Volume 9, Issue 3
June 2020

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

Bidirectional On Board Electric Vehicle Charger

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ABSTRACT

The electric vehicle is the future of transportation in the coming years. This paper proposes an isolated onboard vehicular charger, for the application in an electric vehicle charger. This is a bidirectional charger. This converter allows an electric vehicle to act as an energy source when an emergency occurs. The proposed Bidirectional charger has two parts. During the G2V operation, the supply-side converter act as a power factor corrected boost converter and a battery side full bridge isolated DC-DC converter. During V2G/ V2H mode battery side converter act as a full-bridge boost converter and line side converter work as unipolar PWM inverter. PFC boost converter ensure the power factor improvement. A simulation model is presented in this paper.

Keywords: *EV charger, Bidirectional, PFC Bridge-less boost converter, Full bridge converter, Full bridge boost converter, Hysteresis control, Voltage mode control.*

1. INTRODUCTION

Due to the limited availability of fossil fuel, the universe is trying to find alternate solutions for transportation. The electric vehicle is a good replacement for IC engine vehicles in the coming future. Many of the research focusing on the development of vehicular technology for both fully electric vehicles (EVs) and plug-in hybrid EVs (PHEVs) [1]. Power electronic converters play a major role in improving efficiency, reducing the weight and volume of the system. Many different power electronic topologies were discussed in [2], [3].

The main anxiety of the user is the availability of charging stations, onboard charging has reduced this problem by allowing the vehicle to charge from any available ac power outlet. But onboard charging will increase the weight and volume of EV. A compact lightweight charger is required, which can be achieved by reducing the size of the passive component. Using higher frequency will reduce the size but it increases losses and effectively efficiency will reduce. That can be avoided by using Silicon-Carbide devices (SiC). SiC devices have many advantages compared to conventional Si devices [4] due to its wide bandgap property.

A microgrid is a small-scale power grid that can operate independently or collaboratively with other small power grids [5]. Microgrids are typically supported by generators or renewable wind and solar energy resources and are often used to provide backup power or supplement the main power grid during periods of heavy demand. A microgrid can operate in standalone mode, which is essential in many cases. Long-time operation in stand-alone mode will cause problems like the deficiency of power source during any emergency condition occures.

In the coming future EV can act as an energy source to microgrid when an emergency occurs. For that, a bidirectional charger topology is required. A bidirectional charger topology is presented in [6]. A non-isolated bidirectional topology was presented. Also, the charger in [6] is not an onboard type. The availability of the charging station will limit the application of this charger. A better bidirectional topology is required.

This paper presents an isolated bidirectional onboard charger using SiC devices. The proposed bidirectional charger has two bidirectional converters, a line side converter and a battery side converter separated by a DC link capacitor. The battery side converter is electrically isolated by a high-frequency transformer. G2V and V2G/V2H operation of the proposed converter is explained. The simulation model of the proposed converter is shown. The use of SiC devices will allow increasing the switching frequency, which reduces the inductor and capacitor size hence the weight can be reduced.

2. PROPOSED CHARGER

Volume 9, Issue 3
June 2020

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

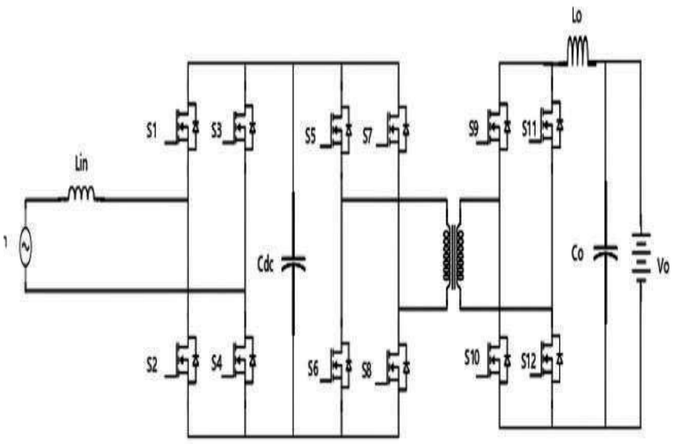

Figure 3 Proposed Bidirectional On Board Charger

The proposed bidirectional converter has two parts as shown in fig.1. Two operations are possible, charge the EV battery from the available ac source (G2V) and supply energy stored in the battery to ac grid or household load(V2G/V2H). All the switch used in the charger is SiC MOSFETs. A high-frequency transformer will electrically isolate the battery side and grid side.

