International Journal of Innovative Research in Engineering
Volume 4, Issue 6 (November-December 2023), PP: 05-09
www.theijire.com ISSN No: 2582-8746

Multifunctional integrated DC/DC converter for plug-in electric vehicles

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How to cite this paper: Shikha S, "Multifunctional integrated DC/DC converter for plug-in electric vehicles", IJIRE-V4I06-04-09.

Abstract: *A single-staged based integrated power electronic converter has been proposed for plug-in electric vehicles (PEVs). The proposed converter achieves all modes of vehicle operation, plug-in charging, propulsion and regenerative breaking mode with a wide voltage conversion ratio 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 the least components compared to those existing converters which have stepping up and stepping down capability in all modes.*

Key Word: *Plug-in charging, propulsion mode, regenerative braking, pulse width modulation.*

I. INTRODUCTION

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 universal voltage range of a single phase is around 90–260 V and a majority of commercially available battery voltage ranges are between 200 and 450 V [1-3]. Therefore, the buck/boost operation of the 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 the case of the 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 is usually higher or near 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 the boosting capability. The bi-directional dc-dc converter with a proper charging-discharging profile is required to transfer energy between the battery and electric traction system. The converter for PHEV conversion should minimize the electrical impact on the HEV power system, particularly from the point of view of fault current. In PHEV vehicles, a power-conditioning unit such as a dc-dc converter for matching the fuel cell voltage with the battery pack is necessary. In addition to power electronics, the technology of the electric motor plays a major role in the vehicle's dynamics and the type of power converter for controlling the vehicle's operating characteristics [4-5].

II. LITERATURE OVERVIEW

In the olden days, there are 3 types of automobiles which are electric, steam and gasoline automobiles. From these three the electric automobile is the type with very little pollution. The gasoline type emits CO, NOx, Non-Methane Organic Gases (NMOG). Power conversion and control function forms the basis of what has come to be known in this field of power electronics. The power electronic technology is used for efficient control of motor [5]. Hybrid electric vehicle technology (HEV) provide an effective solution for achieving higher fuel economy better performance and lower emission compared with a conventional vehicle. Plug-In hybrid electric vehicles are HEV's with plug-in capabilities and provide a more all-electric range; hence PHEV's improve fuel economy and reduce emissions even more. PHEV's have a battery package of high energy density and can run solely on electric power for a given range. The battery pack can be recharged by a neighbourhood outlet. Power electronic DC to DC converters in plug-in hybrid and electric automotive applications demand high power bi-directional power flow capability, with a wide input voltage range. The converter needs to provide a successful voltage regulation on the load side for a wide range of input voltage. In PHEV DC-DC converter provides both buck and boost operation. In conventional DC-DC converters, the circuit is complex and a large number of components are used [1-2]. The power converters regulate power flow between batteries and motors during propulsion and regenerative braking. Among the available power devices gate-turnoff thyristor (GTO), power bipolar-junction transistor (BJT), Power metal-oxide field-effect transistor (MOSFET), insulated-gate bipolar transistor (IGBT), MOS-controlled thyristor (MCT) are particularly suitable for an EV propulsion [3-4]. Pulse width modulation, or PWM, has become an accepted method for generating unique signals, due to the advancement of microcontrollers and their power efficiency. To create a sinusoidal signal, PWM uses high-frequency square waves with varying duty cycles. The duty cycle is the percentage of time the signal is on relative to the period. This means as the duty cycle increases, more power is transmitted. PWM requires rapid on and off signals, which can be achieved using high power MOSFETs. MOSFETs are ideal switches due to the low power loss when the device is activated. It should be noted, however, that when a MOSFET is in transition between on and off, the power loss can be significant. For this reason, the transition times and frequency should be engineered to be as short as possible. This can be achieved by minimizing the amplitude between the on and off stages and lowering the PWM frequency, however as the frequency decreases so does the signal quality [6].

III. WORKING OF THE CONVERTER

The proposed integrated converter operates in three modes: plug-in charging, propulsion, and regenerative braking of charging.

