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BATTERY INTERFACE CONVERTER: DC-DC BIDIRECTIONAL NON-INVERTING BUCK BOOST CONVERTER FOR EV, HEV, PHEV APPLICATION

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Abstract— The need for a bidirectional DC/DC converter in electric vehicles is studied. Here, a universal power electronic interface that can be used in any type of electric vehicles (EV), hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV) is discussed. This power electronic converter interfaces the energy storage device of the vehicle with the motor drive and the charging unit. The fully directional converter is capable of working in buck or boost modes in any direction with a non-inverted output voltage. The output of the converter is improved with a feedback control loop. This is verified with MATLAB/SIMULINK (MATLAB version R2010a).
Keywords— Electric vehicles (EV), Hybrid electric vehicles (HEV) and Plug-in hybrid electric vehicles (PHEV), energy storage device, bidirectional DC/DC converter.

INTRODUCTION

Transportation industry always look forward for an alternate source of energy to reduce the adverse effects on environment and to increase the system efficiency. With the increased concern about eco friendlier & higher fuel economy vehicles, the need for electrification of transportation industry become unavoidable (essential). There are many versions of Electric Vehicles (EV) available nowadays. The fuel (electricity) can be the output of conventional energy producing means such as from hydro, diesel, thermal, etc. or can be from renewable energy sources like wind, solar, geo-thermal, etc. as in recent years the renewable energy sources plays a vital role in today's grid.

EVs are of different types like: 1) a simple EV where the traction motor draws power from the battery source which was earlier charged from the supply. 2) Hybrid Electric Vehicle (HEV) in which an ICE in addition to a battery source will be provided. During peak power requirement, the motor draw power from the ICE and from the battery in case of low power requirement. For ultra-high power requirement, both battery and ICE supplies the load. 3) Plug-in Hybrid Electric Vehicles (PHEV). PHEVs consist of an ICE and battery of which battery acts as the primary energy source.

Fig.1 shows the simplified block diagram of a PHEV.

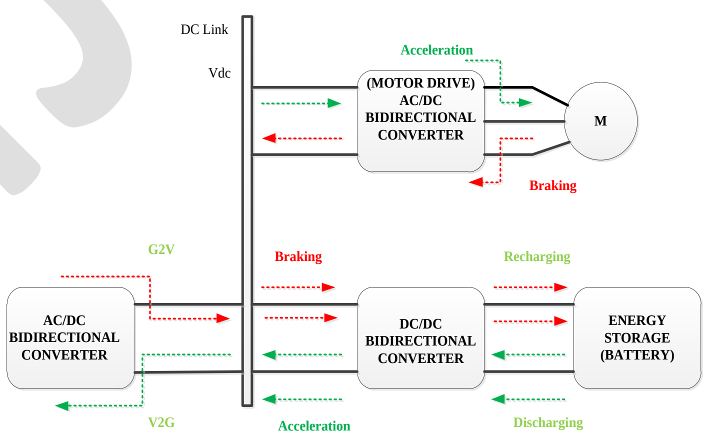

Fig.1. Power electronics interfaces in an Electric Vehicle

The AC/DC converter provides the charging unit. It converts the AC supply from the utility grid to the required DC voltage. This is shown as a bidirectional converter to facilitate vehicle to grid charging (V2G) concept. The power electronic interface between the DC link bus and the battery (storage unit) should essentially be a bidirectional converter inorder to facilitate charging and discharging of battery. In acceleration or cruising mode, it should deliver power from the battery to the dc link, while during regenerative mode, it should deliver power from the dc link to the battery. In the case of an EV or PHEV, the bidirectional dc/dc converter also interfaces the battery with the ac/dc converter during charging or discharging from or to the grid.

In grid connected mode, the bidirectional DC/DC converter should have the capability to convert the output voltage to the required level to recharge the batteries and vice versa while injecting power back to the grid. In driving mode, the converter must regulate the dc link voltage. Usually, in driving mode, the battery voltage is stepped-up during acceleration. DC link voltage is stepped-down during braking, where Vdc>Vbatt. However, if motor drive's nominal voltage is less than battery's nominal voltage, Vdc < Vbatt, the battery voltage should be stepped-down during acceleration and the dc link voltage should be stepped-up during regenerative braking. Thus the need for a universal bidirectional DC/DC capable of operating in all directions with stepping-up and stepping-down functionalities is evident. Here such a bidirectional DC/DC converter (shown in fig. 2) that can be used in any kind of electric vehicle is discussed.

