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Bidirectional AC-DC Converter and DC-DC Converter for Charge/Discharge Applications

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Abstract: Conventional structure of PFC AC-DC converter integrated with DC-DC converter is used in electrical vehicle and battery charging applications. AC- DC converter is to convert AC voltage to specify DC level with near to unity power factor and DC-DC Bidirectional converter is used to charge and discharge the battery at specified operation. These converters preferably used to charge the li-ion battery in lean hours and in peak hour battery is discharged to give power back to grid. A PI controller is used control the battery current and voltages. The operating principle and different mode of operations are clearly discussed in this paper. The Simulink model is developed using MATLAB-Simulink and sim-power system tool boxes and results has been carried out.

Keywords: power factor correction (PFC), bidirectional DC- DC converter, AC- DC converter.

1. INTRODUCTION

The demand for energy will continue to increase as long as world population increases and people continue to demand a higher standard of living. Now the challenge is to decrease the gap between supply and demand and to maintain load profile at better efficiency of a grid and maintain good voltage and current profile with minimum harmonic content [1].

Renewable energy sources are better choice to improve the load profile But currently facing many drawbacks. One major drawback is its dependency on geographic location. Another drawback that renewable energy suffers from its intermittent nature. It is clear that an energy storage system is needed in order to solve the problems associated with both peak demand loading and the intermittent nature of renewable energy.

Vehicle to grid technology one of the most emerging technology to manage energy distribution with low cost [2]. Environmental and economic problems have led us to think of generating power on-site. Electric Vehicles (EV) and Plugin Hybrid Vehicles (PHEV) are the main concern for vehicle to grid (V2G) technology as in general vehicles are parked approximately 15 hours per day and give the opportunity to use them as a power generation source. The main idea for V2G technology is to use the vehicle as a generation unit. The vehicle will provide power to the grid when it is parked or plugged in. For that reason, the EV or PHEV should be equipped with bidirectional converter with an additional powerful battery pack. With the help of the bidirectional converter, two ways energy flow can be operated, flow from the grid to the vehicle and flow from the vehicle to the grid.

In this paper a configuration of two stages of bidirectional converters are clearly explained with different modes of operation. The bidirectional battery charger is shown in fig 1. In first stage AC voltage is rectified to DC voltage at required level with minimum harmonic content. In second stage high voltage DC is step down to low voltage to charge battery at required level. Battery power can also be used to supply load. Meanwhile battery power can also be used to pump back the energy whenever utility need power.

This paper is organized as follows: system configuration and principle of operation, design procedure is introduced Section-II. Control algorithm for PFC AC-DC boost converter, BDC buck/boost converters are clearly given in Section –III, MatLab modeling is given in Section-IV. Detailed simulated results have been discussed in Section-V. Conclusive remarks are given in Section-VI.

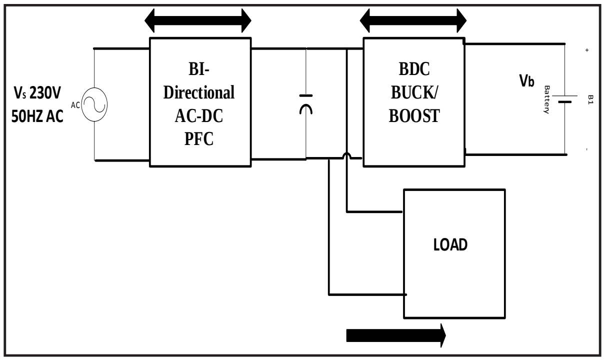


Fig. 1: Bidirectional grid connected battery charger

II. Converter Operation

This paper consists of two converters. In which first converter is used to rectify 230V AC 50 HZ supply is converted to 380 V DC. H Bridge Bidirectional full bridge converter is used to rectify AC power to DC with bidirectional current flow by keeping polarity of voltage is unchanged. These converters uses two loop PI controller for PFC operation. Another converter is bidirectional buck/boost converter which act like buck converter in charging operation boost converter in discharging.

A. AC – DC Single Phase H- Bridge converter

Full bridge AC- DC converter is working like grid tied inverter during discharging and grid tied rectifier during charging. PFC controller is a technique in which outer loop control desired dc level and inner controller control the desired input current which follow the input voltage waveform [3],[4].

