Reactive Power Compensation using Vehicle-to Grid enabled Bidirectional Off-Board EV Battery Charger

ABSTRACT:

Abstract—This paper investigates the application of a grid connected off-board Electric vehicle (EV) battery charger on the reactive power compensation and simultaneously use as a battery charger (grid-to-vehicle (G2V)) and power generator (vehicle-to-grid (V2G)). The topology of the charger consists of a grid facing front-end AC-DC cascaded H-bridge bidirectional converter, which controls the power flow between the grid and EV battery using a back-end DC-DC bidirectional converter. The charger configuration provides galvanic isolation at the user end from the rest of the system as a safety measure. The proposed control algorithm follows the active power command for G2V and V2G operation along with reactive power command from the utility grid when requested, by controlling EV current and battery current. Furthermore, an adaptive notch filter based controller is designed for system phase estimation and generated reference current synchronization. The proposed control algorithm eliminates phase locked loop (PLL) from the controller design. As a result, the computational complexity of the controller reduces with improved steady-state and trainset performance. Furthermore, a 12.6 kVA off-board charger simulation model is developed in MATLAB/Simulink environment and the performance of the proposed control algorithm is tested during G2V, V2G, and reactive power compensation operation of the EV charger.

CHAPTER-1

INTRODUCTION

## Introduction

According to the international energy outlook report, the world transportation energy usage is going to increase by 44% in 2035 (compared to 2008) [13]. Therefore, technologies related to reducing oil consumption have one of the utmost challenges in today’s vehicle research.

Alternative vehicle technologies to replace conventional vehicles include hybrid electric vehicles (HEVs), PHEVs, and EVs (also known as battery electric vehicles (BEVs)). The dichotomy between HEVs and EVs/PHEVs is the presence of a charger in the latter group. PHEVs and EVs will be termed collectively as PEVs in this study.

The charger is a power conversion equipment that connects the vehicle battery to the grid. Chargers for these vehicles have the ability to foster the interaction of vehicle and the external power source, i.e. the utility grid. Chargers convert the ac voltage to a dc magnitude for the speciﬁc battery needs of PEVs. In order for the

utility to be spared by the impact of the large number of PEV connections, chargers play an important role in the grid integration of these new technology vehicles.

It is possible to incorporate more than one operation mode in a charger by allowing the power to ﬂow bidirectionally. Usually, the bidirectional power transfer stands for two-way transfer of active power between the charger and the grid. The general term of sending active power from the vehicle to the grid is called V2G. The economic beneﬁts of this operation has been a research subject for more than a decade because of the large energy reserve of an electric vehicle battery and the potential of thousands of these connected to the grid [14–16].

While PEVs potentially have the capability to fulﬁll the energy storage needs of the electric grid, the degradation on the battery during this operation makes it less preferable by the auto manufacturers and consumers unless a properly structured battery warranty and compensation model is implemented [17–20]. On the other hand, the on-board chargers can also supply energy storage system applications such as reactive power compensation, voltage regulation, and power factor correction without the need of engaging the battery with the grid and thereby preserving their lifetime.

Reactive power consumed at the load side is transmitted from the energy source to the load through the transmission and distribution system. This causes increased energy losses and decreases the system eﬃciency. For long distances, line reactance for line “k” (*Xk*) becomes much larger than the line resistance (*Rk*). Because reactive power losses are proportional with line susceptance (*Bk* = −*Xk/*(*R*2 + *X*2))

*k*

*k*

and real power losses are proportional with line conductance (*Gk* = *Rk/*(*R*2 + *X*2)),

*k k*

the relative losses of reactive power become much greater than the relative losses of active power on the transmission lines [21]. Therefore, reactive power is best utilized when it is generated close to where it is needed. Moreover, residential appliances such as microwaves, washing machines, air conditioners, dishwashers, and refrigerators consume reactive power for which the residential costumers do not pay, but the utility



**Utility grid**

**ig**

**Lg**

**Rg**

**iL**

**PCC**

**ic**

Other

customers

Customer with

plug−in vehicle

**Figure 1.1:** Proposed reactive power support diagram using PEVs.

is responsible to deliver. PEVs can readily supply this reactive power need locally without the need of remote VAR transmission.

Fig. 1.1 shows the proposed application of PEVs. Customers with a PEV that carries an on-board charger can negotiate with the utility grid to allow the usage of the charger for grid support. The charger compensates for the reactive current (*ic*) that either the customer with the PEV or other customers without a PEV demand from the utility grid. Generating reactive current at the point of common coupling (PCC) provides increased eﬃciency of power transfer through transmission lines and decreases transformer overloading.

A vehicle can provide reactive power irrespective of the battery state of charge (SOC). The charger can supply reactive power at any time even during charging. However, the selected topology and the eﬀect of the reactive power on the operation of the charger and the battery should be well analyzed. On-board single-phase charging systems have been researched in terms of diﬀerent power factor corrected (PFC) rectiﬁer topologies that can be used for unidirectional charging operation [22, 23]. Other studies have surveyed bidirectional single-phase ac-dc converter topologies that are suitable for V2G applications [24–26]. Single-phase battery-powered renewable energy systems have also been well researched in terms of ac-dc power transfer calculations, second harmonic current ripple elimination, and reduction of electrolytic dc-link capacitors [27, 28]. However, there is a need in the literature for technical

analysis and survey of topologies suitable for V2G reactive power operation for single- phase on-board PEV charging systems and its eﬀect on both the charger design and battery charging operation.

A charger is composed of two power conversion stages: a single/three-phase ac-dc conversion stage, and a dc-dc conversion stage. This study focuses on single-phase chargers that are mostly suited for on-board charging applications. The front-end ac-dc conversion stage can have PFC unidirectional and four-quadrant bidirectional power transfer options. The design of the charger changes considerably between the diﬀerent options and applications. Moreover, single-phase power conversion also adversely aﬀects the energy storage requirements during reactive power operation due to increased ripple energy storage at the dc-link. Another concern is the limitation of the ac line current harmonics either during charging the traction battery or when the vehicle supplies power back to the grid. DC-DC conversion stage can either have an isolated or non-isolated topology based on the mandated protection requirements by the auto manufacturers. Another concern is the limitation of battery charging current harmonics which adversely aﬀect the lifetime of the battery.

