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PHEV Battery Charger using a New Bi-Directional Converter Structure

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Abstract

PHEV is a hybrid electric vehicle that uses rechargeable batteries or another energy storage device that can be recharged by plugging it into an external source of electric power. By using the PHEVs with grid connection we can decrease the fossil fuel consumption, therefore it provides stability, voltage control and frequency control. Uncoordinated charging of plug-in hybrid electric vehicles (PHEVs) will produce a series of negative effects on the electric grid. To solve this problem, we have to make smart-charging strategy by knowing PHEV charging characteristics. Here we use a bidirectional ac-dc converter and a bidirectional dc-dc converter. The main objective is to use bidirectional switching converter for PHEV to obtain high energy density, low volume and low weight. With the help of these bidirectional converters the excess charge in battery after charging PHEV can be fed back to the grid which can be utilized for load demands. This bi-directional charger must have the capability to charge a PHEV's battery pack while producing minimal current harmonics and also have the ability to return energy back to the grid in accordance with regulations. There are two modes of operations i.e. charging and discharging modes of battery. The ac-dc controller act as a regulator during charging mode and as an inverter during discharging mode. Also, we use integrated controller for both modes to obtain performance of battery.
Keyword- PHEV, Grid Connection, Bidirectional AC-DC Converter, Integrated Controller

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I. INTRODUCTION

Today's transportation system confronts a number of challenges related to environmental sustainability. Plug-in hybrid electric vehicle is a hybrid electric vehicle that uses rechargeable batteries or another energy storage device, which can be recharged by plugging it into an external source of electric power.

Plug-in hybrid electric vehicles (PHEVs) can not only reduce emissions from traditional vehicles and fuel consumption as a potential solution but also improve economic efficiency and energy security. However a large number of PHEVs will have certain impacts on the electric grid. For instance, uncoordinated charging gives a series of challenges to electric grid, especially the distribution system, in terms of the security and reliability of the grid. These challenges include voltage deviations, line congestion and so on. However, smart charging strategy will improve the economic efficiency of the power system. Because of increasing in fuel price and environmental issues application of available and adaptive to environment sources are increasing. One of the specifications of smart grid is ability of bidirectional power transmission. In this situation, PHEV with ability of grid connection can receive its sufficient energy by connecting to electric grid. Also at peak of consumable power transmits its extra power to grid. Connection of vehicle to grid (V2G) in addition to load responding at the peak of consumption can help to stability of grid including lines. V2G is a system in which PHEV communicate with power grid to sell demand response services by either returning electricity to grid or by throttling their charging rate.

Supply required power for grid by these vehicles can reduce unnecessary power plant costs and besides can be used as uninterruptible power supply (UPS) for household applications. In these vehicles, bidirectional power transmission requires a converter which can return battery power to grid. Charger of these vehicles is either two converters including one bidirectional AC-DC converter and then a bidirectional DC-DC converter or directly a bidirectional AC-DC converter that connect to energy storage system. Different topologies for these chargers are proposed in both single-phase and three-phase systems. Depending on position of charger placement, chargers can be on-board or off-board.

Greater use of electricity as an energy source for transportation could substantially reduce oil consumption. Electric motors are inherently more efficient than internal combustion engines; they do not consume energy while vehicles are stationary and they provide the opportunity to recover energy from braking. Current hybrid electric vehicle technology demonstrates some of the potential of this approach. The introduction and wide spread use of plug-in hybrid technologies (PHEVs) with an all-electric range sufficient to meet average daily travel needs could reduce per vehicle petroleum consumption by 50 percent, meaning half of the energy would come from electricity. Out of this ambience the promise for more efficient individual transportation is partly represented by PHEVs, mitigating vehicle technology to an increased electrification. However, the mitigation process intuitively entails several impacts for the transportation as well as for the power sector which need to be investigated and resolved. PHEVs are being developed around the world, with much work aiming to optimize engine and battery for efficient operation, both during discharge and when grid electricity is available for recharging. However, the general expectation has been that the grid will not be greatly affected by the use of PHEVs because the recharging will occur during off-peak hours, or the number of vehicles will grow slowly enough so that capacity planning will respond adequately.

