New Family of Zero-Current-Switching PWM Converters Using a New Zero-Current-Switching PWM Auxiliary Circuit

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Abstract—A new family of zero-current-switching (ZCS) pulsewidth-modulation (PWM) converters using a new ZCS-PWM auxiliary circuit is presented in this paper. The main switch and auxiliary switch operate at ZCS turn-on and turn-off, and the all-passive semiconductor devices in the ZCS-PWM converters operate at zero-voltage-switching (ZVS) turn-on and turn-off. Besides operating at constant frequency and reducing commutation losses, these new converters have no additional current stress and conduction loss in the main switch in comparison to the hard-switching converter counterpart. The PWM switch model and state-space averaging approach is used to estimate and examine the steady-state and dynamic character of the system. The new family of ZCS-PWM converters is suitable for high-power applications using insulated gate bipolar transistors (IGBTs). The principle of operation, theoretical analysis, and experimental results of the new ZCS-PWM boost converter, rated 1.6 kW and operating at 30 kHz, are provided in this paper to verify the performance of this new family of converters.

Index Terms—Converter, state-space averaging approach, zero-current switching (ZCS).

I. INTRODUCTION

The pulsewidth-modulation (PWM) technique is praised for its high-power capability, fast transient response, and ease of control. The PWM dc–dc converters have also been widely used in the industry. For minimization of size and weight, increasing the switching frequency in the PWM converter is required. However, increasing the switching frequency will result in more switching losses and electromagnetic interference (EMI). Recently, for improving this problem, a number of soft-switching PWM techniques were proposed, aimed at combining desirable features of both the conventional PWM and resonant techniques [1]–[9]. The zero-voltage-switching (ZVS) approaches are desirable for majority of carrier semiconductor devices such as MOSFETs since the turn-off loss caused by the output capacitance is large. The zero-current-switching (ZCS) approaches are suitable for the minority of carrier semiconductor devices such as insulated gate bipolar transistors (IGBTs) since the turn-off loss is large due to the current tail characteristics. In recent years, IGBTs have been preferred for high-power applications since IGBTs have a higher voltage rating, higher power density, and lower cost compared to MOSFETs. However, IGBTs are relatively slow in switching speed, so the switching losses and the high frequency of operation are two well-known problems [5]. In order to overcome previous problems, a number of ZCS-PWM techniques have been proposed [6]–[9]. In the approaches proposed in [6] and [7], ZCS of the active switches is achieved by using a resonant inductor in series with the main switch and a resonant capacitor in series with the auxiliary switch. Unfortunately, switching losses in the approaches proposed in [6] and [7] can be reduced only at the expense of much increased current stresses of the main switch, which leads to a substantial increase in conduction loss. This phenomenon is eliminated in the approaches proposed in [8] and [9] whereby the resonating current for ZCS flows only through the auxiliary circuit, thus, the current stress of the main switch is eliminated. However, it presents two power diodes in the power transfer path, which increases conduction losses of the diodes. This paper proposes a new ZCS-PWM auxiliary circuit that improves the drawbacks of the previously proposed ZCS-PWM converters. The proposed auxiliary circuit provides the ZCS condition for both the main switches and auxiliary switch, and the all-passive semiconductor devices in the ZCS-PWM converters operate at ZVS turn-on and turn-off. Since the circulating current for the soft switching flows only through the auxiliary circuit, the conduction loss and current stress of the main switch are minimized. A new family of dc/dc PWM converters based on the proposed ZCS-PWM switch cell is proposed. Besides operating at constant frequency and with reduced commutation losses, these new converters have no additional current stress and conduction losses in the main switch in comparison to the hard-switching converter counterpart. The new family of ZCS-PWM converters is suitable for high-power applications using IGBTs. Among the new family of dc/dc converters, the principle of operation, theoretical analysis, and experimental results of the new ZCS-PWM boost converter, rated 1.6 kW and operating at 30 kHz, are provided in this paper to verify the performance of this new family of converters.