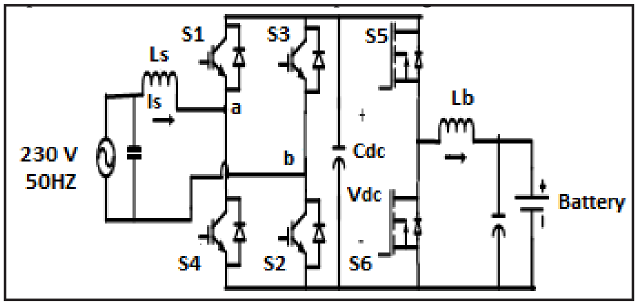


Fig. 2: Two stage AC- DC bidirectional converter [5]

Full H bridge converter controlled by unipolar switching scheme. In positive half cycle the converter voltage i.e voltage across H bridge converter is rectified with +Vdc,0. In negative half cycle voltage become –Vdc,0. Here two poles are controlled with 180 degree phase delay. Fig. 3 shows the switching wave forms in positive half cycle during charging condition i.e during energy transfer between grid to battery. Fig. 3 consist of four gate pulses and voltage across rectifier and current flowing through the inductor waveforms. H bridge converter operation is somewhat familiar to boost converter operation. Like boost converter charge the inductor in on period and discharge it in off period

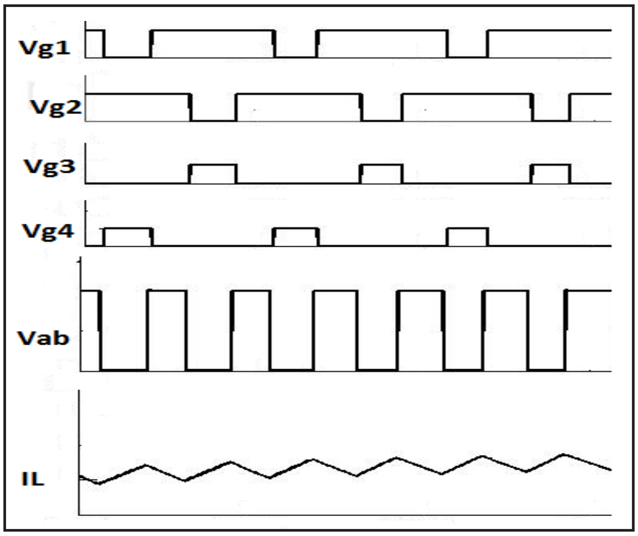
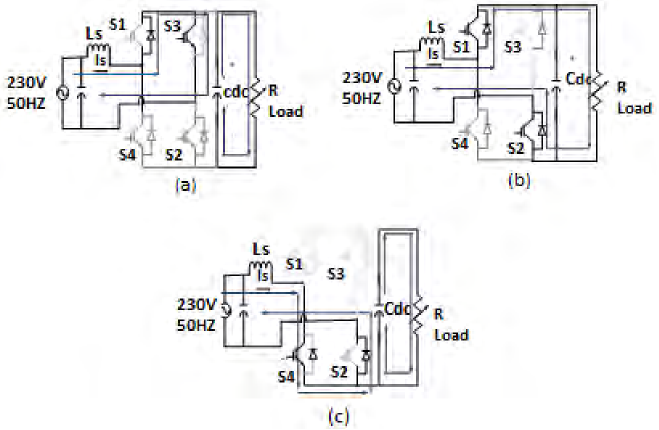


Fig. 3: Key waveforms of rectifier in positive half cycle

Fig. 3 shows the switching waveforms of gate pulses (vg1-vg4), voltage across converter and current flowing through the inductor during positive cycle during charging condition.



(a) (b) (c)

Fig. 4: Rectifier operation in positive half cycle (a) Mode-I when S1 & S3 ON, (b) Mode-II when S1 & S2 ON, (c) Mode-III when S1 & S2 ON.

Fig. 4 illustrates different modes of operations in positive half cycle. H bridge full converter will be controlled in PFC operation using unipolar switching. During positive cycle the converter voltage will become +Vdc and 0.