## PHEV and EV Technology

##### Deﬁnitions of HEV, PHEV, and EV

Today, there are three types of passenger vehicles available in the market operating with an electric traction motor powered by a battery: HEVs, PHEVs, and EVs or BEVs. HEVs have the smallest size battery pack, and therefore an electric motor is used to drive at very low cruise speeds or to assist the internal combustion engine (ICE) during higher power requirements. Therefore, HEVs oﬀer customers a way to increase gasoline mileage by having batteries and electric drive systems work with the ICE. The most eﬃcient hybrid vehicles reduce the gas consumption by around 40% compared to similar size conventional ICE vehicles. However, HEVs lack the

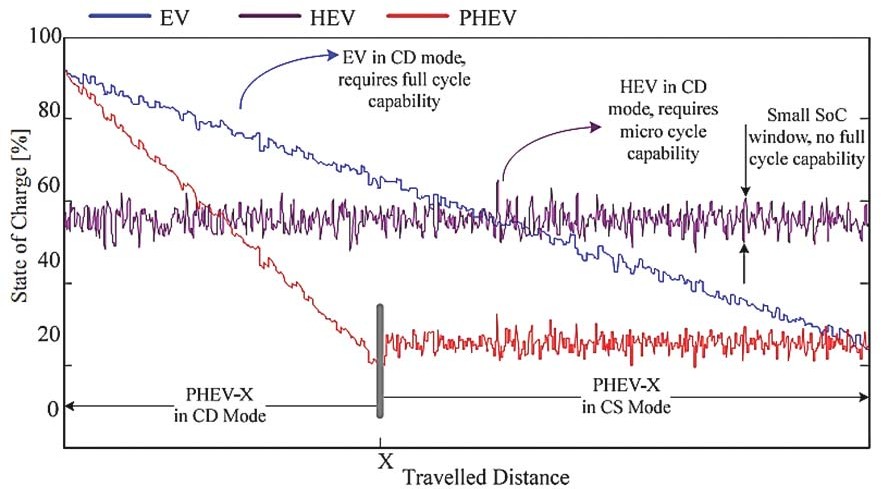
availability to go for more than just short distances at low speeds with only electric power because the battery is not capable of storing enough energy to power the vehicle for a daily commute.

PHEVs, however, provide an all-electric range up to a pre-speciﬁed distance with a larger size battery pack, which is not inherent in HEVs. There are several deﬁnitions on how a PHEV is deﬁned. According to [29], the battery pack capacity should be at least 4 kWh, and the PHEV must be rechargeable by an external source of electricity. Another deﬁnition adds the ability to drive the vehicle at least 10 miles in electric-only mode without consuming any gasoline as a requirement for a vehicle to be classiﬁed as a PHEV. By deﬁnition, an EV has only an electric motor in the traction drive which is powered by an on-board battery, and conventional vehicles have only combustion engines. The 2010 Toyota Prius HEV has only 1.3 kWh on-board traction battery capacity. As a comparison, the 2011 Chevrolet Volt PHEV has a 16 kWh battery capacity [30], and 2011 Nissan Leaf EV has a capacity of 24 kWh on-board battery energy storage [31].

PHEVs operate in charge-depleting (CD) mode when most/all of the energy comes from the battery during the all-electric mode; hence, the battery is in the deep cycle mode. If the battery reaches its minimum state of charge, the control system switches to the charge-sustaining (CS) mode where the battery experiences only shallow cycles. PHEVs are usually described as PHEV-X where X is the number of miles that a PHEV can go just with the electric energy. The explanation of the diﬀerent operation modes in EV, HEV, and PHEV are demonstrated in Fig. 1.2.

##### The current status of PEVs

Light-duty passenger PEVs that have demonstrated successful market penetration and that will be in mass market in upcoming years prove that the challenges regarding the grid connection issues of these vehicles need to be taken very seriously. This



**Figure 1.2:** Charge depleting and charge sustaining modes for the EV, HEV, and PHEV [9].

section lists the market vehicles in terms of their grid-related features such as energy storage and charging speciﬁcations.

Table 1.1 lists the important speciﬁcations of the surveyed vehicles. As shown in this table, the battery pack voltage has an increasing trend compared to older versions of the vehicles. Most of the vehicles have more than 330 V nominal pack voltage. However, mechanical conﬁguration of cells changes from vehicle to vehicle. The on-board dedicated charger output power rating generally stays between 3 kW to 7 kW.

Design of the charger of a vehicle traction battery includes diﬀerent options in terms of where to place the charger and how to design the charger. The circuit topology, location, connection type to the vehicle, electrical waveform of the charging coupler, and the direction of power ﬂow can totally change the design of the charger (more on this classiﬁcation is explained in [32]). Although the surveyed market vehicles employ diﬀerent combinations of the above classiﬁcation, most of the vehicles carry its charger on-board for increased charging availability. Although carrying the

charger on-board increases the availability of charging the vehicle, it also brings added cost and weight to the vehicle. Also, the power rating of the charger is inversely proportional to the charging time necessary to fully charge the vehicle battery. Therefore, it is desired to have a high power charging rate to make the EV charging experience comparable to the ﬁlling time of a gasoline tank. However, due to space and weight limitations on a vehicle, the on-board charger must be restricted in power rating. So, these two objectives contradict with each other and a compromise should be made. The power rating is also related to the type of the vehicle. For instance, EVs usually require a charger with a higher power rating compared to PHEVs due to having a larger battery. As shown in Table 1.1, battery sizes of an EV in the U.S. market change between 16 kWh - 53 kWh whereas a PHEV has its pack with 4.4 kWh

- 20.1 kWh energy capacity. Therefore, for comparable charging time, an EV usually requires its charger to have a higher power rating. For instance, EVs with integrated chargers∗ (BMW Mini E and Tesla Roadster) have higher on-board charging power capability (*>* 11 kW).

## Why V2G Reactive Power Support?

A potential beneﬁt of PEVs is the ability to maintain the reliable operation of the grid by coordination between the vehicle and the utility. There are various services that PEVs can supply to the grid. Since every PEV has a charger that can convert ac to dc, this charger can be developed so that it can also send power back to grid for V2G operation. Based on the speciﬁc service provided, the utility can beneﬁt by using a considerable amount of energy storage at the distribution system level. Coupled with this, the design of the charger can alleviate some of the problems that the utility are concerned with the integration of PEVs. These issues are listed below. First, reactive power consumed at the load side are transmitted from the energy source to the load through the transmission and distribution system. This causes increased energy losses and decreases the system eﬃciency. With on-site generation of reactive power, the amount of reactive power that need to be transmitted from the

generation side will decrease.

