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Analysis and Implementation of Pulse-Width Modulated DC-DC Converter for Electric Vehicles with Improved Efficiency

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Abstract—This paper presents new gating techniques to improve the efficiency of zero-voltage zero-current switching (ZVZCS) full-bridge DC-DC converter for battery charging in electric vehicles. The converter is assisted by a passive auxiliary circuit to extend the zero voltage switching range. The uncontrolled auxiliary circuit current increases the conduction losses of the converter when gated with conventional phase-shift modulation (PSM) technique. The controlled auxiliary circuit current with the proposed pulse-width modulation (PWM) gating techniques increases the efficiency of the converter especially at light-load conditions compared to PSM. In this paper, the steady-state analysis of the converter auxiliary circuit with the PWM gating techniques is presented. A comparative loss analysis with PWM and PSM gating techniques is also given. A 1.2-kW, 100-kHz converter is implemented on ORCAD-Pspice and the simulation results are presented to validate the improvement in efficiency of the converter with the proposed PWM gating techniques.

Keywords—Full-bridge converter, zero voltage switching (ZVS), zero current switching (ZCS), current-driven converter, battery charging, electric vehicles.

I. INTRODUCTION

Zero emission vehicles (ZEVs) are promising solutions for nowadays transportation to reduce the greenhouse gas emissions. Electric vehicle (EV) is one of the ZEVs used for city commute [1]. The high-voltage traction battery pack in EVs is generally charged from utility grid by an EV charger. The charging power is processed through AC-DC power factor correction (PFC) stage followed by DC-DC converter stage [2]. This paper focuses on the DC-DC converter stage of EV charger.

Full-bridge converter topology is the preferred choice for the DC-DC converter because of its high efficiency, high power density, high reliability and isolation capability. However, it has some drawbacks, such as narrow zero-voltage switching (ZVS) load range, excessive duty cycle loss, higher circulating losses and severe parasitic ringing on secondary rectifier diodes. An auxiliary circuit is added to the conventional full-bridge DC-DC converter to increase ZVS load range which provides the extra reactive energy during switching transitions. Several modified full-bridge converter topologies and control methods have been proposed in [3]-[18].

The novelty of these topologies and methods lies in achieving ZVS for all active switches over full-load range of operation. In [3], a simple one pole inductor assisted auxiliary circuit for each leg increase the losses of converter at heavy-load conditions due to the load independent nature of auxiliary circuit current. The load adaptive control strategies in [4], [5] increases the efficiency of the converter [3] compared to the conventional phase-shift modulation (PSM). Further modified topologies of converter [3] in [6]-[8] reduce the conduction losses of the converter at the cost of increased component count. In adaptive passive auxiliary circuit assisted topologies [9]-[15], the auxiliary circuit current is controlled adaptively with load conditions. The adaptive current results in improved efficiency at heavy-load conditions.

In battery charging applications, wide ZVS range is important since the converter has to operate from almost no-load to full-load conditions. The voltage rating of secondary rectifier diodes has to be low and the circulating losses have to be at minimum [16]. The current-fed converters in [17], [18] inherently reduce the diode reverse-recovery losses and the large voltage spikes on secondary diodes. An improved trailing-edge pulse-width modulation (PWM) is used in [17]. The efficiency of the converter in [18] is higher than that of the converter in [17] due to ZVS of all active switches over full-load battery charging range. The efficiency of the converter in [18] can be further improved with a change in gating technique.

In this paper, two PWM gating techniques are presented and corresponding steady-state operational analysis of the auxiliary circuit is explained in detail. A power loss comparison using the analysis given in [19] is also presented to show the advantage of the proposed PWM gating techniques.

This paper is organized as follows: Section II presents the converter and proposed gating techniques. The steady-state analysis of the converter auxiliary circuit and a comparative analysis are provided in Section III. The simulation results are given in Section IV, followed by conclusion in Section V.

II. FULL-BRIDGE CONVERTER AND PROPOSED GATING TECHNIQUES

The passive auxiliary assisted zero-voltage zero-current switching (ZVZCS) full-bridge DC-DC converter is shown in

Fig. 1. Passive auxiliary assisted ZVZCS full-bridge DC-DC converter.

Fig. 1. In converter, S_1 - S_4 are the active switches, D_{S1} - D_{S4} are the respective antiparallel body-diodes, C_1 - C_4 are the capacitors which represent the respective equivalent body and snubber capacitors, L_{se} is the external series inductor, T_r is the high-frequency power transformer, D_1 - D_4 are the output rectifier diodes, C_f is the output filter capacitor and V_{bat} represents the traction battery pack. C_{a1} - C_{a4} are the auxiliary capacitors and L_{a1} , L_{a2} are the auxiliary inductor poles for each leg of the converter.

