SINGLE-STAGE ZETA-SEPIC-BASED MULTIFUNCTIONAL INTEGRATED CONVERTER FOR PLUGIN ELECTRIC VEHICLES

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ABSTRACT:

A single-stage-based integrated power electronic converter has been proposed for plug-in electric vehicles (PEVs). The proposed converter achieves all modes of vehicle operation, i.e. plug-in charging, propulsion and regenerative braking modes with wide voltage conversion ratio (M) [$M < 1$ as well as $M > 1$] in each mode. Therefore, a wide variation of battery voltage can be charged from the universal input voltage (90–260 V) and allowing more flexible control for capturing regenerative braking energy and dc-link voltage. The proposed converter has least components compared to those existing converters which have stepping up and stepping down capability in all modes. Moreover, a single switch operates in pulse width modulation in each mode of converter operation hence control system design becomes simpler and easy to implement. To correctly select the power stage switches, a loss analysis of the proposed converter has been investigated in ac/dc and dc/dc stages. Both simulation and experimental results are presented to validate the operation of the converter.

Keywords: SEPIC, PEV, plug in electric vehicle, Regenerative braking operation.

1. INTRODUCTION

The electric vehicles or plug-in electric vehicles (PEVs) are now a promising solution to curb the air pollution that uses pollution-free battery power to produce clean energy for the vehicle. The PEVs are combination of on-board charger, battery, and the inverter-drive system. In majority of PEVs, a bidirectional dc/dc converter is interfaced between the battery and dc-link of machine inverter for power flow during propulsion and regenerative braking operation. Therefore, an individual ac/dc converter is used to charge the battery from the grid side. In this conventional structure, two separate power electronic converters are needed for two independent operations (charging and discharging of the battery). The bidirectional dc/dc converter in conventional structure can be integrated with the on-board charger, to have one power electronics interface for complete operation of PEVs. The overall block diagram of an integrated charger with single power electronic is shown in Fig. 1*a*. This integration reduces the number of components because some of the switches and inductors are utilised both in ac/dc and dc/dc stages. Therefore, reduced number of switches and inductors lead to higher power density, compact size and lower cost. In this regard, this paper proposes, a new ZETA-SEPIC-based integrated converter for PEVs, as shown in Fig. which has buck/boost capability in each mode of operation. In addition, buck/boost operation in each mode allows selection of wide range of the battery voltage, efficient control of dc-link voltage and capturing the regenerative braking with a wide variation of the motor speed. A comparison of existing integrated converters and other competitive converters with respect to the proposed converter is described in the following paragraph. An integrated converter in [9] utilises a number of semiconductor devices to achieve each mode; therefore, it may not be an efficiency optimised and cost-effective solution. In addition, the presence of a large number of devices, this converter requires a complex control strategy to turn on the switches. An integrated converter in [1] has only boost charging capability; thus, the selection of wide range of battery voltages is compromised. In [2], an integrated converter does not have buck/boost operation in any mode; thus, selection of the dc-link and battery voltage range is sacrificed. A three-level quasi two-stage converter in [3] with two inductors has buck/boost operation only in charging mode as a result, aforementioned advantages of buck/boost operation in each mode is sacrificed. n SEPIC-based converter has been proposed for the battery charging using three inductors and at least one extra inductor is also required for propulsion and regenerative braking modes. Thus, the increase of magnetic components has a negative effect on weight, cost and volume of the charger. Previous Authors have proposed a CuK converter based on-board battery charger, which operates only in charging mode, does not include propulsion and regenerative braking modes. A single-stage converter operates only battery charging mode using four switches, eight diodes and two inductors.

2 RELATED STUDY

The universal voltage range of single phase is around 90–260 V and a majority of commercially available battery voltage range are between 200 and 450 V [20– 22]. Therefore, the buck/boost operation of converter is needed in plug-in charging mode for universal voltage supply. Moreover, in propulsion mode, usually, the battery voltage is stepped up to the dc-link voltage (inverter dc-link voltage) to propel the motor drive system. In a case of high state of charge (SOC) of the battery, the battery voltage may be more than the dc-link voltage, in such case, the dc/dc converter with buck operation is required. Furthermore, in regenerative braking, a step-down operation is typically required because the dc-link voltage usually higher or near to the battery voltage. However, at low speed, boost operation is also required to capture all the available regenerative braking energy. It is explained as: at a lower speed, the propulsion machine induces lower back electromotive force. If the generated voltage across the motor terminals is lower than the battery voltage, a bidirectional converter between the propulsion inverter and the battery must have boosting capability. Therefore, the buck/boost capability of converter is also needed during regenerative braking operation. Hence, it is concluded that buck/boost operation of converter is essential in each mode of vehicle operation.