A. Plug-in Charging Mode

The plug-in charging mode of the vehicle is possible when the vehicle is not in motion and the charger plug is connected to a single-phase supply to charge the battery. In this mode, the realized converter act as the bucked converter and switch S1 is pulse width modulation (PWM) gated while switch S2 and S3 are in OFF-state. When switch S1 is turned ON, inductor L1 stores energy through the path |Vg|-Lf -S1-L1-|Vg| and inductor L2 stores energy through the path |Vg|-Lf-S1-C-L2-Vb-|Vg|, as shown in Fig.1. When switch S1 is turned OFF, inductor L1 discharges by supplying its stored energy to the capacitor C, and the voltage across the capacitor gradually increases to the battery voltage Vb. While inductor L2 supplies energy to the output stage shown in Fig. 3.1 and current through L2 decreases linearly. The capacitor Chv is charged to Vg, max through the body diode of S3 in a very short duration.

If the duty ratio of the converter is d1 then voltage-second balance either of inductor L1 or L2 for one switching period, Ts, we get:

$$V_{gmax}|\sin(\omega t)| * d_1(t) = V_b * (1-d_1(t)) * T(s) \qquad (1)$$

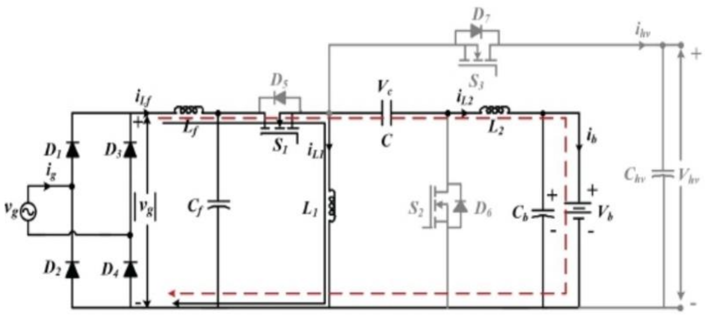

Fig.1 *Operating circuit of plug-in charging mode.*

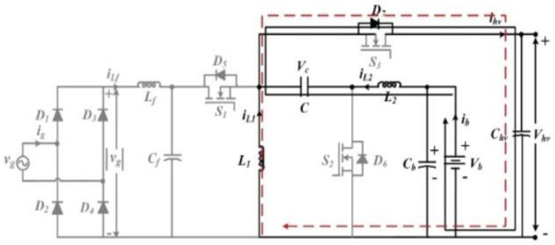

Fig.2 *Operating circuit of propulsion mode*

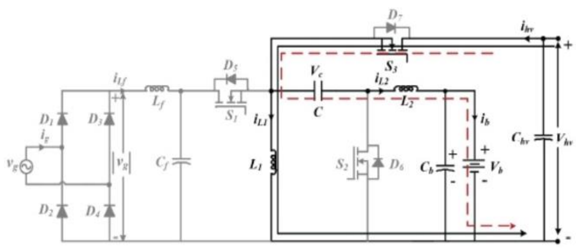

Fig.3 *Operating circuit of regenerative braking mode*

B. Propulsion mode

When this mode begins, the battery starts supplying power to the dc-link of the inverter and the vehicle comes in running mode. During the motion of the vehicle, the SOC of the battery continuously decreases. In this mode, switches S1 and S3 are kept in OFF and switch S2 is gated through PWM signal. When switch S2 is turned ON, inductor L2 stores energy through the path Vb-L2-S2-Vb, and capacitor C discharges through inductor L1, as shown in Fig. 3a and inductor current through L1 is linearly increasing. When S2 is turned OFF, inductor L2 transfers its stored energy in the capacitor C and dc-link capacitor Chv through the path Vb-L2-C-D7-Vhv-Vb and capacitor C is charged to the battery voltage. The inductor L1 transfers its stored energy to the dc-link through the path L1-D7- Vhv- L1, as shown in Fig. 2, and current through L1 gradually decreases.