II. BLOCK DIAGRAM

Components are:
- AC-DC Converter
- DC-DC Converter
- AC Grid
- Battery
- Controllers

III. BIDIRECTIONAL CONVERTERS

The world now is going to exercise the power electronic applications device for complex systems when most difficulty face for human being in many stream of fields. Over the last three to four decades power efficiency become the main concern of researches for power conservations as a result these leads to grow compact power supplies grows significantly. Power electronics circuits primarily process the energy supplied by utility or storage devices to a form which matches with required load or storage device through the application of semiconductor devices to control the voltage and current values. The energy can supplied from utility grid or bank of batteries; with the application ranging from high power conversion equipment of MW to the very low power equipment of a few watts.

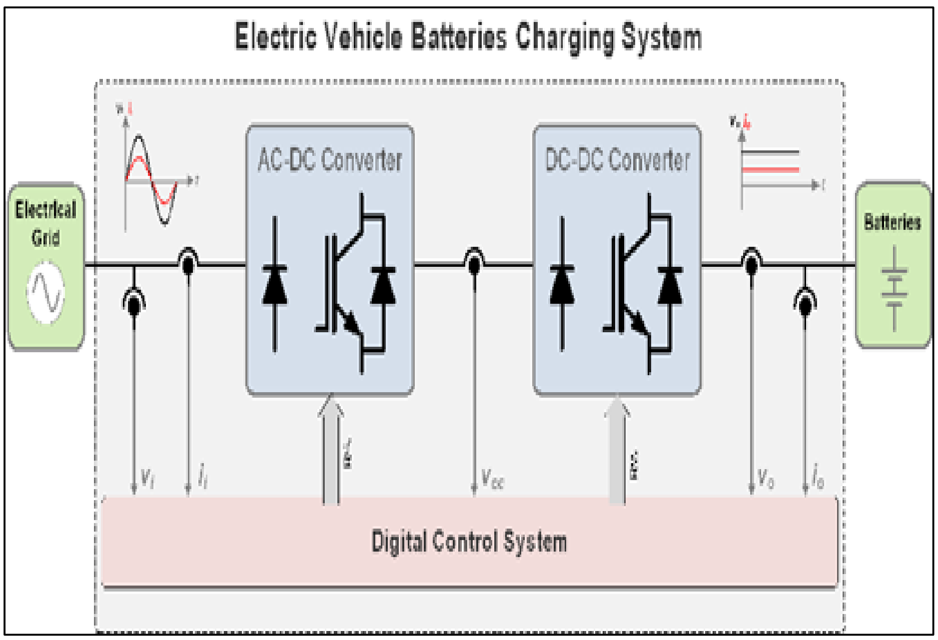

Fig. 1: Block Diagram Representation

Most of power converter devices have common unidirectional application with power being supplied from the source to the load. However different types of applications require dual direction; the applications such as motor drives, uninterruptible power supplies (UPS), alternate energy system, telecommunication, space technology, hybrid automotive, battery charger and discharger etc. require using another system of conversion which is not similar to unidirectional. Therefore these applications introduce power converter with bi-directional power transfer property.

Conventionally, the two independent unidirectional converters can be used together parallel for achieving bi-directional power transfers. Bidirectional DC-DC converters recently gates awareness due to application of bidirectional power transfer between different dc sources buses. The demand for development of complex, compact and efficient power system implementation has encouraged scientists in bi-directional converter development.

A. Bidirectional AC-DC Converter

Distribution grid acts as an input supply voltage for charging battery. Bidirectional AC-DC converter regulates AC input voltage and then it should supply DC link voltage and battery voltage. Actually, on battery charging mode converter acts as a regulator and on battery discharging period acts as an inverter.

