A New Phase Shift Full Bridge LLC Resonant Converter with Auxiliary Circuit

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***Abstract*—A new Phase-Shift Full-Bridge LLC auxiliary circuit converter (PSFBLLC) controlled by phase-shift pulse width modulation and LLC resonance is proposed in this paper. The proposed converter integrates an LLC resonant circuit and an auxiliary circuit to transfer energy as well as to achieve zero voltage or zero current switching. The advantages include lower circulating current, less conduction loss and secondary side ringing, and less required components, thereby improving overall efficiency. The converter is of input voltage of 400V, frequency of 38kHz, output voltage of 48V, and output power of 850W. The efficiency of proposed converter at light load increases by 2.54% compared with the traditional LLC converter. The converter efficiency at half load is 97.73%, and the efficiency is up to 98.51% at full load.**

***Index Terms*—full-Bridge, phase-shift, LLC**

I. INTRODUCTION

Pulse Width Modulation (PWM) is a common control for switching power converters. Due to the system constant period, the supplied power may be much smaller than the rated power under different load conditions. The duty ratio must be controller to maintain the optimal output state. Due to the fixed cycle limit, it is not possible to vary the load and supply the optimum output power. Phase-Shift (PS) pulse width modulation is widely used in Full-Bridge (FB) converters, mainly to prevent short-circuiting of both arms at the same time, and then derivative zero-voltage phase-shift pulse-width-modulation technology. Switches with zero voltage and zero current switching (ZVS/ZCS). It can be minimized switching losses and achieves high efficiency at high power. In order to decrease the secondary side conduction loss and ringing phenomenon of the conventional converter, a ZVS/ZCS conventional auxiliary circuit converter is propose. Although the circulating current loss and the secondary side ringing phenomenon are reduced, the secondary circuit is caused by the auxiliary circuit. The conduction loss on the side increases, resulting decrease efficiency.

Phase-shift pulse width modulated DC buck converters are widely used in automotive battery charger [1]. Whether the load is light or full, the efficiency was better than the traditional phase-shifted full-bridge converter (PSFB). Due to the soft switching of the switch, the switching loss and the circulating current will reduced, and the transmission loss and the voltage stress of the component are reduced by the secondary side auxiliary circuit resonance. Because the hybrid buck converter can easily switch the resonance and the PWM mode to make the capacitor energy. The inductive energy is selectively transferred to the diodes in the output current path to easily transfer energy. However, the primary side non-resonant element can resonance, the transformer must transmit the energy in a large current at a short time, resulting in unnecessary energy loss.

The soft-switching hybrid converter was using in the Power Factor Corrector (PFC) stage to charge battery with a Phase-Shifted Full-Bridge converter (PSFB) and a half-bridge resonant converter (HBLLC). In addition to the wide output range and zero voltage switching, the circuit uses a full-bridge (FB) converter to reduce freewheel conduction loss and clamp the voltage of the secondary rectifier when it resonates on the secondary side. Although the circuit architecture has a wide output voltage range (250V-450V), which can meet different loads, when the output power is 1.2 kW output voltage is 332V, the efficiency starts to drop rapidly to 97.3% [2]. The closer to the minimum output voltage of 250V, will be the lower efficiency. As stated above, the wide output voltage range and efficiency of this circuit must alternative.

Today many battery charger architectures integrate full-bridge PWM converters with full-bridge LLC converters [3]. Many different control methods and architectures are proposed in the literature [4]-[9]. As stated above, wide output voltages must have trade-offs. However, integrated LLC converters can improve efficiency. The good phenomenon makes the overall efficiency improved. Although most of them was used variable frequency control, the efficiency is not good at light load, but the energy required for the load could transmitted by the resonance, and the ZVS/ZCS can reduce the switching loss. Compared with the traditional phase-shift full-bridge converter, it can reduce circulating current loss ,and reduce the stress on the switching element and reduce the size in the dead zone, but an additional set of converters requires twice the number of components required, increase cost.

This paper presents a new phase-shift full-bridge LLC converter with an auxiliary circuit, as shown in Fig. 1. The LLC resonance is mainly use to transmit the energy required by the load, and the reduced secondary side

Manuscript received July 22, 2019; revised November 25, 2019.

doi: 10.18178/ijeee.7.4.65-69

conduction loss and reduce the circulating current, and avoid the disadvantage that the LLC is inefficient light load at the same time. Inductor and capacitor in the auxiliary circuit start to store energy due to the energy transfer from the primary side, which can reduce circulating current, secondary side conduction loss and ringing. The proposed converter can simultaneously improve the shortcomings of the above traditional phase shift converter and improve the efficiency.

