An Isolated Bi-Directional Converter with Improved Power Conversion Efficiency for DC Distribution Systems

Sujitha Surendran and V. Sruthy

Abstract— *A bidirectional AC-DC and DC-DC converter is proposed for DC distribution systems with high frequency isolation and bidirectional power flow capability. The topology is based on a non-isolated bidirectional AC-DC converter for grid-connected operation and an isolated bidirectional DC-DC converter to interface between DC bus and DC link of the rectifier. The proposed converter has the ability to not only transfer energy from the grid to the vehicle, but also transfer energy from the vehicle to the grid (V2G). So, this converter can be used as a power backup for the grid. This converter allows fast control and high power density and requires proper controlling method for the switches which is implemented via programming. The prototype model of the bidirectional charger topology can be used for the hybrid electric vehicle applications and they provide a flexible power processing interface between an energy storage device and the rest of the system.*

Index Terms— *Non-Isolated Bidirectional AC-DC Rectifier, Bidirectional Isolated DC-DC Converter, Electric Drive Vehicle, Vehicle to Grid Concept*

I. INTRODUCTION

RECENT developments and trends in the electric power consumption clearly indicate an increasing use of DC in end-user equipment. Computers, TVs, and other electronic-based apparatus use low-voltage DC obtained by means of a single-phase rectifier followed by a DC voltage regulator. In factories, the same input stage is used for process-control equipment, while directly-fed AC machines have been replaced by AC drives that include a two-stage conversion process. Electrical energy production from renewable sources is at DC or requires a similar two-stage conversion as in AC drives, e.g. variable-speed wind turbines and natural-gas micro turbines. By using DC for distribution systems it would thus be possible to skip one stage in the conversion in all these cases, with consequent savings and higher reliability due to a decreased number of components. Moreover, energy delivery at DC is characterized by lower losses and voltage drops in lines. A DC distribution system also allows direct connection of battery for back-up energy storage.

The majority of power converters are unidirectional with the power being supplied from the source to the load.

But, a number of applications like motor drives, uninterruptible power supplies, renewable energy sources, battery charger/dischargers and smart grid power systems require the additional exchange of energy from the load to the source. These applications utilize power converters with bi-directional transfer properties. Especially, an isolated bidirectional AC-DC-DC converter [1] has been developed for high frequency galvanic isolation for DC power distribution systems and that can supply clean and stable power for the power systems. The topology introduced here is based on a non-isolated bidirectional AC–DC converter and an isolated bidirectional DC–DC converter to interface between DC bus and DC link of the rectifier. This proposed converter is used to transfer electrical power from the grid to battery and vice versa [2].

Some isolated full-bridge bidirectional DC–DC converter topologies have been presented in recent years. An isolated full bridge bidirectional DC–DC converter with a flyback snubber is developed for high-power applications which can operate independently to regulate the voltage of the clamping capacitor. But the need of extra flyback snubber circuits increases circuit complexity and decreases power conversion efficiency [3]. A bidirectional phase-shift full-bridge converter was proposed with high-frequency galvanic isolation for energy storage systems [4], [5]. This converter can improve power conversion efficiency using a zero-voltage transition feature; however, it requires input voltage variations to regulate constant output voltage because this topology can only achieve the step-down operation. Therefore, the novel bidirectional AC-DC-DC converter is proposed for DC distribution system for bidirectional power flow control.

II. SYSTEM DESCRIPTION

High power isolated bi-directional AC-DC-DC converters have become key components in alternative energy systems. Upon operation, the converter controls bi-directional flow of electric power between a voltage bus that connects an energy storage device such as a battery or a super capacitor, to provide clean and stable power to a DC load.

Sujitha Surendran, Dept. of Electrical and Electronics, Amrita School of Engineering, Kollam, India. E-mail: sujithachunakkara@gmail.com
V. Sruthy, Dept. of Electrical and Electronics, Amrita School of Engineering, Kollam, India. E-mail: sruthyv@am.amrita.edu

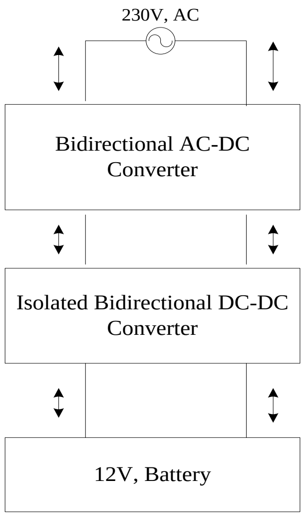

Fig. 1 Block diagram of the proposed scheme

Fig. 1 shows the block diagram of the proposed scheme. It consists of an AC-DC inverter/rectifier stage, a DC-DC converter stage and a battery. In charge mode, the AC grid acts as the source and the battery acts as the load. In V2G mode, the AC grid acts as a sink while the battery acts as the source [2].