A recent DOE report predicts that the annual sales of EVs and PHEVs combined can reach up to 300 thousand vehicles by the year 2035 [13]. Another study claims that the annual sales of EVs and PHEVs combined would reach up to 500 thousand by the year 2020 with more than a cumulative of 2.5 million of them on the road [68]. The PEV charging is one of the primary concerns of smart grid applications due to its eﬀect on power generation, transmission, and distribution when the large scale of PEV load is considered. While the requirement for more power generation will be a concern with an increased number of PEVs, the distribution system level issues raise more questions. Several studies look at the eﬀect of PEV charging at distribution system level. Studies show that depending on the number of PEVs connected, the rating of the chargers in those PEVs, size of the energy storage, rating of the distribution transformer (25-100 kVA), harmonic content of the charging current, geographical location, and if any charging management control is employed, the lifetime of the distribution transformer may reduce down to its 30% of regular life expectancy [69, 70]. To prevent such problems on the distribution system, the utilities must build infrastructure to enable smart grid incentives like variable rates, smart meters, grid communications, and distributed energy management.

A regular microwave oven consumes up to 0.5 kVAR and a washing machine consumes up to 0.8 kVAR of reactive power. Other loads of reactive power in a residential house include air conditioner, dishwasher, and refrigerator, etc. Although appliances consume reactive power, the customers are not billed for the reactive power they use. Instead, utility pays for the reactive power for residential customers. However, with increased number of PEV connection and the aforementioned issues of transformers makes the on-site generation of reactive power an important add-on value. Therefore, generating V2G reactive power will help the utility by providing increased eﬃciency of power transfer through transmission lines and decreasing overloading of transformers

Consequently, of utmost importance is the need to regulate PEV - grid interaction. The design of the battery charger will be crucial in this eﬀort to eﬀectively control the power ﬂow and, as a result, maintain continuous service of eﬃcient electrical energy supply.

**CHAPTER-2**

**DISCUSSION AND DEFINITION OF PEV BATTERY CHARGING**

This section describes the important battery, charger, and charging terminologies and deﬁnitions that are used throughout this study.

##### 2.1.Battery and charging deﬁnitions

###### State of charge

In order to predict how many driving miles are left for the electric mode in a PEV, one needs to interpret the fuel gauge of the battery. SOC is the gauge that is used to understand the amount of charge which is proportional to the amount of energy that can propel the vehicle with only electric power. It is analogous to the fuel gauge that is used to show how much gas is left in the tank in an ICE vehicle.

There are diﬀerent methods used to determine the electrical energy that exists in the chemical bonds of the battery. One simple and eﬃcient method is to measure the current, thereby charge, entering and leaving the battery which is called coulomb counting. Based on this method, SOC can be found using Eq. 1.1:

A math equation with numbers and symbols

Description automatically generated

where *Qo* is the initial electric charge present before charging/discharging the battery [C], *Qn* is the nominal electric charge capacity of the battery [C], and *ibt* is the battery current [A]. *ibt* can be either negative or positive depending on the current direction. If the current is entering the battery, SOC will increase and vice versa. As shown in Eq. 1.1, SOC is a normalized value that is written in percentage for easier readability of the battery gauge.

###### State of discharge

Another deﬁnition is also used to measure the discharge state of the battery, state of discharge (SOD). It stands for the complement to SOC, meaning that it describes how much electricity has been taken out of the battery. Therefore SOC and SOD always sum to one. Mathematically, it follows as:

*SOD* = 1 − *SOC* (1.2)

SOD is also termed as depth of discharge (DOD) which corresponds to the same deﬁnition.

###### State of health

A method of assessment to determine the condition of the battery cell is called state of health (SOH). It measures the condition of the battery to determine if battery operates above its factory guaranteed operating conditions. It is a relative measurement to the brand new battery cell. However, there is no direct method of assessing SOH like SOC. Rather, the history on the usage of battery is recorded in battery management system (BMS) to derive representation of SOH. The function of the BMS will be explained later.

###### Charging rate

Every individual battery cell has a charging current rate as a default manufacturer value. This is often termed as “C-rate”. *C* stands for the rated charge current of the battery cell that will fully charge the battery in one hour. All the charging currents are often referred to the rated current using the *C* rate such that *n* × *C* is a charge rate equal to the *n* times the rated charging current where *n* is a real number. For instance, 0.1*C* charging rate means the charging current is 10% of the rated charging

current of the battery cell. As *n* increases, the charging time required to fully charge the battery cell decreases and vice versa.

##### Charging proﬁles

The common charging proﬁles used in the industry for lithium-ion (Li-ion) batteries are constant current (CC) and constant voltage (CV) charging. During CC charging, the current is regulated at a constant value until the battery cell voltage reaches a certain voltage level. Then, the charging is switched to CV charging, and the battery is charged with a trickle current applied by a constant voltage. Lithium-ion batteries with a cathode composition being lithium-cobalt-oxide, which is mostly used in consumer applications, (cell phone, camera, mp3 players, etc) have the following charging proﬁle shown in Fig. 1.3. These batteries have a maximum charging voltage of 4.2 V. One observation from the charging proﬁle is that the battery cell requires around 50 min to ﬁnish CC charging phase starting from 0% SOC with 1C charging current. At the instant when the battery reaches 75% SOC, the charger switches from CC to CV charging. The CV charging takes around 2 h 40 min resulting in a total charge time of 3.5 h [10]. Therefore the charge time required to charge the battery cell up to 75% SOC is around 25% of the total charge time. In comparison, to cover only 25% SOC, the charger needs to charge for 75% of total charge time during CV charging. In comparison, Li-ion LFP batteries present a diﬀerent charging proﬁle compared to Li-ion LCO batteries because of the diﬀerence in the chemical structure. For LFP batteries, CC charging stage takes 75% of the total charging time whereas CV charging occupies 25% of the total charging time as shown in Fig. 1.4.

##### Charging levels in the U.S.

There are three charging levels based on the voltage and current ratings used to charge a vehicle battery: Level 1, Level 2, and dc fast charging. However, only Level 1 and Level 2 have been standardized [57]. DC charging, or previously known as Level 3

**A diagram of a charge voltage

Description automatically generated**

**Figure 1.3:** Li-ion LCO battery CC-CVcharging proﬁle [10].

charging, is still under development [57]. Fig. 1.5 shows the map of the U.S. standard outlet receptacle ratings. There are diﬀerent chargers; most of them are introduced in the next chapter, rated at Level 1, Level 2, or dc charging schemes.

Level 2 charging is much more preferred because of reduced charging time compared to Level 1 charging. This method employs standard 208-240 V ac single phase power outlet that has a continuous current rating less than 80 A [57]. For example, Nissan Leaf EV has a total of 8 h charging time using its 3.3 kW on-board charger to fully charge its 24 kWh depleted battery pack [31]. Also, it takes around 4 h to fully charge the depleted 16 kWh Chevrolet Volt PHEV battery [30].

