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Non-Isolated Bi-directional DC-DC Converters for Plug-In Hybrid Electric Vehicle Charge Station Application

Sureshkumar B. Tank[1], Kelvin Manavar[2], Nitin Adroja[3]
[1,2]PG Student, [3]Asst.professor
Electrical Engineering Department, Atmiya Institute of Technology & Science, Rajkot

[1]suresh90pe@gmail.com
[2]kelvinmanavar@gmail.com
[3]nhadroja@aits.edu.in

***Abstract*— There is a growing interest on plug-in hybrid electric vehicles (PHEV's) due to energy security and green house gas emission issues, as well as the low electricity fuel cost. As battery capacity and all-electric range of PHEV's are improved, and potentially some PHEV's or EV's need fast charging, there is increased demand to build high power off-board charging infrastructures. A charge station architecture has been proposed, which has a DC micro grid to interface with DC-DC chargers and energy storage. Several non-isolated bidirectional DC-DC converters suited for charge station applications have been reviewed and compared. Half bridge converter is a good candidate.**

***Keywords*— Plug-in hybrid electric vehicle, Bidirectional DC-DC Converter, Battery charger, Energy management.**

I. INTRODUCTION

Nowadays about 62% of crude oil used in United States is refined into gasoline for transportation. The associated energy security and green house gas emission problems are well known. Hybrid electric vehicles (HEV's) is one of the solutions to address these issues, because the fuel economy has been improved by optimizing internal combustion engine (ICE) efficiency, regenerating brake energy and shutting down ICE during the idle time.**[1]** After more than one million HEV's are driven on the road today, there is a growing interest on plug-in hybrid electric vehicles (PHEV's), which is defined by IEEE-USA's Energy Policy Committee as (1) A battery storage system of 4kWh or more, used to power the motion of the vehicle (2) A means of recharging that battery system from an external source of electricity (3) An ability to drive at least 10 miles in all-electric mode consuming no gasoline. PHEV's can be power by electricity from various sources, including emerging renewable power generations, and benefit from lower fuel (electricity) cost. Green house gases such as CO2 emission is expected to be greatly reduced due to much less petroleum consumption for daily commuters who drive PHEV's mainly in all-electric mode. Major automakers are preparing to launch the first models in a new generation of PHEV's in 2010. Several global and U.S. market research reports indicate there will be a rapid growth on PHEV's sales. **[2]**

Currently major PHEV's are designed for an all-electric range of several tens miles to meet daily commute requirement, due to the high cost of on-board battery energy storage system. An on-board charger is usually employed for slow overnight charging in home garage. However, as battery capacity and all-electric range of PHEV's are improved, and potentially some PHEV's or EV's in the future need fast charging to extend all-electric drive range, there is increased requirement to build off-board charge station infrastructures.

Several non-isolated bi-directional DC-DC converters suited for charge station application have been reviewed and compared. Half bridge converter is considered to be a good candidate but it is difficult to maintain high efficiency in wide battery pack voltage range.

II. MOTIVATION TO BUILD CHARGE STATION INFRASTRUCTURE

Currently most PHEV's use single-phase on-board charger to refuel their batteries, which is the common practice for both converted PHEV's and several ones that will be commercialized soon. On-board charger can either use independent power converter, or leverage the power stage of drive train and motor inductance.

The power rating of onboard charger is low, limited to the current rating of wall plug. With advancement of battery technology, the energy density and power density of battery packs are improved and battery cost decreases, the desire of more on-board battery capacity for more all-electric range and less gasoline consumption is possible for future PHEV's or EV's. Therefore there will be a trend for battery chargers to shift from compact low power onboard installation to shared large high-power off-board charging station in the future.

The second motivation to build this charge station infrastructure is to use a DC link to interface with distributed renewable power generations, which can be considered as a micro grid.