A. G2V Operation

During G2V operation the power flow is from the grid to vehicle battery. During this operation line side converter act as a bridgeless (BL) PFC boost converter. The MOSFET S2, S4 are controlled and body diodes of S1 and S3 are used. S2 is controlled for the positive half cycle of input supply and S4 will be controlled for the negative half cycle as shown in fig2.

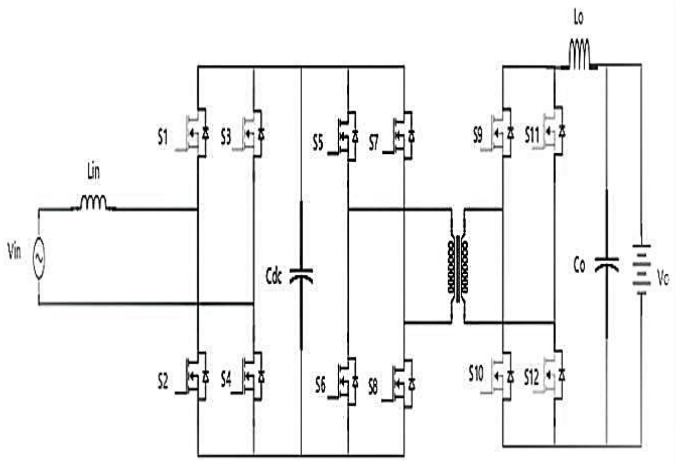

Figure 4. G2V operation.

Lines shown in dark color is the current-carrying path. Grey colored line doesnt participate in the operation. The expected waveforms are shown in fig3.

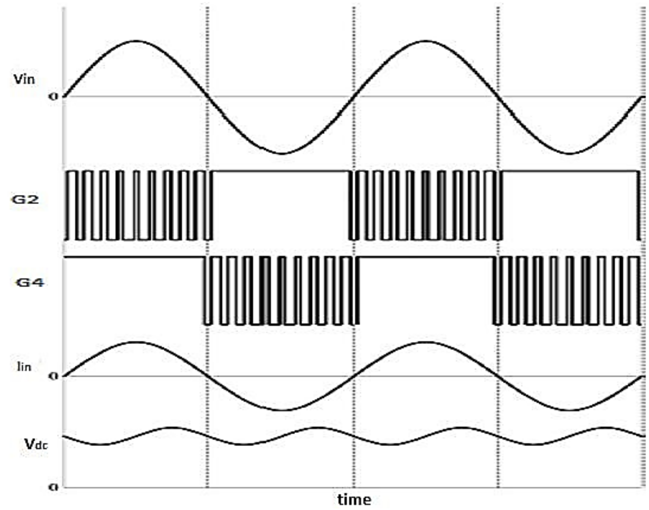

Figure 5. Expected waveforms of BL boost converter

The battery side converter act as Full bridge converter, MOSFET S5, S6, S7, S8 are controlled and body diodes of S9, S10, S11, S12 are used.

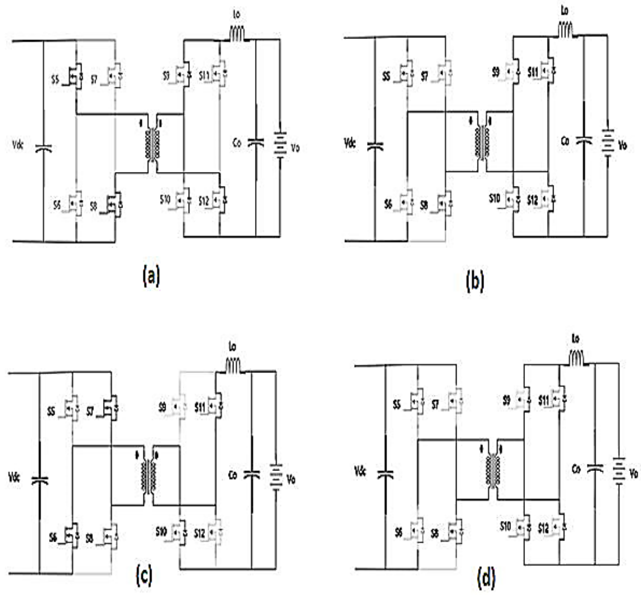

Figure 6. Working of Full bridge boost converter

The switches S5 and S8 are initially turned on simultaneously by keeping S6 and S7 turned off, the voltage across the primary side of the transformer is Vdc. The diodes of S9 and S12 are forward biased and then inductor Lo is energized. Now all the switches are in the off state, then inductor will de-energize by freewheeling through the diodes