Another charging method is fast charging or dc charging. At these charging stations, ac voltage is converted to dc oﬀ the vehicle and the vehicle is dc coupled to the charging station. Charging power can go up to higher values compared to the on board charging.Therefore, it will help vehicles to be charged in shorter amount of times. However, decreased battery lifetime is an issue because of the increased heat generation of the batteries at higher rates of current charging. As an example to decreased charging time for this type of station, Nissan Leaf EV will be charged with an oﬀ-board quick charge station in 30 min from a depleted SOC to 80% SOC [31].

**4**

**A diagram of a charge

Description automatically generated**

**Figure 1.4:** Li-ion LFP battery CC-CV charging proﬁle.

##### Battery charging security and charging power quality

For lithium-ion batteries, the precautions in handling a secure battery operation are more important than other type of batteries. Since they are prone to failure in harsh working conditions, it is mandatory to have the utmost protection in vehicle applications both for customer and expensive battery safety point of views. Therefore, battery manufacturers also sell battery management systems, BMS for short, with added price to the battery cost. BMS is responsible for overseeing safety in charging and discharging operation. The key protection goals for Li-ion batteries include over-voltage, deep discharge, shutting-oﬀ in case of over temperature, shutting-oﬀ in case of over-current, and individual cell charge balancing [52, 58]. Especially for inrush current conditions, the BMS needs tight regulation not to allow any overcharging current entering the battery cells. BMS should also perform SOC and SOH determination, history (log book) function, and communication with other system components such as charger, grid, and the motor drive.

Since the battery manufacturer is responsible for the BMS, the charger only sends power to the battery pack where the BMS is also included. However, there is another issue that can cause problem for the battery cells related to the operation of the charger. This is the quality of the waveform of the dc voltage output of the battery

Charger current, (A)

**A diagram of a charge current

Description automatically generated**

**Figure 1.5:** Charging outlet circuit breaker map with respect to receptacle voltage and current ratings [11].

charger. The chargers’ output voltage waveform must be well regulated. In other words, the low/high frequency components present at the output voltage must be less than the maximum allowed voltage ripple harmonics to protect the health, and thereby the lifetime of the battery.

Currently, there is not much information about the effects of ripples on lifetime of the Li-ion batteries in the literature. It is difficult to find direct impacts of the ripple on the battery especially considering that each different Li-ion technology has different structures. However, there is a mature experience about lead-acid batteries in the literature and in the market [6, 59–67]. Hence, this experience can give the designer of the charger an idea about the limits on voltage and also current ripples.

Battery manufacturers give ripple limits to which a battery can be exposed. Table 1.3 summarizes the ripple limits taken from different manufacturers for lead- acid valve-regulated lead-acid (VRLA) batteries. The design of the charger should be optimized by selecting correct inductance, capacitance, switching frequency, and feedback compensator values to meet these requirements.

In order to understand the adverse effects of ripple on batteries in general, one needs to know how the ripple current converts to extra heat. A typical single-phase

**Table 1.3:** Different battery manufacturer limits for charging current and voltage ripple [6].

|  |  |  |  |
| --- | --- | --- | --- |
| Manufacturer | Battery type | Voltage ripple | Current ripple |
| Yuasa | Lead-acid | N/A | C/10 |
| Dynasty, Johnson  Controls | Lead-acid | 1.5% rms and  4% peak-peak | N/A |
| C&D Tech | Lead-acid | N/A | C/20 |

charger output voltage has two main ripple frequencies: one is at the second harmonic with respect to grid frequency, and the other is at the converter switching frequency. Assuming a simple battery model shown in Fig. 1.6, the extra ripple current will convert into extra heat due to the internal resistance of the battery pack, *Ri* in Fig. 1.6.

To calculate the total ripple current, the ripple output voltage of the charger at the specified frequency must be known. For example, the ripple current at a specified frequency can be related to the ripple voltage and the internal resistance by the

equation:

*Ibt*−*ripple*

= *Vbt*−*ripple*

*R*

(1.3)

*i*

where *Ri* is the equivalent internal resistance of the battery pack [Ω], *Vbt*−*ripple* is the voltage ripple root mean square (rms) value present in the charger dc output voltage [V], and *Ibt*−*ripple* is the ripple rms current value present in the battery charging current

**ibt**

**ibt**



**R**

**ibt**



**i**

**Vbt**



**Figure 1.6:** A simple equivalent circuit of the battery pack.

[A]. However, the internal resistance is not constant in different frequencies, and it decreases as the frequency of the ripple current increases. Assuming that each cell has the same internal resistance, and this resistance is the worst case resistance measured at the low frequency ripple current, the added dissipated power because of the total ripple becomes equal to:

2

*Ploss* = *I*

*bt*−*ripple*−*total*

*× Ri* (1.4)

where *Ibt*−*ripple*−*total* is the rms sum of the ripple currents at different frequencies. It is important to note that *Ri* also changes dynamically with different rms current values and temperature. Temperature increase should be limited by controlling this extra current. To show the effect of temperature increase on batteries, some of the derived assumptions about lead-acid batteries in the literature are: 1) a temperature increase of about 7-10 ◦C causes half of the lifetime of the battery to vanish [59, 61],

2) each degree C rise in battery temperature can decrease calendar life by 10% [6], 3) maximum allowable temperature increase should be around 3-5 ◦C, and 4) corruption and wear in the battery can also cause capacity loss [60].

In conclusion, the charger design procedure should include the battery ripple restrictions into account to reduce the extra heat dissipation in the battery cell. Therefore, the output voltage of the battery charger must be limited in its ripple voltage magnitude both in second harmonic ripple and in converter switching frequency ripple. Due to the electro-chemical process in the battery, the lower frequency ripple current will cause more heat dissipation compared to a higher frequency ripple current that has the same rms value.

##### Grid Connection Power Quality

One of the important requirements of an EV/PHEV charger is the amount of current distortion that it draws from the grid. The harmonic currents need to be well regulated not to cause excess heat which decreases the distribution transformer lifetime. Therefore, if this distortion is not limited, it can pose a threat on the

utility grid. There are two definitions to measure the harmonic content of the battery charger current. The first parameter is THD is defined as follows.

*THD* = *Ic,h*

*Ic,*1

(1.5)

where *Ic,h* is the rms sum of the harmonics (usually up to n=39) of the charger current

[A], i.e. *Ic,h* = Σ39 *Ic,n*2 and *Ic,*1 is the rms fundamental (60 Hz) component of the

charger current [A]. However, this definition is not enough to account for all charging currents of a charger. When there is a need to control the charger input current to help reduce the demand from the grid, the rms charger current may need to be reduced to less than 50% of the rated current. As loading on the grid decreases, the harmonic content of the charger current is not as disturbing to the grid as when the loading is high. In such cases, total harmonic distortion (THD) does not reflect the real impact of the harmonic content of the charger on the grid. Therefore, total demand distortion (TDD) can be used to accurately evaluate the harmonic content of the charger between 0 – 100% loading range. The definition of the TDD is shown

*n*=2

in (1.6).