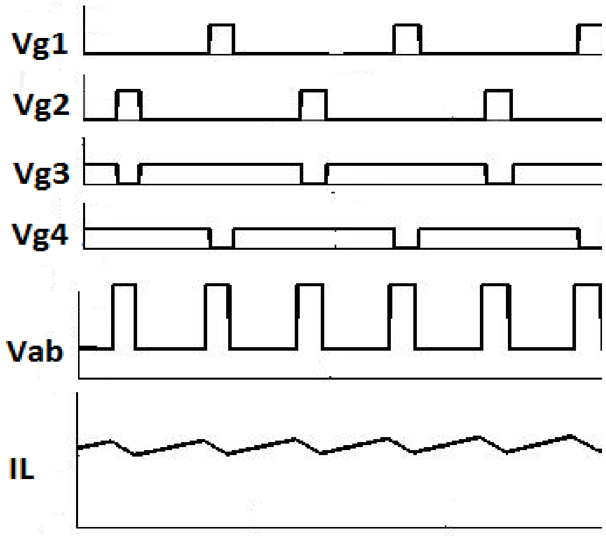
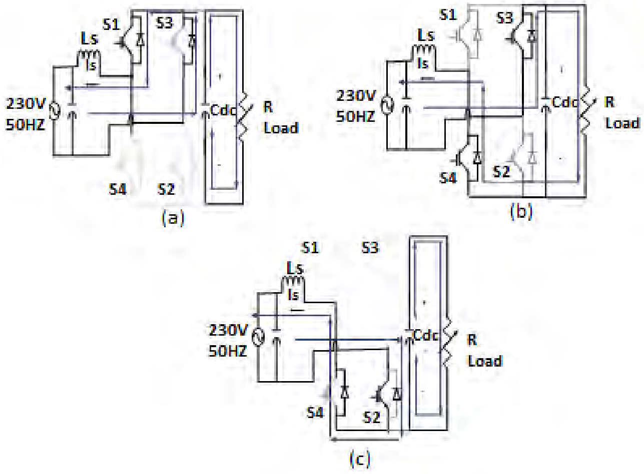


Fig. 5: Key Waveforms of rectifier in negative half cycle

MODE I and III : In mode-I switch S1 and S3 will conduct where as in mode-III S4 and S2 will conduct. During this mode of operation converter voltage will become zero. In this mode total supply voltage is applied across inductor. So in this mode of operation inductor will start charging and continue till inductor current reach maximum reference current. MODE II : During this mode switch S1 and S2 will conduct. So current will take the path from supply- S1 body diode- load(dc-link)- S2 switch- supply. During this operation inductor discharges and gives supply to load. In this mode voltage across converter +Vdc. Here voltage across dc link capacitor will become sum of voltage across inductor and supply.



(a)

(b)

(c)

Fig. 6: Rectifier operation in negative half cycle (a) Mode-I when S1 & S3 ON, (b) Mode-II when S3 & S4 ON, (c) Mode-III when S4 & S2 ON.

Fig. 5 shows switching wave form of H- bridge full wave converter in different modes of operation of negative cycle during AC- DC Rectification mode. In this operation three different mode of operations are shown. The converter voltage will become –Vdc,0 in different modes.

Fig. 6 shows different modes with current flowing paths. In mode I switch S1 and S3 are ON whereas in mode III switch S4 and S2 are turned ON. In this operation inductor will charge in negative direction. So voltage across converter will become zero. Total supply voltage will be applied to inductor. Mode II: switch S3 and S4 are turned on. Now converter voltage will become –Vdc. The voltage across inductor will be equal to Vs – Vc.

Fig. 7 and 8 shows the switching waveform of inductor current and converter voltage waveforms. In this mode DC voltage inverted to ac voltage . 380 v dc will be inverted to 230 V ac waveform.