II. NEW ZCS-PWM AUXILIARY CIRCUIT

The new proposed ZCS-PWM auxiliary circuit is shown in Fig. 1. It is formed by two switches $S_1$ and $S_2$, a diode $D$, and...
Based on these assumptions, circuit operations in one switching cycle can be divided into seven stages. The seven dynamic equivalent circuits of the new ZCS-PWM boost converter during one switching period is shown in Fig. 4, where the main switch $S_1$ starts conducting at $t = t_0$ and turns off during the time interval $t_4 < t < t_5$, and the auxiliary switch $S_2$ starts at $t = t_2$ and turns off the time interval $t_4 < t < t_5$. The ideal relevant waveform of the new ZCS-PWM boost is shown in Fig. 5.

**Stage 1**—[$t_0$, $t_1$] [Fig. 4(a)]: Before $t = t_0$, the main switch $S_1$ maintains the turn-off state, and the current $I_{in}$ flows through $D_1$, $L_r$, and $V_o$. This stage begins when $S_1$ turns on with ZCS at $t = t_0$. The resonant inductor $L_r$ discharges linearly to output voltage $V_o$ from $I_{in}$ to zero. The stage ends when the resonant current reaches zero and diode $D_1$ turns off with ZCS at $t = t_1$. The resonant $i_{L_r}(t)$ and $v_{C_r}(t)$ can be described, respectively, as

$$i_{L_r}(t) = I_{in} - \frac{V_o}{L_r}(t - t_0)$$  \hspace{1cm}(1)

$$v_{C_r}(t) = 0$$ \hspace{1cm}(2)

$$\Delta t_1 = \frac{I_{in}L_r}{V_o}.$$ \hspace{1cm}(3)

**Stage 2**—[$t_1$, $t_2$] [Fig. 4(b)]: In this stage, the current $I_{in}$ remains flowing through the main switch $S_1$. The remaining semiconductors are in the off state. The resonant $i_{L_r}(t)$ and $v_{C_r}(t)$ can be described, respectively, as

$$i_{L_r}(t) = 0$$ \hspace{1cm}(4)

$$v_{C_r}(t) = 0$$ \hspace{1cm}(5)

$$\Delta t_2 = DT_s - \Delta t_1$$ \hspace{1cm}(6)

where $D$ is the duty cycle of control, $T_s = 1/f_s$ is the switching period, and $f_s$ is the switching frequency.

**Stage 3**—[$t_2$, $t_3$] [Fig. 4(c)]: In this stage, the resonant $i_{L_r}(t)$ increases and then decreases when it arrives at its peak value. The resonant voltage $v_{C_r}(t)$ also increases via the resonance of $L_r$ and $C_r$. This state ends when the current $i_{L_r}(t)$ in $L_r$ drops to null again at $t = t_3$. The resonant $i_{L_r}(t)$ and $v_{C_r}(t)$ can be described, respectively, as

$$i_{L_r}(t) = -\frac{V_o}{Z_o} \sin \omega_r(t - t_2)$$ \hspace{1cm}(7)

$$v_{C_r}(t) = V_o - V_o \cos \omega_r(t - t_2)$$ \hspace{1cm}(8)

$$\Delta t_3 = \frac{\pi}{\omega_r}$$ \hspace{1cm}(9)

where $Z_o = \sqrt{L_r/C_r}$, $\omega_r = 1/\sqrt{L_rC_r}$. In this state, there are two resonant peaks given by

$$I_{L_r, peak1} = i_{L_r}\left(t = t_2 + \frac{\pi}{2\omega_r}\right) = -\frac{V_o}{Z_o}.$$ \hspace{1cm}(10)

**III. OPERATION PRINCIPLE**

It should be noted that the principle of operation and features of these new converters are the same as those of the new ZCS-PWM boost converter. A new ZCS-PWM boost converter shown in Fig. 3(b) will be taken as an example and be analyzed in this paper. To simplify the analysis, it is assumed that the converter is operating in steady state and the following assumptions are made during one switching cycle.

1) All components and devices are ideal.

2) The input filter inductance $L_{in}$ is large enough to assume that the input current $I_{in}$ is constant and is much greater than the resonant inductor $L_r$.

3) The output capacitor $C_o$ is large enough to assume that the output voltage $V_o$ is constant and ripple free.

4) The input voltage $V_{in}$ is constant.

5) The voltage of the resonant capacitor $C_r$ is equalized to zero and the resonant currents of the resonant inductor $L_r$ is equalized to input current $I_{in}$ before the main switch turns on.