*Ic,h*

*TDD* =

*Ic,*1*,rated*

(1.6)

where *Ic,*1*,rated* is the rated fundamental current of the charger [A]. The only difference between TDD and THD is the change in the denominator. TDD is equal to THD when charging occurs at the rated current, i.e. *Ic,*1 = *Ic,*1*,rated*. Table 1.4 lists the limits for the harmonic content of the single-phase chargers operating either as a load or as a distributed generator based on the limits shown in [7, 8]. It is important to note that the charger should meet the individual harmonic limits as well as the TDD limit which are calculated separately, i.e. *Ic,*3*/Ic,*1*,rated <*4.0%, *Ic,*13*/Ic,*1*,rated <*2.0%, etc. and TDD*<*5% using (1.6).

**Table 1.4:** Maximum Harmonic Current Distortion for Single-phase On-board Bidirectional Chargers [7, 8].

|  |  |  |
| --- | --- | --- |
| Individual harmonic order | Max. distortion in percent of *Ic,*1*,rated* | |
| Odd harmonics | Even harmonics*a* |
| h*<*11 | 4.0 | 1.0 |
| 11*≤*h*<*17 | 2.0 | 0.5 |
| 17*≤*h*<*23 | 1.5 | 0.375 |
| 23*≤*h*<*35 | 0.6 | 0.15 |
| 35*≤*h | 0.3 | 0.075 |
| TDD | 5.0 | 1.25 |

*a*Even harmonic limits are 25% of the odd harmonics

**CHAPTER-3**

**PHEV/EV BATTERY CHARGERS**

## Discussion and Classification of Battery Charg- ers

Since the inception of the first EVs, there have been many different charging systems proposed. The chargers can be classified based on the circuit topologies (dedicated or integrated), location of the charger (either on or off the vehicle), connection (conductive, inductive/wireless, and mechanical), electrical waveform (dc or ac), and the direction of power flow (unidirectional or bidirectional) as listed in Table 2.1. More on this classification can be found in [32].

There is not a single charging method that will fulfill all the customer expectations. It will most likely be a combination of different methods that will maximize the charging availability of a PEV. Among the noteworthy chargers of the industry and literature which initially attracted the attention of several number of vehicle manufacturers, are dedicated, on-board, conductive, ac, and unidirectional chargers.

**Table 2.1:** Charger classification chart.

Classification type Options

Topology Dedicated or Integrated

Location On-board or Off-board

Connection type Conductive, Inductive, or Mechanical Electrical waveform AC or DC

Direction of power flow Unidirectional or Bidirectional

However, there is a great potential to further develop the topologies and make the charger design more advanced with functions for future smart grid applications such as V2G support. In the next section, the literature will be presented in the framework of V2G support.

## PHEV/EV Charger Power Electronics and Configurations

The focus of this section is to analyze the available topologies applicable for on- board conductive bidirectional power transfer operation. Bidirectional power transfer means that the active power can either be transferred from the utility to the vehicle (charging) or from the vehicle battery to the grid (discharging). The charger topologies investigated in this section are single-phase Level 1 and Level 2 compatible bidirectional chargers. Some other charger topologies including unidirectional topologies are also highlighted to compare with the surveyed bidirectional topologies. There are basically two power conversion stages required to charge the battery using grid electricity: one is the alternating current (ac)-direct current (dc) rectification and the other is the dc-dc conversion as shown in Fig. 2.1. Each of these stages can be formed with many different passive and active component combinations (inductors, capacitors, and semiconductor switches). Any combination of the two aforementioned stages will result in a different topology. Rather than giving different

EVSE

**110 V / 240 V**



**Vehicle**

**Battery Pack**

**DC-link**

**>400V**

**DC**

**output 270-400V**

**Includes master and slave units**

**BMS**

**AC-DC**

**DC-DC**

**N number of cells**

**Charger**

**Motor-drive and Accessory power**

**50/60 Hz**

**1-phase**

**Figure 2.1:** Schematic of an on-board charger with other charging components.

available ac-dc power conversion circuits, only the ones that are found promising in the literature to be used with on-board Level 1 and Level 2 charging are listed here.

The discussion includes single-phase Level 1 and Level 2 chargers. Off-board dc fast charging topologies can be analogous to the ones discussed here. However, this charging level employs a three-phase system. Therefore, it will require increased number of component and higher ratings for the devices.

As shown in chapter 1, the common nominal battery voltage levels in PHEVs and EVs that are in the market, are in between 300 V- 400 V. The terminal voltage levels of PHEVs/EVs are higher than HEVs mainly because of increased power requirement from the battery. Higher terminal voltages will allow for smaller cabling size and considerably decrease the current ratings of active and passive devices for a given power level. Due to high battery voltage and a 120 V/240 V grid connection, a boost rectification stage is preferred over a buck rectification stage to prevent an unnecessarily high conversion ratio between the dc link and the battery terminals.

A charger can be configured in two different ways in terms of its active and reactive power transfer capability with the utility grid as shown in Table 2.2. The first option is the PFC unidirectional charger that is mostly in use in todays PHEVs and EVs. Its operation boundary is shown in Fig. 2.2a as the red line on the positive power axis of the P-Q power plane. This charger operates close to unity power factor

**Table 2.2:** Different types of chargers based on power transfer operation.

|  |  |  |
| --- | --- | --- |
| Charger type | Active power direction | Reactive power direction |
| Power factor-corrected unidirectional | Grid-to-vehicle charging | Zero |
| Four-quadrant  bidirectional | Grid-to-vehicle charging or  Vehicle-to-grid discharging | Inductive or capacitive |

and only allows controlling the active power used to charge the battery. Therefore, it operates only on the positive x-axis of the P-Q power plane. Second, the four- quadrant bidirectional charger operates in the full circle shown in Fig. 2.2b. All of the charger types have a maximum power limitation marked as *Pmax* and *Qmax*, which are defined by the charger apparent power rating and the outlet power rating that the charger gets power from.

The following section will present an overview of the power electronics topology of the charger types listed in Table 2.2. The topologies listed here in the next section only include ac-dc rectification. The dc-dc conversion circuits are separately explained later in this chapter in section

##### Power Factor-Corrected Unidirectional Chargers

PFC unidirectional chargers only transmit power from the utility to the vehicle battery and operate with almost unity input power factor. In other words, they are not designed to exchange reactive power with the grid. Today, all of the PHEV and EV manufacturers that are in the market use this type of charger. Some of the ac-dc rectification stages are highlighted in the next sections.

