# Letters

# Using Multilevel ZVZCS Converters to Improve Light-Load Efficiency in Low Power Applications

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***Abstract*—In this letter, the use of three-level (TL), zero-voltage-zero-current switching (ZVZCS) converters is investigated as a way of improving light-load efficiency in full-bridge converters with MOSFETs. The general operation of an example TL-ZVZCS full-bridge converter is briefly explained and the basic principles as to how it can how improve light-load efficiency are discussed. Experimental results that compare the efficiency of a prototype of the example TL-ZVZCS converter to that of the conventional zero voltage switching (ZVS)-pulsewidth modulation full-bridge are presented to confirm the superior light-load efficiency of TL-ZVZCS converters.**

***Index Terms*—DC–DC converter, pulsewidth modulation (PWM), zero current switching (ZCS).**

## I. INTRODUCTION

THE standard zero voltage switching (ZVS)-pulsewidth modulation (PWM) dc–dc full-bridge converter, implemented with MOSFETs as shown in Fig. 1, is widely used in applications with loads $\geq$500 W. Its MOSFET switches can operate with ZVS if inductive energy stored in the transformer leakage inductance ($L_{\mathrm{lk}}$) is used to discharge their output capacitances before they are turned ON [1]. When the converter is operating with light loads, however, this energy is not enough and so the switches turn ON with switching losses, which results in poor efficiency for light loads. Such efficiency is becoming less acceptable as ever-increasing demands for power are placed on the utility grid to satisfy consumer demands.

A number of methods have been proposed to improve light-load efficiency in full-bridge converters, with most requiring the use of complex control methods [2], [3] or complicated auxiliary circuits [4], [5]. Multilevel dc–dc converters such as the ones proposed in [6] and [7] that are typically used in applications with high dc bus voltages (>800 V) can be used to reduce light-load turn-ON losses for converters operating with conventional dc bus voltages (i.e., 400 V), as was proposed in [8]. The multilevel converter used in [8], however, did nothing to reduce the freewheeling mode circulating current that exists under these conditions, which limited its effectiveness in reducing light-load operation losses.

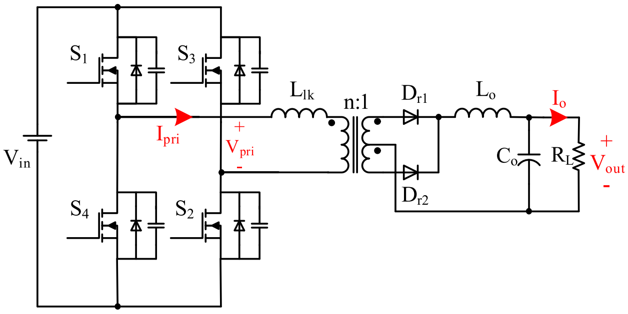

Fig. 1. FB-ZVS-PWM dc–dc converter.

In this letter, the use of three-level (TL), zero-voltage-zero-current switching (ZVZCS) converter topologies that are implemented with insulated-gate bipolar transistor (IGBT) and that are typically operated at higher power levels (>1 kW) with high dc input bus voltages (>800 V) is investigated as a way of improving light-load efficiency in lower power full-bridge PWM converters (<1 kW) that are implemented with MOSFETs and operated with lower, more standard dc bus input voltages (400 V). This has not been previously done in the literature, to the best of the authors' knowledge. The general operation of an example TL-ZVZCS full-bridge converter is briefly explained in this letter and the basic principles as to how it can improve light-load efficiency are discussed. Experimental results that compare the efficiency of a prototype of the example TL-ZVZCS converter to that of the conventional ZVS-PWM full-bridge are presented to confirm the superior light-load efficiency of TL-ZVZCS converters. It should be noted that the novelty of the letter is not with the example TL-ZVZCS topology, but with the way this topology is used to improve light-load efficiency in lower power full-bridge converters with MOSFETs.

