A ZCS-PWM Full-Bridge Boost Converter for Fuel-Cell Applications

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Abstract—A new ZCS-PWM dc-dc full-bridge boost converter is proposed in the paper. The proposed converter is well-suited to be used as a fuel cell converter where low input voltage / high output voltage conversion is required. In the paper, the operation of the proposed converter is explained in detail, and its features and design are discussed. The feasibility of the converter is confirmed with results that are obtained from an experimental prototype.

I. INTRODUCTION

Current-fed PWM full-bridge boost converters like the one shown in Fig. 1 are very attractive in fuel cell power conversion applications where an output dc voltage that is considerably larger than the input voltage is needed. Standard voltage-fed PWM full-bridge converters that have a bulk capacitor at the input of the full-bridge are not typically used in these applications because a large turns ratio of the main power transformer is needed and this exacerbates the transformer non-idealities. In particular, the leakage inductance and the winding capacitance can significantly change converter behaviour by creating high voltage and current spikes.

A PWM full-bridge boost converter can be implemented with either zero-voltage switching (ZVS) or zero-current switching (ZCS) depending on the application. ZVS is implemented in applications where the input voltage is high, the input current is low or medium, and switch turn-on switching losses are dominant. ZCS is implemented in applications where the input current is high (regardless of what the input voltage is) and conduction losses are dominant. The focus of the paper is on ZCS-PWM full-bridge boost converters.

There have therefore been a number of ZCS-PWM current-fed boost full-bridge converters that have been proposed and there is presently considerable interest in these converters due to the needs for dc-dc converters for fuel cell applications. Previously proposed converters of this type, however, have at least one of the following disadvantages:

i) The converter is a fixed frequency resonant converter [7], [11] that generates a considerable amount of circulating current in the full bridge so that the switches can turn off with ZCS. An example of such a converter is shown in Fig. 2(a). The circulating current is not transferred to the load and does little but add to the conduction losses of the converter. Although the converter is more efficient than it would be if ZCS was not implemented, the gains in efficiency are not as much as what they could possibly be due to these losses.

ii) The converter uses an active auxiliary circuit that is connected parallel to full-bridge and used to divert current away from the switches in the bridge before they are to be turned off. This circuit is activated just before any switches are to be turned off and is deactivated shortly afterwards. Since the circuit is active for only a short length of time, there is less circulating current than with fixed frequency resonant converters, but this current is still significant. All the energy from this current is trapped in the primary side of the converter and it contributes to losses [8], [10].

iii) The additional circulating current also contributes to increases peak current stresses in the full-bridge switches as these switches must conduct the current that they are supposed to conduct to feed the load and the circulating current. Devices that can withstand higher peak current stresses than those found in conventional boost full-bridge converters are needed as the converter switches, which increases cost.

iv) Diodes are placed in series with the switches in some converters so that current does not flow through the body-diodes of the switches [10], which is shown in Fig. 2(b). Although conduction losses are increased, they may be

Fig.1. Current-fed PWM full-bridge boost converter
fewer than what they would be if the diodes were not added, but this is at the cost of the additional diodes. Some converters avoid using diodes by using reverse blocking IGBTs [6], but they are more expensive than regular IGBTs and not appropriate for low voltage input applications.

v) A voltage spike and/or significant voltage ringing can appear across the main converter switches because their output capacitances switches resonate with the leakage inductance of the main transformer during their turn off; this spike and ringing will also appear across the secondary diodes as well. This creates a need for higher voltage rated devices that will increase the cost and the losses in the converter. [5], [8]-[12].

vi) When an auxiliary circuit is used, it is typically uses some sort of inductor-capacitor resonance in the circuit to create a negative voltage across the dc bus that will divert current away from the switches in the full-bridge. This negative voltage appears at the transformer secondary so that the peak voltage stress across the output diodes may be at least double the output voltage in some converters. This creates a need for more expensive diodes to be used at the secondary and may mean the difference between being able to use Schottky diodes with reduced forward voltage drop or not [5], [8]-[12].

vii) The auxiliary switch(es) in several previously proposed ZCS auxiliary circuits are at the secondary side of the converter [5], [9] or must be driven with a high side driver [8], [12], which makes the driving of this switch(es) more complicated.

A new ZCS-PWM dc-dc full-bridge boost converter that has none of the above disadvantages is proposed in this paper and is shown in Fig. 3. The proposed converter has an active auxiliary circuit that is connected across its transformer primary side dc bus that helps the full-bridge switches turn off with ZCS.

In this paper, the operation of the proposed ZCS-PWM dc-dc full-bridge boost converter will be explained in detail and a mathematical analysis of the converter’s steady-state operation will be performed. The results of the analysis are used to establish a procedure for the design of the converter. The feasibility of the converter is confirmed with results that are obtained from an experimental prototype.

