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DC –DC Converters Types for Application in Electric Vehicles

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Abstract
The attention towards Electrical Vehicles (EV's) in present scenarios is increasing as they can possibly from a key workable transportation system in upcoming future with less CO_2 emission, reduced dependency on fossil fuel and high efficacy. Bi-directional converter enables energy transfer from vehicle to grid (V2G) and vehicle to home (V2H) along with charging from grid to vehicle (G2V). Inter-connection of the vehicle battery to the AC-DC link in both the modes of charging as well as discharging respectively is simplified by implementation of Non-Isolated Bi-directional DC-DC Converter. Assemblage of DC-DC converter is done by assimilating buck and boost converters, this enables it to work in both the directions charging as well as discharging in both the modes buck as well as boost. In the whole operating range soft- switching is independent of the state-of-charge of electric vehicle, while also ensuring stability of the grid voltage port regardless of load or generation conditions, has been also unified to decrease the losses in transition modes. In endeavour to reduce the size and converters weight, frequency of switching must be enhanced, this is realized by PWM controlled dc-dc bidirectional converter. The PWM switching of duty cycles is analogous to an electrical transformer between input and output voltages, where the amplitudes of positive and negative half cycle of input voltage are same as that of output voltage. This paper deals with in brief discussion about the different converter topologies most appropriate for achieving vehicle-to- grid (V2G) conversion in EV's, also to decrease loss of power and attain greater conversion efficiency.

Keywords: *Bidirectional DC-DC converter (BDC), non-isolated bi-directional DC-DC converter (NIBDC), Vehicle to Grid (V2G), Vehicle to Home (V2H), Grid to Vehicle (G2V), Pulse Width Modulation (PWM)*

I. INTRODUCTION

Electric mobility is the most suitable option to fulfill transportation needs in future. In modern world the emphasis on EV's is rising as they are emerging as a better option over IC engine and also reduces the consumption of fossil fuels this in turn minimizes liberation of greenhouse gases. Above and beyond environmental issues EV's also provide fuel economy and ease in refueling, which can be done from home. Nevertheless, with increasing number of EV's on the road the load on the grid may also get raised. In view of perceiving EV's as an imposition

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on the grid they can be esteemed as 'mobile power-bank' which can store a substantial quantity of energy in them, which is beneficial for the grid. V2G and V2H can be achieved by implementing an essential component, bidirectional dc-dc converter, in the Electric Vehicle. As converters are unidirectional, they only work in G2V mode. In V2G technology the grid is feed by the energy stored in the vehicle battery through the converter, where as in V2H mode the house loads are feed by the converter. The dc-dc converter provides the desired change in the dc input voltage and input current to a chosen dc output voltage or output current. Formerly the conversion of dc supply voltage was to higher voltage, for lower voltage and power application, was achieved by converting it to AC with the use of a vibrator tracked by a transformer and rectifier. DC-DC converter were then industrialized to exploit the energy produce from photovoltaic system. Many dc-dc converters are made to alter power unidirectionally, i.e. from source to load, but there is no scope to enable V2G and V2H technologies through bi-directional transfer of power. Bidirectional DC-DC converters provides desired change in input and output voltage levels, either high or low, alongside maneuvering flow of power from both the sides (from source to load and load to source). By far bi-directional dc-dc converters have been implemented in many applications like-wise storage systems for Hybrid Electric Vehicles (HEV's), Renewable energy storage systems, Fuel cell storage systems and Uninterrupted Power Supplies. Typically, converters were prerequisites for the speed control and regenerative braking in motor drives. In order to achieve regulation of DC bus voltage, along with power flow in both the directions bidirectional dc-dc converter is an essential component in the EV's drive train [1-2]. Likewise, in EV's and HEV's, the high voltage DC bus is linked up to the primary & auxiliary storage system and to the grid via a bidirectional dc-converter.

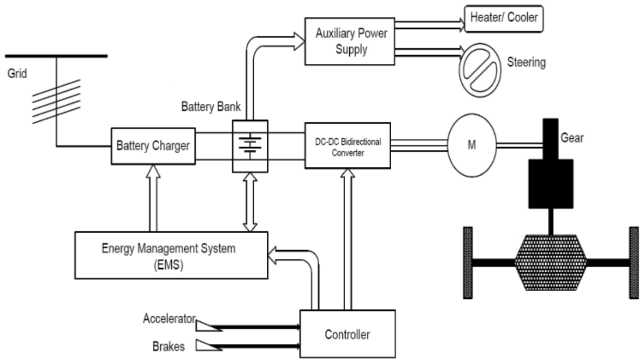

Fig. 1: EV drive train employing a bidirectional dc-dc converter

However, isolated type converter is widely used in battery chargers. Isolation in dc-dc converter can be provided in two forms one is a Dual Active Bridge (DAB) converter and another is a resonant converter. The DAB has many advantages which are soft-switching, simple assembly, and the wide output voltage range. The DAB consists of the two bridges via active device and a high-frequency transformer.