## II. EXAMPLE TL-ZVZCS DC–DC CONVERTER OPERATION

A number of TL-ZVZCS dc–dc converters have been proposed in the literature [9]–[11]. The example TL-ZVZCS converter that was used for this study is shown in Fig. 2; it was

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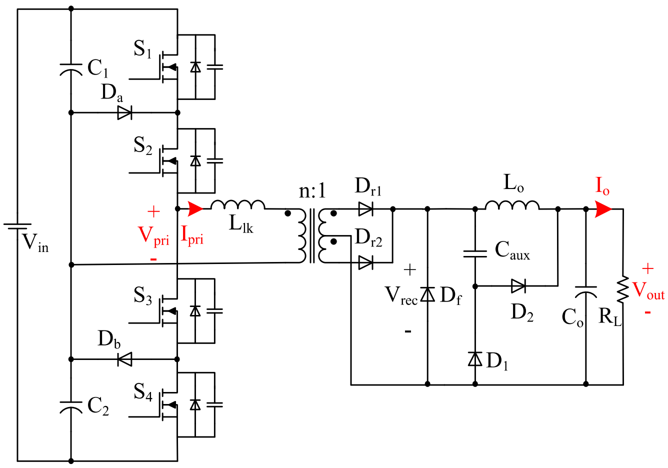

Fig. 2. TL dc–dc converter with secondary clamp circuit.

selected because it is among the simplest of its type. It is a standard three-level dc–dc converter with a secondary auxiliary circuit that consists of $C_{\text{aux}}$, $D_1$, $D_2$, and $D_f$. Since the operation of the standard three-level dc–dc converter is well-known and can be found in the literature (i.e., [12], [13]), it is only briefly summarized in this section. Only the operation of the secondary auxiliary circuit is discussed in detail.

The converter shown in Fig. 2 is in an energy-transfer mode that allows energy from the primary to be transferred to the secondary when either $S_1$ and $S_2$ or $S_3$ and $S_4$ are ON. It is in a freewheeling mode when either $S_2$ or $S_3$ are ON and current just circulates in the primary with no primary/secondary energy transfer taking place. If the input voltage of a TL converter is the same as that of a ZVS-PWM converter, its switches are exposed to less voltage, so that CV$^2$ turn-ON losses are automatically reduced, but exposed to more current and thus more conduction losses as it is essentially a half-bridge converter.

The minimum leakage inductance needed to achieve ZVS in a standard ZVS-PWM converter can be expressed as follows [14]:

$$L_{\text{lk}-\text{min}} = \frac{8}{3.I_{\text{crit}}^2}.C_{\text{oss}}.V_{\text{in}}^2\# \tag{1}$$

where $I_{\text{crit}}$ is the minimal critical/boundary current in the primary for ZVS to be achieved and $C_{\text{oss}}$ is the output capacitance of the converter switches. The leakage inductance for the TL-ZVZCS converter, however, can be as small as possible as there is no need for inductive energy to discharge the converter switches because the devices work with virtual ZVS, which will be explained later.

In terms of an efficiency comparison between the standard TL dc–dc converter and the standard ZVS-PWM converter, what this means is that the TL converter has better light-load efficiency than the ZVS-PWM converter. This is because

1) neither converter has sufficient primary transformer inductance energy to discharge the output capacitances of their switches before that are turned ON;
2) the TL converter has less voltage across its switches before they are turned ON;
3) conduction losses are not dominant at light-load operation.

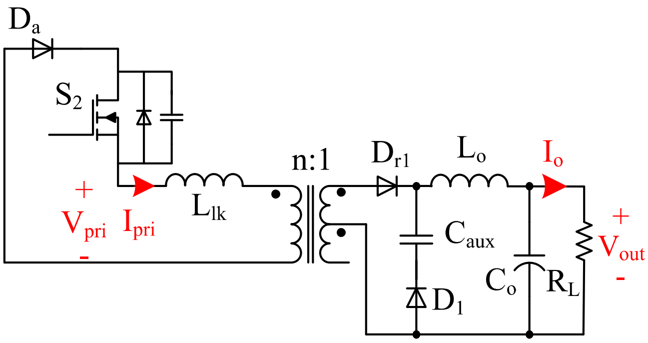

Fig. 3. Start of freewheeling mode of operation.

The TL converter has worse heavy-load efficiency than the ZVS-PWM converter because the ZVS-PWM converter can operate with ZVS as there is sufficient primary transformer inductance energy to discharge the output capacitances of its switches before that are turned ON; conduction losses are more dominant at heavy loads and the primary current of the ZVS-PWM converter is half that of the TL converter.