II. GENERAL OPERATING PRINCIPLES

The proposed converter is a standard PWM full-bridge converter with an auxiliary circuit that consists of an auxiliary switch $Q_{aux}$, a resonant capacitor $C_r$, a resonant inductor $L_{r2}$, a transformer with a center-tapped secondary, and two secondary diodes $D_{s1}$ and $D_{s2}$ are connected to the output. Another small inductor $L_{r1}$ is added at the input of the bridge to help in the ZCS turn-on and off of the full-bridge switches. The sequence of gating signals that the converter operates with in a typical switching cycle is: $Q_1$ and $Q_4$ on, then all bridge switches on, then $Q_2$ and $Q_3$ on then all switches on - in other words, an energy transfer mode when only a pair of diagonally opposed switches is on is always followed by a "boosting" mode where all the switches are on and no energy is transferred. The basic principle behind the converter is that the auxiliary circuit is activated during the time when all full bridge switches are on so that current can be diverted away from these switches and the appropriate pair of switch can turn off with ZCS. Energy in the auxiliary circuit can be transferred to the output through the transformer in the auxiliary circuit. Switches turn on with ZCS due to the leakage inductance of the transformer preventing current from rushing into a switch in a sudden manner.

![Fig. 3. Proposed ZCS full-bridge boost converter](image-url)
III. Modes of Operation

The various modes of operation that the proposed converter goes through during half of a steady-state switching cycle are explained in this section and a mathematical analysis of each mode is performed. Typical converter waveforms are shown in Fig. 4 and the equivalent circuit for each mode is shown in Fig. 5.

Mode 0 \((t < t_0)\) (Fig. 5(a)): Input current \(I_{in}\) flows through switches \(Q_3\) and \(Q_2\), and energy is transferred to the load through diodes \(D_2\) and \(D_3\).

Mode 1 \((t_0 < t < t_1)\) (Fig. 5(b)): At time \(t = t_0\), both \(Q_1\) and \(Q_4\) are turned on. Due to the primary transformer leakage inductance, the transfer of current to these switches is gradual so that they turn on with ZCS, and some energy continues to be transferred to the output. Eventually, no current flows in the transformer primary except the magnetizing current (which is neglected here), and the dc bus is shorted with half of \(I_{in}\) flowing through one full-bridge leg and the other half flowing through the other leg.

Mode 2 \((t_1 < t < t_2)\) (Fig. 5(c)): At \(t = t_1\), the auxiliary switch \(Q_{aux}\) is turned on and \(C_r\) begins to resonate with \(L_{r2}\) and discharge. Energy in the auxiliary circuit is transferred to the load through \(T_{aux}\) and \(D_{s1}\). This mode ends when the voltage of \(C_r\), \(V_{Cr}\), reaches zero and diode \(D_{aux}\) turns on. Voltage \(V_{Cr}\) and current \(I_{L2}\) can be expressed according to the following equations:

\[
V_{Cr}(t) = L_{r2} \frac{di_{L2}(t)}{dt} + V_x
\]  

\[
i_{L2}(t) = i_{C}(t) = -C_r \frac{dV_{Cr}(t)}{dt}
\]  

The transformer primary is clamped to \(V_x = \frac{N_1}{N_2} V_{pri}\) from time \(t_2\) to \(t_4\), and the secondary diode \(D_{aux}\) is forward biased. Circulating energy from the auxiliary circuit is transferred to the output during this time.

Mode 3 \((t_2 < t < t_3)\) (Fig. 5(d)): At \(t = t_2\), the voltage across \(C_r\) reaches zero and \(D_{aux}\) starts to conduct as \(C_r\) continues to resonate with \(L_{r2}\) and the voltage across it becomes negative. This negative voltage appears across the dc bus and thus current begins to be diverted away from the full-bridge switches Voltages \(V_{Cr}\) and \(V_{L1}\) across \(C_r\) and \(L_{r1}\) and currents \(i_{L1}\) and \(i_{L2}\) through \(L_{r1}\) and \(L_{r2}\) respectively and \(i_{C3}(t)\) through \(C_r\) can be expressed according to the following equations:

\[
i_L(t) = i_{L1}(t) + i_{L2}(t) + i_{C3}(t)
\]  

\[
\frac{d^2V_{Cr}(t)}{dt^2} = V_{Cr}(t)\omega^2 - V_{Cr}(t)\omega^2
\]  

\[
V_{L1}(t) = V_{C3}(t) = L_{r1} \frac{di_{L1}(t)}{dt} = L_{r2} \frac{di_{L2}(t)}{dt} + V_x
\]  

Mode 4 \((t_3 < t < t_4)\) (Fig. 5(e)): At \(t = t_3\), the current through the main switches becomes zero and begins reversing direction by flowing through the body diodes of the switches. Switches \(Q_2\) and \(Q_3\) can be turned off softly at any time while current is flowing in their body diodes. Current in the auxiliary circuit is positive but decreasing.
Mode 5 ($t_4 < t < t_5$) (Fig. 5(f)): At $t = t_4$, the body diode of $Q_{aux}$ starts conducting and the switch can be turned off softly after this instant. During this mode, all the body diodes of all converter switches conduct current and the current coming out of the bridge flows through $L_{r1}$ and $D_{aux}$ and charging $C_r$. Energy is transferred from the auxiliary circuit to the load through $T_{aux}$ and $D_{aux}$.