After T/2 period switches S7 and S6 are turned on by keeping S5 and S8 turned off voltage across the primary side

ITEE Journal
Information Technology & Electrical Engineering
ISSN: - 2306-708X

of the transformer is -Vdc, diodes of S11 and S10 are forward biased and then inductor Lo is energized.

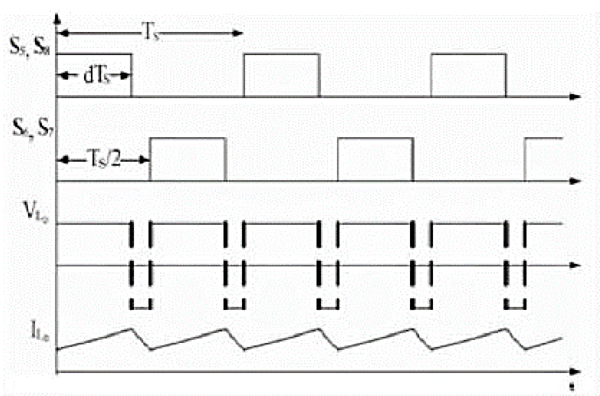

Figure 7. Waveforms of Full bridge converter

Now all the switches are in the off state, then inductor will de-energize by freewheeling through the diodes. This is shown in figure. It is found that the frequency of charging and discharging of the inductor current is twice that of the switching frequency. This will allow reducing the size of the inductor and capacitor. It should be taken care that the maximum duty ratio should be less than 0.5. This is shown in fig.4. The expected waveform of the full-bridge converter is shown in fig.5

B. V2G/V2H Operation

In this mode of operation EV act as an energy source. The charger will convert the dc power of the battery into ac in for feed the grid or to feed household load in the case of an emergency. The fig.6 shows the V2G operation of the proposed charger.

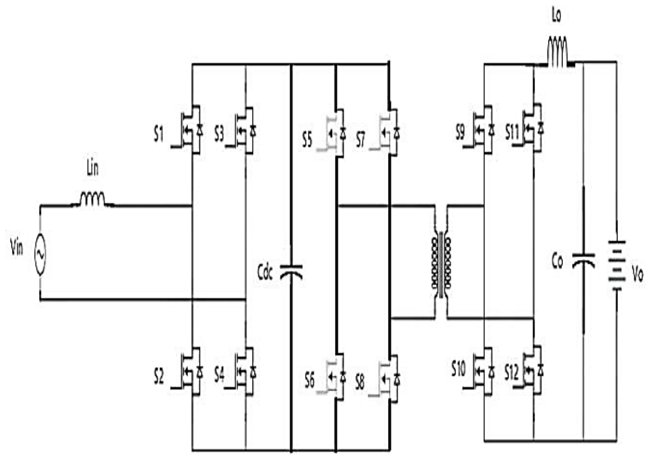

Figure 8 V2G operation of proposed charger

During this operation battery side converter works as a full-bridge boost converter. The switches S9, S11, S12, and S13 are controlled and diodes of S5, S6, S7, S8 are used. Here the duty ratio should be more than 0.5 so that switches in the same leg turn on together to energize the inductor, Lo. Shown in fig.7.

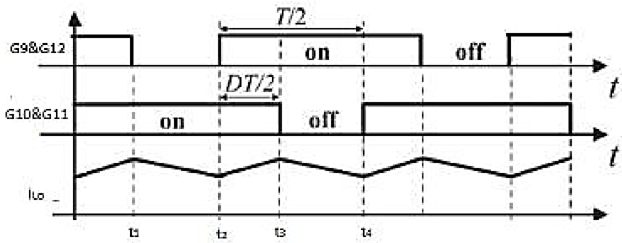

Figure 9. Waveforms of Full Bridge boost converter

Initially, S9, S11, S12, S13 are closed, now the inductor Lo is energized. The current through Lo increases linearly up to time t1. At t1 switches, S9 and S12 are turned off. Now the battery and energy stored in the inductor come across the transformer, so the energy stored in the inductor releases. Now inductor current decreases linearly as shown in fig.8. At t2 switches, S9 and S12 are turned on.