The paper is organized as follows. In section II, the topological overview and the operation modes are presented. In section III, simulation results to evaluate the properties of the dc/dc bidirectional converter are presented. Section IV provides the conclusion.

II. SYSTEM DESCRIPTION AND OPERATING MODES

A. Different DC/DC Converters

There are different DC/DC converters used in electric vehicles. Some of them are; 1) buck-boost converters: they can regulate the DC link voltage or the battery side voltage. It can also step up/down voltages. But, they cannot provide voltage regulation in both directions, i.e., bidirectional power flow is not possible. Also, there is a need of an inverting transformer to get a positive output. 2) Non-inverted topologies: here, the need of bulky transformer can be reduced but these only provide a unidirectional power flow. Also, the PWM control of more than one switch is necessary which will increase the switching losses. 3) Two quadrant converters: By using two quadrant converters the voltage regulation with buck and boost operation is possible in either direction. But only two quadrants of operation are possible. 4) Two cascaded two quadrant converters: here, a four quadrant operation is possible. So the power flow can be in either direction and also voltage regulation can be made effectively. But, there will be a need of more than one inductor. 5) Dual active bridge (DAB) dc/dc converter: here, all switches are operating in PWM mode which increases the switching losses. Also, a transformer is needed which will increase the overall losses, size and cost.

B. Bidirectional DC/DC Converters

The schematic of the bidirectional converter is shown in fig.2. The converter topology consists of five switches (T1-T5) with internal diodes, five diodes (D1-D5), one inductor, L and two capacitors, C1 and C2. Vdc represents the motor drive nominal input voltage during driving mode or the rectified ac voltage at the output of the grid interface converter during plug-in mode The nominal voltage of the vehicle's ESS is represented by Vbatt .

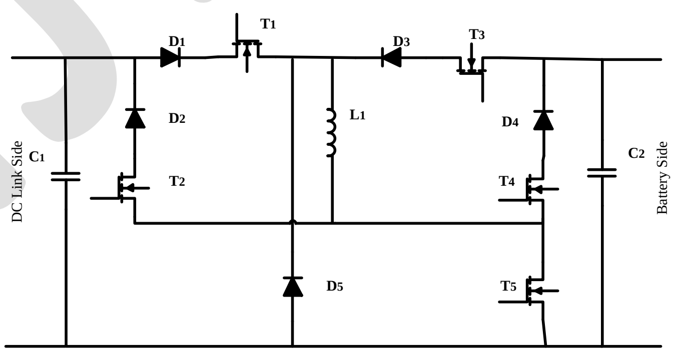

Fig.2. DC/DC bidirectional converter

The converter can be operated in buck or boost modes in either direction as required inorder to regulate the voltage at the dc link side and the battery side. The converter is capable of operating from Vdc to Vbatt boosting, Vdc to Vbatt bucking, Vbatt to Vdc boosting, or Vbatt to Vdc bucking, all with positive output voltage. Also, there is only one inductor needed for its operation. The operational modes are given in the table.1. Of the five switches only three will be PWM controlled for the entire working range, while others will be either completely ON or OFF. Only one switch will be operating in the PWM control for each of the operating modes which will reduce the switching losses.

Table.1. Operating modes of the converter

Direction	Modes	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

T2 and T4 serve as simple ON/OFF switches to connect or disconnect the corresponding current flow paths, whereas T1, T3, and T5 are either ON/OFF or PWM switches with respect to the corresponding operating mode. The different operating modes are explained below.

C. Case 1: Vdc < Vbatt

If the rated dc link voltage is less than battery's rated voltage, the dc link voltage should be stepped-up during charging in grid connected mode and in regenerative braking during driving. Under the same voltage condition, the battery voltage should be stepped-down during plug-in discharging in grid-connected mode, and in acceleration or cruising during driving.

Mode 1: Vdc → Vbatt Boost Mode for Plug-in Charging and Regenerative Braking:

In this mode, T1 and T4 are kept ON, while T2 and T3 remain in the OFF state, as shown in Fig. 3. The PWM switching signals are applied to switch T5.

