters used in the controller for dc-dc converter

The parameters shown in Table 3.3 have been used for the dc-dc controller. The values have been taken from the reference [19].

**Table 3.3:** System parameters of dc-dc controller.

dc-dc controller parameter		
Parameters	Symbol	Values
Proportional constant for P-I controller ( $I_{batt}$ -loop)	$K_p^3$	0.01
Integral constant for P-I controller ( $I_{batt}$ -loop)	$K_i^3$	10
Proportional constant for P-I controller (balance-loop)	$K_p^5$	0.045
Integral constant for P-I controller (balance-loop)	$K_i^5$	0.50

# Chapter 4

## RESULTS AND DISCUSSION

---

### 4.1 Introduction

The simulation is used here for several purposes are:

- To fulfill the input commands.
- To improve the dynamic response of the controller.
- To reduce the THD in the results.
- To verify the mathematical results to investigate the charger in different charging modes.

The assumption is taken here that PEVs are used with the grid during peak hours, when the grid is fully loaded and charger requires full charging. Therefore, the simulation starts with charging only operation. The fully charging operation results in the decrease of voltage at the substation side. This results in increase of active and reactive power consumption at the residential unit. The utility takes an action to support the distribution voltage by using some of the PEVs for reactive power supply. Later, if the utility needs to decrease the voltage, the PEV can also consume reactive power.

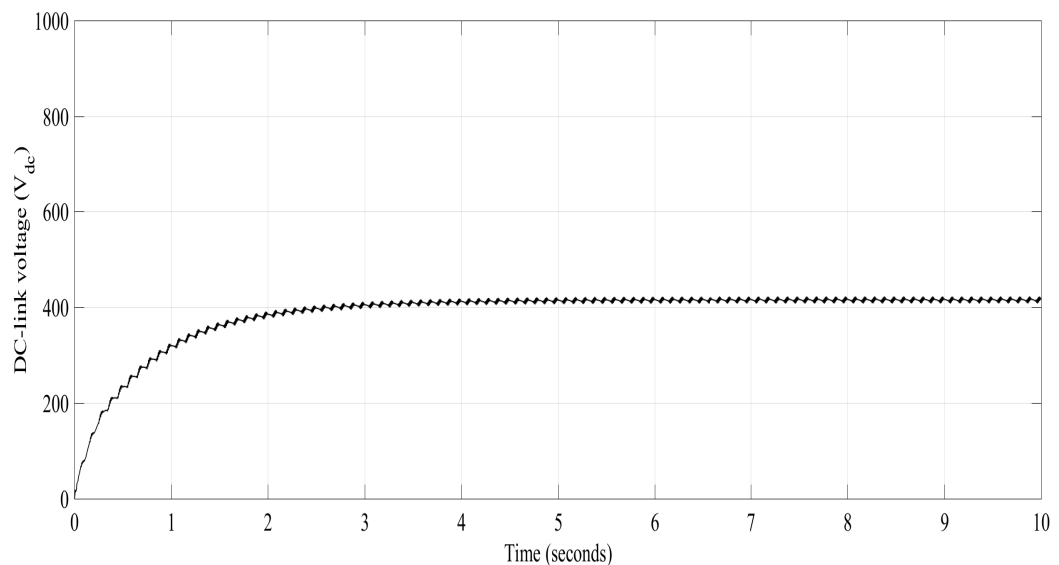
## 4.2 Steps of designing a charger

The proposed charger has been designed in three steps are:

- Design of ac-dc converter
- Design of dc-dc converter
- Design of combination of ac-dc and dc-dc converters with the seperate controllers following the P-Q commands.

### 4.2.1 Results of ac-dc converter

The result of ac-dc boost converter shows the output voltage of the converter, which is stepped up from 120 V a.c to 400 V d.c voltage. The input side inductor in series with the ac source is used for this purpose and the appropriate value of the dc-link capacitor is used to reduce the ripples present in the dc-link voltage.



