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A Bidirectional Universal Dc/Dc Converter Topology for Electric Vehicle Applicationsand Photovoltaic Applications

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Abstract: - This paper proposes a fully directional dc/dc converter that interfaces the motor drive of the vehicle withthe energy storage system of the vehicle and the external charger of the vehicle (only in case of PHEVs). This dc/dc converter topology works in all directions in buck or boost modes with bidirectional power flow and noninverted output voltage. Furthermore, the working of the proposed circuit on connecting to a load is also presented in the paper. The output is further improved by actuating a feedback loop. The results are verified by MATLAB Simulink model. Voltage and current waveforms are presented to validate the proposed converter topology and control schemes. This proposed converter can also be used in photovoltaic applications with unidirectional power flow. When the system in unidirectional buck mode is actuated by a 24V dc, an output voltage of 12V is obtained. When the system in unidirectional boost mode is actuated by a 24V dc, an output voltage of 100V is obtained. The power at the output level is improved by using the closed loop feedback and the same is proved by the MATLAB simulated waveforms.

Keywords: -Bidirectional dc/dc converters, electric vehicles (EVs), energy storage system, universal dc/dcconverter, photovoltaic applications.

I. INTRODUCTION

The increasing popularity of Electric Vehicles and Plug-in Hybrid Electric Vehicles is contributed to the savings in fuel costs compared to conventional Internal Combustion Engine vehicles. EVs and PHEVs save energy due to the employment of reverse regenerating braking during the deceleration cycle. This energy is typically stored in batteries and Ultra-Capacitors. The incorporation of onboard Energy Storage Systems (ESS) and generation in PHEVs has been facilitated and dictated by the market demands for enhanced performance and range. Electrification of the transportation industry is essential due to the improvements in higher fuel economy, better performance, and lower emissions [1], [2], [6].

In the case of a hybrid electric vehicle (HEV), a bidirectional dc/dc converter interfaces the energy storage device with the motor drive inverter of the traction machine. So the converter is placed between the battery and the high voltage dc link bus. In acceleration mode, it should deliver power from the battery to the dc link, whereas in regenerative mode, it should deliver power from the dc link to the battery. In the case of an EV or PHEV, while accomplishing the aforementioned task, the converter also interfaces the battery with the ac/dc converter during charging/discharging. Fig. 1 shows the role of the bidirectional dc/dc converter in the electrical power system of an electric vehicle.

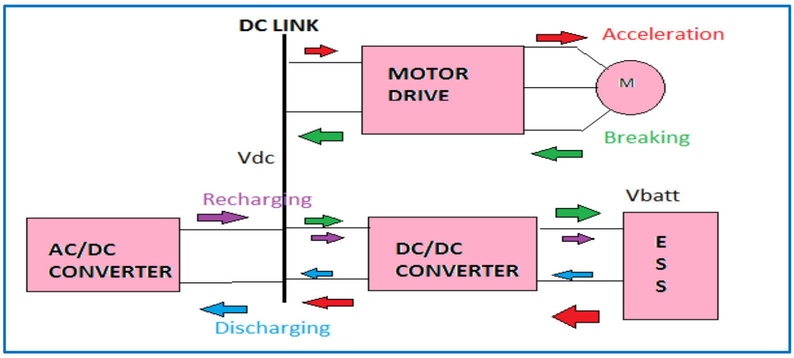

Fig. 1: Basic block diagram of an electric vehicle

In grid-connected mode, the bidirectional dc/dc converter must have the capability to convert the output voltage of the ac/dc converter into an appropriate voltage to recharge the batteries and vice versa when injecting power to the grid. In driving mode, the dc/dc converter should be able to regulate dc link voltage for wide range of input voltages. In driving mode, usually the battery voltage is stepped up during acceleration. DC link voltage is stepped down during braking, where $V_{dc}>V_{batt}$. However, if motor drive's rated voltage is less than battery's nominal voltage, $V_{dc}<V_{batt}$, the battery voltage should be stepped down during acceleration and the dc link voltage should be stepped up during regenerative braking. . Moreover, in an HEV to PHEV conversion, the grid interface converter's output voltage might be less or more than the battery's nominal voltage [4], depending on the grid's Vac voltage and the grid interface converter's topology. In addition to these

Cases, the rectified grid voltage should be stepped up if $V_{rec}<V_{batt}$ in vehicle to grid charging mode or the battery voltage should be stepped up for vehicle to grid discharging mode. If the rectified grid voltage is more

Than the battery's nominal voltage, i.e., $V_{rec}>V_{batt}$, the rectified voltage should be stepped down in charging mode and the battery voltage should be stepped up in discharging mode. With all these possibilities considered, the need for a universal fully directional dc/dc converter is obvious which must be capable of operating in all directions with stepping up and stepping down functionalities.