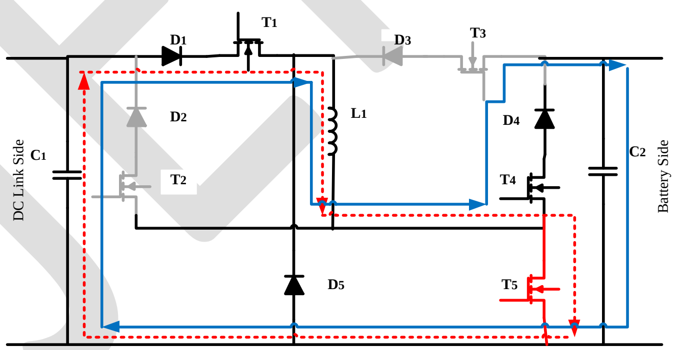

Fig.3. Vdc to Vbatt boost mode of operation

Therefore, from Vdc to Vbatt, a boost converter is formed by D1, T1, L, T5, D4, and T4. Since D1 and D4 are forward-biased, they conduct whereas D3 and D2 do not conduct. Since T5 is in PWM switching mode, when it is turned ON, the current from Vdc flows through D1, T1, L, and T5 while energizing the inductor. When T5 is OFF, both the source and the inductor currents flow to the battery side through D4 and T4. During this mode, Vdc and Vbatt sequentially become the input and output voltages. So by controlling the switching of T5 alone we can control this entire mode of operation. Since the inductor current is a state variable of this converter, it is controllable. Therefore, the charging power delivered to the battery in plug-in mode or high-voltage bus current in regenerative braking can be controlled.

Mode 2: Vbatt → Vdc Buck Mode for Plug-in Discharging and Acceleration:

The circuit schematic of this operation mode is provided in Fig 4. In this mode, T1, T4, and T5 remain OFF, while T2 is kept in ON state all the time. The PWM switching signals are applied to switch T3. Therefore, from Vbatt to Vdc, a buck converter is formed by T3, D3, D5, L, T2, and D2. When T3 is turned ON, the current from the battery passes through T3, D3, L, T2, and D2, while energizing the inductor. When T3 is OFF, the output current is freewheeled through the D5, T2, and D2, decreasing the average current transferred to the load side. D3 and D2 are forward-biased, whereas D1 and D4 do not conduct. D5 only conducts when T3 is OFF. In this mode, Vbatt and Vdc are the input and output voltages, respectively. During stepping-down the battery voltage while delivering power from battery to the dc link, the inductor is at the output and its current is a state variable. Therefore, the dc link voltage and the current delivered to the dc link can be controlled in driving mode.

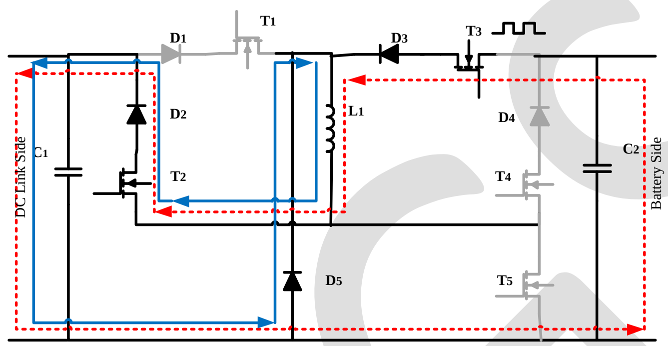

Fig.4. Vbatt to Vdc buck mode of operation

D. Case 2: Vdc > Vbatt

If the rated dc link voltage is more than the battery rated voltage, dc link voltage should be stepped-down during charging in grid-connected mode and in regenerative braking while the vehicle is being driven. Under the same voltage condition, the battery voltage should be stepped-up during plug-in discharging in grid-connected mode and in acceleration or cruising while driving.