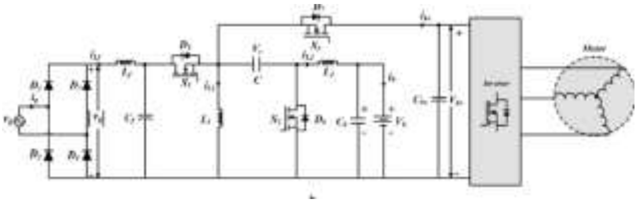

Fig.2.1. Proposed model.

3. LITERATURE SURVEY

1) An overview of power electronics in electric vehicles By C.C. Chan; K.T. Chau

In response to concerns about energy cost, energy dependence, and environmental damage, a rekindling of interest in electric vehicles (EVs) has been obvious. Based on the "California rules" on zero emission vehicles in the United States, as well as similar tightened air pollution regulation in Europe, Asia, and much of the rest of the world, the market size of EVs will be enormous. Thus, the development of power electronics technology for EVs will take an accelerated pace to fulfil the market needs. This paper reviews the current status of multidisciplinary technologies in EVs. Various challenges of power electronics technology for EV propulsion, battery charging, and power accessories are explored.

2) **Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles by Ali Emadi; Young Joo Lee; Kaushik Rajashekara**

With the requirements for reducing emissions and improving fuel economy, automotive companies are developing electric, hybrid electric, and plug-in hybrid electric vehicles. Power electronics is an enabling technology for the development of these environmentally friendlier vehicles and implementing the advanced electrical architectures to meet the demands for increased electric loads. In this paper, a brief review of the current trends and future vehicle strategies and the function of power electronic subsystems are described. The requirements of power electronic components and electric motor drives for the successful development of these vehicles are also presented.

3) **An improved two-stage non-isolated converter for on-board plug-in hybrid EV battery charger by Ankit Kumar Singh; Mukesh Kumar Pathak**

This paper presents a single-phase two-stage non-isolated converter for on-board plug-in hybrid electric vehicle battery charger. The first stage is a conventional boost converter and the second stage is a bi-directional dc-dc converter (battery-interface) having a wide range of output voltage with low component stress in both directions compared to conventional SEPIC, Cuk, Zeta and inverting buck-boost converters. In addition, the second stage bi-directional dc-dc converter also has improved efficiency over two switches non-inverting buck-boost converter) in the buck mode from one-direction and in boost mode from another direction. Simulation results are given to demonstrate the effectiveness of the proposed system.

4) **Evaluation and Efficiency Comparison of Front End AC-DC Plug-in Hybrid Charger Topologies by Fariborz Musavi; Murray Edington; Wilson Eberle; William G. Dunford**

As a key component of a plug-in hybrid electric vehicle (PHEV) charger system, the front-end ac-dc converter must achieve high efficiency and power density. This paper presents a topology survey evaluating topologies for use in front end ac-dc converters for PHEV battery chargers. The topology survey is focused on several boost power factor corrected converters, which offer high efficiency, high power factor, high density, and low cost. Experimental results are presented and interpreted for five prototype converters, converting universal ac input voltage to 400 V dc. The results demonstrate that the phase shifted semi-bridgeless PFC boost converter is ideally suited for automotive level I residential charging applications in North America, where the typical supply is limited to 120 V and 1.44 kVA or 1.92 kVA. For automotive level II residential charging applications in North America and Europe the bridgeless interleaved PFC boost converter is an ideal topology candidate for typical supplies of 240 V, with power levels of 3.3 kW, 5 kW, and 6.6 kW.