The third motivation is to fast charge a PHEV/EV battery pack. In order to improve the all-electric range of PHEV's and EV's, one will either increase the on-board battery capacity or recharge the battery pack in very short time at a fast charging station. However, all-electric range will be eventually limited by battery capacity due to the size and weight as well as the cost of batteries. Therefore, high power fast charging will potentially solve EV range problem by recharging its battery in 10 to 30 minutes, like what people do in today's gasoline station, as long as the battery packs are capable of accepting high rate charging current.[2]

III. ARCHITECTURE OF PLUG-IN HYBRID ELECTRIC VEHICLE CHARGING STATION

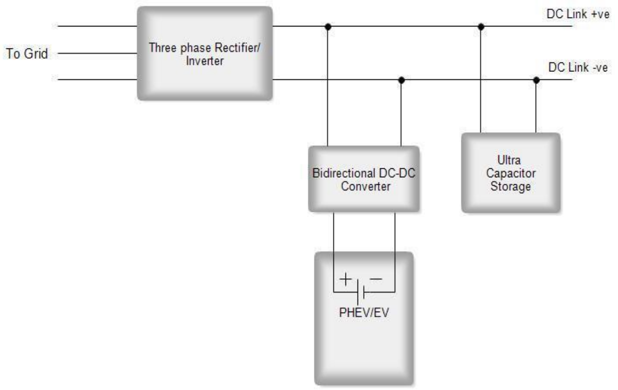


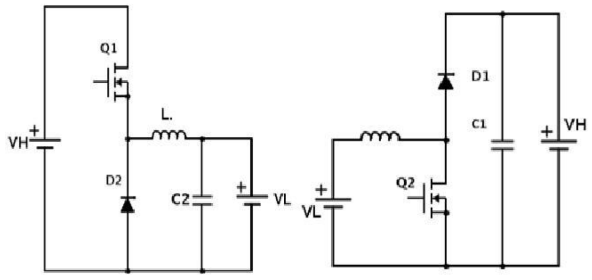
Figure 1 Proposed Charging Station Architecture with DC Power Distribution

The proposed architecture of PHEV'S charge station is shown in Figure 1. Compared to discrete AC-DC and DC-DC chargers, the proposed charge station uses higher DC distribution bus with one high power three-phase AC-DC converter as grid interface. This architecture has several advantages. The specific cost of high power AC-DC stage is lower than that of discrete low power AC-DC converters if AC power distribution bus is used. The three phase rectifier is rated for average power rather than peak power if ultra capacitor energy storage is installed to filter the ripple power. The power of each DC-DC channel is rated for normal slow charge rating to minimize cost. The parallel of several DC-DC stages provides a high power fast charging channel, assuming only small portion of PHEV's will require this service. With bi-directional DC-DC converters, energy stored in PHEV batteries can be fed back to grid, which is called V2G operation. An intelligent energy management system (IEMS) with wireless Zigbee communication platform can coordinate system operation. The charge station can provide several grid support functions such as reactive power injection, peak power generation, harmonic current filter, and load balance .[3]

The bi-directional DC-DC converters are basic building blocks for Plug-in Hybrid Electric Vehicle charging stations and they are the interface between PHEV battery system and the DC distribution grid. Bi-directional DC-DC converters with low cost, high efficiency and high reliability are important for the charging stations. The non-isolated bi-directional DC-DC converters can be considered for this application and their performance is compared in the following sections.[4]

IV. NON-ISOLATED BIDIRECTIONAL DC-DC CONVERTERS

Basically a non-isolated bidirectional DC-DC converter can be derived from the unidirectional DC-DC converters by enhancing the unidirectional conduction capability of the conventional converters by the bidirectional conducting switches. Due to the presence of the diode in the basic buck and boost converter circuits shown in figure 2, they do not have the inherent property of the bidirectional power flow. This limitation in the conventional Boost and Buck converter circuits can be removed by introducing a Power MOSFET or an IGBT having an anti parallel diode across them to form a bidirectional switch and hence allowing current conduction in both directions for bidirectional power flow in accordance with the controlled switching operation. [4,5]



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(a) (b)

Figure 2 (a) Buck Converter and (b) Boost Converter

Buck Boost Converter

The first bidirectional topology can be directly derived from the conventional buck boost topology by the introduction of the bidirectional conducting switch as shown in figure 3.