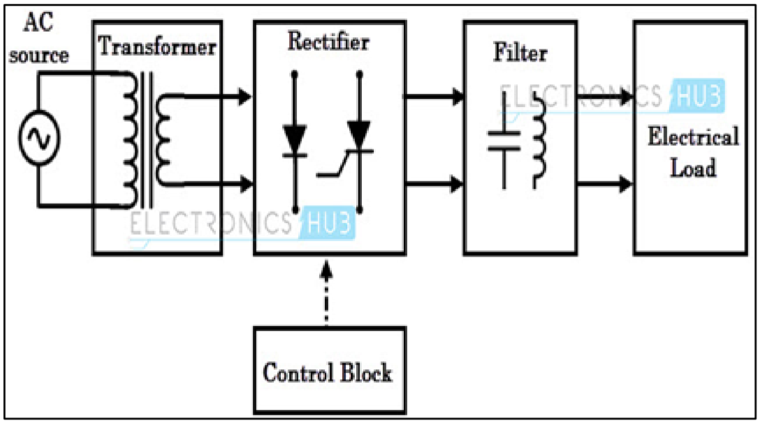

Fig. 2: Block diagram representation of AC-DC converter

Among the practical inverters exist two kinds of inverters with PWM output: Three phase bridge inverters and multilevel inverters. Multi-level inverters have various topologies. Cascaded H-bridge inverter, floating capacitors inverter and clamp diode inverter are three kinds of multilevel inverters. N-level inverters produce voltage with n-value at the output. Increasing levels of inverter causes increasing steps of output waveform. So, total harmonic distortion (THD) will reduce. This increases complexity of system and makes complex keep balance of various voltages.

In practical, three-phase Bridge, numbers of electric elements are less than three-level diode clamp and because of three-phase Bridge has less complex control and make product easier. In clamp diode converters because of increasing in number of switches in each leg, stress of voltage across switches, in off period, is less than three-phase bridge converter and so switches have long lifetime. On the other hand, because of increasing in output PWM levels clamp diode converter has better voltage THD than three-phase Bridge in its inverter mode. In diode clamp converters, like floating capacitor converters it is difficult to balance voltage of capacitors, otherwise causes unbalanced and finally causes capacitor to burn out. Such problems do not exist in three-phase bridge converter and voltage ripple can be improving. Negative point of cascade converters in comparison with diode clamp converters is regulation operation mode. In diode clamp converters has common sources and output voltage produce from cascading two capacitor in output, but in cascade converter, because of existing independent sources, it is difficult to tune voltage in rectification mode. Actually with cascading Hbridge converters, battery cells are cascading, too.

To choose proper DC-AC converter for grid connected hybrid vehicle chargers three criteria of simply, reliability and cost are in priority. According to applied comparison, three-phase Bridge has a simple schematic and also has a simple control. Three phase bridge have more high reliability and low cost than multi-level converters including diode clamp, because of less elements and simple schematic.

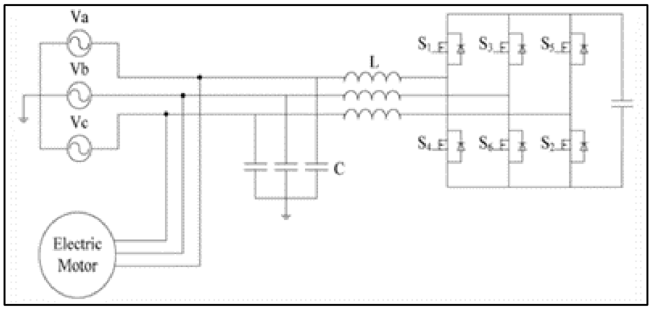

Fig. 3: Three phase bridge bidirectional DC-AC converter

B. Bidirectional DC-DC Converter

Energy storages in general uses bidirectional DC-DC converter for charging and discharging applications may be either in half-bridge or full-bridge arrangement of semi-conductor switching devices. The buck type of converter has energy storage on the high voltage side, whereas boost type of converter has energy storage on the low voltage side.

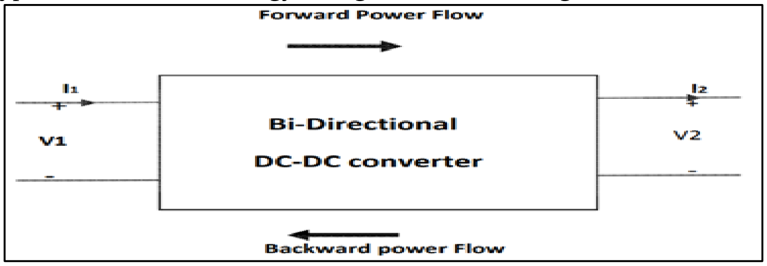

Fig. 4: Block diagram representation of DC-DC converter

The concept of power flow in both direction for bidirectional dc-dc converter is operation of switching devices realize current flow in each way. Bidirectional dc-dc converters are developed from two unidirectional semiconductor switching devices such as; MOSFET, Transistors and IGBT power switches constructed with parallel diodes. These parallel diodes serve double sided power flow. Even though there are many topologies of bidirectional dc-dc converter; basically they are divided into two types such as an isolated bidirectional DC-DC converters and nonisolated bidirectional DC-DC converters based on the isolation material between input and load.