II. LITERATURE REVIEW

With the purpose of serving conversion of voltage level from high to low and vis-versa, and provide bidirectional power flow. DC-DC bidirectional converter are employed in many power electronics applications. Electric Vehicles are one such most popularly used applications. The bidirectional DC-C converter provide bidirectional flow of electric power in between the electric vehicle, the grid and the battery source, thus enabling grid-to-vehicle and also grid-to-vehicle. Hence, bidirectional DC-DC converter is a vital part of an EV. Many topologies of DC-DC converters are available which can be implemented in any system depending upon the application for which it is used. The modelling of dc-dc converter for application in HEV and the prerequisite of the power electronics in the HEV technology was examined and described in [1-4]. The comparison between the various NIBDC's has been done on the basis of their performance in [3-6, 15-20]. The concept of soft switching techniques and stress reduction of the bidirectional converter has been presented in [10]. The controlling of BDC by pulse width modulation has been presented in [15].

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III. Classification Of Bidirectional Dc-Dc Converter With Different Topologies

BDCs are categorized on the basis of the current or voltage from one end. The location of a secondary energy storage system often characterizes BDCs as step-up (buck) and step-down (boost) type. In the step-down mode, energy storage system is located on the greater voltage side whereas, in step-up mode it is situated on the lower voltage side. In order to achieve power flow in both the direction, the power switches must be able carry current in all possible directions. Due to absence of power switches which permits current flow in both sides, so unidirectional semiconductor power switches are preferred likewise a MOSFET or an IGBT shunted with a body diode. For modulating the input voltage different DC-DC converter are used, depending on targeted application [6].

Prerequisites for the BDCs designed for the EVs and HEVs are as follow:

- Greater productivity
- Lightweight and compressed size
- Low electromagnetic Interference
- Low current ripple at input and output
- Measured power in spite of widespread variation at input.

Normally, BDCs can be classified in two types as isolated and non -isolated [1-2]. Mainly, a unidirectional DC-DC converter is advanced into a non -isolated bidirectional converter by upgrading the unilateral conduction ability of the regular converters by the bilateral conducting capability of the switches [6-13]. The regular unilateral converters (Buck & Boost) doesn’t show the intrinsic property bilateral flow of power, this is due to presence of basic diode in it. This drawback of the basic converter (step-up & step-down) circuits can be improvised by implementing an antiparallel diode across a MOSFET or an IGBT which make a bilateral switch. This facilitates current flow in both the directions for bilateral flow of power in correspondence with the measured switching action [1-2]. Non-isolated, and isolated bidirectional DC-DC converter topologies will be discussed in this section.

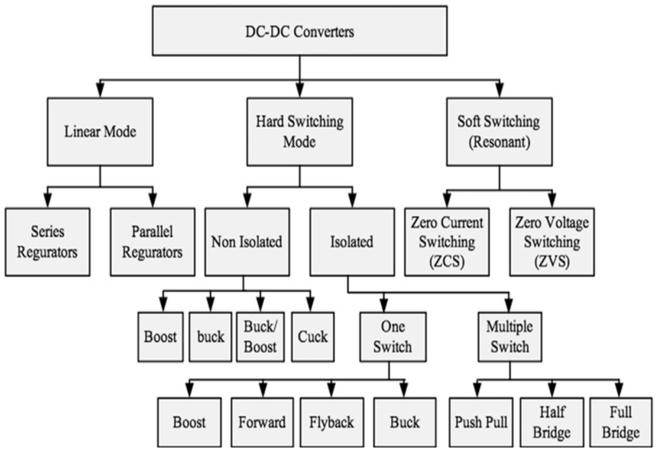
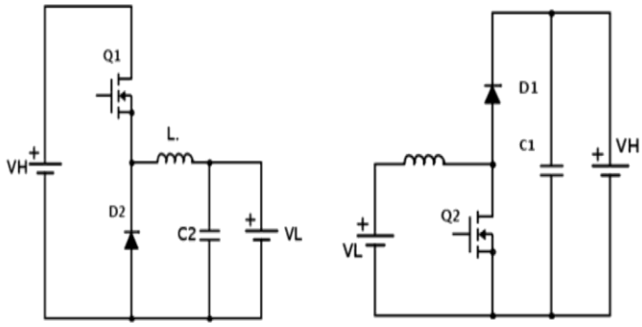