**Figure 4.1:** Output voltage of ac-dc converter.

### 4.2.2 Results of dc-dc converter

The purpose of the dc-dc converter is to maintain the charging according to the given command. Therefore, In the dc-dc converter, a few current commands are set as reference in the look table of the simulation and results are obtained. The commands are given as shown in the table 4.1:

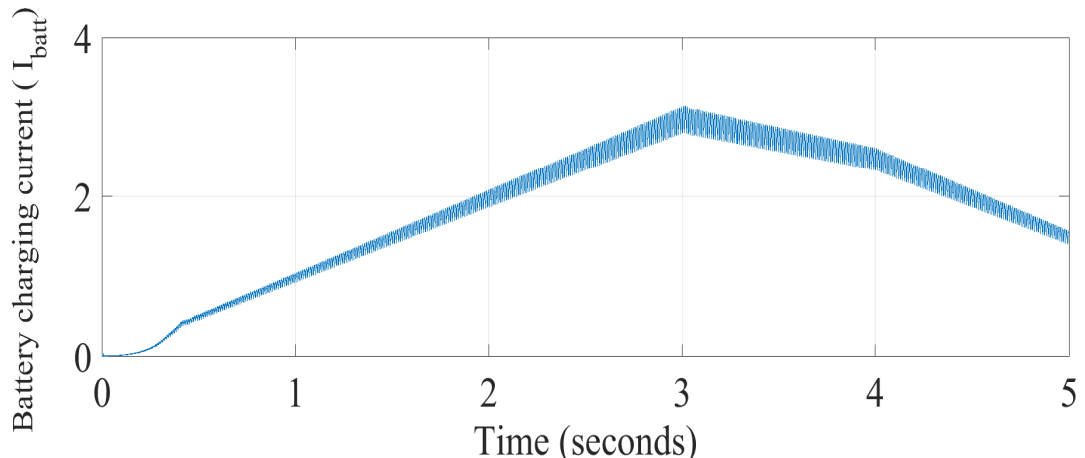
In the first command: 1 A of battery charging current is given as reference, which results in charging rate (c-rate) of 1 A till the one second of time.

In the second command: 3 A of charging current is given, now the c-rate of the battery will be 3 A from the 1 A held at previous case. The c-rate continues to be held at 3 A until next command is given.

In the third command: the command given to the controller is 2 A c-rate, the charger will charge the battery with 2 A c-rate till the 3rd second.

In the fourth command: the c-rate command of 2.5 A is given to the controller which charge the battery at 2.5 A of current till the 4th second.

In the fifth command: 1.5 A of charging command is given to the controller which charge the battery at 1.5 A c-rate till the 5th second of time.



**Figure 4.2:** Battery charging current ( $I_{batt}$ ) for dc-dc converter.

The maximum current the charger can provide is 3.5 A. Therefore, the charger cannot charge the battery above the 3.5 c-rate. To increase the c-rate of the charger above the rated

value input voltage at the dc-dc converter has to be increased. The waveform shows the battery charging current in the Fig. 4.2. The simulation of the feedback controller for dc-dc converter uses the look up table in this dissertation. The look up table given a different values of the current at different time. The ripples in the charging current of the battery is reduced by using appropriate value of inductor in series. The ripples in the capacitor voltage is reduced by using the appropriate value of the capacitor in parallel with the battery.