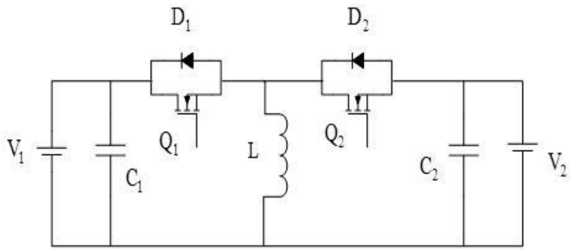

Figure 3 Bidirectional Buck Boost Converters

During step up operation Switch Q1 is conducted at the required duty cycle whereas the switch Q2 is kept off all the time. Similarly during the step down operation the switch Q2 is made to conduct at required duty cycle whereas the switch Q1 is always off. Small Dead time is provided during mode transition in order to avoid the cross conductance through two switches and the converter output capacitance.

Buck Boost Cascade Converter

The second Bidirectional topology as seen in the figure 4 can be obtained by cascading the bidirectional buck converter with bidirectional boost converter. This topology allows the output voltage to be either higher or lower than the input voltage depending up on the switch combinations used and the direction of the current. For the step up operation in the forward direction, the switch S1 is always on and S2 and S4 are always off, whereas the switch S2 is conducted depending on the duty cycle. During forward step down operation the switch S1 is operated with the required duty cycle and the switch S2, S3, S4 are always off. Diode D2 and D3 are always reverse biased whereas the D3 is always forward biased. Diode D4 acts as a freewheeling diode. Similarly in the backward step up operation, switch S3 is always on whereas the switch S4 is operated with the required duty cycle with the diode D1 acting as a freewheeling diode.

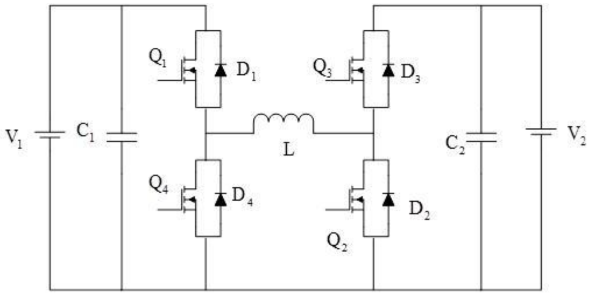

Figure 4 Bidirectional Cascade Buck-Boost Converter

Cuk Converter

The third topology is obtained by replacing the unidirectional switches of the conventional Cuk converter by the bidirectional switches. The resulting circuit is as shown in the figure 5. The capacitor C acts as the main storage element whereas the capacitors C1 and C2 act as the coupling capacitors. It can step up or step down the input voltage like a buck-boost converter but with inverted polarity.

Half-Bridge DC-DC converter

When the Buck and the boost converters are connected in anti parallel across each other with the resulting circuit is basically having the same structure as the fundamental Boost and Buck structure but with the added feature of bidirectional power flow. The below figure 6 shows the basic structure of the non-isolated Half-Bridge Bidirectional DC-DC converter. **[6]**

The above circuit can be made to work in buck or boost mode depending on the switching of the MOSFETs Q1 and Q2. The switches Q1 or Q2 in combination with the anti parallel diodes D1 or D2 (acting as freewheeling diode) makes the circuit step up or step down the voltage applied across them. The bi-directional operation of the above circuit can be explained in the below two modes as follows:

Mode 1 (Boost Mode): In this mode switch Q2 and diode D1 enters into conduction depending on the duty cycle whereas the switch Q1 and diode D2 are off all the time. This mode can further be divided into two interval depending on the conduction on the switch Q1 and diode D2 as shown in the Figure 6.

Interval 1 (Q2-on, D2-off; Q1-off, D2-Off): In this mode Q2 is on and hence can be considered to be short circuited, therefore the lower voltage battery charges the inductor and the inductor current goes on increasing till not the gate pulse is removed from the Q2 . Also since the diode D1 is reversed biased in this mode and the switch Q1 is off, no current flows through the switch Q1.

Interval 2 (Q1-off, D1-off; Q2-off, D2-on): In this mode Q2 and Q1 both are off and hence can be considered to be opened circuited. Since the current flowing through the inductor cannot change instantaneously, the polarity of the voltage across it reverses and hence it starts acting in series with the input voltage. Therefore the diode D1 is forward biased and hence the inductor current charges the output capacitor C2 to a higher voltage. Therefore the output voltage boosts up.