Now all switches are in on state, the inductor Lo is energized. The current through Loin creases linearly up to time t3. At t1 switches S10 and S11 are turned off, so the energy stored in the inductor releases. Now inductor current decreases linearly.

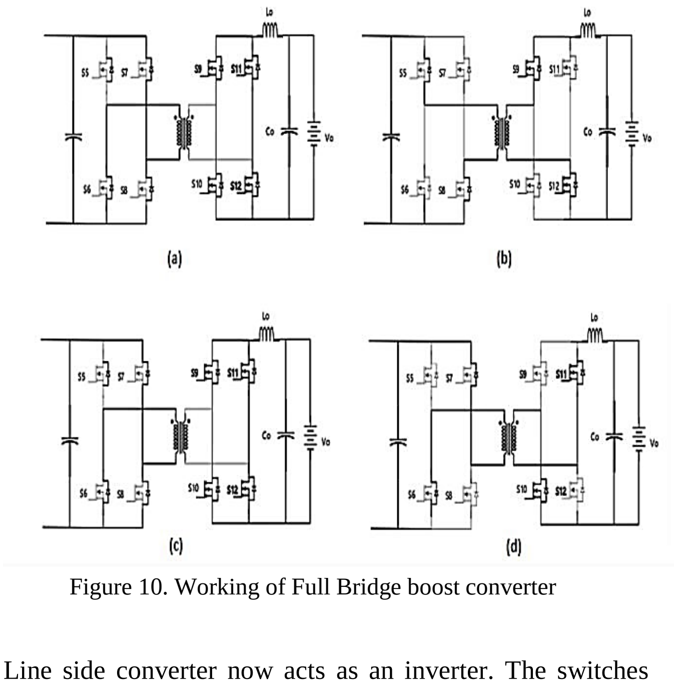

Figure 10. Working of Full Bridge boost converter

Line side converter now acts as an inverter. The switches S1, S2, S3, and S4 are controlled by the unipolar PWM method. The output ac voltage can be can synchronized with the grid or can be given to ac load directly.

3. COMPONENT DESIGN

Volume 9, Issue 3
June 2020

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

The components used in the bidirectional converter should satisfy both G2V operation and V2G operation. The choice of passive component values should be carefully designed so that both operations work perfectly.

A. G2V Operation

During G2V operation design specification is shown in the table I.

TABLE I
DESIGN CONSIDERATION FOR G2V OPERATION

PARAMETERS	VALUE
Line side Voltage	200-250 V
DC link Voltage	350V
Battery side Voltage	425-450V
Maximum Output Power	3kW
Switching Frequency	150kHz

L boost converter design consist of inductor Lin design a DC link capacitor Cdc design, the inductor value can be designed with current ripple of 1% of the input current. The percentage of voltage ripple of the DC link capacitor selected was 15%. The choice of high voltage ripple is because the size of the capacitor will increase when ripple reduces. The full-bridge converter design consists of an output inductor design, transformer design, and output capacitor design. The turns ratio of the transformer is chosen as 1:2

B. V2G Operation

During V2G operation design specification is shown in the table II.

TABLE II
DESIGN CONSIDERATION FOR V2G OPERATION

PARAMETERS	VALUE
Battery side Voltage	425-450V
DC link Voltage	400V
Line side Voltage	230V
Switching Frequency	150kHz

Full bridge boost converter design consists of inductor design Lo, transformer design, and output capacitor design Cdc. The turns ratio of the transformer is chosen as 2:1. The line side inductor will filter the harmonics of the inverter. The choice of inductance value is done by taking the cut off frequency 150 Hz and the filter capacitor (Cin) value is taken as 0.1 µF.

TABLE III
PASSIVE COMPONENT VALUES

COMPONENT	VALUE
Line side Capacitance (Cin)	0.1 µF
Line side Inductance (Lin)	200 µH
DC Link Capacitance	660 µF
Battery side inductance	200 µH
Battery side Capacitance	200 µF

The table III shows the final values of the designed values. During G2V operation the line side capacitor and battery side capacitor in V2G operation will not affect the performance of the proposed charger, this is verified during the simulation.