Mode 6 ($t_5 < t < t_6$) (Fig. 5(g)): At $t = t_5$, the current in the body diode of $Q_{aux}$ goes to zero. During this mode, the voltage across $C_r$ increases in resonance with $L_{r1}$ while the current flows through the body diodes of the full-bridge switches. At the end of this mode the voltage across $C_r$ reaches $V_{pri}=V_o/N$.

Mode 7 ($t_6 < t < t_7$) (Fig. 5(h)): At $t = t_6$, the current in the body diodes of the full-bridge switch becomes zero, and some input current starts to flow through $L_{r1}$, $Q_1$ and $Q_4$. The remaining input current continues to charge $C_r$ and the voltage across it rises. Energy begins to be transferred to the load through $D_1$ and $D_2$. At the end of this mode the voltage across $C_r$ charges up to $V_{Cr0}$. The differential equations that describe this mode are

\[ I_{in} = C_r \frac{dV_{Cr}(t)}{dt} + i_{L_{r1}} \]  
\[ V_{Cr}(t) = L_{r1} \frac{di_{L_{r1}}(t)}{dt} + \frac{V_o}{N} \]

Mode 8 ($t_7 < t < t_8$) (Fig. 5(i)): At $t = t_7$, all the input current flows through the bridge and none through $C_r$. The converter is in an energy transfer mode.

IV. CONVERTER FEATURES

The proposed converter has an auxiliary circuit that can transfer energy from the primary side of the converter to the output. Moreover, the auxiliary transformer can be considered like a voltage source that acts counter to the voltage across $C_r$, thus affecting the resonant cycle. As a result, many of the drawbacks of other previously proposed converters are avoided.

- The peak current stress of the switches is the same as that of a switch in a conventional PWM boost full-bridge converter. Auxiliary circuit diode $D_{aux}$ blocks any auxiliary circuit current from flowing into the full-bridge.
- The converter can operate with better efficiency as energy is transferred to the load and is not trapped in the auxiliary circuit or made to circulate on the primary side of the converter.
- Additional diodes are not needed to block circulating current as there is little circulating current.
- The auxiliary circuit is on the primary side of the converter so that it is easy to drive.
- Capacitor $C_r$ in the auxiliary circuit can also be used to limit voltage overshoots and ringing.

V. DESIGN GUIDELINES

General considerations that should be taken into account when trying to design the proposed converter are discussed in this section in the paper. The key component values in the design of the converter are those for $C_r$, $L_{r1}$, $L_{r2}$ and $N_x$ (the ratio of the secondary winding to a primary winding of auxiliary transformer). The following should be considered when trying to select values for these components:

i) Commutation Time: The reverse recovery losses in the auxiliary circuit diode $D_{aux}$ should be minimized. The duration of Mode 7 in which the input current gets...
diverted from the auxiliary capacitor $C_r$ to the inductance $L_{r1}$ should be greater than $3t_{rr}$ (reverse recovery time) for the auxiliary diode. The value for the commutation time in which the input current gets diverted from the auxiliary capacitor $C_r$ to the bridge section, must be greater than the value of $3t_{rr}$ of the auxiliary diode.

ii) **Inductor $L_{r1}$**: $L_{r1}$ is placed in series with the main power switches so that it can slow the rise of current when $Q_1$ – $Q_4$ are turned on. When these switches turn on, the whole current will flow through them. If $L_{r1}$ is too small, then this current transfer will happen too quickly so that there will be considerable reverse recovery current. $L_{r1}$ should therefore be large enough to make the current transfer slow enough to minimize reverse recovery current.

iii) **Capacitor $C_r$**: $C_r$ affects the amount of time needed for the auxiliary circuit to operate when it is activated to turn the main switches off with ZCS. The higher the value of $C_r$, the more time is needed for the auxiliary circuit to operate as the resonant cycle determined by the interaction of $C_r$ and $L_{r2}$ is increased. The length of time that the auxiliary circuit operates should only be a small fraction of the switch cycle so that auxiliary circuit component current stresses are low and the effect of the circuit on the operation of the main power converter is minimized. Also, $C_r$ helps in regulating the maximum voltage stress across the bridge switches. Greater the value of $C_r$, lower will be the value of the voltage stress across the bridge switches. A trade-off must therefore be done between these two criteria to choose the value of $C_r$.