**Table 4.1:** Commands for battery charging current ( $I_{batt}$ )

<b>Commands given as a reference</b>	
<b>Battery charging Current (<math>I_{batt}</math>)</b>	<b>Time (seconds)</b>
$I_{batt} = 1$ A	1
$I_{batt} = 3$ A	2
$I_{batt} = 2$ A	3
$I_{batt} = 2.5$ A	4
$I_{batt} = 1.5$ A	5

#### **4.2.3 Results of complete charger with separate controllers following P-Q commands.**

The proposed charger in this dissertation improves the THD present in the source current shown with the different commands in Fig 4.4. The charger also improves the dynamic response of the output compared to results shown in dissertation [19]. The appropriate values of the inductor and capacitor filter have been used to reduce the harmonics present

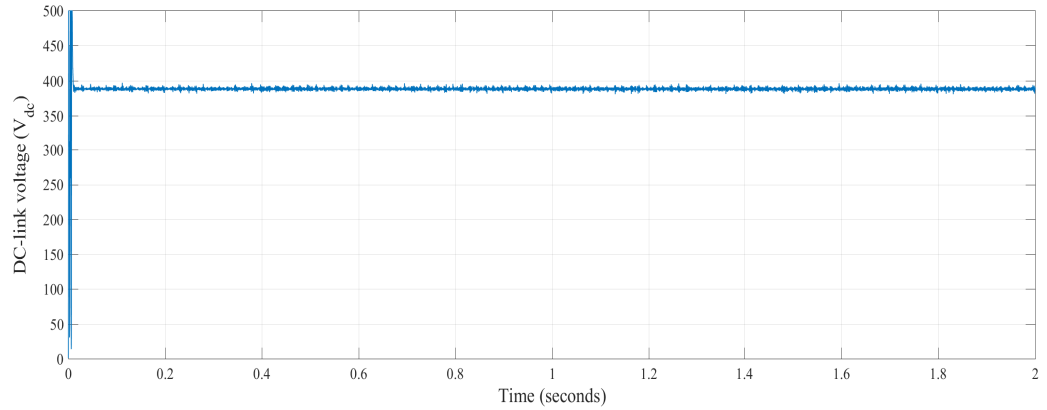
at the ac and dc side. The saturation limits have been modified to obtain the better results. The improved results show the improved performance of the charger. The proposed charger responds quickly to the input commands given by the user. The reduction in the harmonics makes the charger more economical.

The results of the charger are shown at different input commands with different kVA ratings of the charger. Firstly, the charger rating taken is 1.44 kVA. The active power as a input command is given to the charger is 1.44 kW. Secondly, the charger rating taken is 3 kVA. In 3 kVA only charging operation, the input command given is 3 kw and zero to the reactive power command. As  $P_{cmd}$  and  $Q_{cmd}$  changes by user, first  $V_{dc}^*$  changes then  $P_{ref}$  and  $Q_{ref}$  changes accordingly. The change in  $V_{dc}^*$  results in change in reference current of the charger and finally results in source current and battery reference charging current  $I_{bt}^*$  accordingly. The results of the charger have shown in three configurations are:

- $P_{ac} = 1.4$  kW and  $Q_{ac} = 0$  kVAR.
- Charger at  $P_{ac} = 3.0$  kW and  $Q_{ac} = 0$  kVAR.
- Charger at  $P_{ac} = 0$  kW and  $Q_{ac} = -1.4$  kVAR.