Conduction losses in the TL converter caused by freewheeling primary current can be reduced by adding the passive auxiliary circuit at the secondary to extinguish this current when the converter is in a freewheeling mode of operation, as shown in Fig. 3. In Fig. 3, it can be seen that 1) the output current circulates though $D_1$ and $C_{\text{aux}}$ and 2) $C_{\text{aux}}$, which has been charged from a previous mode, is placed across the transformer's secondary winding. The voltage across $C_{\text{aux}}$ is reflected to the primary winding, where it puts a negative voltage across the leakage inductance, thus extinguishing the current in the primary eventually. The required time to extinguish the leakage inductance current can be expressed as follows:

$$\Delta t = \frac{< I_{L_o} > L_{\text{lk}}}{nV_{C\text{aux}(t2)}} \tag{2}$$

where $V_{C\text{aux}(t2)}$ is the value of $V_{C\text{aux}}$ at $t_2$, and $< I_{L_o} >$ is the average output inductor current. $C_{\text{aux}}$ resonates with $L_{\text{lk}}$ at the start of a power transfer mode for a half-cycle of their resonant frequency and the voltage across $C_{\text{aux}}$ becomes twice the voltage across the tank. Since $V_{C\text{aux}}$ does not change from $t_1$ to $t_2$, the $V_{C\text{aux}(t1)} = V_{C\text{aux}(t2)} \cdot V_{C\text{aux}(t1)}$ can be expressed as follows:

$$V_{C\text{aux}(t1)} = 2.\left(\frac{V_{\text{in}}}{2n} - V_o\right). \tag{3}$$

Since a portion of the load current flows through $C_{\text{aux}}$ at the start of a power transfer mode, $< I_{L_o} >$ can be expressed as follows:

$$< I_{L_o} >= I_o - 2f_{\text{sw}}C_{\text{aux}}\left(\frac{V_{\text{in}}}{2n} - V_o\right). \tag{4}$$

Using the following definition:

$$I_o = \frac{V_o}{R_L} = \frac{\left(\frac{V_{\text{in}}D}{2n}\right)}{R_L}. \tag{5}$$

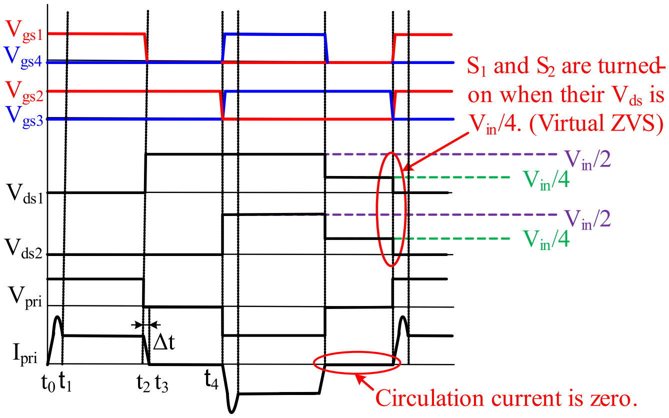

Fig. 4. Typical waveforms of TL dc–dc converter.

By combining (2)–(5), the time needed to extinguish the current can be expressed as follows:

$$\Delta t = \frac{L_{\mathrm{lk}}\left[\frac{D}{2} + f_{\mathrm{sw}}C_{\mathrm{aux}}\left(D-1\right)R_L\right]}{nR_L\left(1-D\right)}. \tag{6}$$

Afterward, with no current flowing in the primary, the dc bus voltage is evenly divided across the four switches so that the voltage across each switch only has $V_{\mathrm{in}}/4$ volts across it when it is turned ON.

Typical converter waveforms are shown in Fig. 4. The following should be noted.