4. CONTROL STRATEGY

The proposed charger can be divided into four converters sections. Line side PFC bridgeless boost converter and a battery side full-bridge converter during G2V operation similarly Battery side full bridge boost converter and line side unipolar PWM inverter during V2G operation. So the controller for each case is designed separately.

A. PFC BL Boost Converter

Hysteresis current control method is used to control the PFC boost converter [7]. In this control a reference DC link voltage is compared with actual dc-link voltage, the error is fed to a PI controller. PI controller gives the amplitude of reference input current. A unit sine signal which has the same phase and frequency of input ac supply voltage is multiplied with the output of the PI controller to get a reference input current. This is compared with the actual input signal and error is given to the hysteresis control block. Hysteresis control block will generate gate pulses to control the switches S2 and S4

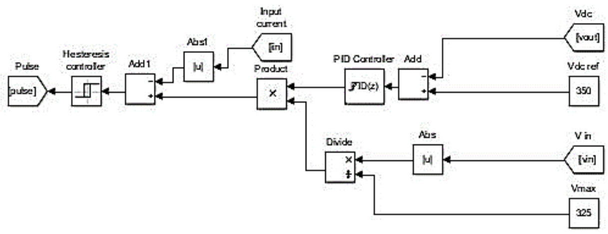

Figure 11. Hysteresis control of BL boost converter

B. Full Bridge DC-DC Converter

Voltage mode control is used to control the full-bridge converter. The reference battery side voltage is compared with the actual battery side voltage, the error is given to the PI controller which gives a duty ratio. A gate pulse is generated accordingly and given to switches S5, S8 and S6, S7. The maximum limit of duty the ratio is fixed as 0.5

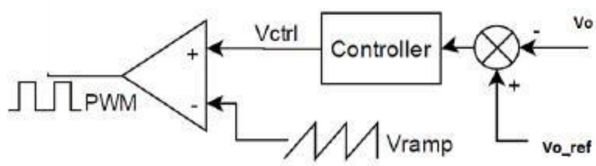

Figure 12. Voltage mode control full bridge converter

C. Full Bridge Boost DC-DC Converter

Voltage mode control is used to control the full-bridge boost converter. The reference DC link voltage is compared

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with the actual DC link voltage, the error is given to the PI controller which gives a duty ratio. A gate pulse is generated accordingly and given to switches S9, S12, and S10, S11. The maximum limit of the duty ratio is fixed as 1 and the minimum duty ratio is fixed as 0.5.

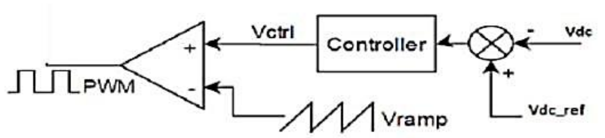

Figure 13. Voltage mode control full bridge boost converter

D. Unipolar PWM Inverter

Switches S1, S2, S3, and S4 are controlled by unipolar modulation techniques. A sine wave of required frequency and phase of the grid is generated and compared with the carrier signal of higher frequency. When a sine wave becomes greater that carrier wave S1 is turned on otherwise S2 is turned on. Similarly, a 180 phase-shifted sine signal is also compared with the carrier signal. When the phase-shifted sine wave becomes greater that carrier wave S3 is turned on otherwise S4 is turned on. Using a proper filter inductor output can be made sinusoidal. A mode selector in the control algorithm will select the mode of operation which is shown in fig.12. During G2V operation hysteresis control and Voltage mode control of full-bridge converter is selected.

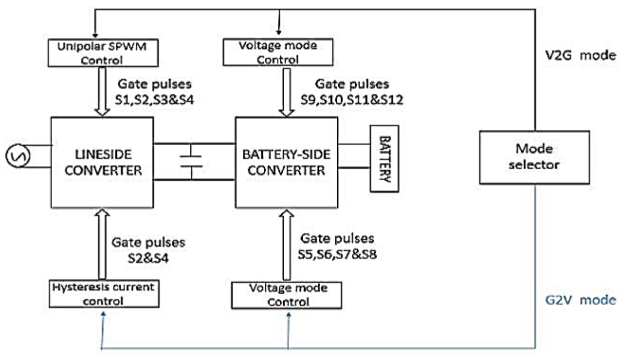

Figure 14. Block diagram of control scheme

During V2G or V2H operation voltage mode control of full-bridge boost converter and unipolar modulation of the inverter is selected.