The proposed asymmetrical pulse-width modulation (APWM) and trailing-edge pulse-width modulation (TEPWM) gating techniques are shown in Fig. 2 and Fig. 3 respectively. G_{S1} - G_{S4} are the gating signals to S_1 - S_4 respectively. T_s represents the time period of one switching cycle, D is the duty cycle of switch and t_d is the dead-time for gating the switches within the same leg. In these techniques, the output voltage of the converter is regulated through the duty cycle control of the switches.

In APWM, the phase-shift between the gating signals of leading and lagging leg is fixed at 180° . The high-side switches/low-side switches are gated with a duty cycle D and their complimentary signals are given to low-side switches/high-side switches respectively. In TEPWM, the low-side switches/high-side switches are operated with a duty cycle of 50% and the high-side switches/low-side switches are operated with a duty cycle D respectively. The dotted gating signals represent the duty cycle control of low-side switches and un-dotted gating signals represent the duty cycle control of high-side switches in Fig. 2 and Fig. 3. In both PWM techniques, the auxiliary circuit current is controlled through auxiliary capacitor voltages V_{ca1} - V_{ca4} , which is explained in the following section.

III. STEADY-STATE ANALYSIS OF AUXILIARY CIRCUIT

The steady-state analysis of the auxiliary circuit is explained in this section. The APWM and TEPWM result in similar auxiliary circuit waveforms as shown in Fig. 2 and Fig. 3 respectively. The peak value of auxiliary inductor currents I_{La1P} , I_{La2P} with APWM and TEPWM is calculated from V_{ca1} and V_{ca2} , V_{ca3} and V_{ca4} respectively. In the converter, the auxiliary circuit components are chosen to be $C_{a1} = C_{a2} = C_{a3}$

$= C_{a4}$ and $L_{a1} = L_{a2} = L_a$. Since the d.c. input voltage V_{in} is split across auxiliary capacitors and it can be noticed that $V_{ca1} + V_{ca2} = V_{in}$ and $V_{ca3} + V_{ca4} = V_{in}$. Under steady-state, the voltage-time balance of voltage across auxiliary inductors is given by $V_{ca1}DT_s = (1-D)T_sV_{ca2}$ and $V_{ca3}DT_s = (1-D)T_sV_{ca4}$. Therefore,

$$V_{La1}^+ = V_{La2}^+ = V_{ca1} = V_{ca3} = (1-D)V_{in} \quad (1)$$

$$V_{La1}^- = V_{La2}^- = -V_{ca2} = -V_{ca4} = -DV_{in} \quad (2)$$

Fig. 2. Theoretical operational waveforms of the converter with APWM.

Fig. 3. Theoretical operational waveforms of the converter with TEPWM.

The peak value of auxiliary inductor currents with APWM and TEPWM is given by

$$I_{LaP} = I_{La1P} = I_{La2P} = \frac{V_{in}D(1-D)}{2L_a f_s} \quad (3)$$

In case of phase-shift modulation (PSM), all switches are operated with a duty cycle of 50% and the output voltage is regulated through the phase-shift between the gating signals of two legs [18]. Therefore,

$$V_{La1}^+ = V_{La2}^+ = V_{ca1} = V_{ca3} = V_{in}/2 \quad (4)$$

$$V_{La1}^- = V_{La2}^- = -V_{ca2} = -V_{ca4} = V_{in}/2 \quad (5)$$

$$I_{LaP} = I_{La1P} = I_{La2P} = \frac{V_{in}}{8L_a f_s} \quad (6)$$

The variation of voltage across auxiliary capacitors with APWM, TEPWM and PSM is shown in Fig. 4(a). The comparison of peak auxiliary inductor current with APWM, TEPWM and PSM is shown in Fig. 4(b). A summary of gating techniques and soft-switching details of the current-driven full-bridge converter is given in Table I.

The specification details of the converter are given in Table II. The characteristics of battery charging load profile with different load points $P_1 - P_{10}$ are shown in Fig. 5. The controlled auxiliary inductor current with APWM and

Fig. 4. (a) Duty cycle vs. auxiliary capacitor voltage. (b) Duty cycle vs peak auxiliary current.