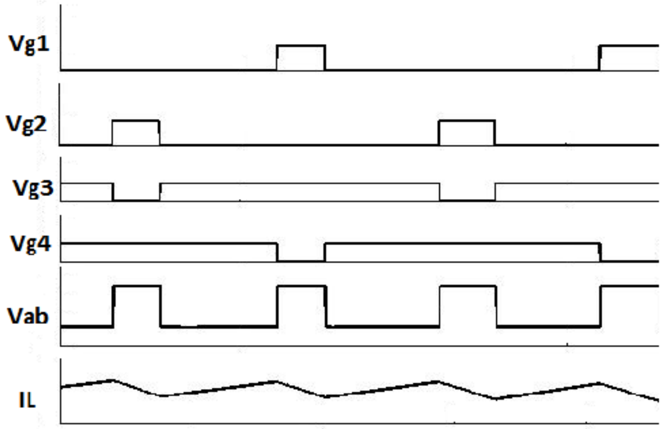


Fig. 7: Key waveforms of inverter in positive half cycle

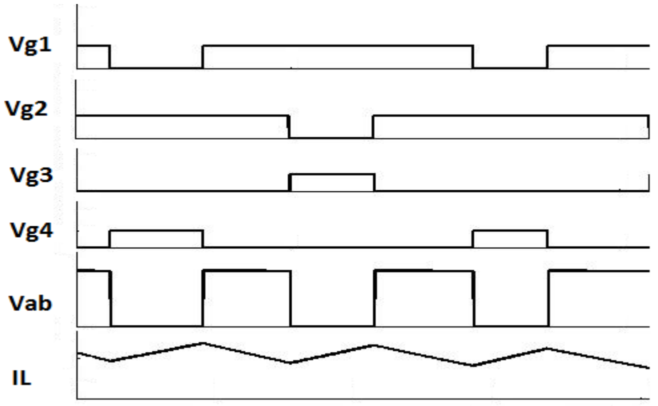


Fig. 8: Key waveforms of inverter in negative half cycle

B. DC – DC Single Phase Bidirectional DC- DC waveform

There are many applications in DC power system that needs to Transfer energy in both directions between two or more dc buses or sources. Fig. 9 shows the bidirectional dc- dc converter. In this configuration the voltage polarities remain same but directional of current flowing will changes from dc link to battery and battery to dc link [6].

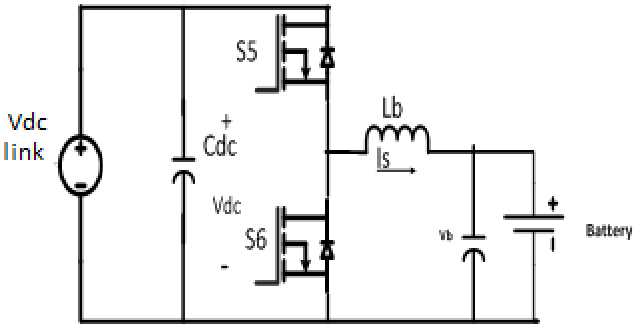


Fig. 9: DC – DC bidirectional buck are boost converter

By controlling one switch at a time i.e in one mode of operation only S5 switch controlled and S6 switch gate pulse kept as zero. In this mode converter act like buck converter. In another mode of operation switch S6 is controlled and S5 is act like freewheeling diode. So in this operation converter act like boost converter [7].