In aspect of improving in efficiency, size, volume and cost, transformer less converters are more interesting, especially in high power systems like electric vehicle which weight and size are the most important problems. To choose bidirectional DC-DC converter in hybrid vehicles charger there are some standards like simple topology, high efficiency, size, weight and low cost. The proposed topology is a four-phase interleaved converter based on buck-boost topology that being parallel with Converter is extended version of three-state interleaved converter which is transformerless and in DCM has small inductors. So, the proposed converter is useful in high power density fields. ZVRT exists for this converter to improve lifetime of switches and increase efficiency. Multi-phase converters have some advantages like low current stress, because of paralleling. Also with aspect of coupling inductance, it can improve ripple and efficiency. Fig. 5 shows a four-phase interleaved DC-DC converter with soft switching. It is a four-phase interleaved bidirectional converter, since it uses four inductors in parallel. Using this interleaved bidirectional converter we can reduce losses across high switching devices and help to reduce current ripple in DC load. In LV side, battery pack or super capacitor is placed and in RV side high frequency capacitor as energy buffer is placed in output of AC-DC converter. In this model switches S_1-S_8 operate in buck mode and boost mode, both. Each switch has an antiparallel diode to pass current in freewheeling cycle. On the other hand, a capacitor as lossless snubber placed parallel with each switch. These regenerative snubber circuits for boost provide less switching losses of IGBT. It has simple control strategy, low cost, high efficiency, small control strategy, low cost, high efficiency and small size. Four-phase inductors act as boost inductor in boost mode, although act as filter in buck mode. HV and LV capacitors are energy buffers.

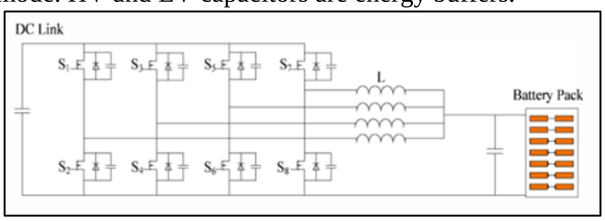

Fig. 5: Four-phase interleaved bidirectional DC-DC converter

1) DCM Operation

DCM means discontinuous conduction mode. To reach high power density converter should operate in DCM to minimize inductors. On the other hand, DCM operation increases current ripple, so it is important to use multi-phase interleaved converters. The other important advantage of DCM is zero loss when switches are on and also reverse recovery loss for diode is very low. Weakness of DCM is parasitic ringing which produced by output inductor and capacitors when current is zero. Actually, in tum off mode, inductor resonates with output capacitor and this reduces efficiency and produces EMT. Also, other weakness of DCM is increasing in turn off losses. These problems are solved by using capacitor snubber and soft switching technique.

2) ZVRT Soft Switching

ZVRT means zero voltage ride through i.e. the switches turn ON when the voltage equals zero. New soft switching techniques for turning on and turning off transistor with capacitor snubber have been introduced. In Fig. 5 the gate signals for each leg of interleaved converter is shown. Soft switching is a possible way of reducing losses in power electronic switches. It refers to operation of power electronic switches as zero voltage switches or ZCS.