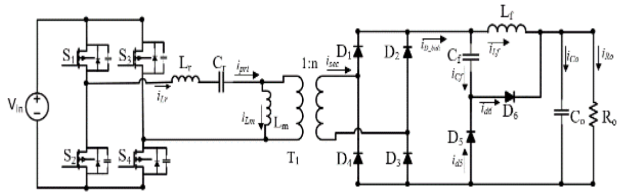


Figure 1. Circuit of the proposed converter.

II. The Proposed Converter of Mode Analysis

In this paper, the full-bridge phase-shift LLC auxiliary circuit converter controls the switches S_1-S_4 with phase-shift pulse width modulation. As shown in Fig. 2, α is the phase shift angle, L_r is the resonant inductor, C_r is an resonant capacitor, D_1-D_4 is a rectifying diode, and D_5, D_6, Cr, L_r are auxiliary circuits, C_o is an output capacitor, and R_o is a load.

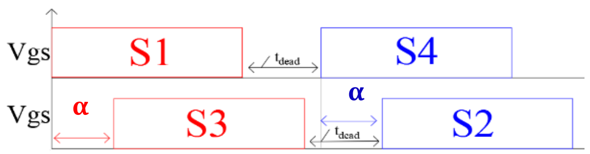


Figure 2. Key waveforms of switches.

The analysis of the proposed converter is analyzed with ideal components in this paper. There is a dead zone (t_{dead}) in each cycle to prevent two arms turned on at the same time, causing a short circuit, as shown in Fig. 3. According to the switching of the switches at steady state, it is divided into eight different modes, as shown in Fig. 4. Since the positive and negative half-cycle modes are the same, only four of them were described below. Fig. 5 shows the equivalent circuit from mode 1 to mode 4. Different modes have different resonant frequency.

According to the following formula calculates LLC resonant frequency:

$$f_{r1}=\frac{1}{2\pi\sqrt{L_r C_r}} \tag{1}$$

$$f_{r2}=\frac{1}{2\pi\sqrt{(L_r+L_m)C_r}} \tag{2}$$

Since the secondary side auxiliary circuit participates resonance, the resonant frequency expressed by:

$$f_r=\frac{1}{2\pi\sqrt{(L_r+L_m+n^2L_f)*C_rC_f}} \tag{3}$$

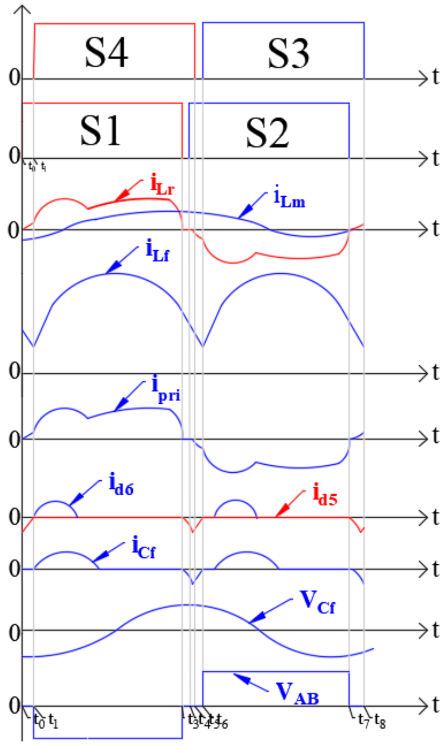


Figure 3. Key waveforms of the proposed converter.