II. CIRCUIT SCHEMATIC AND OPERATION

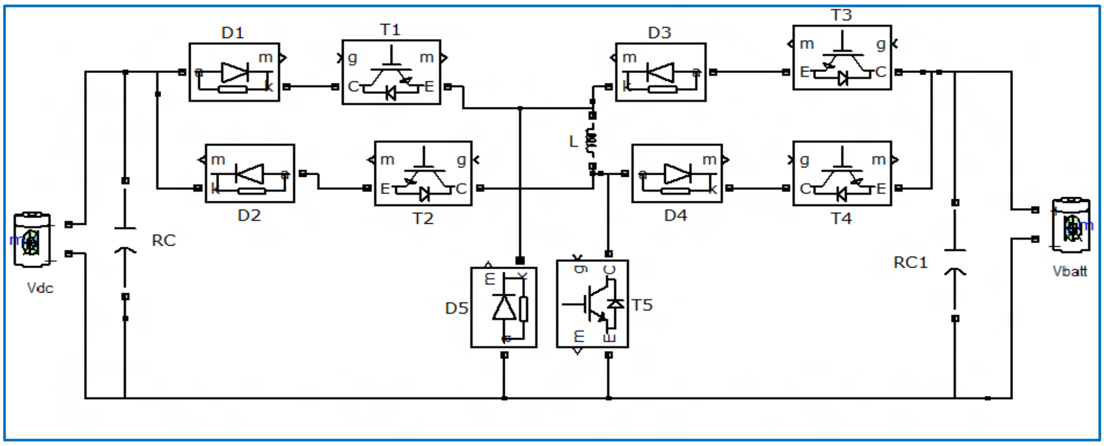

Fig. 2: Circuit schematic of proposed dc/dc converter

The circuit diagram of the proposed bidirectional converter is depicted in figure 2. The converter has five power switches ($T_{1\text{-}5}$) with internal diodes and five power diodes (D_1–D_5), which are properly combined to select buck and boost modes of operation. In the circuit, V_{dc} represents the motor drive nominal input voltage during driving mode or the input voltage of the grid interface converter to be inverted to ac and also the rectified ac voltage at the output of the grid interface converter during plug-in mode. The nominal voltage of the vehicle's Energy Storage System is indicated by V_{batt}.

The conventional two-quadrant bidirectional converters can operate buck mode in one direction and boost mode in the other direction; however, they cannot operate vice versa [9], [14], [15]. Conventional buck–boost converters can step-up or step down the input voltage. But, they are not capable of providing bidirectional power flow. Moreover, their output voltage is negative with respect to input voltage. So they require an inverting transformer to make the output voltage positive [5]. The noninverted operation capability of the proposed circuit totally eliminates the need for an inverting transformer, which reduces the overall size and cost. Although there are some non inverted topologies [6]–[10], some of them require two or more switches being operated in PWM switching mode that causes higher total switching losses [6]–[8], [10], [11]. Among these topologies, bidirectional power flow cannot be achieved in the topologies of [6], [10], and [12]–[13]. Two cascaded two-quadrant bidirectional converters may achieve bidirectional power flow with bucking or boosting capabilities; however, they require more than one high-current inductor [7]. In the case of a dual active bridge dc/dc converter, all switches are operated in PWM mode and therefore, switching losses are four times higher in the half-bridge case or eight times higher in fullbridge case than that of the proposed converter circuit [16]. Moreover, having more than one switch operating in PWM switching mode would make the control system more complicated. However, in the proposed dc/dc converter, the controls are as simple as the conventional buck or boost dc/dc converters in spite of all the competences.

The different operation modes of the converter are mapped in Table I.

Direction	Mode	T1	T2	T3	T4	T5
Vdc → Vbatt	BOOST	ON	OFF	OFF	ON	PWM
Vdc → Vbatt	BUCK	PWM	OFF	OFF	ON	OFF
Vbatt → Vdc	BOOST	OFF	ON	ON	OFF	PWM
Vbatt → Vdc	BUCK	OFF	ON	PWM	OFF	OFF

Table I: Operating Modes

T_1, T_3, and $T_5$are operated as either ON/OFF or PWM switches with respect to the correspondingoperating mode. But T_2 and T_4 serve as simple ON/OFF switches to connect or disconnect the corresponding current flow paths.

