

ZVS PWM Resonant Full Bridge Converter with reduced Circulating loss and Voltage stresses of Bridge Rectifier and Voltage Doubler for Electric Vehicle Battery Chargers

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Abstract— This paper presents a voltage doubler in to a half bridge converter is derived for electric vehicle battery chargers. The proposed converter provides wide ZVS range, reduced circulating current and also voltage stress. Circulating current during the freewheeling phases of phase shift full bridge circuit are reset by the sum of LLC circuit output voltage and resonant capacitor voltage by achieving minimized circulating losses. In this project based on half bridge converter topology with an additional small inductor and two diodes connected in parallel with dividing capacitors is proposed for battery charger applications. The voltage stress on the secondary side diodes have clamping feature without overvoltage risks.

Index Terms— Battery charger, full-bridge converter, LLC half-bridge converter, resonant and PWM power conversions, minimal circulating losses, minimal voltage stresses , ZVS.

I. INTRODUCTION

PLUG-in hybrid electric vehicles (PHEVs) utilize a high voltage battery pack with high energy density to store energy for the electric traction system. The high-energy battery pack of PHEV can be charged from the ac outlets by an ac-dc charger, which typically includes a front-end power factor corrector (PFC) followed by an isolated dc-dc converter [1-3]. The front-end PFC is used to improve the quality of the input current and to regulate dc bus voltage; the dc-dc converter is used to charge the high-voltage pack and provide isolation between the utility mains and the traction battery pack.

The zero-voltage-switching (ZVS) PWM resonant full-bridge dc- dc as shown in fig 1. converter is the most popular topology in the power range of a few kilowatts (1-5 kW) for battery chargers[3-10].

However there several fundamental limitations with the traditional ZVS PSFB dc- dc converter.

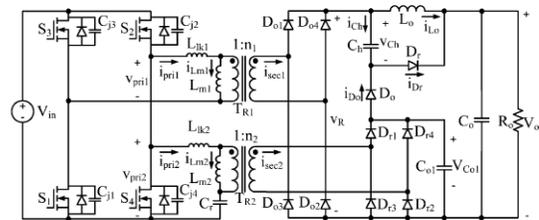


Fig 1. Conventional ZVS PWM resonant full bridge dc-dc converter

The output power range is very wide for battery charger applications, the lagging-leg switches tend to lose ZVS at light load conditions due to limited energy stored in the leakage inductor. As a result of wide battery voltage variation, it has high circulating loss during the freewheeling phases. The battery pack voltage is normally high, the output diodes suffer from severe voltage overshoots and oscillations when they are turned OFF. The first limitation is the limited ZVS range for lagging leg switches. A number of techniques which utilize the inductive energy stored in the additional auxiliary circuits instead of in the leakage or external series inductance to extend the ZVS range have been proposed [8]–[13]. The second limitation is during the freewheeling intervals, the primary current which is reflected from the output inductor current, circulates through the primary the primary side, causing excessive conduction loss. The third limitation for high output voltage applications is the severe voltage overshoots and oscillations across the output diodes when they are turned off [11].

The capacitive turn on losses of the lagging leg switches in this converter also significantly degraded the system efficiency. Moreover, the secondary bridge rectifier diodes still suffered from the voltage spikes due to the lack of clamping feature. The risk of overvoltage stresses on the bridge rectifier diodes decreased the reliability of this converter.

In conventional the lagging-leg switches can achieve ZVS from zero to full load with the assistant of half bridge LLC resonant circuit using the “shared leg” technique as presented. A hybrid-switching circuit formed by the leakage inductor L_{lk1} , output inductor L_o of the PSFB dc–dc circuit, two additional diodes D_o and D_r , and an additional small resonant capacitor C_h is incorporated into the secondary side. This hybrid switching circuit combines the two independent output voltages in together to transfer energy from the input to output within the whole switching period, achieving more efficient and effective energy transfer. Instead of using variable frequency control to regulate the LLC output voltage, LLC the circuit in the conventional converter works as an unregulated bus converter with minimized circulating currents. The final expected output voltage is obtained by the PSFB dc–dc circuit with the traditional constant- frequency phase-shift PWM control.

With the hybrid resonant and PWM operation in the conventional converter, the major disadvantages of the , including narrow ZVS range of lagging leg switches, high primary circulating losses, voltage stress are eliminated in the proposed converter.