Mode 3: Vdc → Vbatt Buck Mode for Plug-in Charging and Regenerative Braking:

In this mode, T1 is in the PWM switching mode. Switches T2, T3, and T5 remain in OFF state while T4 is kept ON all the time. Therefore, from Vdc to Vbatt, a buck converter is made up by D1, T1, D5, L, D4 and T4 as shown in Fig 5. When T1 is turned ON, the current from Vdc passes through D1, T1, L, D4, and T4 while energizing the inductor. When T1 is OFF, the output current is recovered by freewheeling diode D5 decreasing the average current transferred from dc link to the battery. Since diodes D1 and D4 are forward biased, they conduct whereas D2 and D3 do not conduct. D5 only conducts when T1 is OFF. In this mode, Vdc and Vbatt are the input and output voltages, respectively. The dc link voltage can be regulated in driving mode (regenerative braking) by controlling the current transferred to the battery. In plug- in charging mode, the current or power delivered to the battery is also controllable.

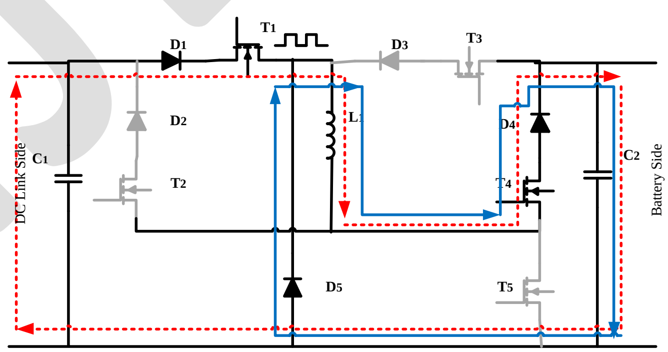

Fig.5. Vdc to Vbatt buck mode of operation

Mode 4: Vbatt → Vdc Boost Mode for Plug-in Discharging and Acceleration:

During this mode, T1 and T4 remain OFF, whereas T2 and T3 remain ON all the time. Switch T5 is operated in PWM switching mode. Therefore, from Vbatt to Vdc, a boost converter is formed by T3, D3, L, T5, T2, and D2, as illustrated in Fig.6. When T5 is turned ON, the current from Vbatt passes through T3, D3, L, and T5 while energizing the inductor. When T5 is OFF, both inductor and the source currents pass through T2 and D2 to the dc link. In this mode, D3 and D2 are forward-biased and they conduct, whereas D1, D4 and D5 are reverse-based and do not conduct.

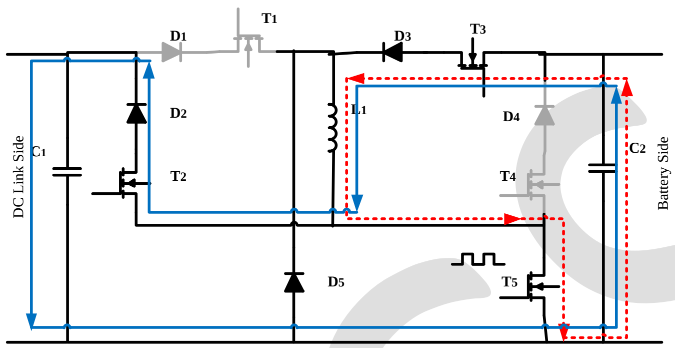

Fig.6. Vbatt to Vdc boost mode of operation

In this mode, Vbatt and Vdc are sequentially the input and output voltages. The dc link voltage can be regulated in driving mode (regenerative braking) by controlling the current drawn from the battery. In plug-in charging mode, the current or power drawn from battery is also controllable.

III. MATLAB SIMULINK MODEL AND RESULTS

The MATLAB/SIMULINK model for electric vehicle applications is shown in fig.7. The circuit parameters chosen are L=1.545mH, Cdc=Cbatt=2200μF. The DC link side is represented by a DC source and the battery side is provided with a battery. There are two cases of voltages at the DC link side and the battery side as already discussed..The input is given as Vdc=12V and the battery side voltage is given as Vbatt~21V for the case Vdc<Vbatt. (mode 1 and 2 of operation). And Vdc= 21 V and battery voltage Vbatt~12V for Vdc>Vbatt.

The gate signals and results obtained for each case is shown in figures 8 to13.