	CIRCUIT PARAMETERS	
L		3mH
Cdc = Cbatt		2200µF
Power Switches		HGTG30N60A4D IGBT
Diodes		FFPF30U60STTU
	Table II: Circuit Parameters	

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In order to provide the same functionality, four dc/dc converters would be needed with conventional converters: two of them would be boost dc/dc converters (one for plug-in and one for driving modes) and other two of them would be buck dc/dc converters (one for plug-in and one for driving modes). In this case, instead of one inductor, four inductors would be needed for each of the converters. In commercially available EVs and PHEVs, currently the capability of injecting power back to the grid does not exist. In plug-in charging, there is a boost converter employed after the rectifier and for the driving mode, they utilize a two quadrant converter to provide both the boost and buck functions either for acceleration or regenerative braking modes. The boost converter after the rectifier can be replaced by a two-quadrant converter in order to have both the grid charging and discharging functionalities.

However, it can be stated that the proposed converter has relatively slightly more conduction loss in all operating modes. The additional conduction loss is mainly due to the additional switches or diodes in the current flow paths of the proposed converter. But the proposed converter reduces the number of inductors from four to one as it is compared to the two buck–two boost converter's approach. Since the inductor core and winding materials are extremely more expensive than the semiconductor devices, it is always desirable to add two more semiconductor devices for reducing the number of inductors by three. Moreover, inductors would require much more space as it is compared to the space requirement of two switches. Therefore, one can state that the proposed dc/dc converter would reduce both the cost and the size of the conventional approach for the same functionality basis.

III. PROPOSED CONVERTER IN PHOTOVOLTAIC APPLICATIONS

The proposed dc/dc converter can even be employed in photovoltaic applications. The proposed circuit's energy storage system is replaced by a load at the end and a feedback loop is provided in the same circuit to rectify the error in the output. The resultant circuit is a dc/dc converter that can be used either for buck operation or for boost operation. The circuit is modified as a closed loop one by providing feedback. So the error is reduced and the efficiency is improved.

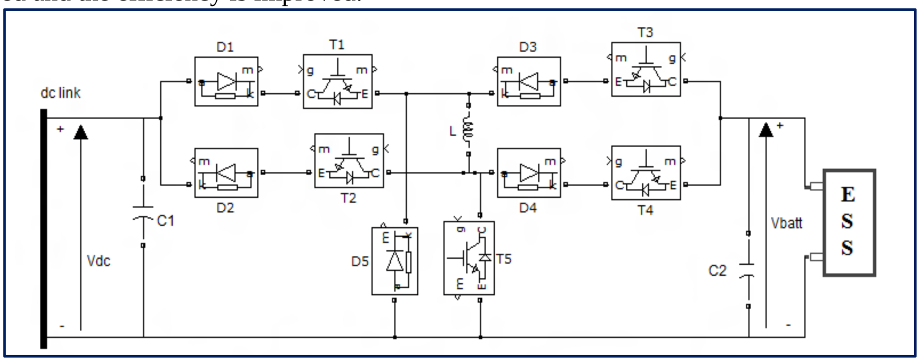


Fig 3: Proposed Circuit in Unidirectional Operation

The circuit schematic is same as that of figure 2. Here power flow occurs only in one direction since energy storage system is replaced by load. Therefore, only two operating modes are employed. The circuit can be used for either buck operation or boost operation. The output of the system is further improved by actuating a feedback loop.