Fig. 2 shows the circuit configuration of the proposed bidirectional AC-DC-DC converter. It consists of the single phase bidirectional rectifier for grid interface and the isolated bidirectional DC-DC converter for galvanic isolation. A battery is provided in the output which is used as the energy storage system and can control the bidirectional power flow. This converter can act in two modes of operation. The AC-DC converter acts as a rectifier during charging mode, to provide DC voltage for the energy storage system and acts as an inverter during discharging mode, in order to provide power back to the grid. The isolated DC-DC converter consists of two H-bridge inverters linked by a transformer. The left H-bridge converter acts as an inverter during charging mode, that provides DC voltage for the battery and the right H-bridge converter acts as an inverter during discharge mode, to provide DC voltage for the AC-DC converter stage.

Non-Isolated Bidirectional AC-DC Converter

In the energy transfer mode from the grid to vehicle and vice versa, the interaction between the grid and bidirectional AC-DC converter is the main issue. In this configuration, the switches remain open in the battery charging mode and the internal diodes rectify the current passively. During the positive half cycle, C_i is effectively connected in parallel with the AC source through the internal diodes of S_1 and S_4 and during the negative half cycle, the internal diodes of S_2 and S_3 conduct to allow C_i to once again in parallel with the AC source, but in a reversed configuration. In this way, the DC-DC converter acquires a DC input voltage more or less equal to the amplitudes of the AC source.

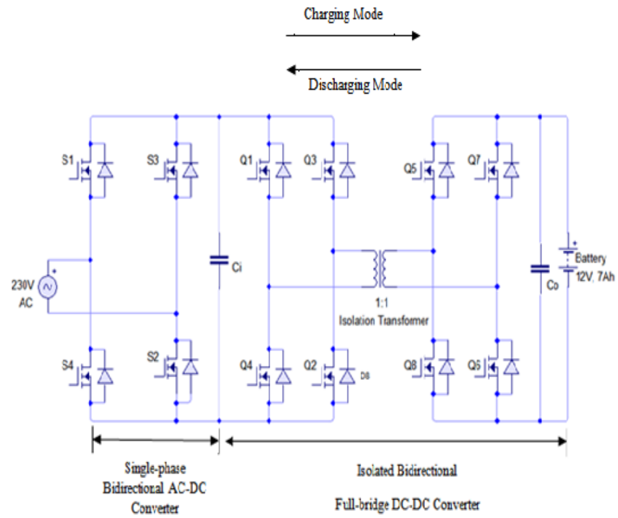

Fig. 2: Circuit Configuration of Bidirectional AC-DC-DC Converter

When the single-phase, full-bridge circuit acts in battery discharge mode, S_1 and S_2 or S_3 and S_4 can be turned on to apply V_{DC-DC} or $-V_{DC-DC}$ respectively across the AC source. Of course, switching S_1 and S_4 or S_2 and S_3 on at the same time would produce 0 volts. When this combination of V_{DC-DC}, $-V_{DC-DC}$, and 0 volt pulses is applied, desired AC sine wave is obtained.

Isolated Bidirectional DC-DC Converter

Bidirectional DC-DC converters (BDC) have recently received a lot of attention due to the increasing need to systems with the capability of bidirectional energy transfer between the DC buses [6]. Apart from traditional application in dc motor drives, new applications of BDC include energy storage in renewable energy systems, fuel cell energy systems, hybrid electric vehicles and uninterruptible power supplies (UPS). In hybrid vehicle applications, BDCs are required to link different DC voltage buses and transfer energy between them. High efficiency, lightweight, compact size and high reliability are some important requirements for the BDC used in such an application.

Galvanic isolation between multi-source systems is a requirement for personnel safety, noise reduction and correct operation of protection systems. Voltage matching is also needed in many applications as it helps in designing and optimizing the voltage rating of different stages in the system. Both galvanic isolation and voltage matching are usually performed by a magnetic transformer in power electronic systems, which calls for an AC link for proper energy transfer [6].