Fig. 2: Classification of Bidirectional DC-DC Converter

A. Buck Boost Converter

Fig. [4] and Fig. [3] shows the first bidirectional topology which is derivative of a straight buck and boost converter by implying bilateral conducting switches respectively. During boost mode T_2 remains OFF for all the time and T_1 remains closed at desired duty cycle. Likewise, during buck mode T_1 remains open for all the time and T_2 remains closed at desired duty cycle. For avoiding short circuits of switches & capacitance small dead time is inserted during the transition mode. Non-Isolated Half-Bridge BDC is the blend of step-up converter coupled with unparallel step-down converter. This is a simple topology and has higher efficiency [10-20].



(a) (b)

Fig.3: (a) Buck Converter (b) Boost Converter

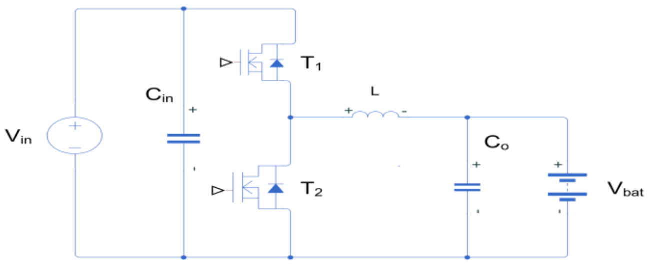


Fig. 4: Bidirectional Buck Boost Converter

B. Buck Boost Cascaded Converter

Fig. 5 shows a Buck Boost Cascaded converter which is fabricated by connecting bidirectional step-up converter in series with bidirectional step-down converter [1-2]. In conducting state, output voltage to be greater or less in comparison with input voltage is determined by the switch combination and direction of current flow. During forward boost mode of operation switches T_2 and T_4 are always OFF while T_1 is always ON, whereas conduction of switch T_2 is subjected to duty cycle. During forward buck mode of operation switches T_2, T_3, T_4 are always OFF, whereas required duty cycle is provided for operation of switch T_1. Body Diode D_3 permanently runs in forward biased mode whereas D_2 and D_4 are continuously in reverse biased mode. Diode D_4 is a freewheeling diode. During backward boost mode switch T_4 is driven with desired duty cycle and T_3 is continuously ON with diode D_1 stand-in as freewheeling diode [5-10].

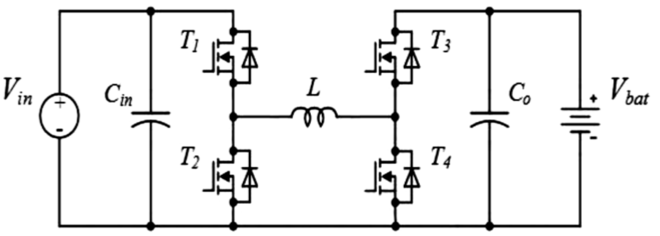


Fig. 5: Bidirectional Buck Boost Cascade Converter

C. CUK Converter

CUK converter is derived from a conventional CUK converter by replacing unilateral switches into bidirectional switches such as MOSFET. Fig. 6 shows a bidirectional CUK converter in which C_{dc} and C_o are the coupling capacitors, while C is an energy storage capacitor [15]. The input voltage can be step down or step up in a same way as done in a conventional buck boost converter but with opposite polarity. With low input and output ripples in current the bidirectional CUK converter is an excellent option for implementation in ultra-capacitor-battery interface circuits, battery equalization, and bilateral converter to regulate the power flow & also ensure good health of storage devices. To decrease input and output ripple currents inductors L_1 & L_2 may be united [6].