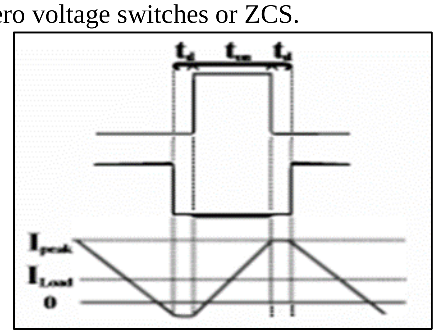

Fig. 6: Gate signal waveform and inductor current in DCM

In buck mode, switches $S_{1,}S_{3,}S_{5,}$ and $S_{7,}$ are the main switches and the others are auxiliary ones. When $S_{1,}$ is on, the battery charges. In td all switches are off, so inductor current causes $C_{1,}$charges and $C_{2,}$discharges. When $C_{2,}$completely discharged, $V_{ce2,}$closes to zero and inductor current flow through $D_{2,}$and at next cycle $S_{2,}$under zero voltage condition will turn on. LV bus voltage (battery side) drop reversely on inductor, so inductor current decreases until it reaches to negative value. At these time, current flows from $S_{2,}$, so diode will tum off without any reverse recovery loss. Flowing current from $S_{2,}$charges $C_{2,}$and begins to discharge $C_{1,}$.when $C_{1,}$fully discharged, $V_{on,}$will be zero and then freewheeling diode, $D_{1,}$will conduct. Then, $S_{1,}$can turn on under zero voltage condition. After $D_{1,}$conduction, difference between HV and LV will drop on inductor and its current will be positive. In this mode, positive current flows from$S_{1,}$. So both upper and lower switches will conduct under ZVS condition. Transmitting inductor current to freewheeling diode causes parasitic voltage effect of lower inductor removes.

C. Converter Models

In this battery have two modes of operations i.e. charging mode and discharging mode. During charging mode the AC-DC converter act as a regulator, while it act as an inverter during discharging mode. Both modes of converter model is shown below.

1) Charge Mode

In charge mode, battery charges from DC link so in primary side exists a V_H source. C_H can be neglected if V_H would regulate. Drop voltage on R_H is very low in comparison with V_H.

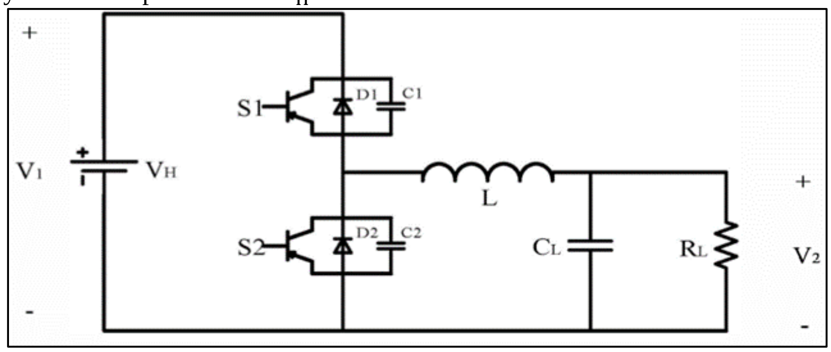

Fig. 7: Simplified model of converter in charge mode

2) Discharge Mode

In discharge mode, battery discharges to electric motor or grid so in secondary exists a voltage source. C_L can be neglected if this voltage is smooth. Because of small drop voltage on R_L against V_L, it can be neglected.

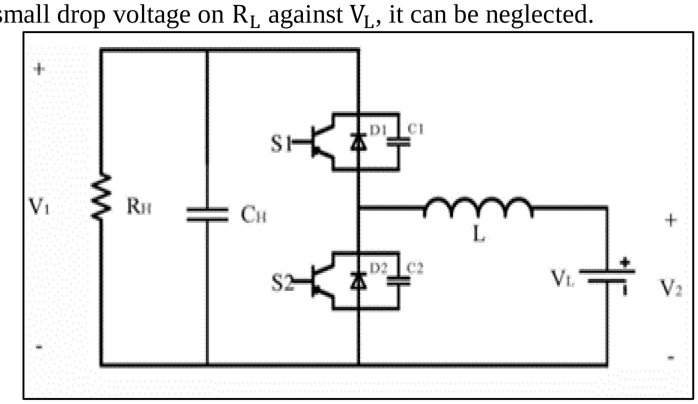

Fig. 8: Simplified model in discharge mode

D. Controllers

For the two modes of battery operations we need controllers to control their functions. Therefore we use two controllers each, for both the modes of operation. These are charge and discharge controllers.