5. SIMULATION RESULTS

The simulation of the proposed converter is done in MAT-LAB Simulink. Both G2V and V2G are simulated separately.

A. Simulation of G2V operation

For simplicity the load is taken for simulation was resistive load. Voltage mode control of the full-bridge converter is done by as explained above. In the hysteresis controller of BL boost converter relay switch is used as the hysteresis block. For easy calculation, absolute values of input current and reference current is taken. To split the gate pulse generated by the hysteresis controller during positive and negative half-cycles for the switches S2 and S4, another model is used.

The DC link voltage is shown in fig.13.

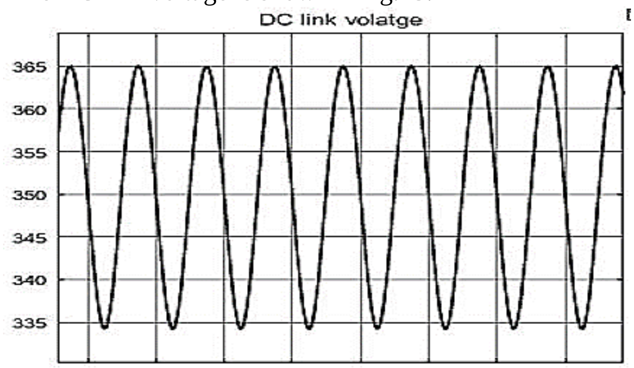

Figure 15. DC link voltage during G2V operation

The DC link voltage has a ripple voltage of 30 V, which is now the input of the full-bridge converter. The controller should keep the output voltage constant. Even though the DC link voltage is in oscillating nature, the load voltage contains very few ripple content. This is shown in fig.14.

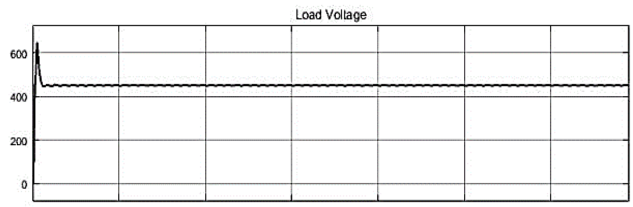

Figure 16. Load voltage during G2V operation

The Main objective of G2V operation is to get constant battery side voltage along with making input current sinusoidal with a power factor close to unity. The simulation result of the input waveforms are shown in fig.15.

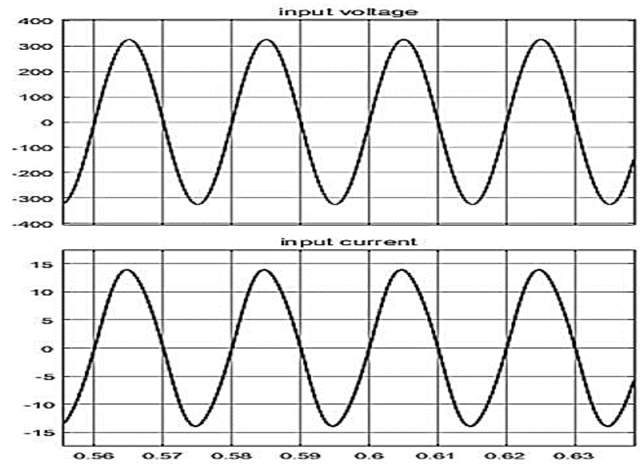

Figure 17. Line side waveforms during G2V operation

From the fig.15 The input current and input voltages are in phase. This indicates that the input power factor is very near to unity. The calculated value of the power factor from the simulation is 0.9996.

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Information Technology & Electrical Engineering

ISSN: - 2306-708X

Fig.16 shows the THD of the input current is measured using the Simulink powergui block. The THD was measured as 2.89% which is less than IEEE standards. Low THD value reduces the distortion factor, also the power quality problem reduced. The efficiency calculated was 92 %.