If the duty ratio of the converter is d2 and applying voltage-second balance either in inductor L1 or L2 for one switching period then we get:

$$Vb * d2 * Ts = Vhv * (1 - d2) * Ts \qquad (2)$$

C.Regenerative Braking Mode

when switch S3 is turned ON, inductor L1 stores energy through the path Vhv S3-L1-Vhv and inductor L2 stores energy through the path Vhv-S3-C-L2-Vb-Vhv. When S3 is turned OFF L1 transfers its stored energy to the capacitor (C) through the path C-L1-D6 and capacitor voltage Vc gradually increases. While L2 transfers its stored energy to capacitor Cb and battery which is shown in Fig.3.

If the duty ratio of the converter is d3 by applying voltage-second balance either of inductor L1 or L2, we get:

$$Vhv * d3 * Ts = Vb * (1 - d3) * Ts \qquad (3)$$

IV.DESIGN AND SELECTION OF COMPONENTS

A. Selection of inductors L1 and L2

The power level is usually high in the PEVs. So continuous conduction mode (CCM) is preferred compared to discontinuous mode (DCM) since current stress in CCM are much smaller than DCM.

Assuming unity power factor, the ratio of input voltage and input current can be expressed by an effective resistor,

$$Re = Vg \div Ig = V2g \div Pg \qquad (4.1)$$

Thus, (CCM) condition for inductor current in L1 can be expressed as

$$L1 > (Vg2 * Vb) \div (Pg * 2fs(|Vgmax| + Vb)) \qquad (4.2)$$

From (4.1), the larger the minimum input power Pg, min and switching frequency fs is, the easier the converter can enter in CCM. Similarly, the boundary condition for L2 can be derived. The CCM condition for inductor current iL2 can be calculated as

$$L2 > (Rlmaz * |Vgmax|) \div ((2|Vgmax| + Vb) * 2fs) \qquad (4.3)$$

According to (4.2), the higher the switching frequency and smaller load resistance Rlmax is, the easier the converter can enter in CCM mode.

B. Selection of capacitor C

The value of the coupling capacitor c will highly affect the quality of the input current. Therefore, it is designed under certain constraints: The resonant frequency of L1, L2 and C during CCM operation must be greater than line frequency fl to avoid input current oscillations at every half-line cycle and lower than switching frequency fs to ensure constant voltage in a switching period, i.e

$$Fl < fr < fS \qquad (4.4)$$

$$fr = 1 \div (2\Pi * ((L1 + L2) C)1/2 \qquad (4.5)$$

here, switching frequency fs is set as 20 kHz, and fr is set as 1 kHz. The capacitor C is selected as 10 µF both in simulation and hardware.

C. **Selection of Lh and Cf**

The design of the input filter is essential for maintaining low harmonic distortion in grid current [23, 24]. The maximum value of filter capacitance is expressed as

$$Cfmax = (Igmax * \tan\theta) \div (2\Pi * fl * Vgmax) \qquad (4.6)$$

where Vg, max and Ig, max voltage, and θ is considered below 5∘ for maintaining a high input power factor. The capacitance Cfmax is calculated as 1.14 µF and the selected value in the simulation and hardware is 1 µF. The filter inductor to maintain low ripple is calculated as

$$Lf = 1 \div (4\Pi 2 * fc2Cf) \qquad (4.7)$$

where fc is cut off frequency, which is selected such that it should be more than the grid frequency fl =50Hz and less than switching frequency fs =20kHz. Therefore, it is chosen as 4 kHz. Lf is calculated as 1.58 mH, and the selected value in the simulation and hardware is 1.5 mH.