iv) **Inductor $L_{r2}$**: $L_{r2}$ should be small enough so that the duration of auxiliary circuit operation is short, but large enough so that the auxiliary switch peak current is not very high. A large value of $L_{r2}$ also reduces turn-on losses as it slows the rise in current when $S_{aux}$ is turned on resulting in a ZCS turn-on.

v) **Turns Ratio $N_x$**: The value of $N_x$ can never be less than one. If $N_x$ approaches one, the voltage that the transformer primary is clamped to approaches that of the output voltage so that $C_r$ will not discharge when $S_{aux}$ is turned on. This means that the auxiliary circuit cannot function properly and the ZCS turn-off of bridge switches cannot occur. $N_x$ should therefore be considerably greater than 1 to create enough window of opportunity for the bridge switches to turn off with ZCS. A very high value of $N_x$ will result in higher current stress for $S_{aux}$.

The converter switches and diodes can be selected once above component values have been determined. It should be noted that the peak voltage stress of the bridge switches can actually be fixed by chosen values of $C_r$, $L_{r2}$ and the maximum load. This choice of fixed maximum voltage stress of the bridge switches is unlike other current fed converters including ZCS current fed converters referred in the literature. Most of these converters have voltage spikes that appear across the bridge switches due to the interaction between parasitic switch capacitances and the leakage inductance of the transformer that occurs when switches are turned off.

VI. EXPERIMENTAL RESULTS

An experimental prototype was built to confirm the feasibility of the example converter. The prototype was designed according to the following specifications: input voltage $V_{in} = 24 \text{ V}$, output voltage $V_o = 300 \text{ V}$, output power $P_o = 600\text{W}$, $N=1:8$ and switching frequency: $f_{sw} = 50\text{kHz}$. The prototype was implemented using the following components values: input inductor $L_{in} = 500\mu\text{H}$, auxiliary circuit inductors $L_{r1} = 300\text{mH}$ and $L_{r2} = 900\text{nH}$, and auxiliary circuit capacitor $C_r = 360 \text{nF}$. It should be noted that the inductor $L_{r2}$ is realized as the leakage inductance at the primary of the auxiliary transformer. The turn’s ratio of the transformer was 1:8.

The following devices were used for the semiconductors in the prototype: IRF540 as bridge switches: IRF520IR as auxiliary switch $S_{aux}$: BYT28B-400, Output diodes: HFA16PA60C $D_{aux}$: FR802, $D_{S1}$ and $D_{S2}$: GUR5H60, saturable reactors implemented on Toshiba saturable cores (SA14x8x4.5) were in series with the switches used to reduce the effect of parasitic resonances during switching transitions.

It can be seen in Fig.6 (a) that the main power switches turn on with zero current. During turn off, they have negative current, which signifies that current is flowing through the body diodes and thus a zero current turn-off can occur. The same can be concluded about the auxiliary switch from its current and voltage waveforms in Fig.6 (b). The most notable feature in the main switch current and voltage waveform is that the switch voltage has a well behaved hump when the switch is turning off and not a spike, which is common in almost all current fed full bridge converters.

From the graphs of the gate pulse waveforms in Fig. 7, it can be seen that the auxiliary switch is activated for a very short duration compared to that of a full switching cycle, before a pair of main switches are turned-off.

VII. CONCLUSION

A new ZCS-PWM dc-dc full-bridge boost converter was presented in this paper. The converter's main power switches can operate with ZCS due to an active auxiliary circuit that diverts current away from the switch just before it is turned off. Unlike other, previously proposed converters, the auxiliary circuit allows the bridge switches to be turned off with ZCS without increasing the peak current stress of these switches, with reduced circulating energy, and with a significantly lower peak bridge switch voltage stress. The active switch in the auxiliary circuit can also operate with soft-switching and conducts current for only a small fraction of the switching cycle. This auxiliary circuit also helps remove unwanted voltage spikes appearing across the full bridge devices during their turn off transient as found in conventional current fed full bridge converters and other converters referred in the literature.
The operation of the proposed converter was explained in detail in the paper and design guidelines were given. The feasibility of the new converter was confirmed with results obtained from an experimental prototype.

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REFERENCES


Fig. 6 (a) Current and voltage in Switches Q1 and Q4 over one full switching period. (V: 30V/div, I: 15Amps/div, t: 5µS/div) (b) Current and voltage in auxiliary switch over one switching period. (V: 30V/div, I: 15A/div, t: 2 µS/div)

Fig. 7 Switch gating pulses (V: 10V/div, t: 5µS/div)