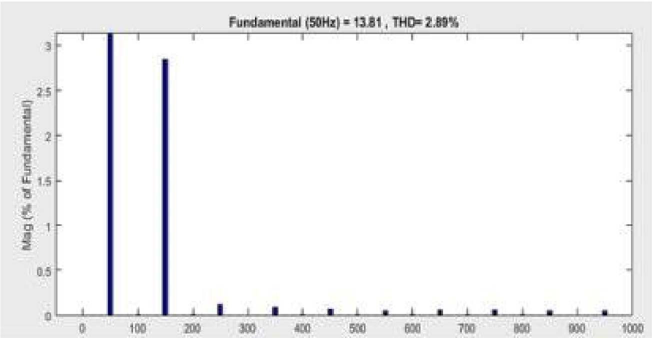

Figure 18. THD graph of input current during G2V operation

Fig.17 shows the waveforms of the full-bridge converter. From the figure inductor current ripple is found as designed value. The waveforms are obtained as expected waveforms are shown in fig.4. From the figure it is clear that the frequency of the inductor current is two times the switching frequency, this advantage full-bridge converter is allowed to reduce the inductor size.

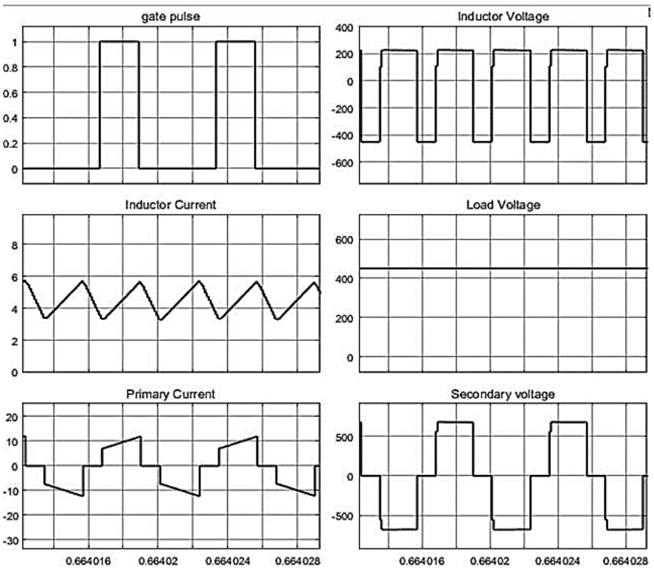

Figure 19. Wave forms of full bridge converter

B. Simulation of V2G operation

Power flows from battery side to line side in this mode of operation. The load is taken as a resistive load and connected in line side of the charger. A DC voltage source is connected to the Battery side for the sake of simplicity.

Voltage mode control of full bride boost converter is done by as explained above. The unipolar PWM control is done using a sine generator block, this sine may be obtained from PLL during V2G operation or generate internally for V2H operation. The objective of V2G operation is to produce a sinusoidal line side current using the vehicle battery. The simulation result of line side waveforms is shown in fig.18.

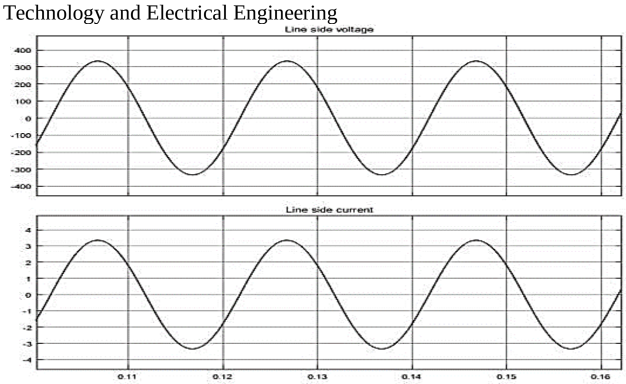

Figure 20. Line side waveforms during V2G operation

From fig.18 it is clear that the input current and input voltages are in phase, because load connected in at line side terminal is resistive. This indicates that the input power factor is very near to unity.

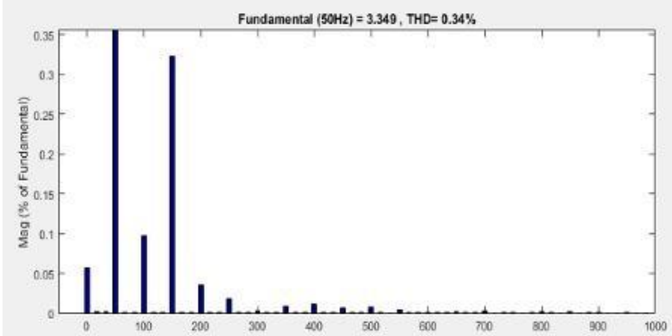

Figure 21. THD graph of Line current during v2G operation

Fig.19 shows the THD of the input current is measured using the Simulink powergui block. The THD was measured as 0.34 % which is very less than IEEE standards. Low THD value reduces the distortion factor, also the power quality problem reduced.The calculated value of the power factor from the simulation is 1 and the efficiency calculated was 89 %.