TABLE I
SUMMARY OF GATING TECHNIQUES AND SOFT-SWITCHING DETAILS

Gating technique	Duty cycle control	ZVS	near ZCS	Peak auxiliary current
APWM	G_{S1}, G_{S3}	S_1, S_2, S_3, S_4	S_2, S_4	$I_{LaP} = \frac{V_{in}D(1-D)}{2L_a f_s}$
	G_{S2}, G_{S4}		S_1, S_3	
TEPWM	G_{S1}, G_{S3}		S_2, S_4	
	G_{S2}, G_{S4}		S_1, S_3	
PSM [18]	$\angle G_{S1}, G_{S3}$		S_1, S_2	$I_{LaP} = \frac{V_{in}}{8L_a f_s}$

TEPWM shown in Fig. 4(b) reduces the switching losses, conduction losses and auxiliary circuit losses. A power loss comparison of the converter with APWM/TEPWM and PSM is shown in Fig. 6. It shows that the proposed gating techniques improve the efficiency of the converter especially at light-load conditions.

IV. SIMULATION RESULTS

A 1.2kW passive auxiliary assisted ZVZCS full-bridge DC-DC converter is simulated to verify the theoretical steady-state analysis of the auxiliary circuit and the efficiency of the converter with the proposed gating techniques.

TABLE II
SPECIFICATIONS OF FULL-BRIDGE DC-DC CONVERTER

Parameter	Value
Input DC voltage	300V
Output DC voltage	209V - 320V
Maximum output DC current	3.75A
Power rating	1.2kW
Switching frequency	100kHz

Fig. 5. Lithium-ion battery charging profile with load points $P_1 - P_{10}$.

Fig. 6. Comparison of power losses between APWM/TEPWM and PSM converter.

Fig. 7. ZVS waveforms of S_1 with APWM/TEPWM. (a) At output 320V, 3.75A. (b) At output 320V, 3.75A.

Fig. 8. ZVS waveforms of S_2 with APWM/TEPWM. (a) At output 320V, 3.75A. (b) At output 320V, 3.75A.

Fig. 9. Operating waveforms of the converter with APWM/TEPWM. (a) At output 320V, 3.75A. (b) At output 320V, 3.75A.

Fig. 10. Auxiliary circuit waveforms with APWM/TEPWM. (a) At output 320V, 3.75A. (b) At output 320V, 3.75A.

Fig. 11. Auxiliary circuit waveforms with PSM. (a) At output 320V, 3.75A. (b) At output 320V, 3.75A.

Fig. 12. RMS current stress measured over battery charging profile. (a) CC charging mode. (b) CV charging mode.

Fig. 13. Efficiency of the converter over battery charging profile. (a) CC charging mode. (b) CV charging mode.

The ZVS results of switches S_1 and S_2 are shown in Figs. 7, 8 at maximum charging point P_5 in constant current charging mode and end point P_{10} in constant voltage charging mode. The primary side operating waveforms of the converter such as pole voltage V_{AB} , primary current i_p , and T_r secondary voltage at load points P_5 and P_{10} are shown in Fig. 9.

The simulation results of auxiliary circuit voltage and current at load points P_5 and P_{10} are shown in Fig. 10 and Fig. 11 respectively when the converter is operated with the proposed APWM and PSM respectively. It is observed from Fig. 10 and Fig. 11 that the peak value of auxiliary inductor current varies as the auxiliary capacitor voltages are dependent on the load conditions with APWM/TEPWM whereas these parameters are constant with PSM. The peak value of auxiliary inductor current with APWM/TEPWM is smaller than that of PSM especially at light-load conditions. This phenomenon reduces the auxiliary circuit losses of the converter.

The RMS current stress of MOSFET switches S_1 - S_4 with APWM/TEPWM is shown in Fig. 12(a) and Fig. 12(b) at different load points over the battery charging profile range. It is observed that the current stress with the proposed APWM/TEPWM is less than that of with PSM due to the controlled auxiliary circuit current.

The efficiency results of the DC-DC converter operated with APWM/TEPWM and PSM at different load points during CC charging mode and CV charging mode are shown in Fig. 13(a) and Fig. 13(b). From the efficiency results, it is seen that the DC-DC converter with the proposed APWM/TEPWM has better efficiency compared to the PSM mainly at light-load conditions. This is due to the reduced switching and conduction losses, auxiliary circuit losses, and the circulating losses.

V. CONCLUSION

In this paper, APWM and TEPWM gating techniques have been proposed. Theoretical operational analysis of the ZVZCS converter auxiliary circuit and a comparative power loss analysis with the proposed APWM/TEPWM and conventional PSM gating techniques have been discussed. The theoretical operational waveforms and simulation results have validated the steady-state analysis of the converter. The theoretical power loss analysis results and simulated efficiency results have confirmed the advantage of the proposed gating techniques over the conventional PSM technique.

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