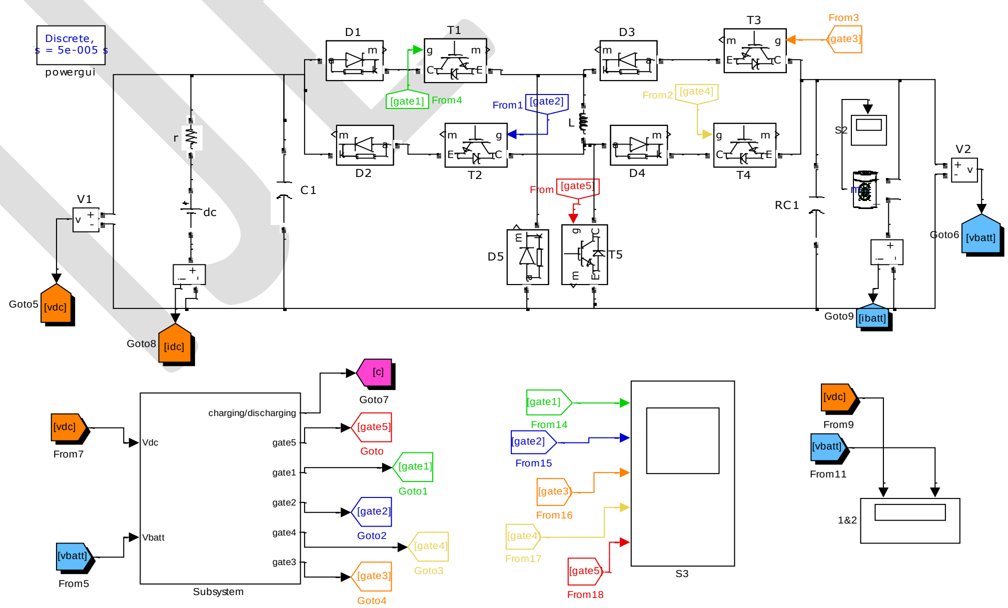

Fig.7. Simulink model of the DC/DC converter

When Vdc<Vbatt and charging/regenerative braking, the power flow is from DC link side to battery side and it is the boost mode of operation [mode1]. When Vdc<Vbatt and discharging/acceleration, the power flow is from DC link side to battery side and it is the buck mode of operation [mode 2]. When Vdc>Vbatt and charging/regenerative braking, the power flow is from battery side to DC link side and is the buck mode of operation [mode 3]. When Vdc>Vbatt and discharging/acceleration, power flow is from from battery side to DC link side and is in the boost mode of operation [mode 4].

A. Mode 1: Boost charging

The input voltage is set for 12V and output is boosted to 21V and thus the battery charges. The corresponding voltages and current obtained are shown in fig.8.

T5 is PWM controlled in mode 1. So the vehicle is in the regenerative mode of operation.

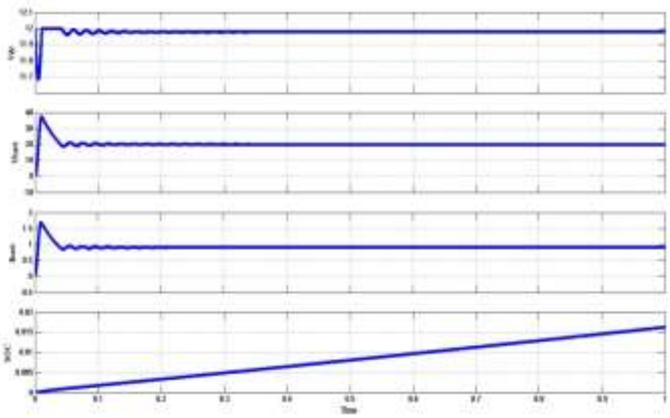

Fig.8. Input, output voltages at the battery SOC% for boost charging mode

B. Mode 2: Buck discharging

The DC/DC converter will step down the 21V input to 12V output at the DC link voltage side. This is shown in the fig.5.9.