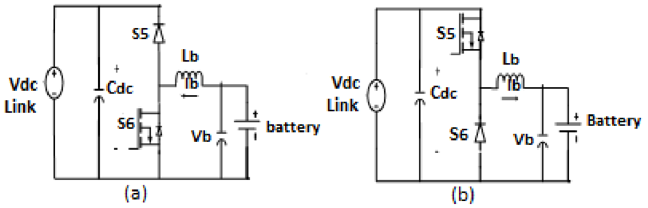


Fig. 10: (a) DC – DC boost converter (b) DC- DC buck converter

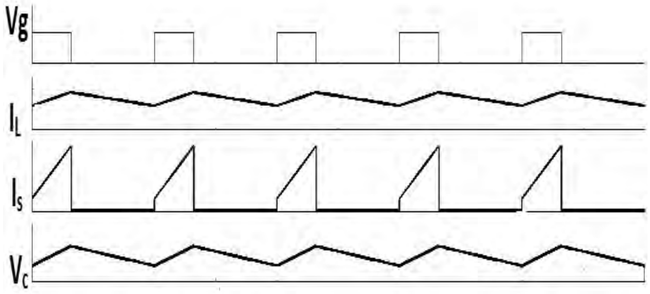


Fig. 11: Key wave forms of buck converter

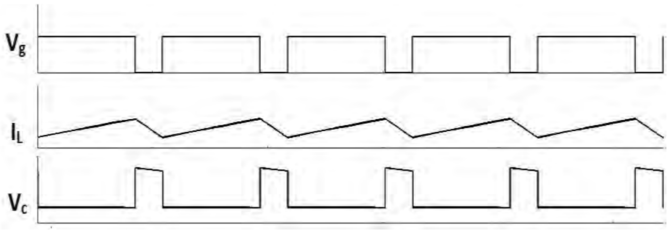


Fig. 12: Key waveforms of boost mode BDC converter

In boost operation mode energy transfer from the low voltage to high voltage. S5 is turned off S6 switch is controlled by PI.

$$V_{hv} = \frac{V_{lv}}{1-\delta} \qquad (1)$$

$$I_{hv} = \frac{\dfrac{V_{shv}}{1-\delta} - V_{shv}}{R_{hv} + \dfrac{R_{lv}}{(1-\delta)^2}} \qquad (2)$$

In buck operation mode power from HV terminal is transferred to the LV terminal. The necessary condition in buck operation δVshv should be higher than the Vslv.

$$V_{lv} = KVhv \qquad (3)$$

$$I_{lv} = \frac{K * V_{shv} - V_{slv}}{(R_{hv} * K^2) + R_{lv}} \qquad (4)$$

In buck mode power from HV will be transferred to the LV. In this mode the second switch S6 will work as diode. And the first switch S5 will be controlled by PI controller to control the energy flow.

III. CONTROL TECHNIQUES

Converter control has two stages one is AC- DC PFC controller. Here 230V AC voltage is controlled to 380 V dc. To satisfy PFC operation the dc-link voltage must be greater than peak value of sine wave voltage. Dc-dc converter is controlled by constant current controller. 380V dc link voltage is converted to 120 v at constant current controller.

A. PFC controller

PFC control require two series loops such one is voltage feedback loop and second one is grid current feedback loop. The voltage feedback loop will regulate the DC-link voltage at constant desired value. The current feedback loop will control input current magnitude and also steer the current signal inphase with the input voltage signal to obtain the nearly unity power factor.

The equation of the switching frequency bridge rectifier can be shown below.

$$V_s = V_1 + V_r = L\frac{di_s}{dt} + V_s \Rightarrow V_s = V_s - L\frac{di_s}{dt} \qquad (5)$$

The output of the current controller produces only the inductor voltage drop required to maintain the sinusoidal source current. So the output of the current controller should be linearized in order that the output current of the converter becomes a first order linear system. This can be done as follows:

The input voltage of the rectifier Vc can be expressed by the duty cycle and the output voltage, Vdc.

$$V_c = (1-d)V_{dc} + V_r = L\frac{di_s}{dt} + V_s \Rightarrow V_r = V_s - L\frac{di_s}{dt} \qquad (6)$$

The controller is divided in 3 parts: the current controller, the voltage controller; and the linearizer. The controller is cascaded suggesting that the inner controller, being a current controller, should have a higher bandwidth than outer controller, which is a voltage controller. In this manner, it can be assumed that the inner control loop is ideal and the outer control loop cannot see it. (The outer control loop sees the gain of inner loop as 1)

The output of the current controller produces the inductor voltage drop to maintain the sinusoidal source current.