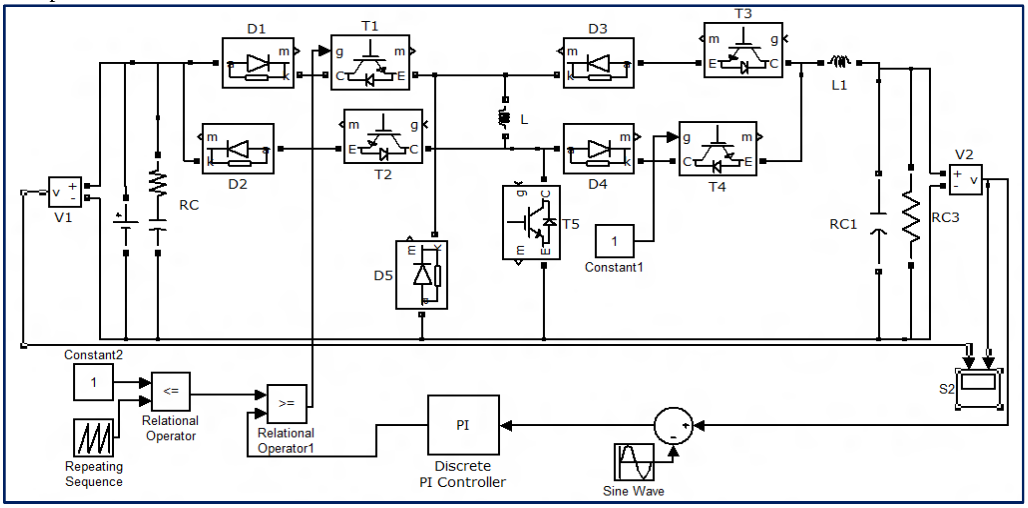


Fig. 4: Buck operation With Feed Back Loop

The circuit diagram for both buck and boost operation with a feedback loop is shown. The simulation of the circuit is done in MATLAB and the results are also displayed.

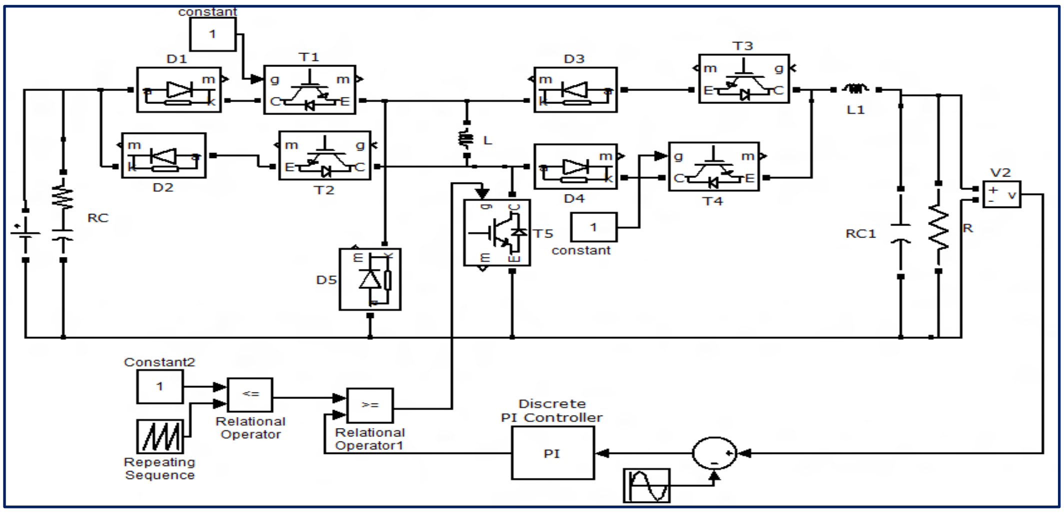
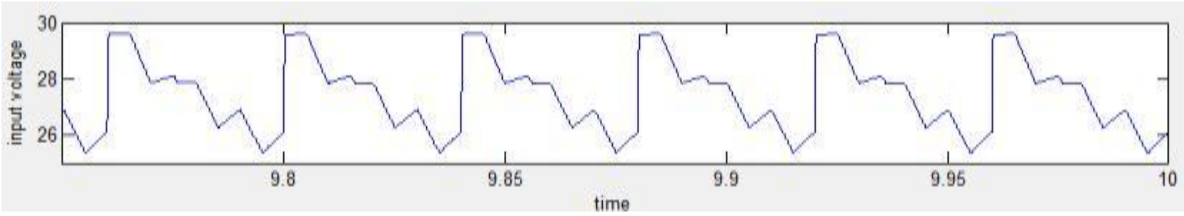


Fig. 5: Boost operation With Feed Back Loop

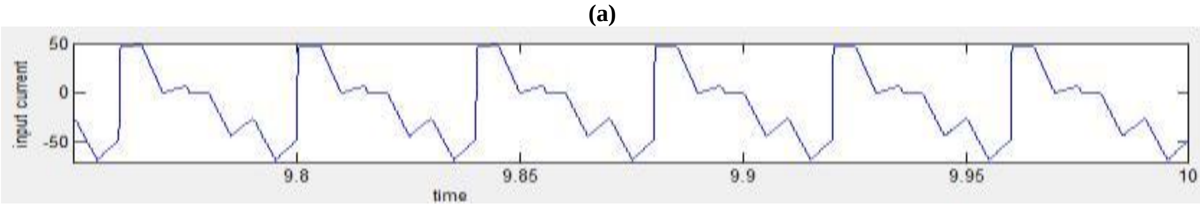
In photovoltaic applications, according to the variations in availability of sunlight, we might step up or step down the input voltage so as to obtain a regulated voltage at the output. For this bucking and boosting operations, we can simply employ this converter. This topology gives reduced number of inductors, directly provides non inverted output voltage and it's switching losses are same as that of conventional type.