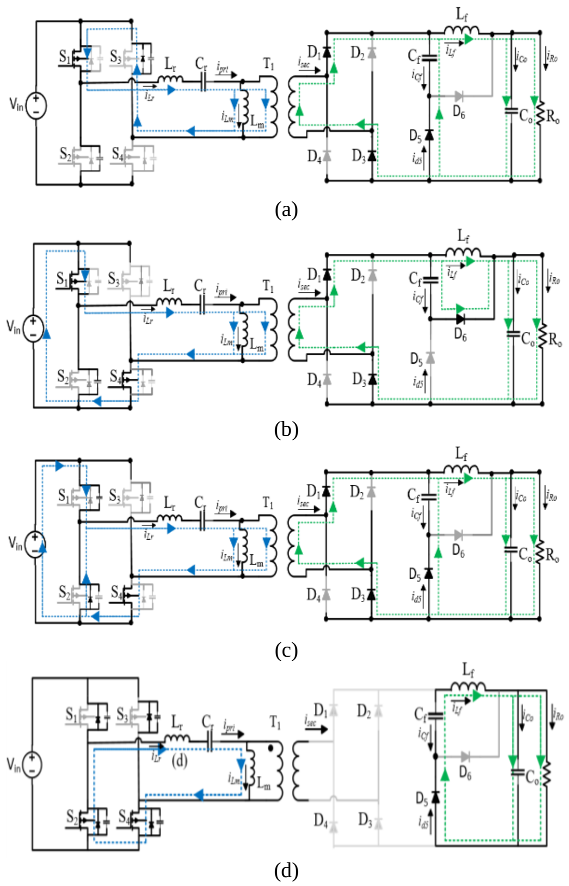


Figure 4. Pattern analysis of the proposed converter. (a) Mode1 ($t_0 \leqq t<t_1$) (b) Mode2 ($t_1 \leqq t<t_2$) (c) Mode3 ($t_2 \leqq t<t_3$) (d) Mode4 ($t_3 \leqq t<t_4$).

Mode 1 [t0, t1]

Switch S_1 is turned on, S_2, S_3, S_4 are turned off, I_{pri} rises from zero, L_r, C_r stores energy, diodes D_1 and D_2 turned on, L_f, C_f start energy storage, when I_{Cf} is less than I_{d5}, diode D_5 turned on, D_6 turned off, because D_5 was turned on, the current will countercurrent to $C_{f,}$ causing C_f to discharge.

Mode 2 [t1, t2]

The switches S_1 and S_4 turned on, S_2 and S_3 turned off, L_r and Cr resonate and transfer energy to the secondary side, and the diodes D_1 and D_2 turned on. When I_{Cf} is equal to I_{D5}, the diode D_5 turned off, and D_6 turned on, C_f Charging. The relevant formula is as follows, using Fourier transformer:

$$I_{pri}(\mathrm{s}) = \frac{\frac{V_{in}}{s}}{sL_r+\frac{1}{sC_r}} \tag{4}$$

$$I_{D\_bid}(\mathrm{s}) = \frac{nI_o}{s} - \frac{V_{in}}{s^2L_r+\frac{1}{C_r}} \tag{5}$$

$$I_{pri}(\mathrm{t}) = \frac{V_{in}\sqrt{C_r}}{\sqrt{L_r}} \times \sin\frac{1}{\sqrt{L_rC_r}}t \tag{6}$$

$$I_{D\_bid}(\mathrm{t}) = \frac{V_{in}\cdot\sin\sqrt{\frac{1}{L_rC_r}}t - L_r\cdot I_o\cdot n\cdot\sqrt{\frac{1}{L_rC_r}}}{L_r\cdot\sqrt{\frac{1}{L_rC_r}}} \tag{7}$$

Mode 3 [t2, t3]

Switch S_4 is turned on, S_1, S_2, S_3 are closed, the voltage across the transformer is zero, i_{D_bidi} is gradually reduced, D_5 is turned on, because i_{D_bidi} is gradually reduced, i_{Cf}, i_{d5} are discharged, auxiliary circuits C_f, L_f release energy, make up the transformer A shortage of energy to supply the load.

Mode 4 [t3, t4]

The switches S_2, S_4 turned on, and S_1, S_3 are turned off, and the i_{D_bidi} drops to zero due to the secondary freewheel. At this time, i_{Cf} and i_{d5} are zero, and the diode D_6 turned on. Since i_{pri} is zero, second side no energy. L_f and C_f to release energy.

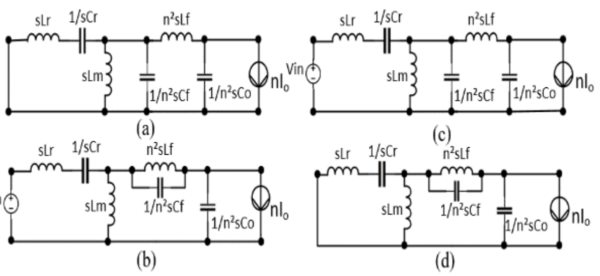
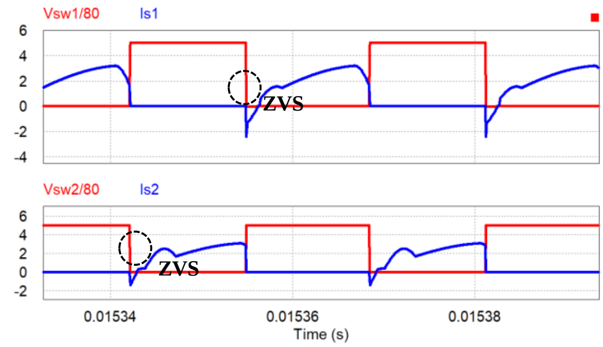