5) **Design of a Soft-Switched 6-kW Battery Charger for Traction Applications by Brendan Peter McGrath; Donald Grahame Holmes; Patrick John McGoldrick; Andrew Douglas McIver**

Auxiliary power converters for traction rolling stock applications have to operate under difficult conditions, including high-input voltages which are subject to wide fluctuations, high temperatures, and harsh environmental constraints. Additionally there is often a need for silent operation, which implies switching frequencies above 20 kHz. Increasingly, high-frequency DC-DC converters are being used for these applications, with their advantages of reduced size and weight. However, the requirement to accommodate high-input voltages and switch at high frequencies is challenging for a conventional hard-switched converter based on IGBTs, which makes soft-switching topologies an attractive alternative. This paper presents the design strategy for a zero-voltage switched (ZVS) 6-kW battery charger switching at 20 kHz using IGBTs. This paper illustrates how the design is a tradeoff between managing the hard-switch turn-on losses at light load, minimizing the duty cycle loss caused by soft-switching delays, and minimizing the effects of tail current-switching losses. These tradeoffs affect the selection of the ZVS capacitors, the determination of the series inductance value, the transformer turns ratio, and the selection of the IGBTs to be used. Design details, theoretical predictions, and experimental results are presented in this paper for the conversion system that was developed.

3. METHODOLOGY AND RESULTS EXPLANATION

The plug-in charging mode of vehicle is possible only when vehicle is not in motion and then charger plug is connected to single phase supply socket to charge the battery. In this mode, the proposed converter operates as ZETA PFC converter and switch *S*1 is pulse width modulation (PWM) gated while switch *S*2 and *S*3 are in OFF-state. When switch *S*1 is turned ON, inductor *L*1 stores energy through the path |*v*g|-*Lf* -*S*1-*L*1-|*v*g| and inductor *L*2 stores energy through the path |*v*g|-*L*f-*S*1-*C*-*L*2-*V*b-|*v*g|, as shown in Fig. 2*a*. When switch *S*1 is turned OFF, inductor *L*1 discharges by supplying its stored energy to the capacitor *C*, and voltage across capacitor gradually increases, which is shown in Fig.

and this capacitor is charged to the battery voltage *V*b. While inductor *L*2 supplies energy to the output stage (capacitor and battery) shown in Fig. and current through *L*2 decreases linearly, as shown in Fig. 3.2. The capacitor *Chv* is charged to *V*g, max through the body diode of *S*3 in very short duration then after it retains this value forever in this mode.

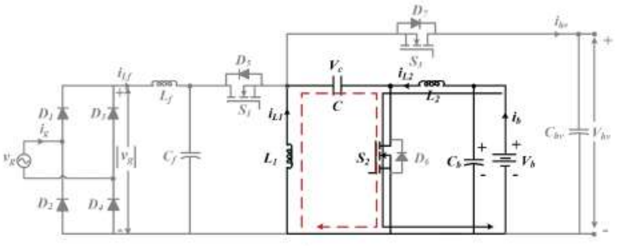

Fig.3.1. SEPIC converter.

When *S*2 is turned OFF, inductor *L*2 transfers its stored energy in the capacitor C and dc-link capacitor *Chv* through the path *V*b-*L*2-C-*D*7-*Vhv*-*V*b and capacitor C is charged to the battery voltage. The inductor *L*1 transfers its stored energy to the dc-link through the path *L*1-*D*7-*Vhv*- *L*1.

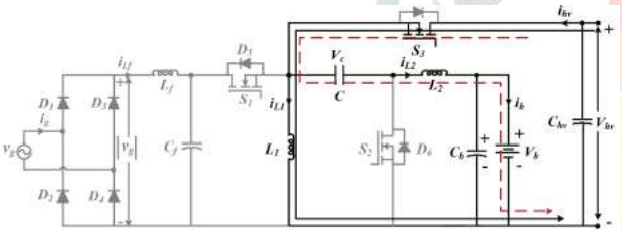

Fig.3.2. Operation Sw2 Activated time.

SIMULATION RESULTS:

The integrated converter has low stresses (voltage and current) like converter, but the major limitation of this converter is only to have a boost charging capability hence selection of the wide range of battery voltage is not possible.