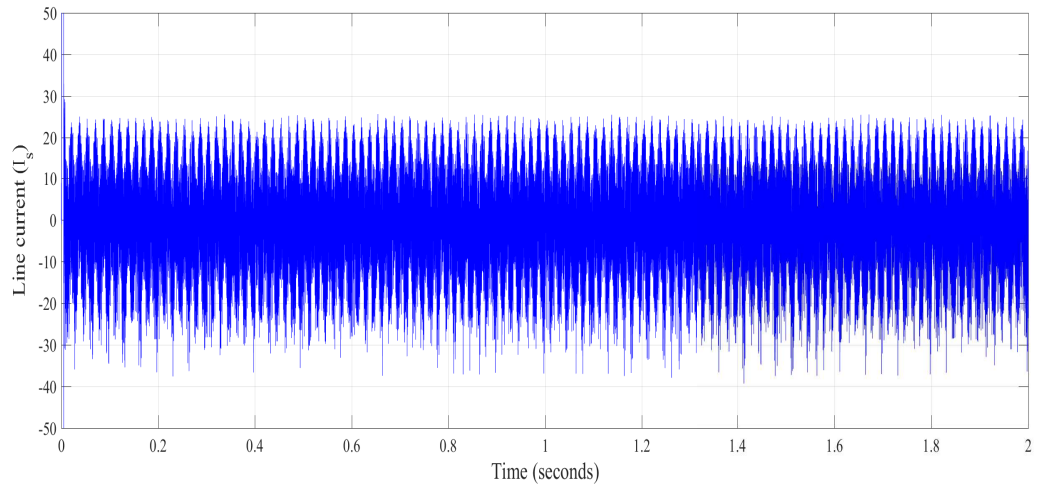
#### 4.2.4 Configuration-1

The command given by the user is 1.4 kW, the battery voltage is 390 V and the full charging current is 3.6 A. Therefore, the battery power equals to the  $390 \times 3.6 = 1.404$  kW. Fig 4.3 represents the DC-link voltage ( $V_{dc}$ ). The  $V_{dc}$  requires above 363 V for charging operation, because the nominal voltage of the battery is kept at 363 V. Therefore the  $V_{dc}$  waveform shows nearly 390 V in Fig 4.3. The THD is calculated for two different values of the source inductance. If a capacitor exhibits more second harmonic ripples in its voltage, the more distortions in the battery charging current ( $I_{bt}$ ) will be. Therefore ripples of  $V_{dc}$  kept at limited value to acquire the specific battery charging demands.



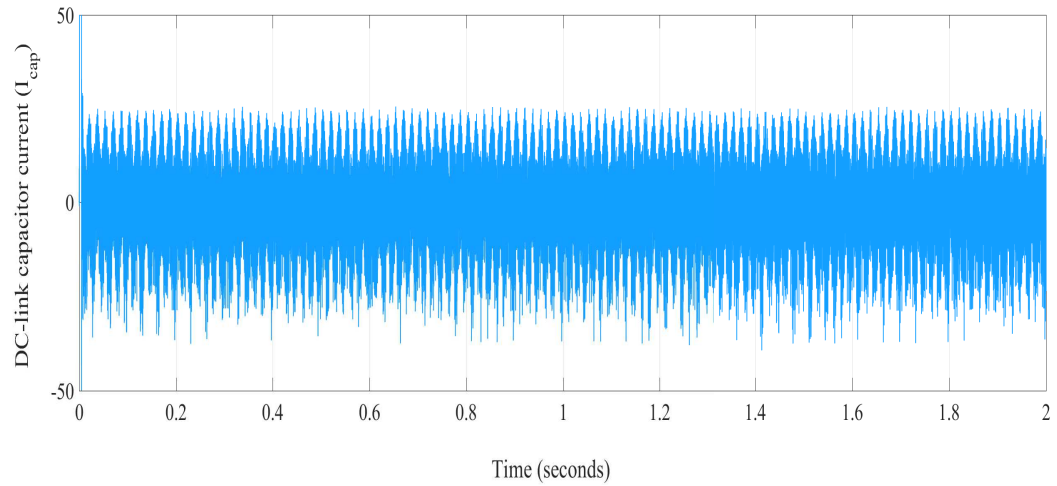
**Figure 4.3:** DC-link voltage for  $P_{ac} = 1.44$  kW.

Next, the Fig 4.4 is shown of the line current, the line current changes according to change in input commands. The reason for this is, apparant power is kept constant all the time.