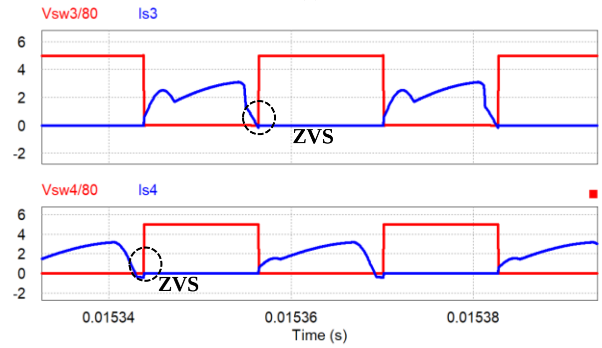
Figure 5. Equivalent circuit of proposed converter.

III. Simulation

Fig. 6 shows the switches key waveforms. The rear arm of the traditional phase-shift converter is susceptible to the phase shift angle, resulting in large switching losses and cannot be zero voltage or zero current switching. However, the converter in this paper can improve this problem. Fig. 7 shows the waveform of the primary and secondary currents. Although the conventional auxiliary circuit converter can improve the secondary side ringing phenomenon and reduce the circulating current, the circuit has no resonant component, and the energy transmission must be transmitted by a large triangular wave. The converter of this paper uses LLC resonance to transmit energy with less current during resonance and reduce circulating current loss. Compared the traditional phase shift converter, the efficiency increased by 8.86%. Compared the traditional phase shift full-bridge auxiliary circuit converter efficiency increased by 15%.



(a)



(b)

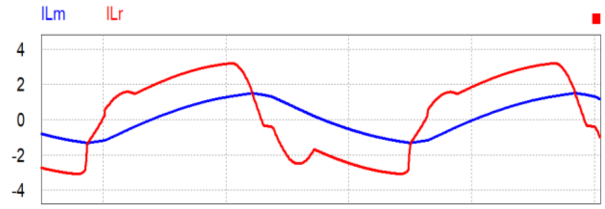
Figure 6. Switches waveform. (a) S_1, S_2 (b) S_3, S_4.

In order to compare the fairness, this paper takes the rated output power as the main reference, and performs efficiency analysis with the parameters of the fixed converter and the turns ratio of the slight drop.

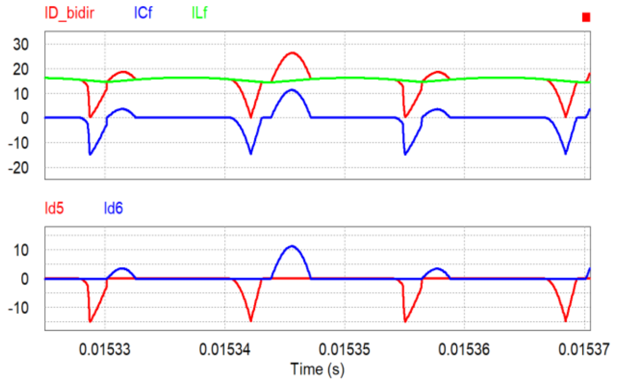
The load efficiency analysis of the converter (PSFBLLC_auxi) and the traditional phase-shifted full-bridge LLC converter (PSFB_tr_LLC), the traditional phase-shifted full-bridge efficiency (PSFB_tr) and the traditional phase-shifted full-bridge auxiliary circuit (PSFB_tr_auxi) converter, As shown in Fig. 8 is the proposed converter primary side and secondary side current.

Table I shows the proposed converter parameters, Table II shows the parameters of the traditional full-bridge phase-shift auxiliary circuit converter, Table III shows the parameters of the traditional phase-shifted full-bridge LLC converter, and Table IV shows the traditional full-bridge phase-shift auxiliary circuit converter parameter.

Fig. 9 shows the efficiency of the converter and the other traditional phase-shifted full-bridge circuit converter. Fig. 10 shows the component loss analysis of the converter and the traditional phase-shifted full-bridge auxiliary circuit converter. The proposed converter greatly reduces losses.



(a)



(b)

Figure 7. Analog current waveforms. (a) primary side (b) secondary side.