II. PROPOSED TOPOLOGY

In order to overcome the aforementioned drawbacks of the conventional full bridge dc-dc converter for high voltage electric vehicle battery charger applications. In proposed system the TR2 is connected voltage doubler. In conventional system TR2 is connected bridge rectifier. Compare to the conventional ZVS full bridge dc-dc converter the proposed system is more effective and achieve high efficiency. The simplest of these circuits are a form of rectifier which take an AC voltage as input and output a doubled DC voltage.

A voltage doubler is a circuit which charges capacitors from the input voltage and switches these charges in such a way that, in the ideal case, exactly twice the voltage is produced at the output as at its input.

In this project, which is based on half bridge converter, topology with an additional small inductor and two diodes connected in parallel with two dividing capacitors is proposed for battery charging applications. In the proposed circuit, we combine the merits of the above-mentioned topology and the discontinuous-voltage mode of operation to achieve a very simple design solution that requires minimal thermal installation for charging applications. In addition to PFC, soft switching, circulating current and voltage stress can be easily achieved with this circuit topology, which is one of the major advantages. Voltage doublers were used to either double the voltage on an winding on the mains transformer or were applied to the waveform on the line flyback coils. Such power conversions can lead to much reduced voltage stress on switches when compared to the best PWM converters with same dc conversion ratio. The proposed converter fig 2 The sum of the hybrid-switching capacitor voltage and the LLC circuit output voltage is applied on the output inductor during the freewheeling phases.

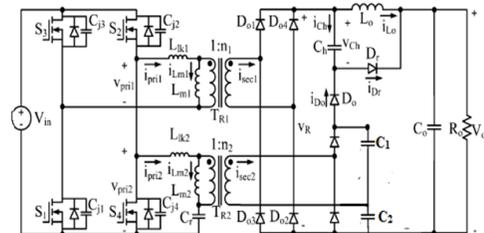


Fig 2 Proposed ZVS PWM resonant full bridge dc -dc converter using voltage doubler.

As a result, the output filter inductance can be reduced and compact size inductor can be used. The circulating current losses of the PSFB dc–dc circuit are minimized as a result of the hybrid-switching capacitor voltage and LLC circuit output voltage resetting the primary side current during the freewheeling phases.

Energy is transferred to the output with the combined resonant power conversion mode and PWM power conversion mode during the active phases, in the freewheeling phases, the capacitive energy stored in the output capacitor of *LLC* circuit and hybrid-switching capacitor and inductive energy stored in the output inductor are transferred to the output simultaneously. Hence, high efficiency can be achieved with the increased total power transfer from the input to the output. A high-performance dual-output dc–dc converter combining the PSFB circuit and *LLC* resonant half-bridge circuit with a shared ZVS lagging leg was proposed system. This proposed converter could obtain two fully regulated output hybrid phase shift and variable frequency control. The lagging leg of this converter could achieve ZVS from zero to full load with the help of *LLC* resonant circuit, solving the narrow ZVS issue of the traditional PSFB dc–dc converter.

With a simple structure, physically smaller output inductor, minimized circulating and voltage stress across the bridge rectifier, and high efficiency over wide output power and voltage ranges, this converter is very attractive for electric vehicle battery charger applications. The circuit operation principles are described in detail in this paper.

III. OPERATION PRINCIPLES

The circuit diagram of the proposed converter is shown in Fig. 1. T_{R1} is the transformer of the PSFB dc–dc circuit with the primary to secondary turns ratio $1:n_1$, and primary-side referred equivalent leakage inductance L_{lk1} and magnetizing inductance L_{m1} . T_{R2} is the transformer of the half-bridge *LLC* resonant circuit with primary to secondary turns ratio $1:n_2$ and primary-side-referred equivalent leakage inductance L_{lk2} and magnetizing inductance L_{m2} . The proposed converter has three distinct operation modes, designated as Mode 1, Mode 2, and Mode 3, according to the following simple quantitative criteria.

Mode 1	Mode2	Mode 3
$t_r < T_{on}$ (Buck)	$t_r = T_{on}$ (Balance)	$t_r > T_{on}$ (Boost)

Where t_r is the half of the resonant period T_r , expressed as

$$t_r = \frac{T_r}{2} \quad (1)$$

and T_{on} , as expressed in (2), is the duration of the active phases of the PSFB dc–dc circuit

$$T_{on} = D \cdot \frac{T}{2} \quad (2)$$

These three operation modes can be distinguished by the resonant current i_{Dr} through the diode D_r .

- **MODE 1:**

The resonant current reaches zero before the converter enters in to freewheeling intervals.