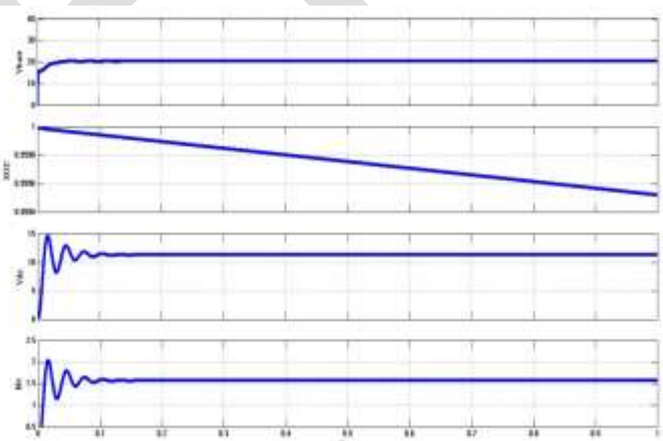

Fig.5.9. Input, output voltages at the battery SOC% for buck discharging mode

C. Mode 3: Buck charging

Here, the dc link voltage chosen is 21V and the battery terminal voltage is 12V. So the input 21V will be stepped down to 12V by the DC/DC converter. The waveforms obtained are shown in fig.5.10.

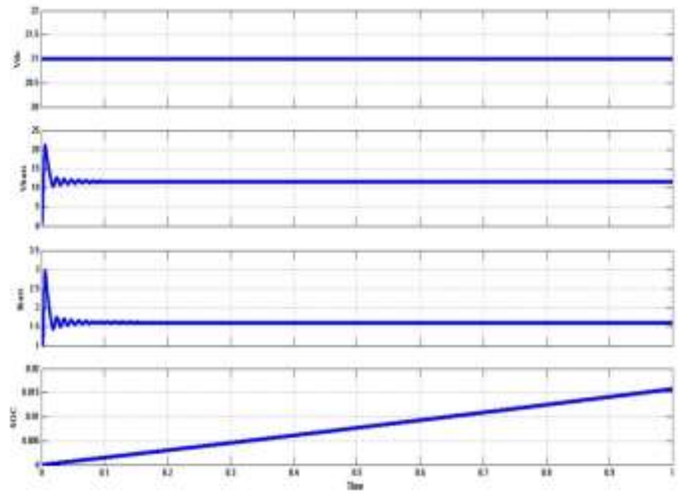

Fig.10. Input, output voltages at the battery SOC% for buck charging mode

D. Mode 4: Boost discharging

Here, the battery terminal voltage is taken as 12V and the required DC bus voltage is 21V, then the bidirectional DC/DC converter will boost up the voltage at the DC link.

The waveforms are shown in the fig.5.11. The battery SOC is shown. In the boost discharging mode, the battery is initially at 100 % charge and it starts to discharge from full charge. The state of charge decreases to 0% during this accelerating mode.

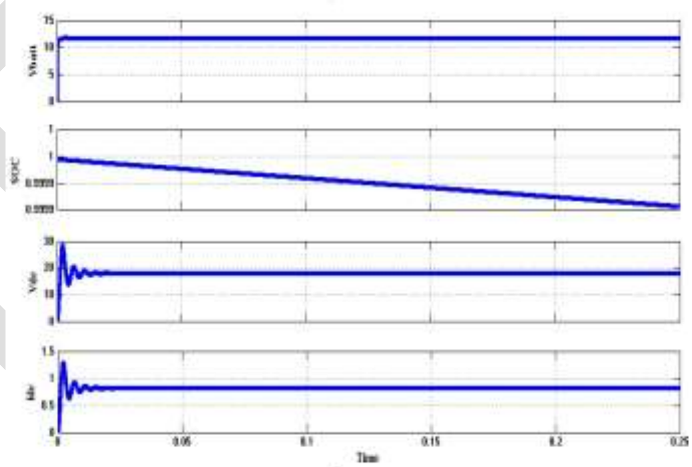

Fig.10. Input, output voltages at the battery SOC% for boost discharging mode

IV. CONCLUSION

This study introduces a dc/dc converter structure that is suitable for both industrial needs and the electric vehicle conversion approaches for all EV, HEV, and PHEVs regardless of their rated dc link voltage and motor drive inverter voltage as well as the battery nominal voltage. The functionalities of the proposed converter provide a broad range of application areas. Due to the operational capabilities, the converter is one of a kind plug-and-play universal dc/dc converter that is suitable for all electric vehicle applications.

Each mode of operation with battery are discussed. The resulting waveforms are obtained and are verified by MATLAB/SIMULINK model (2010).

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