Fig. 3 shows the basic structure of isolated bidirectional DC-DC Converter. This structure consists of two high-frequency switching DC-AC converters and a high- frequency transformer which is primarily used to maintain galvanic isolation between two sources.

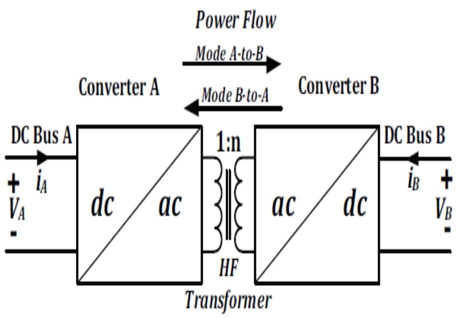

Fig. 3 Basic Structure of an Isolated Bidirectional DC-DC Converter

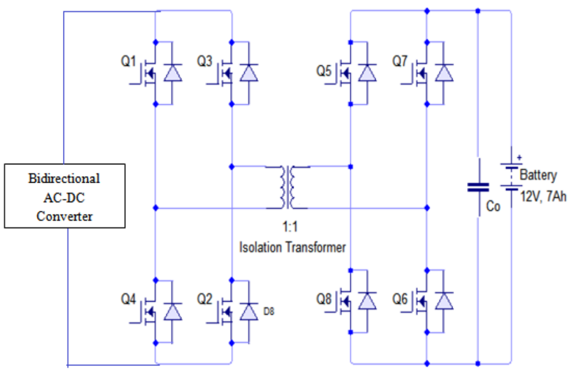

Fig. 4 Bidirectional DC-DC Converter

This transformer is also essential for voltage matching in case of large voltage ratio between two sources. As energy transfer in either direction is required for the system, each DC-AC converter must also have bidirectional energy transfer capability. With the same token, the DC buses in this structure must also be able to either generate or absorb energy. These buses can be connected to a DC source or an active load like battery, ultra-capacitor or dc-link capacitor which resemble an ideal voltage source with stiff voltage characteristics [6].

Fig. 4 shows the circuit configuration of bidirectional DC-DC converter. This consists of two active bridges linked by a transformer. When delivering power from the AC-DC converter to the battery, the active bridge on the left side acts as an inverter while the internal diodes of the switches on the right act as a full-bridge to rectify the AC back to DC. This topology also allows the rectifier to be switched actively. When the converter runs in battery discharge mode, the bridge on the right inverts the DC current of the battery which induces an AC voltage in the left active bridge through the transformer. The internal diodes of the switches on the left side acts as a full-bridge to rectify the current back to DC that is usable by the bidirectional AC-DC converter.

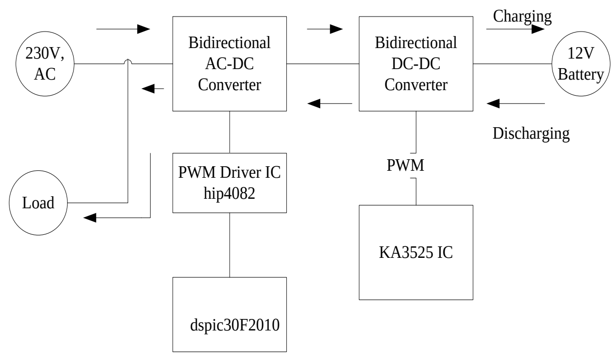

Fig. 5 Block diagram of the prototype model

III. Hardware Implementation

In order to validate the actual performance of the proposed bidirectional AC-DC-DC converter, a hardware prototype was designed and built. The experimental setup of the converter is proposed to demonstrate the proposed scheme. The switching frequency of the AC-DC converter is 50Hz and the DC-DC converter is 10kHz. The input voltage is 230V AC and output is a 12V battery during charging mode and a load is given in order to operate the proposed converter in discharging mode. Instead of using a 230V AC grid source, a scaled down source of 12V AC is used using a step down transformer to give input to the MOSFET since switch of high voltage and current rating is not available and is costly.

Fig. 5 shows the block diagram representation for the prototype model of the bidirectional converter. In this proposed scheme, a 230V, AC is given as the input to AC-DC rectifier section and the DC output voltage passes through the DC-DC converter which is used to charge the battery. When the AC source is not available then the battery acts as a source and discharges through the load. To control the proposed converter, dsPIC is used for the AC-DC converter and a PWM IC KA3525 is used for DC-DC converter.