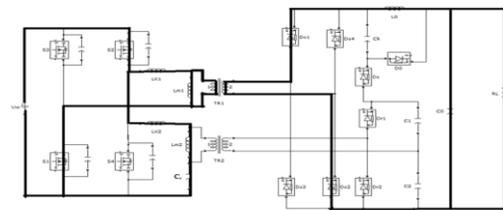
- **MODE 2:**

The resonant current reaches zero at the instant when the converter enters in to the freewheeling intervals.

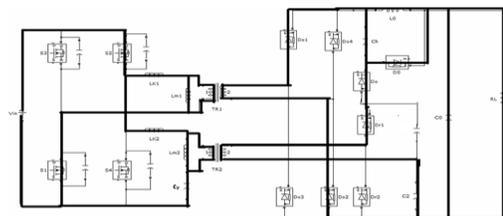
- **MODE 3:**

The resonant current is higher than zero and is interrupted at the instant the converter begins freewheeling intervals.

Since only difference of these three operation modes is the zero current points of the resonant current, only Mode 1 operation is elaborated here. There are seven topological stages within each half switching cycle for Mode 1 operation.



(a)



(b)

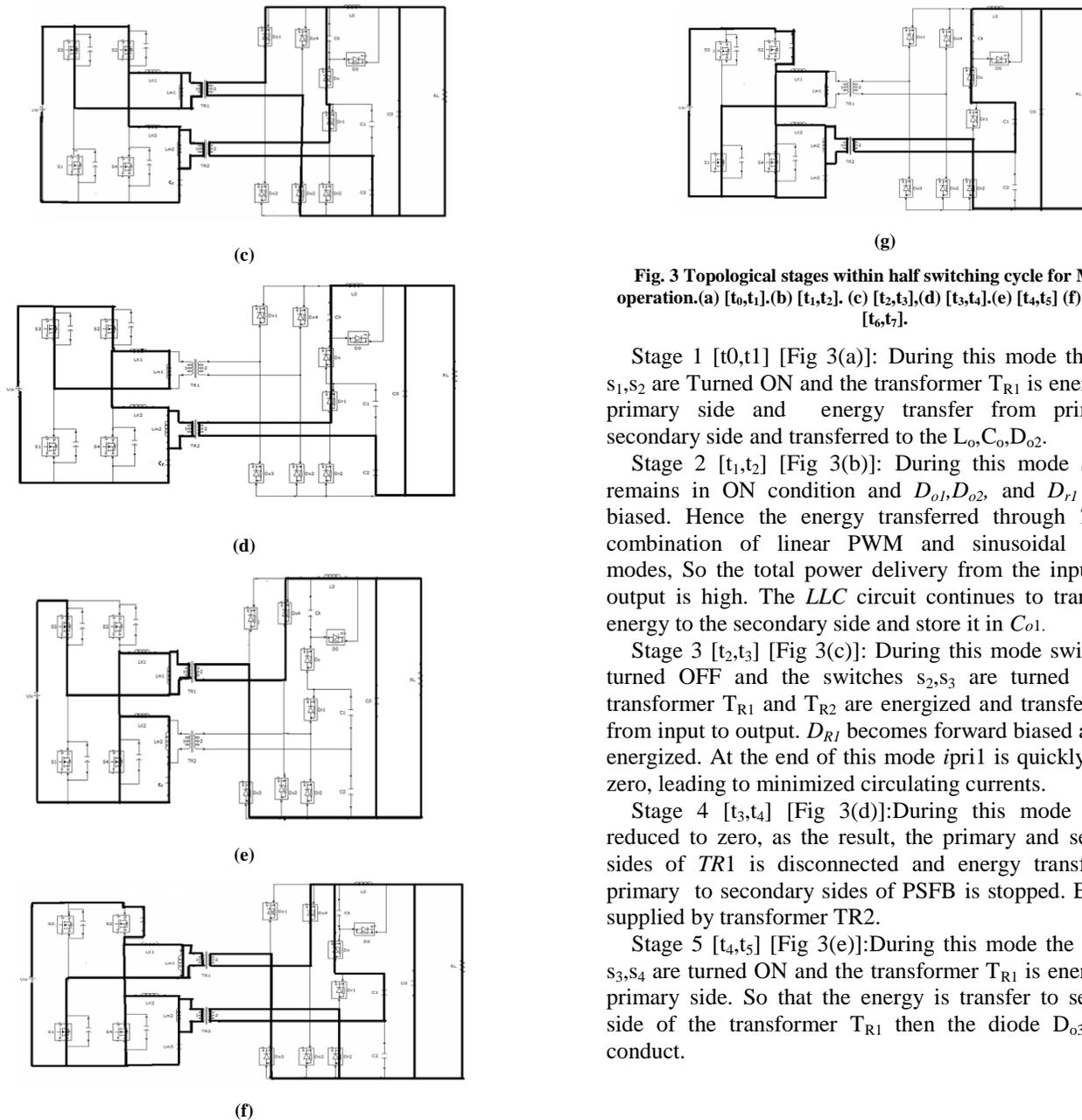


Fig. 3 Topological stages within half switching cycle for Mode 1 operation.(a) $[t_0, t_1]$.(b) $[t_1, t_2]$. (c) $[t_2, t_3]$.(d) $[t_3, t_4]$.(e) $[t_4, t_5]$ (f) $[t_5, t_6]$ (g) $[t_6, t_7]$.

Stage 1 $[t_0, t_1]$ [Fig 3(a)]: During this mode the switch S_1, S_2 are Turned ON and the transformer T_{R1} is energized in primary side and energy transfer from primary to secondary side and transferred to the L_0, C_0, D_{02} .

Stage 2 $[t_1, t_2]$ [Fig 3(b)]: During this mode S_1 & S_2 remains in ON condition and D_{01}, D_{02} , and D_{r1} forward biased. Hence the energy transferred through T_{R1} is a combination of linear PWM and sinusoidal resonant modes, So the total power delivery from the input to the output is high. The LLC circuit continues to transfer the energy to the secondary side and store it in C_{01} .

Stage 3 $[t_2, t_3]$ [Fig 3(c)]: During this mode switch S_1 is turned OFF and the switches S_2, S_3 are turned ON and transformer T_{R1} and T_{R2} are energized and transfer energy from input to output. D_{R1} becomes forward biased and C_2 is energized. At the end of this mode i_{pri1} is quickly reset to zero, leading to minimized circulating currents.

Stage 4 $[t_3, t_4]$ [Fig 3(d)]: During this mode i_{sec1} is reduced to zero, as the result, the primary and secondary sides of $TR1$ is disconnected and energy transfer from primary to secondary sides of PSFB is stopped. Energy is supplied by transformer $TR2$.

Stage 5 $[t_4, t_5]$ [Fig 3(e)]: During this mode the switches S_3, S_4 are turned ON and the transformer T_{R1} is energized in primary side. So that the energy is transfer to secondary side of the transformer T_{R1} then the diode D_{03}, D_{04} are conduct.



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Stage 6 [t_5, t_6] [Fig 3(f)]: During this mode the switches S_1, S_4 are turned ON and the transformer T_{R1}, T_{R2} is energized in primary side that the energy is transfer to secondary side of the transformer. Do is forward biased.