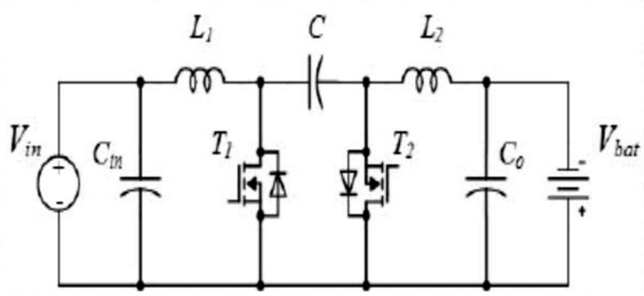


Fig. 6: Bidirectional CUK Converter

D. SEPIC- ZETA Converter

Fig. 7 shows SEPIC-ZETA dc -dc converter which is an improvised version of CUK converter thus, unlike CUK converter output polarity is similar to that of input [6-10]. The converter functions as SEPIC converter, in forward conduction mode and ZETA converter, in negative conduction mode. SEPIC-ZETA converter is capable to work in bidirectional buck as well as boost mode. In forward conduction mode, T_1 is made closed and T_2 remains open i.e. it functions like a step-down converter. In reversed conduction mode, it functions like a step-up converter with T_2 made open. The voltage rating stress and voltage output ripple on power switches may be abridged by coupling inductors L_1 and L_2.

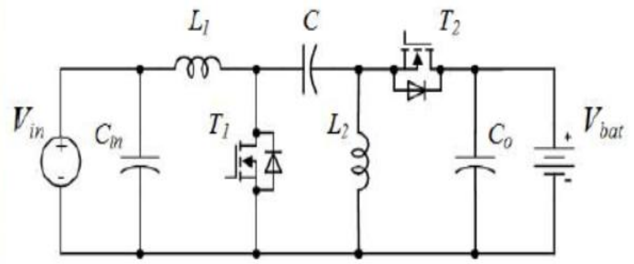


Fig. 7: Bidirectional SEPIC –ZETA Converter

E. Switched Capacitor Bidirectional Converter

Switched capacitor bidirectional converter is the best choice to make when one is working with ICs. Fig. 8

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shows a switched capacitor bidirectional converter topology. It is quite simpler to work with ICs integration, as magnetic elements are absent in NIBDCs. One drawback of this topology is the presence of ripple current on the output, which is very high. Thanks to sizable amount of passive element that results in electromagnetic interference (EMI) [8-11]. Current control and voltage control techniques can be adopted to overcome these issues. The latter can result in substantial increase in the price of the circuit and its complexity.

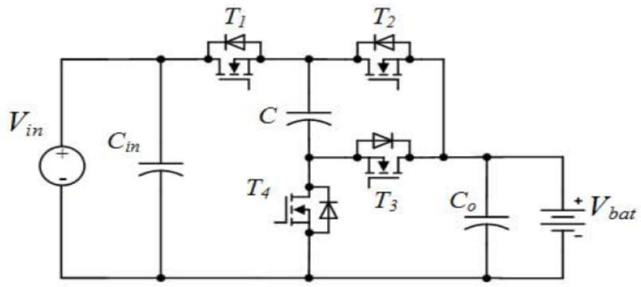


Fig. 8: Switched Capacitor Bidirectional Converter

F. NIBDC- Half Bridge Converter

The Half bridge topology of the dc-dc converter can be effectively devised by coupling the regular step-down & step-up converters in anti-parallel with each other. Eventually, the circuit which come about is of the similar structural design as that of general buck and boost arrangement [1-4]. Fig. 9 shows the converter, so obtained has an additional aspect of bidirectional flow of power. The buck or boost mode of operation of circuit depends on transition state of MOSFET T_1 and T_2. The power switches T_1 or T_2 in anti -parallel with the freewheeling diodes (D_1 & D_2) respectively maneuver the voltage across them either by intensifying or depressing it. The bidirectional operating scheme of circuit is explained below [10].

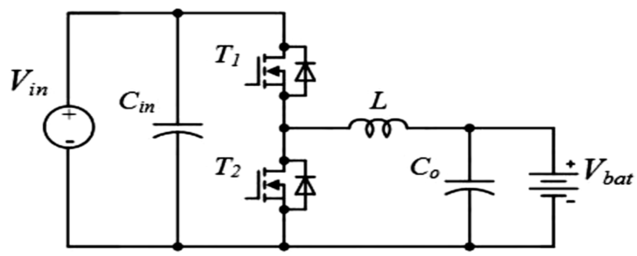


Fig. 9: Non -Isolated Bidirectional Half Bridge Converter

Mode 1: Buck Mode

During this operation, switch T_2 and diode D_1 are kept OFF continuously whereas, T_1 and D_2 are made closed. The turn ON period of T_1 and D_2 depends on the duty cycle. This mode is further elaborated into two intervals depending on the state of switch T_2 and diode D_1.

a) Interval 1 (T_2 off, D_2 off; T_1 on, D_1 off)

In this period T_2 is OFF and T_1 is ON. The inductor starts charging through the battery and output capacitor in
turn gets charged by it.

b) Interval 2 (T_1 off, D_1 off; T_2 off, D_2 on)

In this period switch T_1 and T_2 gets turned OFF, as a result D_2, freewheeling diode, provides path for discharge current from inductor and thus step-down voltage appears across the load.