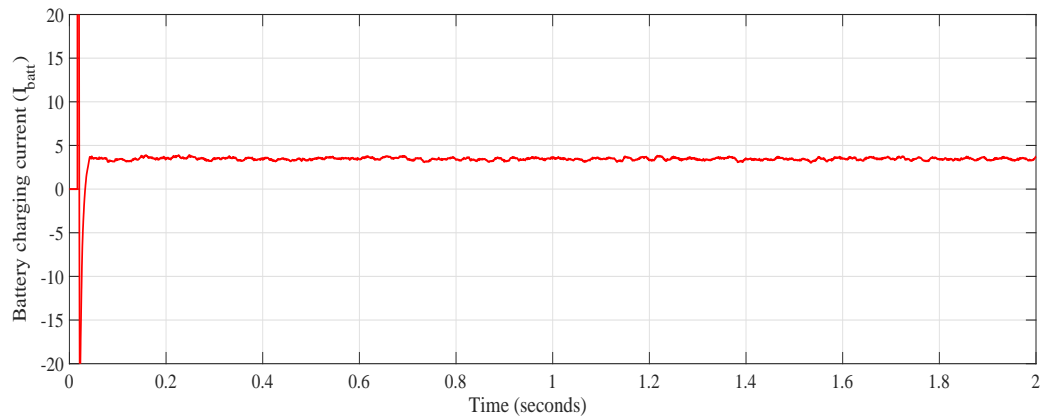


**Figure 4.4:** Source current for  $P_{ac} = 1.44$  kW.

The dc-link capacitor  $C_{dc}$  current is shown in Fig 4.5. The second harmonic of the ripple current has been investigated. The Fig 4.6 shows the  $I_{batt}$ , which maintains the harmonic standards. Otherwise, the battery may get damaged.



**Figure 4.5:** DC-link capacitor current for  $P_{ac} = 1.44$  kW.



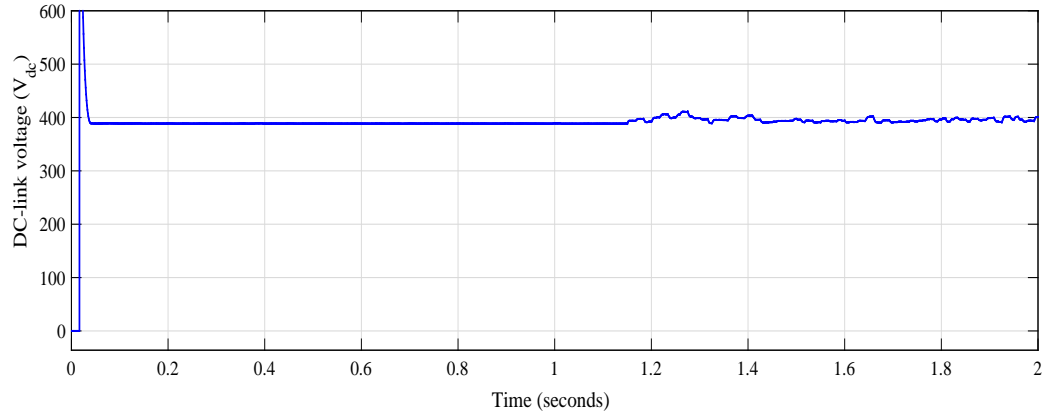
**Figure 4.6:** Battery charging current for  $P_{ac} = 1.44$  kW.