Stage 7 [t_6, t_7] [Fig 3(g)]: During this mode the switches S_1, S_4 are turned ON and the transformer T_{R2} is energized in primary side that energy transfer to secondary side. Do is forward biased. But the secondary part of TR1 is not connected with output port.

IV. MAIN FEATURES

A. More Efficient Energy Transfer by Two Parallel Sources

Energy is transferred to the output with the combined resonant power conversion mode and PWM power conversion mode during the active phases; in the freewheeling phases, the capacitive energy stored in the output capacitor of LLC circuit and hybrid-switching capacitor and inductive energy stored in the output inductor are transferred to the output simultaneously. Hence, high efficiency can be achieved with the increased total power transfer from the input to the output.

B. Minimized Circulating Losses

The circulating current losses of the PSFB dc-dc circuit are minimized as the sum of the hybrid switching capacitor voltage and LLC circuit output voltage is applied to the leakage inductance at the beginning of the freewheeling phases. As a result the primary side current of the phase shift full bridge circuit rapidly reduced to zero, minimizing the primary circulating losses. Mean while since the LLC circuits operates close to the series resonant frequency, the circulating currents are minimized. Hence both the phase shift full bridge dc-dc circuit losses, achieving high efficiency with in the entire operating range. Compare to conventional, the circulating current losses are reduced in the proposed converter.

C. Minimized Voltage Stresses

The battery pack voltage is normally high the output diodes suffer from severe overshoots and oscillations and they are turned OFF.

Moreover the secondary bridge rectifier diodes still suffered from the overvoltage stress on the bridge rectifier diodes decreased the reliability of this converter. The charge balance of the resonant capacitor is satisfied by hybrid linear PWM current and sinusoidal resonant current. Such power conversion can lead to much reduced voltage stress on switches when compared to the PWM converters with the same dc conversion ratio. All the voltage stresses on the secondary side diodes have clamping feature without overvoltage risks. The equation (3) illustrates that the voltage stress on bridge rectifier of PSFB dc-dc circuit. Using this equation the voltage stress value is calculated.