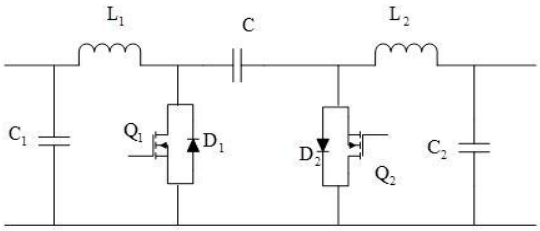

Figure 5 Bidirectional Cuk Converter

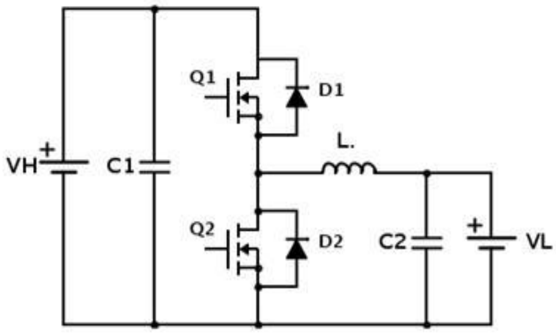

Figure 6 Non Isolated Half-Bridge Bidirectional DC DC Converter

Mode 2 (Buck Mode): In this mode switch Q1 and diode D2 enters into conduction depending on the duty cycle whereas the switch Q2 and diode D1 are off all the time. This mode can further be divided into two interval depending on the conduction on the switch Q2 and diode D1 as shown in the Figure 6.

Interval 1 (Q2-on, D2-off; Q1-off, D2-Off): In this mode Q1 is on and Q2 is off and hence the equivalent circuit is as shown in the Figure below. The higher voltage battery will charge the inductor and the output capacitor will get charged by it.

Interval 2 (Q1-off, D1-off; Q2-off, D2-on): In this mode Q2 and Q1 both are off. Again since the inductor current cannot change instantaneously, it gets discharged through the freewheeling diode D2. The voltage across the load is stepped down as compared to the input voltage.[7]

A comparison between the different features of the non-isolated bidirectional topologies have been presented below: [4]

1. During step up mode, in the buck-boost bidirectional converter the rms value of the current through the inductor and the power switches is greater by an amount equal to the output current as compared to the buck-boost cascade bidirectional converter. Also the capacitor RMS current also exceeds in the former case by an amount of the 1/3rd of the output current. Therefore in the bidirectional buck-boost converter the inductor, power switches and the capacitor operate under more thermal and electrical stresses as

compared to the buck boost cascade converter resulting in the greater power loss and also causing the saturation of the inductor core.

2. However the number of devices required by the cascade buck boost converter is twice the number devices in buck-boost bidirectional converter. This problem can be solved by using the Half-Bridge Bidirectional DC-DC Converter. It has the same no devices as the buck-boost bidirectional converter and can be employed instead of the buck-boost cascade bidirectional converter for the applications that require the boost operation only in one direction and the buck in the other.

3. The main advantages of the half bridge bidirectional converter as compared to the bidirectional Cuk converter is that it only requires one inductor instead of two and that too half the value of latter as well as the power switches ratings required for the half bridge bidirectional converter is much lower as compared to the Cuk converter. Also the efficiency of the half bridge converter is higher than the Cuk converter because of the lower inductor current and therefore lower conduction as well as lower switching losses.[8]

Here half bridge converter use because of simple structure, high efficiency, low cost, high reliability, etc. Half-bridge Converter which operates either in Buck or in Boost mode shown in figure 6. When bi-directional DC-DC converters work in charging mode, the ratio of output voltage Vo to input voltage Vin is lower than 1; when they work in discharging or V2G mode, the ratio of Vo to Vin is larger than 1. Half Bridge is expected to be more efficient and it also has less number of inductor and capacitors. Half Bridge converter is a better candidate in this scenario.