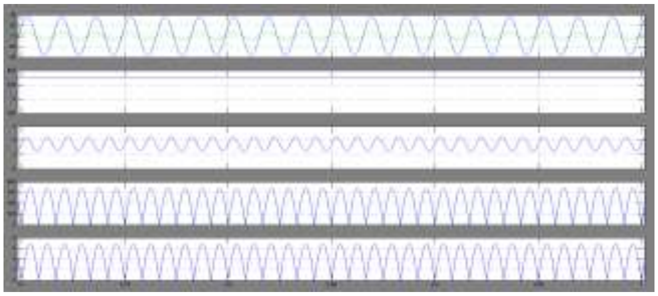

Fig.3.3 Simulation waveforms during plug-in charging mode with 220 *V*RMS of grid voltage

The efficiency plots of the proposed converter and integrated converters of using 1200 V/100 a device and 220 V grid voltages in each mode are shown in Fig. The integrated converter has bridge less nature in plug-in charging mode as well as low-voltage and current stresses in propulsion and regenerative modes and one– two devices come in current path; therefore, this converter will have higher efficiency than proposed converter in each mode. However, the major limitation of this converter is none of the modes have buck/boost operation.

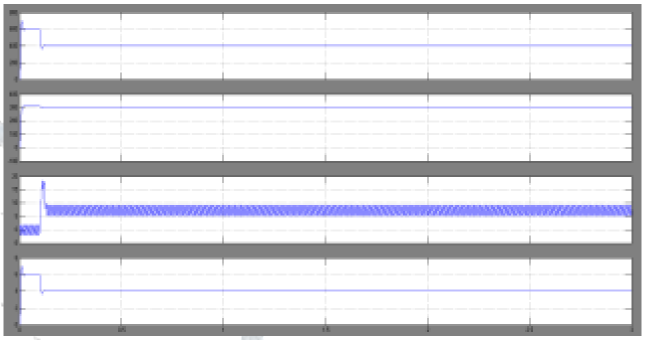

Fig.3.4 Waveforms of propulsion mode

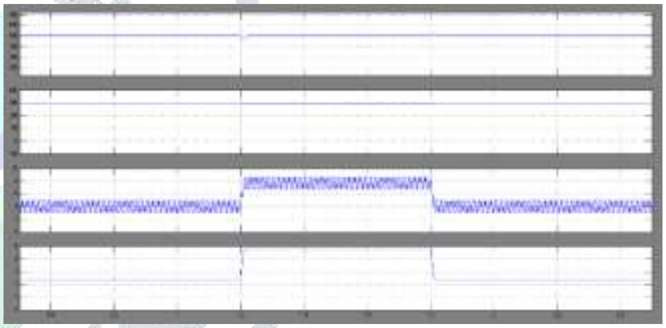

Fig. 3.5. Dynamic operation of propulsion mode with step load variations

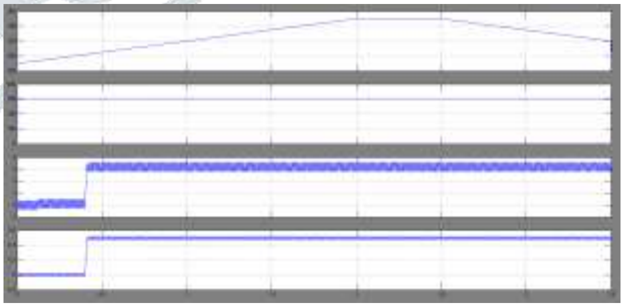

Fig.3.6. Closed loop verification of regenerative braking mode by varying the dc-link voltage

The conventional single-stage battery charger topologies, namely the boost PFC converter, inverting buck/boost PFC converter, SEPIC PFC converter, and CuK PFC converter is shown in Fig. 5. In order to have a fair comparison of the proposed converter with these single-stage converters, the dc/dc converter connected between the battery and dc-link in Fig. 5, is assumed to be a four quadrant bidirectional converter. The boost PFC converter can only charge the battery when battery voltage is more than the peak grid voltage $Vb > Vg$, max . While inverting buck/boost and CuK converter both have negative output voltage with respect to the input. The same polarity between the input and the output has an advantage of solving electromagnetic interference/electromagnetic compatibility problems, and in designing filters easily, because the internal ground of a vehicle, the ground of the on-board battery charger (OBC) and the cathode of the battery can have the same potential.