###### Conventional AC-DC Boost Converter

In this topology, a front-end diode bridge is used to rectify the input voltage, and it is followed by a boost section as shown in Fig. 2.3. This topology is widespread for low power applications. Due to conduction losses of the diode-bridge, it is not well suited for power levels higher than 1 kW [22, 71]. Another problem is the design of the dc

A diagram of a charger

Description automatically generated

**(a)** Power factor-corrected unidirectional charger**(b)** Four-quadrant bidirectional charger operation operation

**Figure 2.2:** Operation regions of different chargers shown in red in P-Q power plane.



**LB**

**DB**

**D1**

**D3**

**vs**

**Cdc**

**D2**

**D4**

**QB**

**DC-DC**

**Converter and Battery**

**Figure 2.3:** Conventional ac-dc boost converter.

inductor at high power levels. As a solution to this problem, interleaving techniques are proposed as shown in the next section.

###### Interleaved AC-DC Boost Converter

Interleaving the boost section of the conventional PFC is first introduced in [72] and shown in Fig. 2.4. The main advantage of this topology is decreased high frequency PWM rectifier input current ripple caused by the switching action. Reducing input ripple decreases the required switching frequency to meet a current TDD limit imposed by the utility. Reducing PWM input ripple current also decreases the ac ripple current supplied by the dc link capacitor, thereby reducing its stress. Another advantage is the reduced current rating of the active switches as the interleaving converter halves the input current. One disadvantage of the topology is the high conduction losses of the input bridge rectifier as well as increased number of semiconductor devices and associated gate control circuitry. This topology is preferred by the industry for on-board charging applications and is used for 3.3 kW Level 2 chargers [73, 74].

###### Bridgeless AC-DC Boost Converters

This converter type eliminates the input diode-bridge to attain higher efficiencies at increased power levels at the expense of using a higher number of active switches, and increased control and sensing circuit complexity. The topology proposed in [75] is called symmetrical bridgeless boost rectifier and is shown in Fig. 2.5. Another topology called asymmetrical bridgeless boost rectifier is proposed in [76] and is shown in Fig. 2.6.

###### Discussion

Although power factor-corrected unidirectional chargers are mostly suited for high power factor applications, they can still be used for reactive power compensation with certain limits. However, there are two main disadvantages of this operation. First, reactive power operation can only be achieved by natural commutation of current through the diodes. This poses a strict limit on the amount of phase difference



**LB1**

**DB1**

**D1**

**D3**

**DB2**

**LB2**

**vs**

**Cdc**

**DC-DC**

**Converter and Battery**

**D2**

**D4**

**Q1**

**Q2**

**Figure 2.4:** Interleaved ac-dc boost converter.



**LC**

**D1**

**D3**

**v**

**s**

**Cdc**

**DC-DC**

**Converter and Battery**

**D2 D4**

**Q1**

**Q2**

**Figure 2.5:** Symmetrical bridgeless boost rectifier.



**Q1**

**D1**

**D3**

**LC**

**v**

**s**

**Cdc**

**DC-DC**

**Converter and Battery**

**Q2**

**D2**

**D4**

**Figure 2.6:** Asymmetrical bridgeless boost rectifier.

that can be introduced between the grid voltage and grid current depending on the inductance value of the boost inductor. Otherwise, the current THD exceeds the allowed limit by the utility. For instance, the application given in [77] has only a maximum of 14% reactive power operation range compared to full power rating of the charger. A second disadvantage is that the charger must always be charging the battery in order to supply reactive power to the grid. In other words, if the battery has full SOC, reactive power operation is not possible. Considering these two limitations, power factor-corrected unidirectional chargers are not promising compared to other type of topologies for reactive power operation. The following sections describe the suitable topologies for this type of application.



**Q1**

**D2 Cdc1**

**vs**

**Lc1**

**Lc2**

**Cdc2**

**DC-DC**

**Converter and Battery**

**Q2**

**D1**

**Figure 2.7:** Dual-buck ac-dc half-bridge converter.

##### Four-quadrant Bidirectional Chargers

###### Dual-buck AC-DC Half Bridge Converter

A dual-buck ac-dc half bridge converter shown in Fig. 2.7 was first introduced in [78] and also employed for a battery storage system to demonstrate four-quadrant operation capability with increased efficiency [79]. By placing the two active semiconductor switches in a diagonal structure rather than symmetrical/asymmetrical structure, four-quadrant operation is achieved. The circuit does not need shoot through protection as there are no active switches connected in series. The circuit requires two split dc-link capacitors and two input inductors.

###### Conventional AC-DC Half Bridge Converter

This type of converter diagram is illustrated in Fig. 2.8. It includes two dc link capacitors, two switches, two diodes, and a coupling inductor for grid interconnection. Two sufficiently large capacitors share the dc link voltage equally. The switches *Q*1 and *Q*2 cannot be on at the same time to prevent any short circuit or shoot through. This requires a dead time when the switches are operated sequentially. When the switch *Q*1 is on, either *Q*1 or *D*1 conducts depending on the direction of the charger current. Similarly, when the switch *Q*2 is on, either *Q*2 or *D*2 conducts depending on the current direction. The topology is suitable to transfer power in four quadrants.



**Q1**

**D1**

**LC**

**Cdc1**

**DC-DC**

**vs Converter**

**and Battery**

**Q2 D2**

**Cdc2**

**Figure 2.8:** AC-DC half bridge converter diagram.

A half bridge converter requires bipolar switching because there are only two possible output voltage levels, +*Vdc* and *−Vdc*.

###### AC-DC Full Bridge Converter

The full bridge converter, shown in Fig. 2.9, is comprised of a dc link capacitor, four transistors (either MOSFETs or IGBTs), four diodes, and a coupling inductor. Voltage of the capacitor is doubled in this configuration. The topology is suitable for four quadrant operation.

The full-bridge converter can operate in unipolar modulation and has three output voltage levels; +*Vdc*, *−Vdc*, and zero. Since there are three output voltage levels for the full bridge inverter, the number of switchings required for the same current THD level is effectively reduced with the full-bridge converter compared to half-bridge converter.

**A diagram of a circuit

Description automatically generated**

**Figure 2.9:** AC-DC full bridge converter diagram.

##### DC-DC Converter Stage

The fundamental bidirectional dc-dc converters are explained in this section. The two dc-dc converters under discussion are half bridge bidirectional dc-dc converter and dual active bridge bidirectional dc-dc converter.