1) Charge Controllers

In charge mode, grid voltage is regulated and then produced DC link by AC-DC converter. This voltage will reduce till battery voltage level (which called buck operation) by interleaved converter. This state needs two controllers. One controller is needed on AC-DC converter with goal of dc link voltage control that does not let the DC link voltage to roll off on full load condition. The other one is needed for battery charging so that according to battery specification can charge battery in two modes of constant current and constant voltage.

In first controller, DC link voltage compares with reference voltage and then produces reference current in dqo frame with cross from PI controller. Now by using current control in dqo frame, carrier wave will produce for three-phase and by comparing with rectangular wave apply AC-DC converter switches pulse.

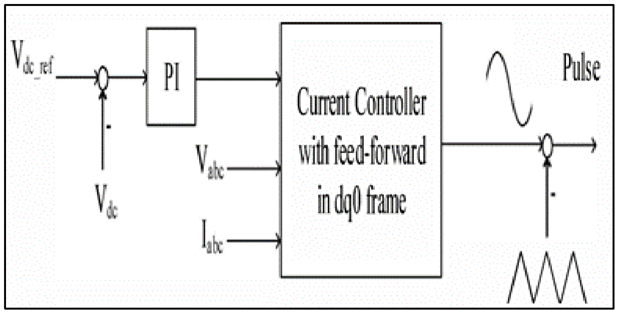

Fig. 9: DC link control by using current controller

In battery charge controller with comparing of battery voltage, if battery voltage be less than nominal value, battery charges in constant current mode and if battery voltage be more than nominal value, battery charges in constant voltage mode. Output of this controller is signals which applied to DC-DC four-phase interleaved converter switches. In Figs. 9 and 10, two charge mode controllers are illustrated. Battery charge control, with comparison of battery voltage, charges battery on constant current if battery voltage be less than battery nominal voltage or charges battery on constant voltage if battery voltage be more than battery nominal voltage. Output of this controller is square pulses that apply to switches of four-phase interleaved converter.

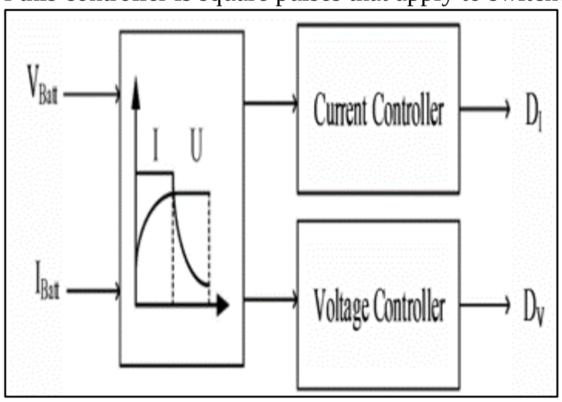

Fig. 10: Battery charge control by using constant current/voltage controller

1) Discharge Controllers

In this mode, DC-DC converter acts as boost converter and increases battery voltage level then power is injected to grid or is given to electric motor by DC link or DC-AC converter. This mode has two controllers, too.

First controller is only for the DC-DC converter to regulate output voltage. To reach this purpose, modeling small signal of interleaved DC-DC converter is done and a simple PI controller has been chosen. In this mode the output voltage taken as the feedback signal for PI controller to it compare with the reference voltage. This error signal is again compared with a saw tooth and its output is given to controller.

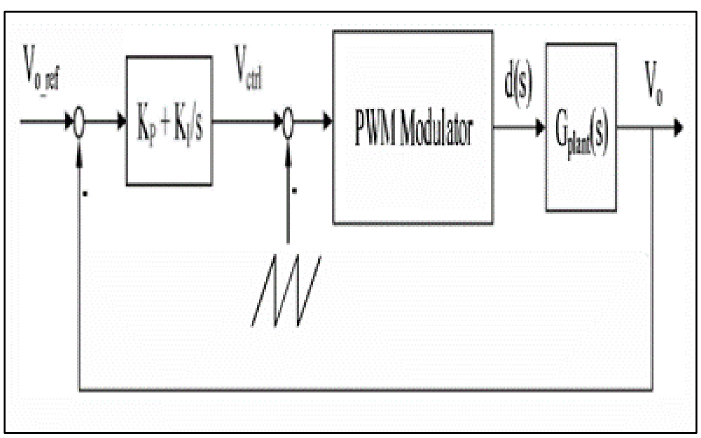

Fig. 11: DC link control with a proportional-integral (PI) controller

Second controller is for inverter to control injected power to grid or electric motor. For this purpose, it should use current control in dqo frame. In Figs. 11 and 12 two discharge mode controllers are illustrated. In this mode we use active power and reactive power control with current mode controller. Here we convert the voltage and current measured into dqo frame and get the input active and reactive powers. This power is then compared with a reference power and their output is used to control.