The inverter section control system is implemented using dsPIC by voltage mode control which is shown in Fig. 6. Therefore, only voltage feedback is used for the control loop which is a cost effective method as no current sensor is required. A PID-type compensator is used for the control loop, and is implemented as a difference equation in software. The result of the control loop computation modifies the duty cycle and therefore maintains a clean output voltage.

Fig. 7 show the experimental setup of bidirectional AC-DC-DC converter topology. The bidirectional AC-DC converter can acts as rectifier and inverter during charging and discharging mode of operation. To control the inverter section, dsPIC microcontroller is proposed because it is cheap and easy to implement the proposed design. The closed-loop design consists of multiple stages. The system requires the following stages: Sense Stages and Control Stage.

Table I. Specifications of Bidirectional AC-DC-DC Converter

Specifications	Values
Input Voltage	AC 230V
Output Voltage	DC 12V
MOSFET	P80NF55-08
C_i	4000μH
C_o	2200μH
Load	40W lamp
dsPIC	30F2010
PWM IC	KA3525

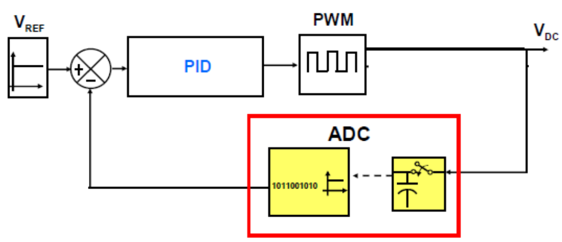

Fig. 6 Voltage Mode Control of Inverter Section

Sense Stages

For the closed-loop system to be able to determine the appropriate operation mode, it needs to sense the grid's voltage magnitude. This enables the control stage to determine which voltage level the inverter output should operate. Not only does the closed-loop system need to sense the grid's voltage but it also needs to determine the grid's current magnitude. This ensures the inverter's output current is in-phase with the grid's 50Hz sinusoidal current during discharge mode. A current transformer is provided to sense the grid current whose output is a voltage which passes through a filter circuit in order to regulate the voltage. The closed loop-system also needs to sense the voltage level of both the DC bus capacitor to ensure that the inverter's output current is in-phase with the grid's 50Hz sinusoidal current during discharge mode.

Control Stage

The closed loop controller was written in mikroC. The code was used to program the control stage or specifically, the dsPIC microcontroller. The dsPIC monitors the mapped signals generated by the sense stages. Fig. 8 shows the interface of dsPIC with full bridge inverter. Four PWM signals are used for driving the inverter. In addition to PWM signals, sinusoidal output voltage and current and the DC input voltage is measured which is fed into high-speed 10-bit Analog to Digital Converter (ADC) of dsPIC.

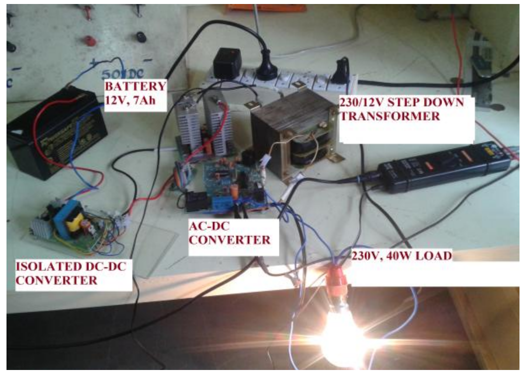

Fig. 7 Experimental Setup

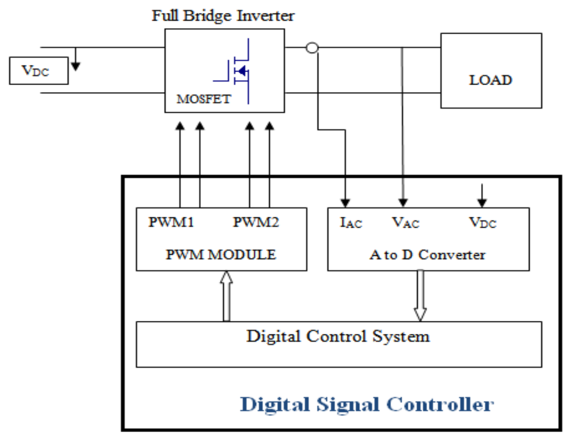

Fig. 8 Interface of dsPIC with Full Bridge Inverter

The analog inputs measured by ADC are then used by digital control system to produce a new duty cycle. The measured output voltage is compared with sinusoidal reference voltage that is obtained from a lookup table stored in the device memory. A lookup table is used that contains all the points of a sine value. The sine values are read from the table at periodic intervals, scaled to match the allowable range of duty cycles, and then written to the duty cycle registers. The sine table values are stored in program memory. It is transferred data to data memory during initialization for faster access. An array is defined for the current location of the lookup table. The logic then determines the appropriate output signals to control the 4 switches of the PWM topology.