###### Half Bridge Bidirectional DC-DC Converter

This converter has two transistors (IGBT or MOSFET), two diodes, a filtering capacitor and an inductor as shown in Fig. 2.10. It can transfer power in both directions. However, it can only operate as a buck converter in one direction and as boost converter in the opposite direction as illustrated in Fig. 2.11.

A diagram of a circuit

Description automatically generated

**Figure 2.10:** Half bridge bidirectional dc-dc converter diagram.

The bidirectional operation of the charger requires a higher dc link voltage value than the peak value of the line voltage to keep the modulation index of the inverter less than one. This is also required for sinusoidal charger current. Therefore, the dc link voltage is usually required to be higher than 350 V for a 240 V grid connection. For increased control stability, the minimum dc link voltage should be selected to be at least 400 V. This value is higher than the regular battery pack voltage which is at 200 V - 390 V level. Therefore, the operation of the dc-dc converter is one way buck (from dc link to battery) and one way boost (from battery to the dc link).

Switches S5 and D6 operate during buck operation when the energy is transferred from dc bus to battery, i.e. charging operation. During this operation, S6 is turned

off. In contrast, when battery is being discharged switch S6 and D5 operate and S5 is turned off. One disadvantage of this converter is the lack of electrical isolation of the battery from the dc link and the grid.

**iconv iconv**



**D5**

Inverter, grid, and filtering

**S5**

**Lf**

**ibt**

**D6**

**Cf**

**vbt**

**S6**



**D5**

Inverter, grid, and filtering

**S5**

**Lf**

**ibt**

**D6**

**Cf**

**S6**

**vbt**

**(a)** Buck mode with S5 operating. **(b)** Buck mode with D6 operating.

**iconv iconv**



**D5**

Inverter, grid, and filtering

**S5**

**Lf**

**ibt**

**D6**

**Cf**

**S6**

**vbt**



**D5**

Inverter, grid, and filtering

**S5**

**Lf**

**ibt**

**D6**

**Cf**

**S6**

**vbt**

**(c)** Boost mode with D5 operating. **(d)** Boost mode with S6 operating.

**Figure 2.11:** Buck and boost mode of operation for the bidirectional dc-dc converter.

###### Dual Active Bridge Bidirectional DC-DC Converter

A dual active bridge dc-dc converter has the merits of providing isolation and a higher buck/boost ratio between the dc link voltage and the battery since it has a HF transformer. The configuration of the converter is demonstrated in Fig. 2.12. This converter requires much more increased number of components than the non-isolated topology: eight transistors (IGBT or MOSFET), eight diodes, an inductor, and a high frequency (HF) transformer. Therefore, it has a more complex control circuitry. The first stage of the converter inverts the dc link voltage into ac voltage during battery charging. Then, the ac voltage is electrically isolated through an HF transformer. Last, the ac voltage again is rectified to appropriately charge the battery.

The process is reversed when the battery has to discharge back to the grid.



**D1**

**D3**

**D5**

**D7**

Inverter, grid, and filtering

**S1**

**S3**

**S5**

**S7**

Battery

**D2 D4 D6 D8**

**S2**

**S4**

**S6**

**S8**

**Figure 2.12:** Dual active-bridge bidirectional dc-dc converter diagram.

This topology is only used if a very high voltage ratio or isolation is required between the dc link and the battery pack. Usually the conversion ratio between the dc link and the battery is not selected to be very high for charger applications. For increased safety of the users, auto manufacturers mandate the electrical isolation requirement between the high voltage battery and charging outlets that are connected to the grid.

##### Integrated Charger Topologies

The literature studies mostly focus on designing chargers with low volume, weight, and cost. Therefore, researchers have looked at partly/completely integrating the charger into the traction drive so that the size, cost, and volume of the charger can be reduced [12, 80–85]. What is more, utilizing the already available high power traction drive, the charging time can theoretically be reduced. While there are different topologies proposed, only the ones used in electric vehicle applications and published with enough technical details are discussed here.

###### ORNL Integrated Charger

One of the recent topologies developed at Oak Ridge National Laboratory (ORNL) shows the performance of an integrated charger described in [12] and shown in Fig. 2.13. Here, authors utilize two inverters that are already present in a Toyota Prius HEV. The first inverter is an auxiliary inverter that is usually used for the air

**A diagram of a wiring diagram

Description automatically generated**

**Figure 2.13:** An integrated charger employing two inverters [12].

compressor drive motor, the water pump motor, or the generator in the vehicle. The main inverter is used to drive the motor. The auxiliary inverter is usually 1/3 of the main inverter in power rating size. Hence, only the main inverter is rated at high power level. By selecting a leg from the auxiliary inverter and another leg from the main inverter, and using the electrical machine inductance, the topology is converted to a single-phase charging circuit as shown in Fig. 2.13. This topology can only be realized using a Y-connected electrical machine.

Level 1 charging with 1.3 kW output charging power shows that the topology is 92.1% efficient, the line current THD is close to 12%, and input power factor is

0.98 [12]. Level 2 charging with 14.5 kW output charging power recorded an efficiency of 93.6%, and the current THD at that level is 6.60%.

Although this topology saves the extra charging circuit, it has several drawbacks. Because of the fixed inductance of the system, the selected switching frequency (15 kHz) is not enough to decrease the line current THD to acceptable levels (less than 5%). To further decrease the current THD, higher switching frequency will be required which will further increase the losses. Another disadvantage mentioned in the paper is the rating of the auxiliary inverter is much lower than the rating of the main inverter that would decrease the proposed fast charging time considerably. To avoid this, an extra diode leg is needed so that the auxiliary inverter will be bypassed as shown in Fig. 2.14. However, this solution will further decrease the equivalent

**A diagram of a motor

Description automatically generated**

**Figure 2.14:** Solution to bypass the auxiliary inverter [12].

inductance of the system that will counteract the THD of the line current. Therefore, an external filter inductance is required for this topology to achieve acceptable line current THD values.

Although not mentioned in the study, the dc-dc converter is necessary to meet charging requirements of the battery. Without a dc-dc converter, due to the conventional power equation of the single-phase inverter, the battery will see a large voltage and current ripple. Therefore, to improve the safety and lifetime of the battery pack, a dc-dc converter is needed. Generally, traction drives such as the one used in the Toyota Prius HEV employ a dc-dc converter between the inverter and the battery. That dc-dc converter can also be employed for battery charging voltage and current regulation.