1) The drain–source voltages of $S_3$ and $S_4$ are identical to those of $S_2$ and $S_1$, respectively, but phase-shifted by 180°.
2) Unlike a ZVS-PWM full-bridge converter, the gating signals of $S_1$ and $S_4$ have a pulsewidth of less than 50%. It is this pulsewidth that sets the converter's duty cycle.
3) The converter switches turn ON with virtual ZVS. Since each switch is turned ON with $V_{\mathrm{in}}/4$ volts across it, the $CV^2$ losses of a switch are naturally reduced to 1/16 (6%) of those of a switch in a ZVS-PWM converter. Since this 6% can be considered practically negligible, it can be said that the converter switches operate with virtual ZVS.
4) When a full-bridge converter is operating with light-loads, it operates with a small duty cycle so that freewheeling modes (and thus the flow of freewheeling mode circulating current) occur for most of the switching cycle. The secondary auxiliary circuit helps to further increase light-load efficiency by eliminating any circulating current during freewheeling modes of operation. This allows the converter switches to operate with ZCS and virtual ZVS when the converter is operating with light loads.
5) The primary current has some resonant humps in its waveform. This is due to the charging of $C_{\mathrm{aux}}$ as the converter gets out of a freewheeling mode.
6) More details about how the auxiliary circuit can extinguish primary current can be found in [15], which shows a two level full-bridge converter with the same auxiliary circuit (2L-ZVZCS-PWM converter).

## III. EXPERIMENTAL RESULTS

Prototypes of the example TL-ZVZCS converter, the standard ZVS-PWM full-bridge converter, and the 2L-ZVZCS-PWM converter in [15] were built to compare their efficiency. The specifications of the prototypes were: Input voltage $V_{\mathrm{in}} = 400$ V, the output voltage $V_o = 48$ V, maximum output power $P_{o,\max} = 900$ W, switching frequency, $f_{\mathrm{sw}} = 50$ kHz. For the ZVS-PWM converter prototype and the 2L-ZVZCS-PWM converter, FDP18N50 MOSFETs were used as the main switches and RURG3060 diodes were used as the secondary rectifier diodes. For the TL-ZVZCS converter prototype, FDP51N25 MOSFETs were used as the main switches, BYV29 were used as primary side diodes and secondary diodes are same as the two-level converters. The ZVS-PWM converter was designed according to [16], the 2L-ZVZCS-PWM converter was designed according to [15], and the TL-ZVZCS converter was designed according to [12] with the secondary auxiliary circuit designed according to [15].

It should be noted that the MOSFETs used as the switches in the TL-ZVZCS prototype had lower voltage ratings than those used as the switches in the two-level prototypes as they need to block only half the dc bus voltage. Such MOSFETs usually have superior switching characteristics and lower ON-state drain–source resistance than MOSFETs with higher voltage ratings, and this can partially offset the drawbacks associated with higher primary current that can still exist in TL converters.

Fig. 5 shows various voltage and current waveforms for the example TL-ZVZCS converter (see Fig. 2) operating at 100 W load in Fig. 5(a) and (b) and at 250 W load in Fig. 5(c). It can be seen that the peak switch voltage is 200 V (50% of the dc bus voltage), the voltage across the $S_1$ and $S_2$ switches when they turn ON is half of that (25% of the dc bus voltage) so that they turn ON with just 6% of the typical turn-ON losses (virtual ZVS), that the primary current falls to almost zero in the freewheeling mode, with the remaining current being just the transformer magnetizing current, and that the primary current has a resonant hump due to the charging of $C_{\mathrm{aux}}$.

Efficiency curves are shown in Fig. 6 for the three converters; the following should be noted.

1) The TL-ZVZCS converter has the better light-load efficiency. As mentioned above, this is because its switches operate with virtual ZVS and with ZCS under light-load conditions. It has no freewheeling mode circulating current thus less conduction losses.
2) All two converters operate with nearly identical medium-load efficiency. The two, two-level converters operate with slightly higher heavy-load efficiency. This is because the TL-ZVZCS converter has more conduction losses due to the fact that it essentially has a half-bridge topology so that its primary current is double of that of the ZVS-PWM converter. Moreover, the freewheeling mode of operation is short when the converter is operating with heavy loads so that the amount of time that freewheeling current circulates in the primary is short as well. This means that few losses are actually saved by the elimination of primary circulating current by the auxiliary circuit.