The inductor core and winding materials are extremely more expensive than the semiconductor devices. Moreover,inductors would require much more space as it is compared to the space requirement of switches. Therefore, one can state that the proposed dc/dc converter would reduce both the cost and the size of the conventional approach for the same functionality basis. A conventional buck boost converter can be used for stepping up or down the input voltage in photovoltaic applications. But the output of conventional buck boost converter is an inverted one compared to the input voltage. So they require an inverting transformer at the output to make the output voltage positive. The non inverted operation capability of the proposed circuit totally eliminates the need for an inverting transformer, which reduces the overall size and cost of the circuit. Although there are some non inverted topologies, some of them require two or more switches being operated in PWM switching mode that causes higher total switching losses.

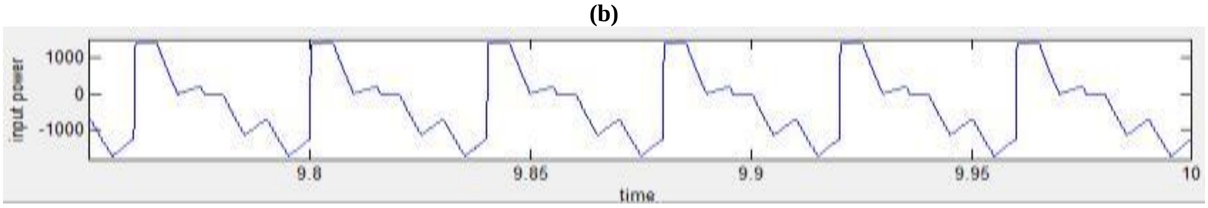
IV. SIMULATION RESULTS



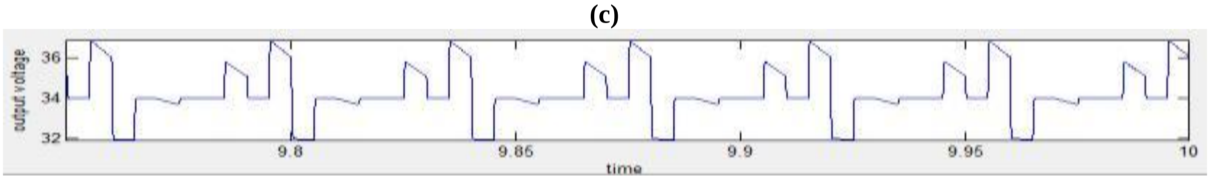
(a)



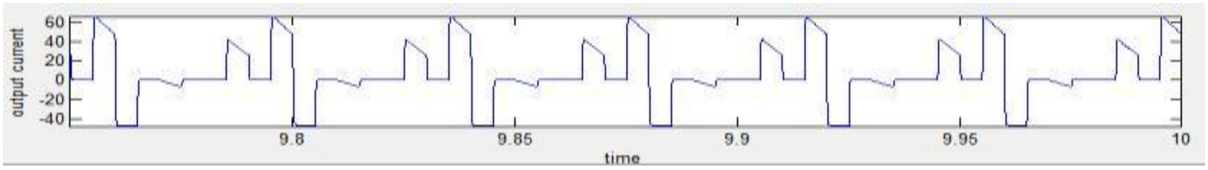
(b)



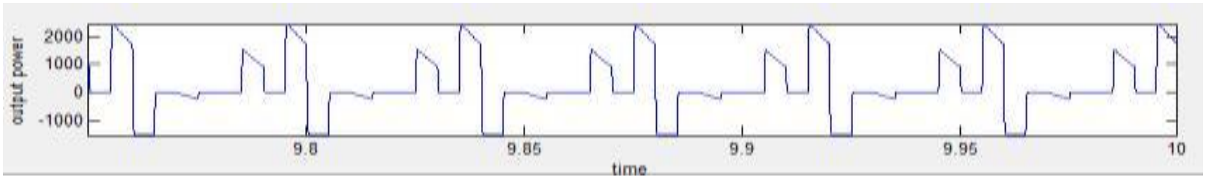
(c)