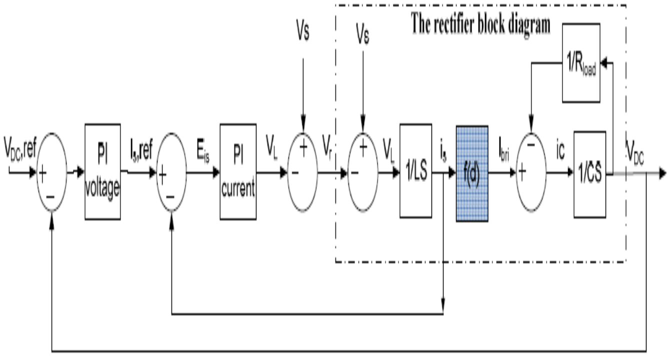


Fig. 13: Control technique for PFC

B. DC- DC current controller

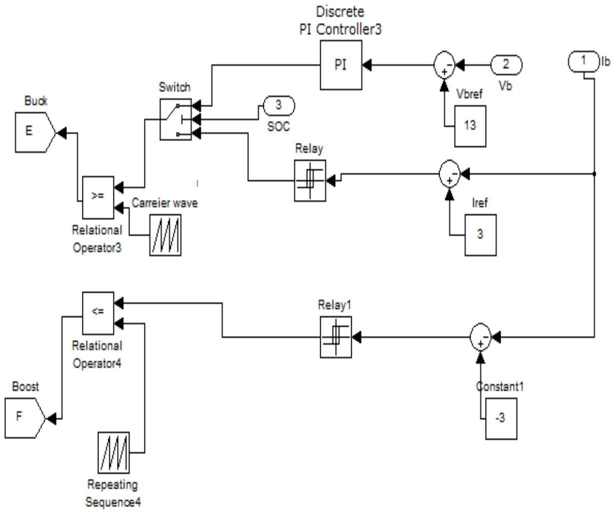


Fig. 14: Control technique for dc-d converter

This converter is controlled by using constant current controller this control is operating using PI controller. For SOC is less than 80% current controller is used. For SOC is more than 80% voltage controller and compared with fixed frequency ramp waveform [8]. In discharging mode S6 is controlled by constant current controller [9], [10].

IV. SIMULATION RESULTS AND DISCUSSION

In order to illustrate the performance of the converters, the simulation results are shown in this section. The electrical specification and circuit parameters are chosen as Vs = 230V 50 HZ AC supply Vdclink = 380V, lithium ion battery 120V 50AH, charging power 1.5 KW and discharging power 1.2 kW, Ls = 2mH, C1= 200uF, Cdclink = 1500uF, Lb = 2.2 mH, Cb = 100uF. Fig 14& 15 shows simulation waveforms of supply voltage and current at unity power factor. And converter voltages and dc link voltage and battery current and voltages during charging discharging. Battery current is controlled at 10A constant current.

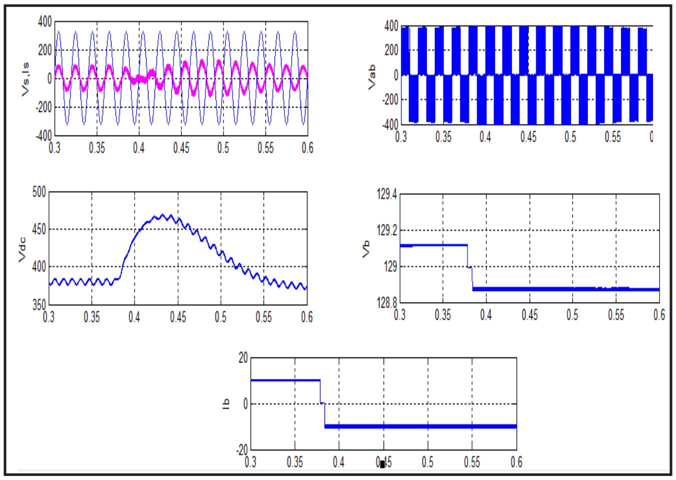


Fig. 15: Charging / Discharging simulated waveforms full profile

Fig. 15 shows full profile of charging discharging waveforms. At 0.4 operation of converter changed from charging to discharging. During 0.4 to 0.5s are transient period. During this period battery current direction will be reversed. And voltage across converter will become high comparative to steady state operation. Dc link voltage increased during this period, and came to normal position within few cycles. Battery also start discharging.