Compare to conventional the voltage stress are reduced in the proposed converter.

$$V_s = V_{in}/D \quad (3)$$

$$= 385/0.6$$

$$V_s = 641.66V \quad (4)$$

Where V_s is voltage stress,

V_{in} is Input voltage

D is duty cycle

The voltage stresses on $D_{01}-D_{04}$,

$$\begin{aligned} V_{D01}-V_{D04} &= V_{ch}+V_0 \\ &= 151.37+300 \\ &= 11.3+440 \end{aligned}$$

$$V_{D01}-V_{D04} = 451.37 \quad (5)$$

The voltage stresses for voltage doubler,

$$\begin{aligned} V_{Dr1}-V_{Dr2}, C1, C2 &= (n_2 * V_{in} / 2) / D \\ &= ((27/32) * 385 / .6) \\ &= 234.4V \quad (6) \end{aligned}$$

V. SIMULATION RESULT

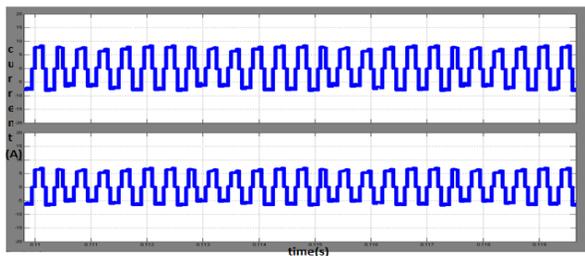


Fig. 4. Current through primary and secondary of transformer for the proposed simulation waveform.

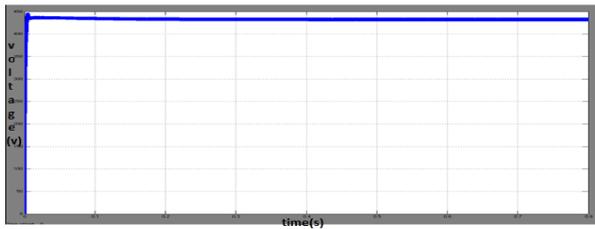


Fig. 5. Output voltage for proposed system

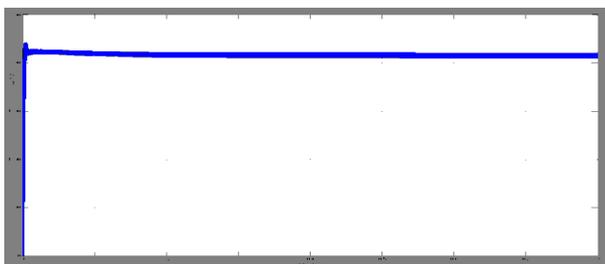


Fig. 6. Output power for proposed system

VI. DETERMINATION OF OUTPUT PARAMETERS

- The average output voltage of resonant capacitor V_{ch} , expressed as

$$V_{ch} = n_1 * V_{in} - V_0$$

$$= (34/29)385 - 440$$

$$V_{ch} = 11.3$$

- The output voltage V_0 , expressed as

$$V_0 = n_1 * V_{in} - V_{ch}$$

$$= (496) - 11.3$$

$$V_0 = 440V$$

Table 1
Comparison between conventional and proposed

PARAMETER	CONVENTIONL	PROPOSED
T_{R2}	Bridge rectifier	Voltage doubler
Circulating losses	13A	8A
Voltage stress	770V	664.16V
Input voltage	385V	385V
Output voltage	310V	440V

VII. CONCLUSION

This paper presents ZVS full-bridge dc–dc converter combining PWM and resonant power conversions. ZVS turn on the lagging leg switches can be achieved over wide load range. The sum of the output voltage of LLC resonant circuit and the resonant capacitor voltage of the hybrid-switching circuit is applied between the bridge rectifier and the output inductor of the PSFB dc–dc circuit during the freewheeling phases. As a result, the primary-side circulating current of the PSFB dc–dc circuit is instantly reset to zero, achieving minimized circulating losses. The voltage stresses on the secondary side diodes have clamping feature without overvoltage risks. Hence, high efficiency can be achieved with the increased total power transfer from the input to the output. Due its structure, high efficiency and high reliability ,the proposed converter is a very attractive design for electric vehicle battery chargers.

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