#### 4.2.5 Configuration-2

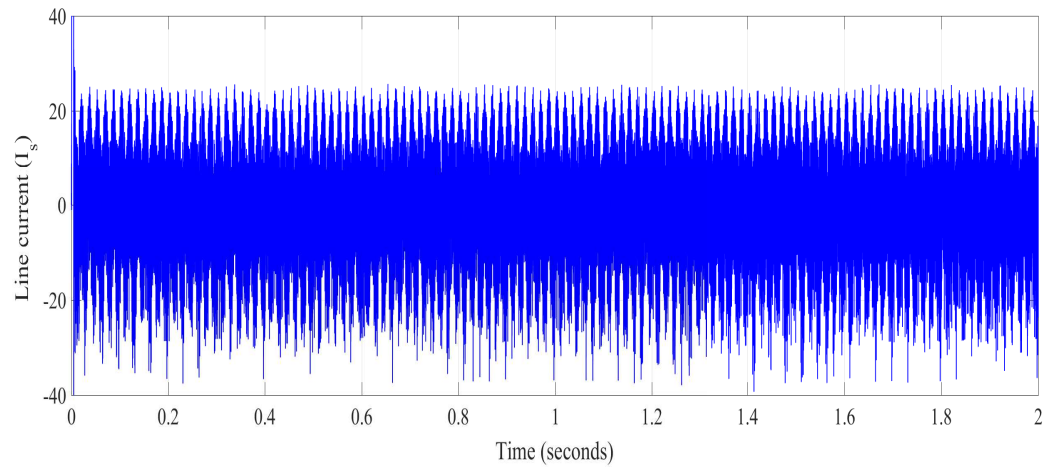
The  $I_s$  is shown in Fig. 4.8 for this operating mode. The  $V_{dc}$  during this operating mode is shown in Fig 4.7. The rms ripples current of the  $C_{dc}$  is shown in Fig 4.9. The dc-link peak-to-peak (p-p) ripple voltage and dc-link rms ripple current values measured in the simulation and calculated using the equations given in chapter-3.

The  $I_{batt}$  is shown in Fig 4.6. Utilizing the battery display depicted some time recently, the converter satisfies the battery charging prerequisites set before.

The results of this simulation are used with  $L_{ac} = 1.0$  mH source side inductance for 3



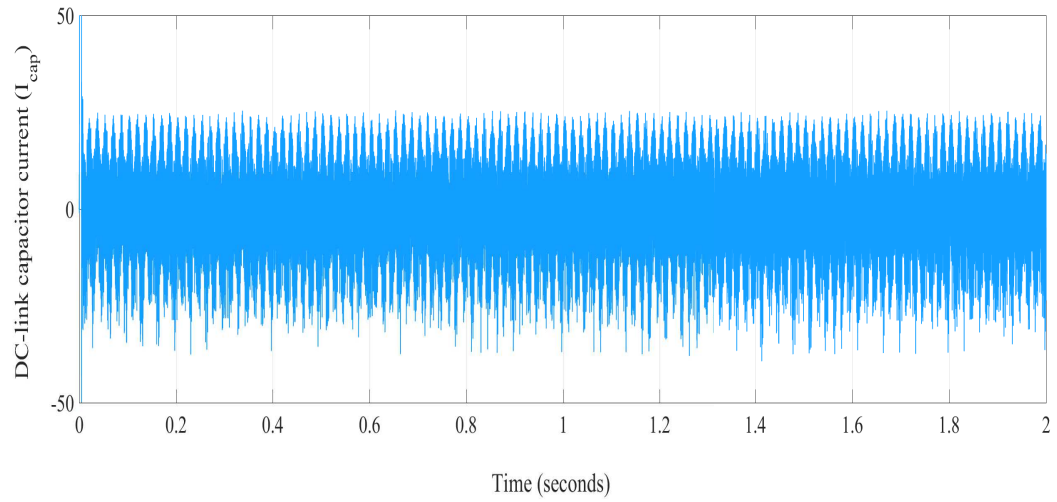
**Figure 4.7:** DC-link voltage for  $P_{ac} = 3.0$  kW.



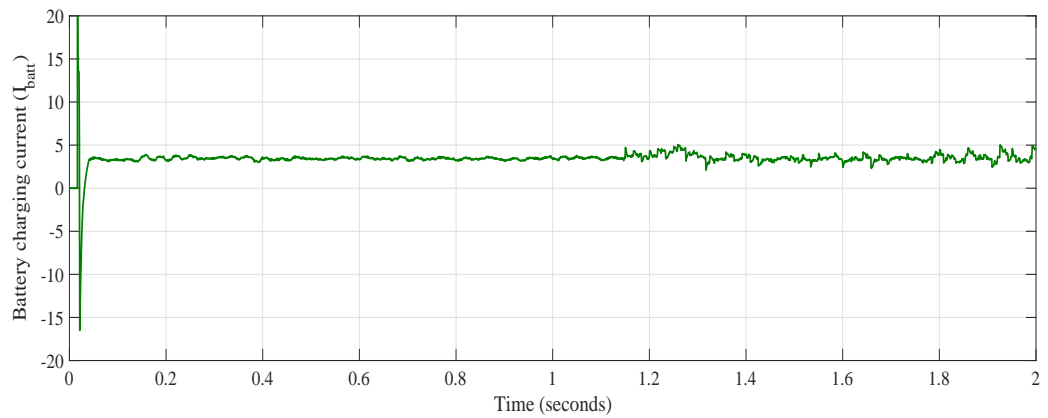
**Figure 4.8:** Source current for  $P_{ac} = 3.0$  kW.