Mode 2: Boost Mode

During this operation, switch T_1 and diode D_2 are kept OFF continuously whereas, T_2 and D_1 are turned ON. The turn ON period of T_2 and D_1 depends on the duty cycle. This mode is further elaborated into two intervals depending on the state of switch T_1 and diode D_2.

a) Interval 1 (T_2 on, D_2 off; T_1 off, D_1 off)

In this period T_2 is turned ON, the inductor is charged by the lower battery and current through it goes on rising, as long as the gate pulse is not removed from switch T_2. Diode D_1 as well gets reverse biased and switch T_1 is turned OFF, so current flowing though T_1 is zero.

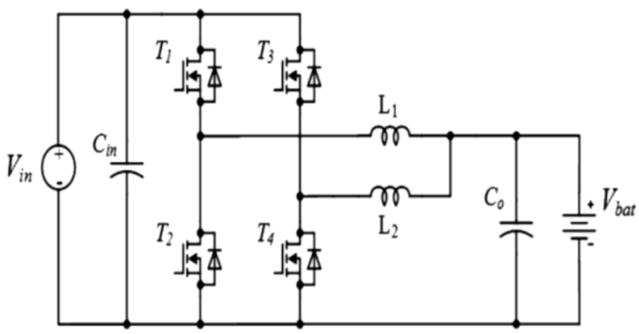
b) Interval 2 (T_1 off, D_1 on; T_2 off, D_2 off)

In this mode both T_1 and T_2 are turned OFF, as the current carried by inductor cannot alter instantly so polarity of voltage gets overturned and it starts pro tem in series with input circuit. The inductor current starts charging the output capacitance through the freewheeling diode D_1, this as a result step up the output voltage.

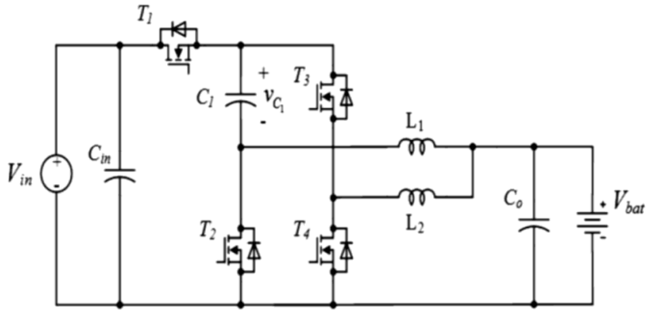
G. Interleaved Converter

In current years, it has been noticed that an interleaving idea i.e., synchronization of parallel power stages is possible with relative phase shift of $360^o/n$ is applicable. Voltage Regulator Modules (VRMs) is a popularly known application [7]. Nevertheless, bilateral converters can also be realized using the interleaved concept. Power converter shunting structure gives numerous advantages: current ripple cancelation, current splitting (I_o/n), improved thermal performance, greater efficiency and improved-power density. Interleaved structures provide some motivating benefits that is, high effectiveness during a widespread power range. Fig. 10 shows elementary two-phase interleaved converter topologies [6-10]. Fig. 10(a) and Fig. 10(b) shows the Half Bridge topology and Charge Pump topology of two -phase interleaved bidirectional converter respectively. The later holds greater conversion percentage than the regular converter.

In this paper, table- 1 shows the significant comparison of Non-Isolated Bidirectional DC-DC Converter [6]. For safety purpose only galvanic isolation will not suffice in Non-isolated Bidirectional DC-DC Converter (NIBDC). Therefore, in many applications, Isolated Bidirectional DC- DC Converter (IBDC) is employed in situ of NIBDC.