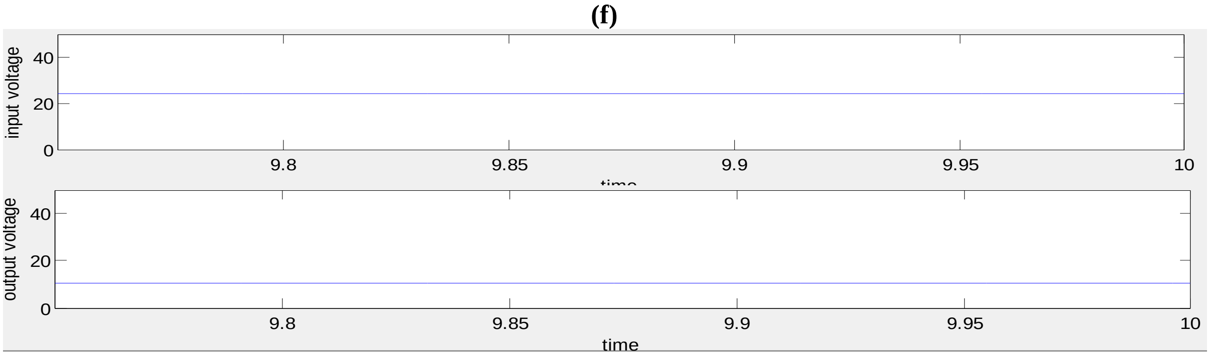
(d)



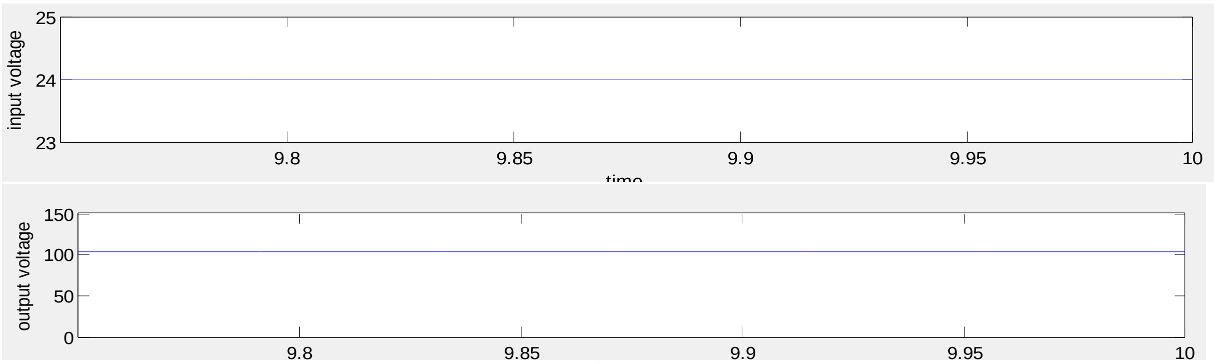
(e)



(f)



(g)



(h)

Fig 7 : (a) input voltage,(b) input current,(c) input power,(d)output voltage,(e)output current, (f) output power, (g) Simulation Results Of Proposed Converter's Unidirectional Buck Operation with Feed Back Loop,(h) Simulation Results Of Proposed Converter's Unidirectional Boost Operation With Feed Back Loop

The only problem associated with this converter topology is that the conduction loss will be slightly higher than the conventional approach. Since the number of switches in the conducting path is higher, either active or inactive, loss will also become slightly higher. But when compared with reduced switching loss and reduced number of inductors, this slight increase in conduction loss can be neglected.

V. CONCLUSION

The paper proposes universal dc/dc converter that is suitable for all electric vehicle applications. The proposed converter facilitates bidirectional power flow provided with fully directional bucking and boosting capabilities. Due to the operational capabilities, the proposed converter is one of a kind plug-and-play universal dc/dc converter that is suitable for all electric vehicle applications. It reduces both the size and cost of the conventional converters. Also the proposed circuit's operation is studied when connected to a load. The circuit is further improved by adding a feedback loop. The resultant circuit is a bidirectional buck boost converter with reduced number of inductors and improved efficiency. This proposed topology can even be employed in photovoltaic applications where bucking and boosting functions are needed due to the fluctuations in available input light intensity. The results are verified by MATLAB Simulink model. When the system in unidirectional buck mode is actuated by a 24V dc, an output voltage of 12V is obtained. When the system in unidirectional boost mode is actuated by a 24V dc, an output voltage of 100V is obtained. Voltage and current waveforms are presented to validate the proposed converter topology and control schemes. The functionalities of the proposed converter provide a broad range of application areas.

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