kVA charger. The total effect of only reactive power operation of the charger on the dc-link component is negligible for 3kVA charger using the value of source inductance  $L_{ac} = 1.0$  mH.

Accordingly, if charging operation is required anytime of the PQ control plane, notwithstanding amid a high capacitive power operation the charging current harmonics will in any case remain beneath the requirements.



**Figure 4.9:** DC-link capacitor current for  $P_{ac} = 3.0$  kW.



**Figure 4.10:** Battery charging current for  $P_{ac} = 3.0$  kW.

### 4.2.6 Configuration-3

The charger in these commands works in fully reactive power mode. The charger current in this mode will be zero. The system acts as a capacitor, which will support reactive power to the grid.

# Chapter 5

## CONCLUSION AND FUTURE WORK

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### 5.1 Conclusions

This dissertation proposed a charger with modified controller with mathematical verification of charging and reactive power operation at different input power commands. The proposed charger receives the input commands by user and changes the dc-link voltage, line current and charging current accordingly. The charger maintains the THD under 5% and improved the dynamic performane and provides a steady state response.

The charger results are shown at two different (1.4 kVA and 3 kVA) ratings and different charging modes. The battery SOC does not affected by reactive power operation. The charger has few changes in its parameters to improve the results and to obtain the better results. The results show the successful implementation of charger with following input commands and has a good dynamic response and steady state response under grid demand variations.

## 5.2 Scope of Future Work

The scope of the work is the improvement in the existing technology, which is coupled with smart grids :

- PEVs have few advantages over conventional vehicles, which are low emissions, less dependent on fuels and energy storage from grid.
- PEVs can also have capability to support grid during peak (maximum) loads, which is called V2G and allows bidirectional flow of power among grid and PEVs.
- V2G technology can create certain unwanted conditions on the smart grid, which are, overloading of grid at peak times and low power factor on higher loads during day time.
- PEVs research is going on from many decades. As fuel reserve deplete, the cost of the fuel will increase. Therefore, PEVs can be used as alternative energy resources with high efficiency and low cost and charging stations are going to developed.
- The single phase chargers can be used in public at malls, parking areas with fast charging mode. The cost analysis will be done of the reactive power support to the grid by PEVs and incentives will be given to the users in return.
- The single phase charger can be reconfigured to three-phase charger using the three legs available in single phase charger. The dc-dc converter can be skipped and directly ac voltage can be converted to dc voltage. Which results in increase of efficiency and reduced ripples in the dc voltage.

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# LIST OF PUBLICATIONS

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1. Neeraj Manwani and M. Singh, “ Single Phase Bidirectional Charger for Electric Vehicles to Support Reactive Power Compensation to Grid” Manuscript under preparation.

# CURRICULUM VITAE OF AUTHOR

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## I. Introduction

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H.S.C	Raj Kamal Inter College, Agra	Uttar Pradesh Board	71.8
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\* Till third semester.

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**2** Kisacikoglu, Mithat C., Metin Kesler, and Leon M. Tolbert. "Single-Phase On-Board Bidirectional PEV Charger for V2G Reactive Power Operation", IEEE Transactions on Smart Grid, 2015. Publication % **1**

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Submitted to Imperial College of Science,