The DC link voltage is shown in fig.20

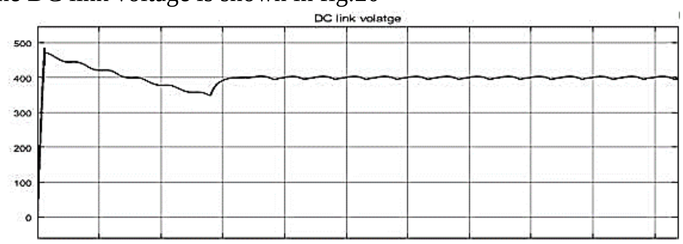

Figure 22. DC link voltage waveform during V2G operation

The DC link voltage has a ripple voltage of 8.6V, which is now the output of the full-bridge boost converter. The controller should keep the DC link voltage constant even though battery voltage reduces after a few working hours. Fig.21 shows the waveforms of the full-bridge boost converter. From the figure inductor current ripple is found as designed value. The direction of the inductor current is opposite to the conventional current direction (grid to the battery).

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Information Technology & Electrical Engineering

ISSN: - 2306-708X

The waveforms are obtained as expected waveforms are shown in fig.7. From the figure it is also clear that the frequency of the inductor current is two times the switch-ing frequency, this advantage full-bridge boost converter is allowed to reduce the inductor size.

The simulation results shows that the proposed converter can operate in both G2V and V2G mode with very low THD and power factor very close to unity. V2G mode shown in this result is actually Vehicle to Home (V2H)mode of operation. For actual V2G operation the sine signal in the unipolar inverter can be obtained using PLL block. Even the V2H mode operation is a applicable in several emergency cases.

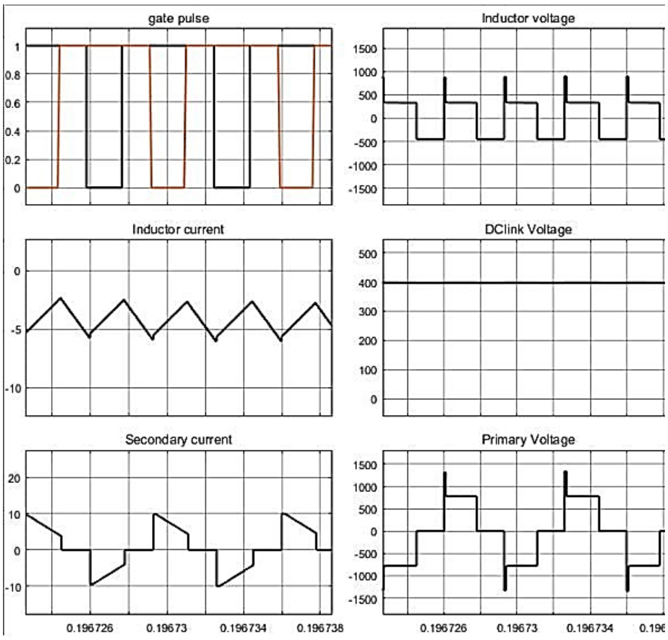

Figure 23. Battery side waveforms during V2G operation

6. CONCLUSION

This paper is based on a bidirectional onboard EV charger. The G2V and V2G operation are described in detail. During G2V operation charger work as cascade combination of BL boost converter and full-bridge converter. During V2G opera-tion full-bridge boost converter followed by unipolar inverter combination will convert DC power of battery into AC. A MATLAB Simulink model of both G2V and V2G operations are performed. The result shows satisfying performance as expected. The proposed converter reduces the power quality problems and working with good efficiency. SiC devices will further have more advantages than conventional Si devices. This allows us to increase the switching frequency effectively the size of passive components hence the weight of the charger can be reduced.

The converter efficiency can further be improved by making the soft-switching technique since full-bridge converter is used ZVS operation can be achieved very easily. This also allows increasing switching frequency further hence the size and weight of the charger can be further reduced.

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ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

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