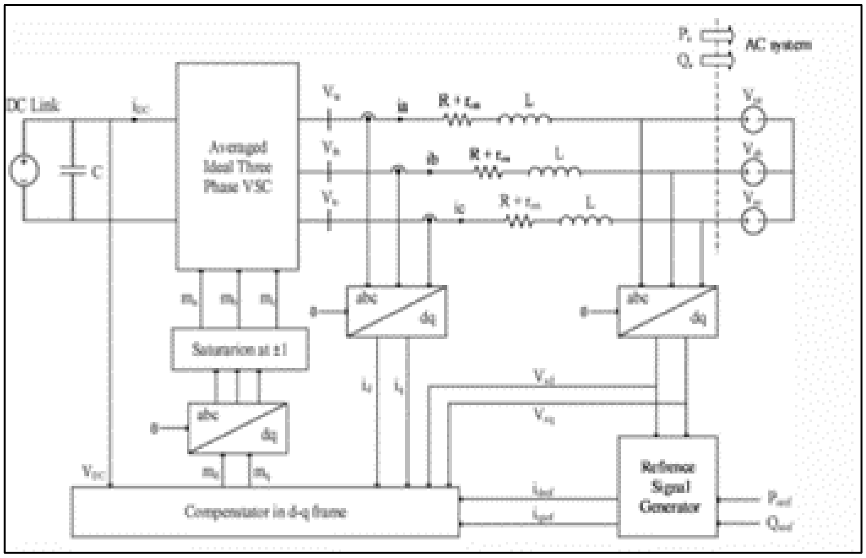

Fig. 12: Active power and reactive power control with current mode controller

IV. CONCLUSION

In this a proper topology for bidirectional switching converter is proposed which is used in PHEV. The topology includes a four-phase interleaved bidirectional DCDC converter and a three-phase bridge bidirectional AC-DC converter. The interleaved converter has high power density and it has proper ripple, efficient, current stress and stability, also. Three-phase bridge AC-DC converter in comparison with multilevel converters including diode clamp and CRB has simple control, low cost and high reliability.

To operate in charge mode and discharge mode of battery, four controllers with aims of DC link control, battery charge control and grid electric motor injected power control are applied. Uncoordinated charging of a large number of PHEVs will challenge the security and reliable operation of the electric grid. The smart charging strategy can improve the economics and security of the entire power system. If more manufacturers begin to produce PHEVs and consumers purchase these PHEVs, the benefits of enabling V2G interactions and the side-effects of proceeding with uncoordinated charging will both continue to grow. With the implementation of V2G technology, the added demand from PHEVs can become a large resource instead of a costly burden for the grid. If the bi-directional interfaces do not function well, the grid could suffer from the consequences of harmonic currents and poor power factor. In order to make V2G technology feasible, an efficient and well-designed bi-directional charger that minimizes current harmonics will be required. If done properly, large scale coordinated charging could vastly improve grid efficiency and cut costs for utilities and ultimately for consumers.

The mentioned controllers are integrated controllers and their condition can change automatically by themselves from charge mode to discharge mode or revers, according to charge battery. Actually, according to vehicle position and value of battery charge, charge mode and discharge mode can occur on little interval from each other. The proposed battery charger is chosen level-2, due to low volume, low cost and distance.

V. FUTURE WORKS

A novel battery charger system with photovoltaic generation can be designed to have function of photovoltaic power conversion and battery charging/discharging. Also, considering sensitive photovoltaic source according to the environment conditions, grid and battery characteristic, operation algorithms of the system can be proposed and these algorithms can be analyzed by four cases according to load conditions in detail. Then it can be applied to battery charging algorithm of hybrid constant current constant voltage control combined merits of constant current control and constant voltage control.

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