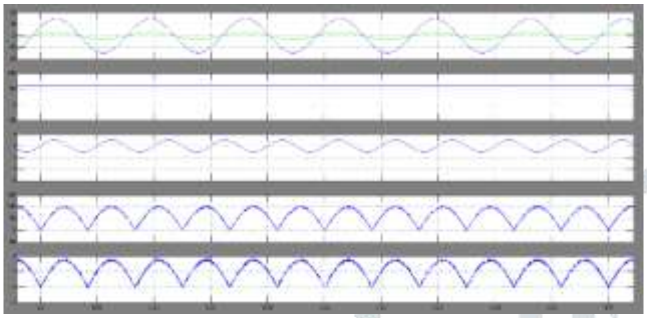

Fig. 3.7. Simulation results during plug-in charging mode with 100 V (peak) grid voltage and 60 V battery voltage (a) Waveforms of vg, ig, VCf and ILf

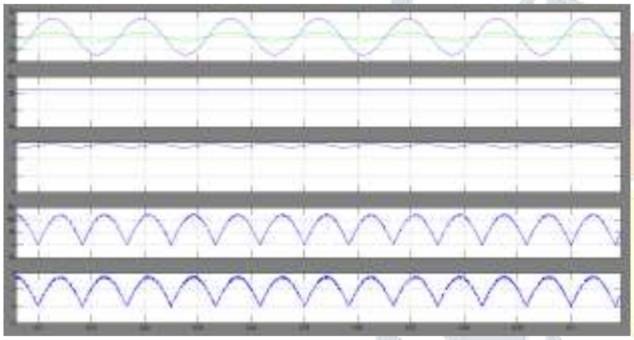

Fig.3.8. Simulation results with grid voltage of 90 V

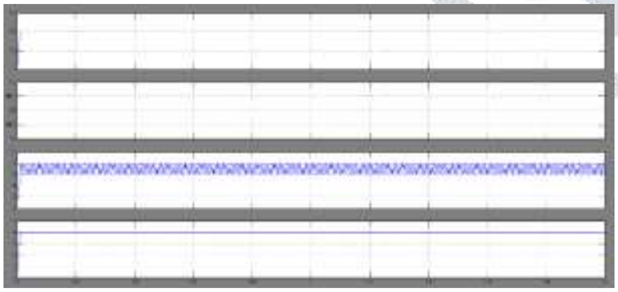

Fig. 3.9. Simulation waveforms during propulsion and regenerative braking with 60 V battery and 100 V dc link (a) Waveforms in propulsion mode with 400 W load

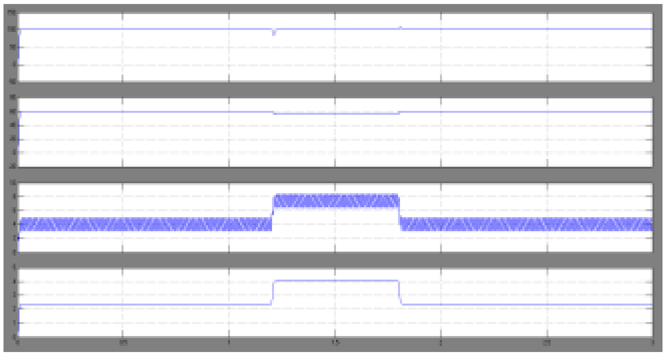

Fig .3.10 Dynamic operation of propulsion mode with load variations

CONCLUSION:

In this work, a ZETA-SEPIC-based single-stage power electronics interface has been proposed for PEVs. The proposed converter operates in three modes, i.e. plug-in charging (PFC mode), propulsion and regenerative modes. In PFC and regenerative braking modes, the proposed converter operates as ZETA converter, while in propulsion mode, it operates as SEPIC converter. It means the proposed converter has buck/boost operation in each mode of converter operation without voltage reversal which allows selection of a wide range of the battery voltage, efficient control of dc-link voltage and capturing the regenerative braking energy with wide variations of the motor speed. In comparison with existing single-stage converters, the proposed converter has the least component to those converters which have buck/boost operation in each mode. The functionality and performance of the proposed integrated converter have been verified through both in simulation and hardware. The performance of control algorithm is tested with the step load variations in propulsion mode and dc-link voltage variations in regenerative braking mode. An extensive loss analysis of the proposed converter is investigated to correctly select the power stage switches. The maximum theoretical efficiency of the converter in plug-in charging, propulsion and regenerative braking modes is found 95.9%, 97.1%, and 96.7%, respectively. While in hardware, the peak efficiency is found 94.76% at 85 W and 60 V peak grid voltage.

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