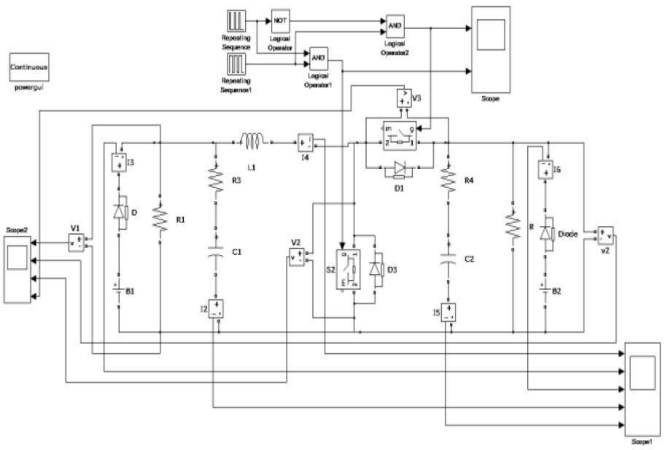

Figure 7 Open loop simulation model.

The battery side voltage can change in wide range. When battery pack voltage is high, the efficiency of Half Bridge is better because the current stress for inductor and switches are lower. However, if battery side voltage is low and constant power charging is assumed to be the worst scenario, current stress in converter increases and the efficiency drops quickly. It is even worse for low power conversion efficiency in lower battery voltage range because during charging process the major portion of charge is injected to battery in lower voltage range.[9,10]

Table 1 Design Specification of Bidirectional DC-DC Converter

Parameter	Nation	Values
Battery High output voltage range	V2,out	12
Battery Low output voltage range	V1,in	5
Switching frequency	fs	20KHz
Inductor	L	150e-6
Capacitor	C1, C2	200e-6, 220e-6

V. SIMULATION AND RESULTS

Open loop Simulation of the bidirectional Converter for PHEV'S with the designed values was done in the Matlab Simulink.

Bidirectional Operational:

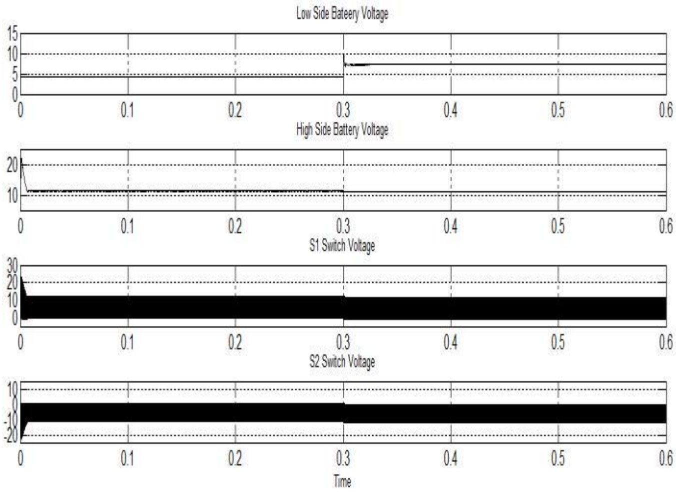

Figure 8 Low & High side Battery Voltage & Switch (S1 & S2) Voltage for bidirectional DC-DC Converter

Boost operation:

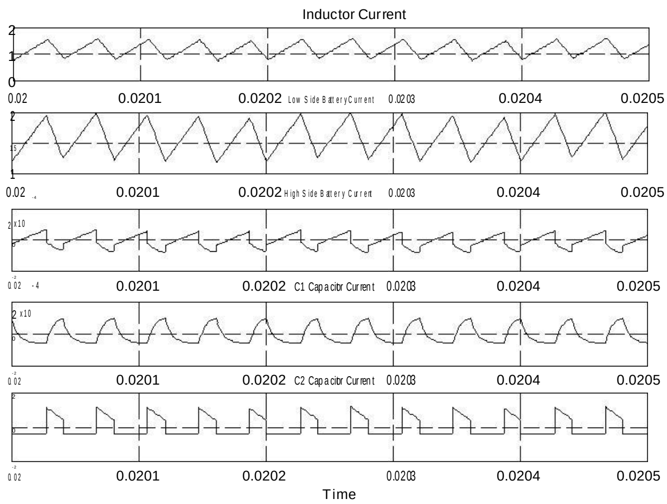

Figure 9 Low & High side Battery Voltage & Switch (S1 & S2) Voltage

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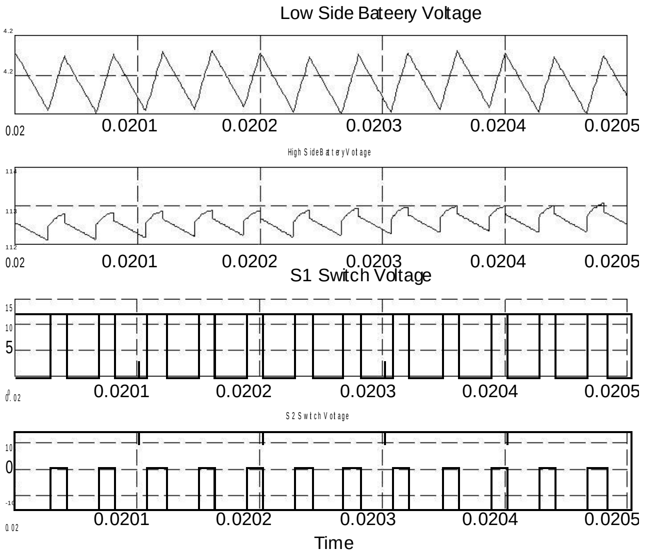

Figure 10 Inductor current, Low & High side Battery current, Capacitor (C1 & C2) Current

Buck operation:

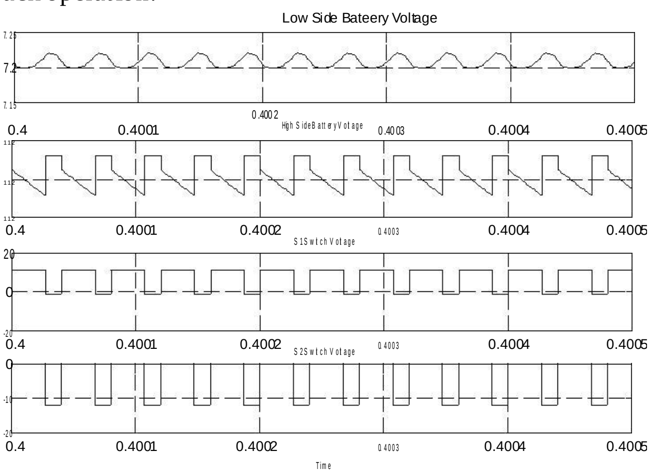

Figure 11 Low & High side Battery Voltage & Switch (S1 & S2) Voltage

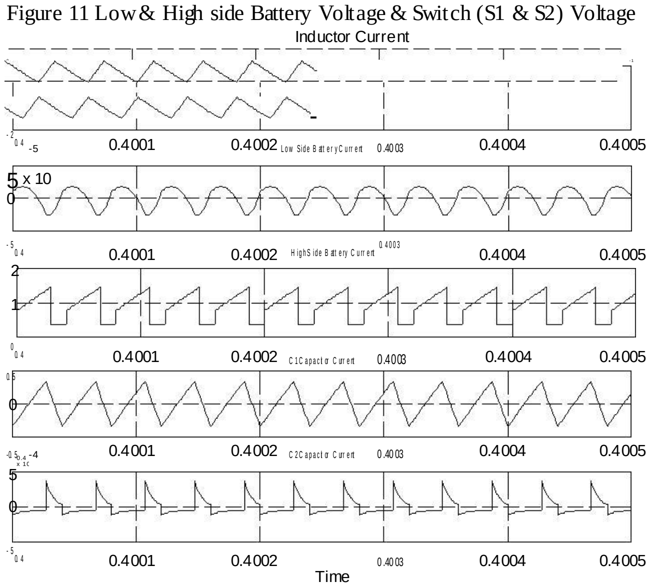

Figure 12 Inductor current, Low & High side Battery current, Capacitor (C1 & C2) Current

CONCLUSION

Several low cost non-isolated bi-directional DC-DC converters suited for Plug-in hybrid electric vehicle charge station applications have been reviewed and compared. Half bridge converter is better than Cuk and SEPIC/Luo converter because of smaller number of passive components, lower switch current stress and higher efficiency. The topology is suitable for high power applications, in particular for controlling the charge discharge of ultra-capacitors that can be used in plug-in hybrid electric vehicle.

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