###### AC Propulsion Integrated Charger

Another topology that is used in the market is the integrated drive and charging system manufactured by AC Propulsion and shown in Fig. 2.15 [85]. This charger is rated from 200 W to 20 kW and can operate with either 120 V or 240 V outlets. Efficiency of the system for 1.44 kW with Level 1 charging is around 85% and it is around 95% for 14 kW input power with Level 2 charging [85]. The relays K1, K2, and K2j are used to switch from motoring to charging mode and vice versa. In

A diagram of a circuit

Description automatically generated

**Figure 2.15:** AC propulsion integrated charger [66].

traction mode, relay K1 is closed and K2 and K2j are open. In charging mode, relays K2 and K2j are closed and relay K1 is open. When charging, switches S1 and S2 are kept open, and switches S3-S6 operate to form a single phase full-bridge ac-dc converter. This system design does not employ a dc-dc converter, but it can be added if desired.

###### Partly Integrated Chargers

In addition to the above approaches, a charger can also partly share the circuitry with the drive-train. Rather than fully embedding the charger into the motor drive, it can only utilize the dc-dc converter already available in the drive-train. This approach is shown in Fig. 2.16. The advantage of this usage is the elimination of one extra dc-dc converter from the charger circuit. For example, Toyota Prius HEV uses a half bridge bidirectional dc-dc converter. Since this boost dc-dc converter is already rated at high power, it can also be used to charge the vehicle battery during charging operation. Moreover, already available large electrolytic capacitor can also be used to filter out second harmonic ripple due to the single-phase charging. The disadvantage of this approach is that the traction dc-dc converter is designed to be non-isolated due to the



**N number of cells**

**Charger**

**DC-DC**

**AC-DC**

**BMS**

**Includes master and slave units**

**DC**

**output 270-400V**

**DC-link**

**>400V**

**Single-phase**

**Battery Pack**

**110 V / 240 V**

**50/60 Hz**

**1-phase**

**Traction**

**Three-phase Drive inverter**

Electric Motor

**Vehicle**

EVSE

**Figure 2.16:** Partly integrated charger into the traction-drive.

efficiency and cost concerns. Using the same converter as a charger will only provide a non-isolated charging option.

**CHAPTER-4**

**PROPOSED SYSTEM**

The off-board EV battery charging model configuration is depicted in Fig. 1. The developed EV charger is used to validate the reactive power compensation capability of the charger along with the G2V or V2G operating mode of the charger. The grid facing front-end AC-DC cascaded Hbridge bidirectional converter (CHBDC) is a single excited voltage source converter. The detailed circuit configuration of the grid facing converter is shown in Fig. 2. The presented configuration of the converter contains three H-bridge modules per phase. Each H-bridge output is connected to the primary side of a single-phase toroidal core transformer. The secondary windings of three transformers are connected in the series, which added up the secondary voltage of each transformer to give per phase output voltage. As presented in Fig. 2, each H-bridge per phase contributes equally i.e. 33.33% of the output phase voltage. The application of toroidal transformers is seen in front-end converter as a highfrequency link, but its application at the output end elevates its performance compared to conventional transformer-based prototypes [13]. The use of the toroidal core transformer enables the converter to operate with a single DC excitation voltage. Furthermore, it eliminates the additional use of voltage matching sensors required to maintain equal power distribution among the modules [13]. The added advantages with the presented H-bridge configuration are very low charging current ripples, both current and voltage control capabilities, and provide galvanic isolation [13]. The grid facing CHBDC is coupled to the power grid through the Lfilter as shown in Fig. 1 to improve the converter output voltage quality. Due to the multilevel structure, L-filter is sufficient to eliminate higher-order switching harmonics. The back-end DC-DC converter (BBDC) is used to charge/ discharge the EV batteries. The detailed circuit configuration of the BBDC is shown in Fig. 1. The presented configuration can operate in two modes (Buck and boost) by controlling the two switches (S1, S2). The control of switch S1 operates the BBDC as a buck converter and boost mode can be achieved by controlling S2. Hence, the charging and discharging of the EV batteries can be achieved by operating the BBDC in buck and boost mode.

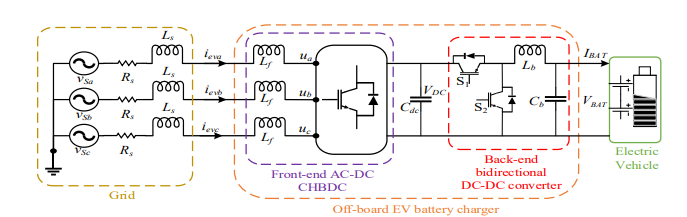
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Fig. 1. EV charger configuration

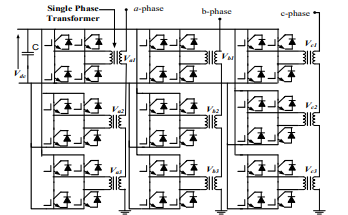
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Fig. 2. CHBDC Circuit configuration

III. CONTROL STRATEGY OF THE EV CHARGER

The controller designed in this paper serves two main objectives first, to charge the EV battery by taking active power from the grid (G2V) and send back active power when requested from the grid i. e. V2G operation. Second, it supplies the reactive power to the grid when requested from the utility grid operator. The detail controller structure is presented in Fig. 3. The proposed control algorithm uses ANF to maintain synchronization between the grid and the charger. The ANF for grid synchronization is first proposed in [14]. The ANF works effectively irrespective of the system disturbances and eliminates conventional PLL from the system controller. The dynamic equations of the ANF can be presented as in [14] are given below

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where (  
) is the input signal, is the estimated frequency of the input signal, and and are two real positive constants. The selection and decide the speed and estimation accuracy of the ANF. For fundamental component frequency with amplitude the ANF has a unique periodic orbit located at [14]:

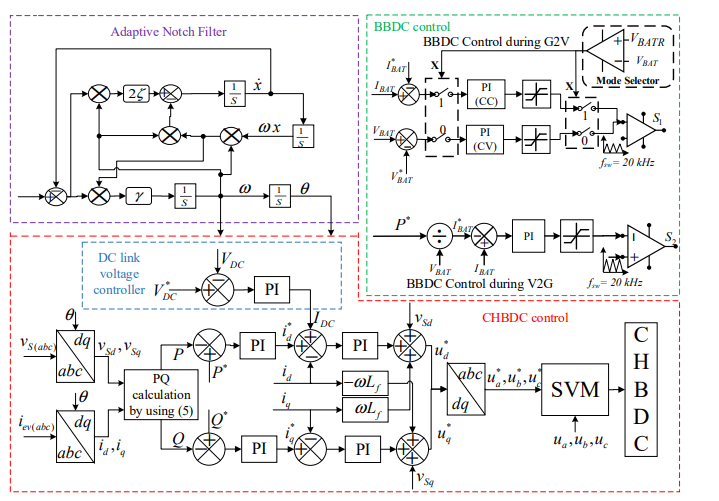
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Fig. 3. Bidirectional EV charger controller block diagram

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