(a)



(b)

Fig. 10: Basic Interleaved NIBDC’s

In Isolated Bidirectional dc-dc converters, galvanic isolation is achieved by inserting transformers with high conversion frequency. In case of overloading, synchronizing the voltage levels at input & output sides and reducing noise galvanic isolation is the prime aspect [1-2]. This converter is implemented to function in two stages, in first stage it acts as an inverter and second stage it acts as rectifier. High frequency transformer is utilized for coupling both the stages to function as an isolated transformer. Fig. 11. shows the basic architecture of an isolated bidirectional dc-dc converter [1-2]. Forward-flyback IBDC, Dual flyback IBDC, Dual push-pull IBDC, Dual half bridge IBDC, Dual-CUK IBDC and Dual active full bridge IBDC are some of the popular topologies of isolated converter. Nonetheless, to get high efficiency half and full bridge converter are widely used. Insertion of a transformer suffices the requirement of an AC link for energy transfer. Also counting all this parameters system becomes complex and hulking.

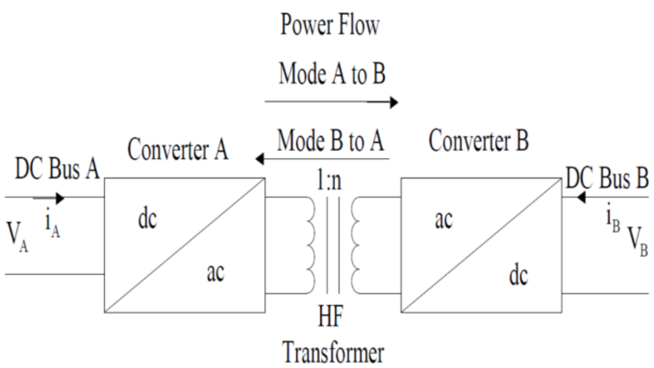


Fig. 11: Basic Structure of IBDC’s

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Table I: Characteristics Comparison of NIBDC's

Topology	Basic Criteria's					
	Voltage conversion ratio V_{bat}/V_{in} (buck mode)	*Voltage conversion ratio V_{in}/V_{bat} (boost mode)*	*Output current ripple (buck mode)*	*Number of switches*	*Number of passive components*	*Magnet required*
Buck Boost Bidirectional (Fig. 4)	$-\frac{D}{1-D}$	$-\frac{D}{1-D}$	$-\frac{V_{bat}(1-D)}{Lf_{sw}}$	2	3	Single inductor
Cascaded Bidirectional (Fig. 5)	D	$\frac{1}{1-D}$	$\frac{V_{bat}(1-D)}{Lf_{sw}}$	4	3	Single inductor
CUK (Fig. 6)	$-\frac{D}{1-D}$	$-\frac{D}{1-D}$	$-\frac{V_{in}D}{L_2 f_{sw}}$	2	5	Single inductor
SEPIC –ZETA (Fig. 7)	$\frac{D}{1-D}$	$\frac{D}{1-D}$	$\frac{V_{in}D}{L_1 f_{sw}}$	2	5	Coupled or two inductors
Switched Capcitor (Fig. 8)	0.5	2	$Cf_{sw}(V_{in}-V_{bat})$	4	3	No
Half Bridge (Fig. 9)	D	$\frac{1}{1-D}$	$\frac{V_{bat}(1-D)}{Lf_{sw}}$	2	3	Single inductor
Interleaved (Fig. 10)	D	$\frac{1}{1-D}$	$\frac{V_{bat}(1-2D)}{Lf_{sw}}$	2n	2+n	n inductors with or without coupling

H. Dual Half Bridge –Isolated Bidirectional DC–DC Converter

Fig. 12 shows the topology of a Dual Half Bridge (DHB) - isolated bidirectional dc-dc converters (IBDC), which includes ZVS attain greater power density, smooth transitions and efficient control. Hence, these features make it a preferred choice for EV's, HEV's and PHEV's applications. DHB -IBDC gives 92 to 94% of efficiency [10].

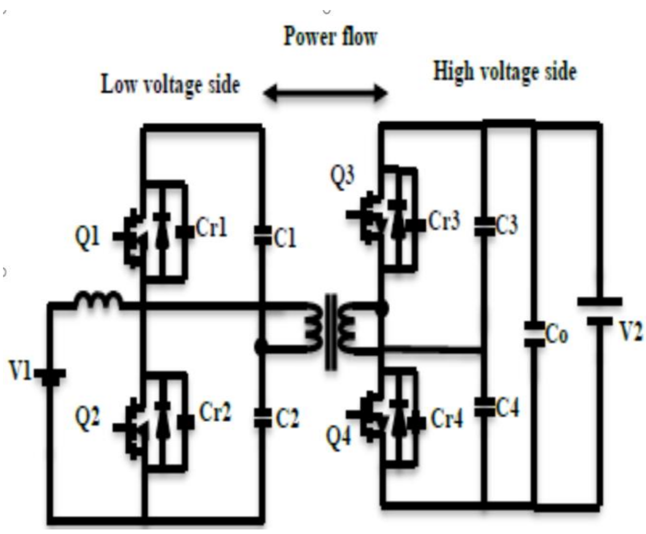

Fig. 12: Dual Half Bridge Isolated Bidirectional DC-DC Converter

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I. Dual Active Full Bridge (DAFB) –Isolated Bidirectional DC–DC Converter (IBDC)