D. Selection of capacitor Cb

With regards to the parallel capacitor across the battery terminal, the switching frequency voltage ripple is negligible as this capacitor is typically very large. Twice of the line frequency voltage ripple is more critical since it

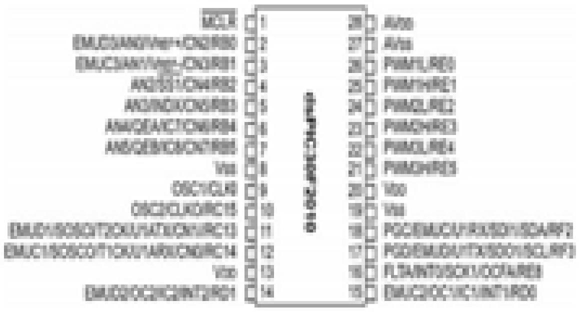

Fig.4pin diagram of Dspic30F2010

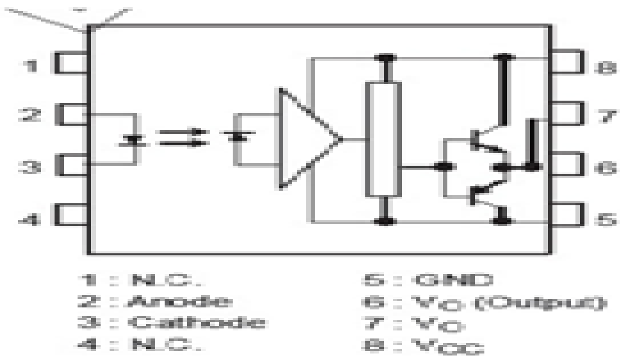

Fig.5Pin diagram of TLP 250

directly affects the charging voltage. The low-frequency voltage ripple on the battery capacitor is given as

$$Cbmin > Pb \div (4fl * \Delta Vb * Vb) \qquad (4.8)$$

E. Microcontroller Dspic30F2010

The main component of this inverter is a microcontroller as it is used to generate control signals. The theory of encoding a sine wave with a PWM signal is relatively simple. A sine wave is needed for the reference that will dictate the output, and a sawtooth wave of higher frequency is needed to sample the reference and actuate the switches. The process can also be done with a microcontroller and crystal oscillators. Since the control technology which will be used is sinusoidal pulse width modulation (SPWM), dsPIC30F2010 was chosen to generate the required signal.

Fig.4 shows the pin diagram of dsPIC30F2010. This microcontroller features a high-speed core optimized to perform complex calculations quickly i.e., it has a dedicated DSP module inbuilt in it and includes 12KB internal flash memory and a wide range of timers together with several PWM modules for adjustable motor speed control. It also includes a 5-channel 10-bit A/D converter with fast time together with support for SPI and I^2C communication.

F. TLP250 isolated MOSFET driver

Fig.5 shows the pin diagram of TLP250. TLP250 is a MOSFET driver, has an input stage, an output stage and a power supply connection. TLP250 is an optically isolated driver, meaning that the input and output are “Optically isolated”. The isolation is optical-the input stage is an LED and the receiving output stage is a photodetector. The TL)250, being an isolated driver, has relatively slow propagation delays. The propagation time will typically lie between 0.15 µs and 0.5 µs.

G. IRFZ44N Switch

Advanced HEXFET® Power MOSFETs from International Rectifier utilize advanced processing techniques to achieve extremely low on-resistance per silicon area. This benefit, combined with the fast-switching speed and ruggedized device design that HEXFET power MOSFETs are well known for, provides the designer with an extremely efficient and reliable device for use in a wide variety of applications. The TO-220 package is universally preferred for all commercial-industrial applications at power dissipation levels to approximately 50 watts. The low thermal resistance and low package cost of the TO-220 contribute to its wide acceptance throughout the industry. Its features include Advanced Process Technology, Ultra-Low On-Resistance, Dynamic dV/dt Rating,175°C Operating Temperature, Fast Switching, Fully Avalanche Rated.

V.CONCLUSION

This multifunctional integrated power electronic interface has been proposed for PEV's. The proposed converter operates in three modes, i.e. plug-in charging (PFC mode). propulsion and regenerative modes. The proposed converter has buck/boost operation in each mode of converter operation without voltage reverse which allows selection of a wide range of the battery voltage, efficient control of dc-link voltage and capturing the regenerative braking energy with a wide variation of motor speed. In comparison with existing converters designed converter has the least component to those converters which have buck/boost operation in each mode. The functionality and performance of the integrated converter have been verified through simulation.

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