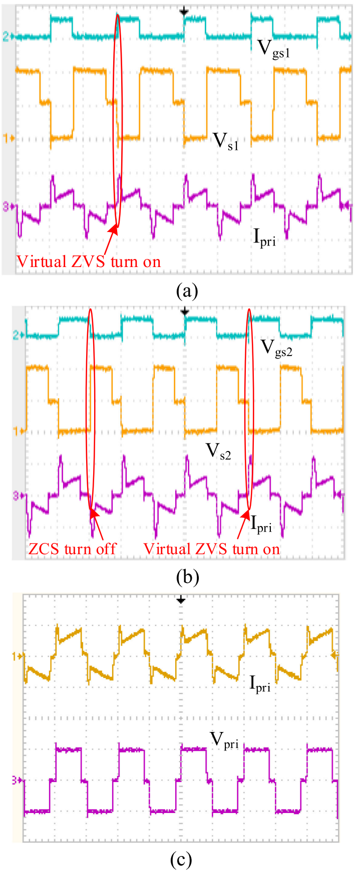

Fig. 5. TL-ZVZCS converter waveforms. (a) ($V_{gs1}$ : 25 V/div., $V_{s1}$ : 200 V/div., $I_{\text{pri}}$ : 1 A/div., $t$ : 10 $\mu$s/div.) (b) ($V_{gs2}$ : 25 V/div., $V_{s2}$ : 200 V/div., $I_{\text{pri}}$ : 1 A/div., $t$ : 10 $\mu$s/div.) (c) ($V_{\text{pri}}$ : 200 V/div., $I_{\text{pri}}$ : 1 A/div., $t$ : 10 $\mu$s/div.).

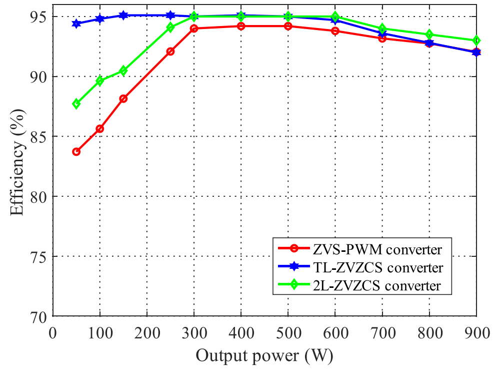

Fig. 6. Three-level and two-level converter efficiency comparison.

3) The passive auxiliary circuit in the ZVZCS converters allows the secondary diodes to turn OFF softly, which is not the case for these diodes in the ZVS-PWM converter. The loss of ZVS of two of the switches in the 2L-ZVZCS converter is offset by the savings in efficiency due to reduced current-related losses. This is why the two two-level converters have comparable heavy-load efficiency.

4) The TL-ZVZCS converter has some extra components compared to the ZVS-PWM converter: two diodes in the primary side and three diodes and a capacitor in the secondary side. Most of these components are relatively inexpensive components that can be offset by using cheaper MOSFETs with lower voltage ratings. The auxiliary circuit is analogous to the ones added to PWM dc–dc boost converters to allow their main switch to operate with ZVS (i.e.,[17], [18]) except that the auxiliary circuit is purely passive and the result is superior light-load performance.

5) If desired, other, more sophisticated auxiliary circuits that make the converter into a ZVZCS converter can be used, such as the one proposed in [19] and [20], which is an active auxiliary circuit that causes the primary current to have a much smaller resonant hump. The passive secondary auxiliary circuit used for the ZVZCS converter in this study was chosen because it was the simplest approach to ZVZCS operation.

## IV. CONCLUSION

This letter was a study of how TL-ZVZCS converter topologies, which are typically used in high voltage/high power applications, can be used to improve the light-load efficiency of full-bridge converters that are implemented with MOSFETs. Light-load efficiency has become a source of concern in recent years due to vast proliferation of power converters supplied by the utility grid and the fact that power converters often do not operate at full load, or even medium load. The letter compared the efficiency of an example TL-ZVZCS converter to that of a standard ZVS-PWM full-bridge converter.

In this letter, the general operation of an example TL-ZVZCS converter was briefly explained as was how its MOSFET switches can naturally operate with virtual ZVS and with ZCS. Efficiency results of the two converters were then presented. These results showed that the example TL-ZVZCS converter has a much better light-load efficiency (about 10% better) than the ZVS-PWM converter, an identical medium-load efficiency, and a slightly worse heavy-load efficiency (about 1%).

It should be noted that the novelty of this letter is not with the topology, as TL-ZVZCS converters are well-known in the literature, but with the use of such converters to improve light-load efficiency. Further improvements in light-load efficiency can be achieved with more sophisticated control methods such as burst-mode control if desired. Any additional method that can be used to improve light-load efficiency in a ZVS-PWM converter can be used to improve light-load efficiency in a TL-ZVZCS converter.

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