Fig. 13 shows the Dual Active Full Bridge -isolated bidirectional dc-dc converters which attains high-power density and high efficiency, these features make it the best preferred option for hybrid energy driven system. Power capacity of DAFB -IBDC is higher than another topology as the power switches has high power capacity. Efficiency of this converter 95%. Hence, this converter proves to be the best choice for higher power applications [10].

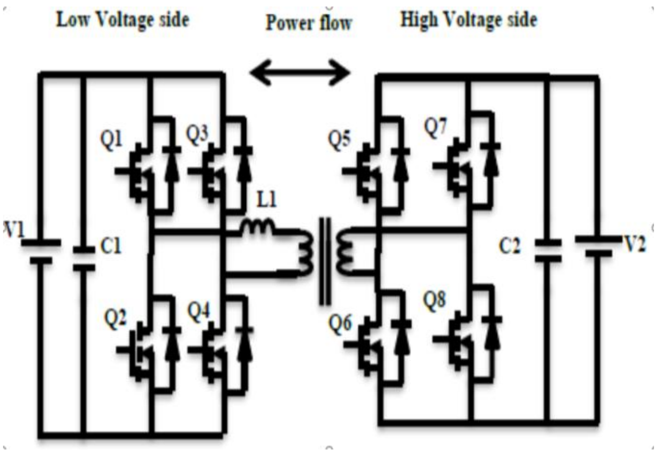

Fig. 13: Dual Active Full Bridge Isolated Bidirectional DC -DC Converter

IV. SWITCHING TECHNIQUES

Switching losses are primarily caused due to hard switching in converter circuits. Hence, to tackle this issue scientists have recognized the soft switching approach which minimalizes the losses in switching. Soft switching is implemented by using passive component, this in effect make the system bulky and sophisticated. Table- II gives the assessment of the two kinds of switching techniques [10].

Table II: Comparison between Soft and Hard Switching

Hard Switching	Soft Switching (ZVS and ZCS)
Large switching losses	Near zero switching losses
High EMI due to high di/dt and dv/dt	Low EMI loss
Limited range of switching frequency	High range of switching frequency
Low power density	High power density
Low efficiency	High efficiency
Easy control	Complex control
Low cost	High cost due to a greater number of switches

V. DESCRIPTION OF TWO STAGE DC-DC CONVERTER

Fig. 14 shows the two-stage DC-DC converter suggested in this paper [4]. Isolated resonant converter is coupled with the non-isolated half-bridge dc-dc converter to get a two-stage dc-dc converter. The resonant converter has a symmetric a CLLC-type structured resonant tank. Which means that the resonant capacitance and inductance at the primary and secondary side are same and the transformer ratio is unity. In this case, the voltage gains of the charging mode (CM) and discharging mode (DM) are same so that the operating frequency is also same regardless of the operation mode. The role of the resonant converter is the high- frequency isolation because the voltage gain is fixed to unity [4]. The half-bridge type is used as non-isolated converter. This converter is responsible for the charging and discharging control. This two-stage converter uses SiC-MOSFET to attain high efficiency and to minimize the converter power loss during switching.

Assuming that the AC-DC converter has a constant primary voltage as it controls the DC link voltage. The resonant converter performs only the high-frequency electric isolation without any control. Therefore, the operating mode determines the switching state of the converter. In CM, the bridge of the primary side is operated as inverter and the other bridge is operated as the rectifier [5]. On the other hand, the role of the bridges is also changed in each case. The operating frequency is constant which is

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near to the resonant frequency for the operation in the fixed gain condition. In the two-stage dc-dc converter, the power flow is controlled by the half-bridge dc-dc converter. In CM, this converter performs the constant-voltage (CV) and constant-current (CC).