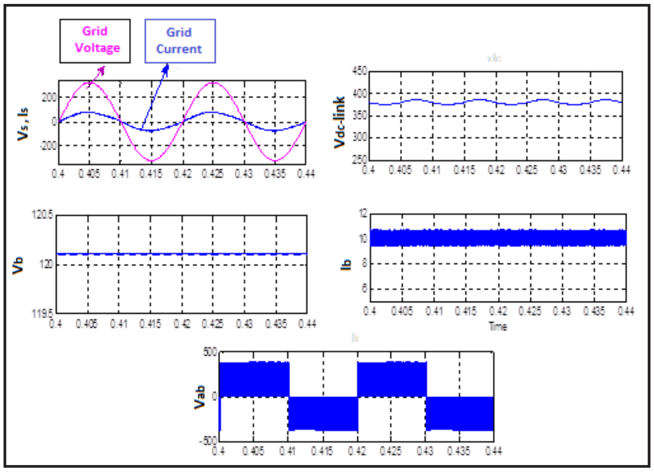


Fig. 16: Simulation waveforms in charging mode

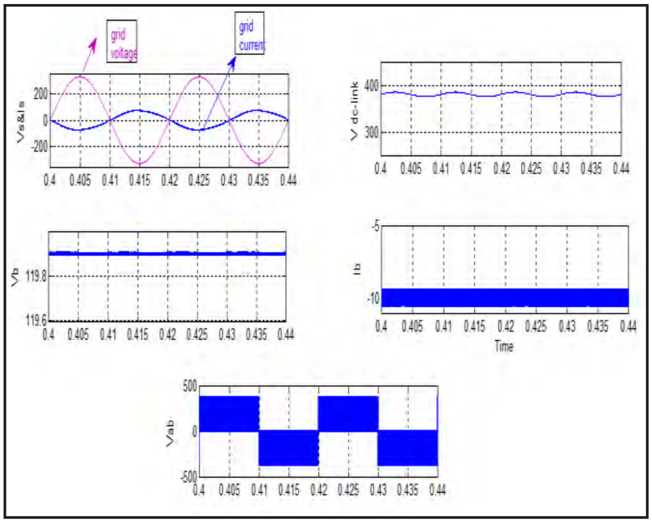


Fig. 17: Simulation waveforms in discharging mode

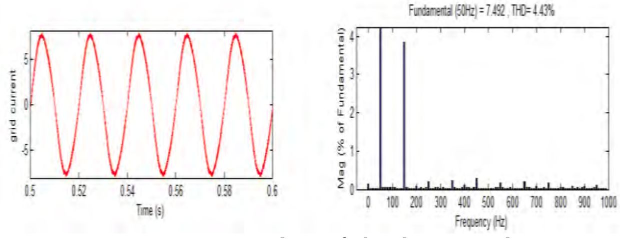


Fig. 18: Harmonic spectrum analysis of the charging grid current

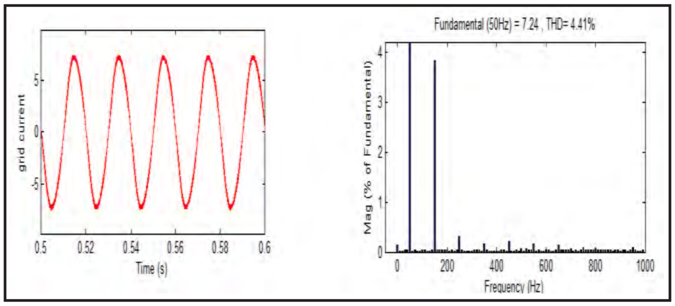


Fig. 19: Harmonic spectrum analysis of the discharging grid current

Fig. 16, 17 shows supply current and voltage waveforms during charging and discharging. In charging operation supply current following supply voltage, and in discharging supply current 180^o out pf phase with supply voltage. It can be prove that discharging mode of operation battery powering back to grid. Fig. 18 & 19 shows THD of grid current. During conversion operation THD is 4.43%. During inversion THD is 4.41%. By analyzing the harmonic spectrum of grid current it is clear that the third harmonic content is high compared to other harmonics i.e, 3.86% for converter operation and 3.82% for inverter operation. Third order harmonic component is most dominating compared to other harmonics. By this analysis if we can control 3rd harmonic we can improve the THD of grid current further more. By selecting proper switching frequency and control techniques which control third order harmonic we can improve grid current power factor and THD.

V. CONCLUSION

This paper presents AC-DC bidirectional full bridge PFC converter and bidirectional DC-DC converter. These converters used in hybrid vehicles for charging and discharging purpose at unity PF condition. During base load condition battery can be charged and during peak load condition battery can supply power back to grid with less harmonic content and THD. During charging THD value of grid current is 4.43%. In discharging period THD is 4.41%.

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