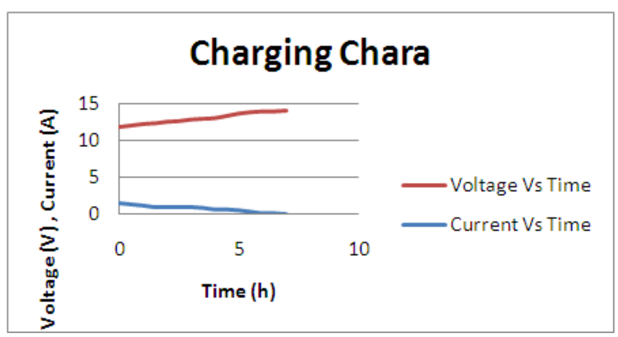

Fig. 9 Charging Characteristics

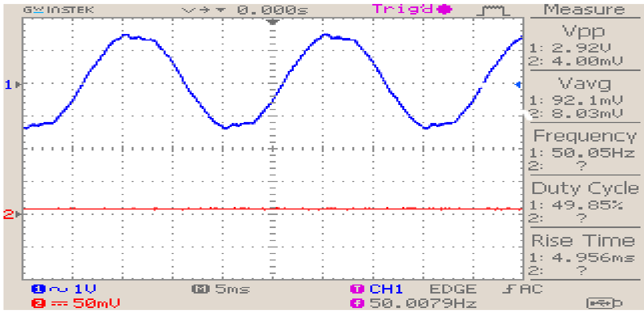

Fig. 10 Inverter output voltage

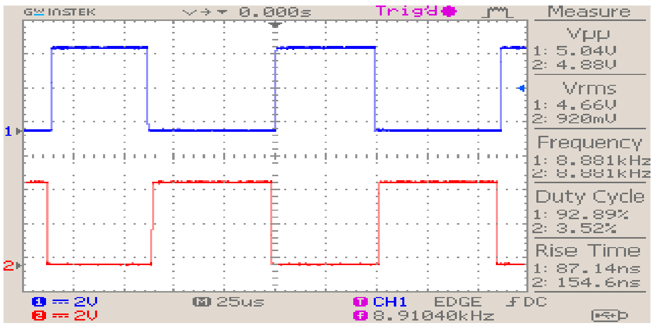

Fig. 11 Switching waveforms of AC-DC converter with 40W load

For DC-DC converter, instead of using 8 MOSFET and a high frequency transformer, 4 MOSFET and a centre tapped transformer is proposed in this hardware circuit so that the switching losses can be reduced. The PWM IC KA3525 is used to generate a PWM signal to switch the MOSFET. The output of DC-DC converter is connected to a 12V lead acid battery.

IV. Results And Discussion

In the proposed energy storage system, a bidirectional AC-DC-DC converter with a proper charging-discharging profile is required to transfer energy between the battery pack and the ac grid. The output of the bidirectional converter is analyzed which works in two modes of operation.

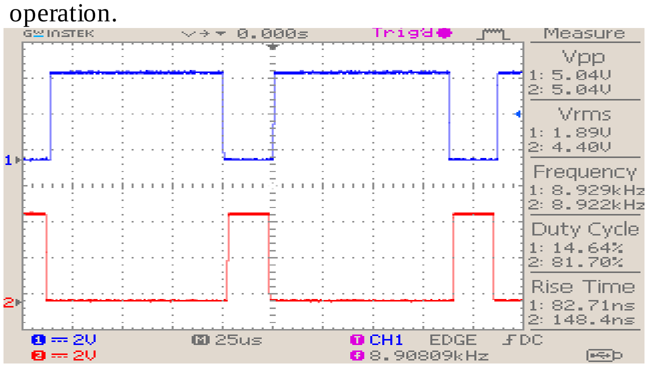

Fig. 12 Switching waveforms of AC-DC converter with 15W load

During charging mode, 230V AC is given as the input source, the bidirectional AC-DC converter works as rectifier and the output DC voltage is given to DC-DC converter which charges the 12V battery. The battery voltage and current is analyzed with 0 to 100% charge and is shown in Fig. 9. The battery voltage and current with 0% charge is 11.8V and 1.5A and for fully charging condition it is 14V and 0.1A.