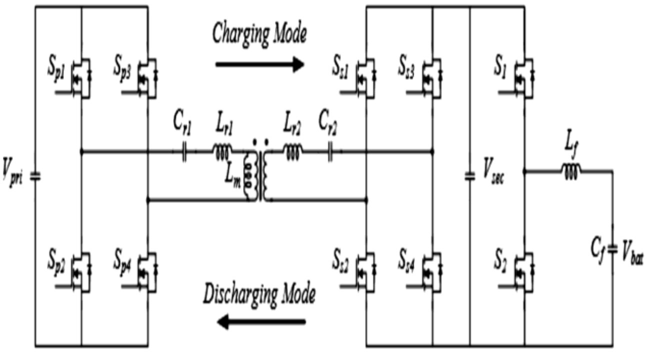

Fig.14: Construction of the proposed two-stage isolated bidirectional DC/DC converter

VI. Pulse Width Modulation

Switch controlling scheme like Pulse Width Modulation (PWM) is performed by varying width of trigger pulse given to the power switches. These controlled pulses regulate the duty cycle of the power switches, through this method total harmonic distortion (THD) present in the load current can be minimized. There are several power electronics applications of PWM. Mostly for DC source, PWM is performed to supply AC devices and for DC-to-AC alteration. Output amplitude of the waveforms can be controlled by changing the duty cycle. PWM provides these two significant advantages likewise reduced THD and regulated dc output voltage [15]. Besides this, it comes with complex switching technique which contributes to increased losses due to recurrent transitions. Output sinusoidal PWM requires a reference signal, which is a carrier signal in the form of sine wave, which is in from of a triangular wave that manipulates the switching frequency.

PWM can also regulate the average power supplied by an electrical signal, this can be achieved through effective chopping up of electrical signal into discrete parts. By changing the switch state between source and load from ON to OFF and vis-versa very frequently. The power supplied to the load rises with increase in the ON time of the switches as compared to the time for which the switches are OFF. Laterally with MPPT (maximum power point tracking), PWM is the prime technique of regulating the output of solar panels, which can be utilized by a battery or any other load [15]. Exclusively, PWM is exercised for driving loads like motors, whose working is also affected by its inertia, which are less suffered by discrete switching. Because they contain inertia, motors tend to respond slowly. In effect to not affect the load operation, the switching frequency of PWM must be sufficient high enough. Which mean that the waveform at output received by load must be as soft as possible.

In PWM generation, frequency modulation and amplitude modulation ratio are the two very important factors.

a) Frequency Modulation Ratio, (m_f):

The ratio of carrier frequency to the reference signal is termed as Frequency Modulation Ratio. As because of high frequencies number of harmonics are larger than the fundamental harmonics and for demolish them a low pass filter can be effectively used. If the frequency of carrier signal is increased the frequency of harmonics can also increase.

$$m_f = \frac{f_{carrier}}{f_{reference}} = \frac{f_{triangular}}{f_{sine}} \quad (1)$$

b) Amplitude Modulation Ratio, (m_a):

Amplitude Modulation Ratio is defined as the ratio of amplitude of the reference signal and the carrier signal.

$$m_a = \frac{V_{m,reference}}{V_{m,carrier}} = \frac{V_{m,sine} or V_{m,control}}{V_{m,triangular}} \quad (2)$$

From (3) it can be inferred that the amplitude voltage V_o, is directly proportional to m_a i.e.,

$$V_o = m_a * V_{dc} \quad (3)$$

Which also means that by varying m_a the fundamental frequency of the output voltage along with its amplitude can be varied as per the desired output.

VII. Conclusion And Future Scope

Non-isolated bidirectional dc-dc converter is a finest option over IBDC's, as it excludes transformer. NIBDC is less complex, less bulky, less costly and overall efficiency is more than the latter. This make non-isolated bidirectional DC-DC converter best fit for EV application. IBDC`s are the preferred choice for providing galvanic isolation in hybrid energy system. Transition losses can be minimized by using soft switching techniques in replacement of hard switching. Whereas required switching and controlling scheme is used depending upon circuit architecture and target application. Interleaved topology can be utilized to reduce the ripple current in the inductor, which may rise due to discontinuous operation of inductor.

The stress on the high side capacitor will be minimized by applying multiphase interleaved topology. Due to this the value of capacitor can be minimized. It is preferred to build a prototype of higher power, for the purpose of measuring and optimizing the efficiency of the converter. Device's rating must be defined, so that components of specified ratings can be bought or constructed. Especially, inductors rating must be wisely chosen such that it must withstand higher ripple current. Appropriate drivers should be utilized to enhance switching frequency.

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