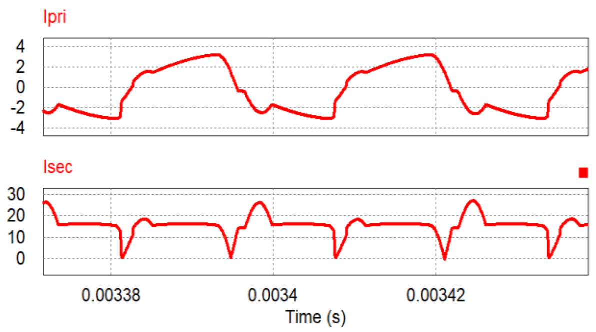


Figure 8. Proposed converter current.

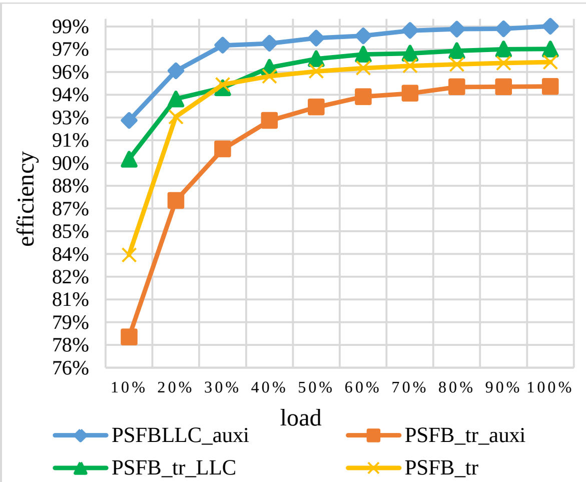


Figure 9. Converter efficiency comparison.

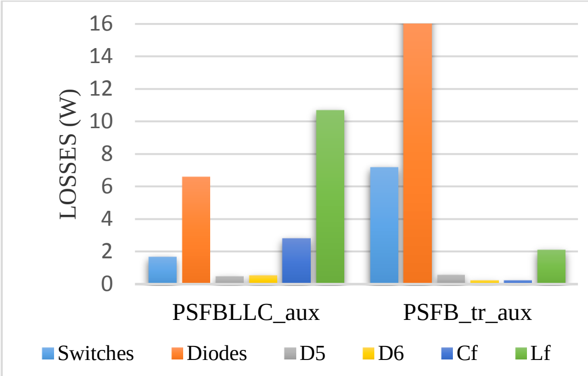


Figure 10. Loss analysis.

TABLE I. PARAMETERS OF THE PROPOSED CONVERTER

Parameter	Value	Parameter	Value
V_{in}	400V	C_r	51nF
V_o	48V	L_f	60μH
P_o	850W	C_f	94μF
f_s	38kHz	C_o	220μF
L_r	46μH	n	8.33

TABLE II. PARAMETERS OF THE TRADITIONAL PSFB CONVERTER

Parameter	Value	Parameter	Value
V_{in}	400V	f_s	25kHz
V_o	48V	C_o	220μF
P_o	850W	n	8.33

TABLE III. PARAMETERS OF THE TRADITIONAL LLC CONVERTER

Parameter	Value	Parameter	Value
V_{in}	400V	L_r	225μH
V_o	48V	C_r	180nF
P_o	850W	C_o	470μF
f_s	25kHz	n	8.33

TABLE IV. PARAMETERS OF THE TRADITIONAL AUXILIARY CONVERTER

Parameter	Value	Parameter	Value
V_{in}	400V	L_f	20μH
V_o	48V	C_f	660μF
P_o	850W	C_o	940μF
f_s	1kHz	n	8.33

IV. CONCLUSION

The new full-bridge phase-shift LLC converter with auxiliary circuit proposed in this paper can effectively improve the characteristics of the traditional converter, and the full load efficiency can reach 98.51%. With the integration of the converter, the number of components can be reduced by half, thereby reducing conduction losses, switching losses and system costs, and greatly improving the overall efficiency of the circuit. The proposed converter achieves zero voltage or zero current switching, which allows it operate at high frequency, thus to reduce conduction loss and switching loss. The circuit resonance is utilized to transfer energy to the secondary side with minimum current.

The proposed converter has the following advantages:

1) Zero voltage or zero current switching can reduce switching losses.
2) Reduced circulating current and conduction loss, the efficiency is effectively increased.
3) The number of components is reduced by half, thus significantly reduces system costs.
4) The efficiency of the proposed converter at light load is 8.86% higher than that of the conventional converter with auxiliary circuit.
5) Reduced secondary side ringing and conduction loss.
6) The efficiency of the traditional LLC circuit at light load increases, which is improved by 2.54%.
7) The efficiency of proposed converter at full load can reach 98.51%.

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