During discharging mode, the 230V AC is disconnected and the 12V battery acts as the source which supplies power to the load. Under this condition, the bidirectional DC-DC converter gives a DC output to the bidirectional AC-DC converter which acts as an inverter and gives a 206V AC as the output which is a 50Hz pure sine wave. The inverter output is shown in Fig. 10 which is measured in DSO using a differential probe whose multiplier is 200 so peak voltage*200= 1.46*200= 292V whose rms voltage is 206V will be actual AC voltage. The switching pulses of the AC-DC converter is analyzed in which the duty cycle is varied according to the load that is connected at the output. The duty cycle variation for a 40W and 15W load condition is shown in Fig. 11 and 12. For a 15W load, the duty cycle varies upto a maximum of 82% and for 40W load, a maximum of 94% is obtained. The battery is allowed to discharge fully and is shown in fig. 13. The fully discharging battery voltage is 9.8V and the current is 3.8A. Thus the bidirectional converter operates in charging and discharging mode and the current flows in the opposite directions is analyzed. Hence the proposed bidirectional charger can be used to plug the electric vehicle.

Fig. 14 shows the efficiency curve of the proposed converter with different loads. Even for loads less than 20W, the efficiency is not decreasing and it is still at 90%. For nearly full load condition, efficiency is 94% which is the peak efficiency of the overall converter system. Thus the bidirectional converter has good efficiency characteristics under light and nearly full load condition with less conversion losses.

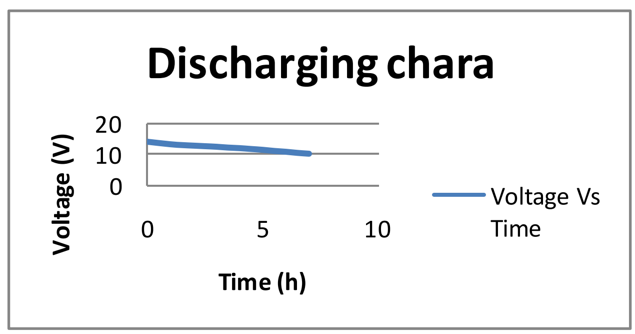

Fig. 13 Discharging Characteristics

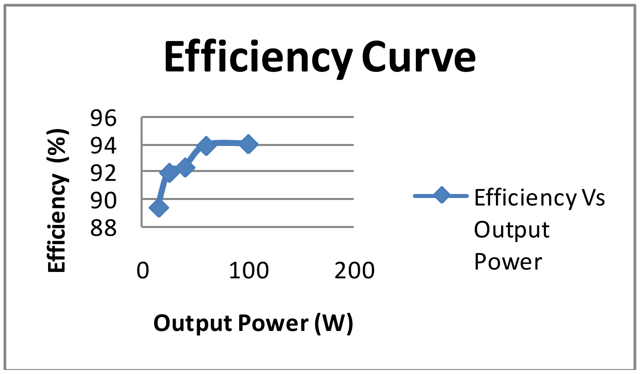

Fig. 14 Efficiency Curve

V. CONCLUSION

A new bidirectional converter is incorporated for electric drive vehicle applications. The bidirectional converter consists of bidirectional AC-DC converter and isolated bidirectional DC-DC converter. A battery is provided in the circuit inorder to analyze the charging as well as discharging mode of operation. The bidirectional AC-DC converter works as the interface between the DC-DC converter and the ac grid, which needs to meet the requirements of bidirectional power flow capability and to regulate the DC side power regulation. The bidirectional DC-DC Converters are one of the key elements in electrical systems. They provide a flexible power processing interface between an energy storage device ie., battery and the rest of system. Also the efficiency of the proposed converter is analyzed with different loads with improved efficiency of 90% at light load and 94% at nearly full load condition is obtained.

The proposed converter can be used as a bidirectional charger to provide plug-in electric vehicles the ability to transfer energy from the grid to the vehicle and also transfer energy from the vehicle to the grid (V2G). The V2G mode allows power utility companies to offset peak power consumption thus allowing household consumers and industry corporations to save money on their electricity bills.

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