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Zero Current Switching PWM Full-Bridge DC–DC Converter with Auxiliary Circuits

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P.RAMESH CHANRA HOD,ASSOCIATE PROFESSOR,DEPT.OF EEE, GDMM COLLEGE OF ENGINEERING AND TECHNOLOGY A.P, INDIA

D.KRANTHIKUMAR ASSISTANT PROFESSOR, DEPT.OF EEE, GDMM COLLEGE OF ENGINEERING AND TECHNOLOGY A.P, INDIA

Abstract**—**A new soft-switching pulsewidth modulated (PWM) full-bridge converter is proposed in this paper. The outstanding fea-ture of the new converter is that it allows its main power switches to operate with zero current switching (ZCS) and with fewer con-duction losses than conventional full-bridge converters. This is achieved by using two very simple active auxiliary circuits—one active, the other passive. The paper presents the new converter and then discusses its operation, steady-state characteristics, and design. Experimental results obtained from a 3 kW converter pro-totype are presented to validate the converter's performance and the concepts presented in the paper.

1. INTRODUCTION

. For lower power applications, where the converters are mostly im-plemented with MOSFETs, zero-voltage-switching (ZVS) tech-niques are used to improve the efficiency of the full-bridge con-verter [1]–[8]. For higher power applications, where IGBTs are the preferred devices as they have lower conduction losses than MOSFETs due to their fixed collector–emitter voltage drop, zero-current-switching (ZCS) techniques are preferred. This is because ZCS methods can significantly reduce the tail in the IGBT device current that appears when the device is turned off. Reducing this current tail helps an IGBT operate with fewer turn-off losses and allows it to operate at higher switching frequencies.

Previously proposed soft-switching techniques for higher power dc–dc full-bridge converters have at least one of the following drawbacks:

1) They are resonant techniques in which resonant elements such as capacitors and inductors are used to shape the current through a converter switch so that it can fall to
zero to allow the switch to turn off with ZCS [9]–[12]. The resonant elements, however, are large and bulky, which makes their use impractical for many applications, and the converter is operated with variable frequency control, which makes the design of the converter more difficult and also increases the size of the converter as it must operate with low switching frequencies at lighter loads.
2) They are ZCS-PWM techniques that use active auxiliary circuit consisting of active switches and passive compo-nents to help the main converter switches turn off with ZCS. Most of these techniques use complicated auxil-iary circuits to remove current from the main switches to turn off the main switches with ZCS; for example, aux-iliary circuits with two auxiliary switches are proposed in [13]–[18] to achieve ZCS for the main switches. The increased cost of having two auxiliary circuits, however, is a key drawback of these converters as it increases their cost and complexity.
3) They are passive snubber techniques [19]–[22]. Although the use of multiple auxiliary switches is avoided with these converters, the passive circuits themselves can be quite sophisticated and the overall converter efficiency is lower than that of the aforementioned converters that use multi-ple auxiliary switches.
4) They are zero-voltage–zero-current-switching (ZVZCS) techniques. These techniques either use a secondary-side auxiliary switch [23]–[27] or a secondary-side passive cir-cuit [28]–[32] to create a counter voltage in the converter primary that helps extinguish the current that would other-wise circulate in the full-bridge whenever the converter is in a freewheeling mode and do nothing but create conduc-tion losses. Regardless of what method is used to extin-guish the freewheeling current, ZVZCS converters allow only their lagging leg switches to operate with ZCS so that IGBTs cannot be used in their leading leg. This forces the use of MOSFETs in this leg instead of IGBTs to avoid high current losses at turn-off. As a result, not only does this increase the price of these converters as two different types of devices must be used as the main power switches in the converter, but the converter is limited to lower power applications due to the specifications of MOSFETs.
5) They require the placing of reverse blocking diodes in series with main power switches to prevent current from flowing through their body diode or require that IGBTs with reverse blocking capability be used [33], [34]. The use of reverse blocking devices increases the amount of conduction losses in the converter, thus reducing converter efficiency.

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II Converter Operation

The proposed converter is shown in Fig. 1. It operates like a ZVZCS-PWM converter except that the auxiliary circuit is activated whenever the main power switches in the leading leg to which it is attached are about to turn off. It should be noted that in this diagram, as in other circuit diagram present in this paper, the transformer leakage inductance is not shown as a separate element, but is assumed to be a part of the transformer. Equivalent circuit diagrams of the modes of operation that the proposed converter goes through during a half switching are shown in Fig. 2 and ideal converter waveforms are shown in Fig. It should be noted that in Fig. 3, a current waveform such as I_{S_1} shows the current flowing through a switch (positive part of the waveform) and its body diode (negative part of the waveform). Moreover, the I_{S_a} waveform is also the waveform

Mode 1 ($t_0 \leq t \leq t_1$) *[see Fig. 2(a)]:* Switches S_1 and S_2 are on before this mode and the input power is transferred to the output through D_3 and D_4. At the beginning of this mode, auxiliary switch S_a is turned on and C_a starts to discharge, resonating with L_a. This mode ends when the current flowing through S_a reaches zero.

Mode 2 ($t_1 \leq t \leq t_2$) *[see Fig. 2(b)]:* At the beginning of this mode, current in S_a starts flowing in the opposite direction from its flow in Mode 1, through the antiparallel diode of S_a, i.e., D_{S_a}. S_a can be turned off softly while current is flowing in D_{S_a}. Voltage across C_a starts increasing as C_a resonates with L_a. Current in S_1 starts decreasing in this mode and reaches zero at the end of this mode. The currents I_{S_1} and $I_{C_a} = I_{L_a}$ follow the same equations as in Mode 1. The equivalent circuit of Mode 2 is shown in Fig. 4(b). It is very similar to that of Mode 1except that the direction of $I_{C_a} = I_{L_a}$ current is different due to it being the negative portion of a resonant cycle.

Mode 3 ($t_2 \leq t \leq t_3$) *[see Fig. 2(c)]:* At the beginning of this mode, current in S_1 starts flowing in the reverse direction through the antiparallel diode of S_1, i.e., D_{S_1}; therefore, S_1 can be turned off in this mode softly with ZCS

. The voltage across C_a continues to rise as C_a resonates with L_a. The current in the auxiliary switch flows in the negative direction, through D_{S_a}. The equivalent circuit of Mode 3 is shown in Fig. 4(c). The voltage across C_a and the current flowing through L_a can be expressed.

III. Converter Features and Drawbacks

What is new and novel about the proposed converter is that the combination of an active ZCS auxiliary circuit and a passive ZVZCS auxiliary circuit has never been previously proposed before to the best of the authors' knowledge. It is this combi-nation that allows the converter to have a very simple topology that can be implemented with IGBTs for all four main power switches and with ZCS turn-on and turn-off for all four switches and the active auxiliary switch as well. These properties cannot be found in previously proposed ZVZCS full-bridge converters, which have leading leg switches that must operate with a ZVS turn-on (which is unsuitable for IGBTs) nor can they be found in previously proposed ZCS full-bridge converters, which require more sophisticated topology, blocking diodes, and/or bulky res-onant components.

The proposed converter, however, has the following drawbacks:

1) Since it is a ZCS-PWM converter, it is not a suitable topol-ogy if a converter is to be implemented with MOSFETs it is standard practice to operate MOSFETs with ZVS.
2) The current in any given switch in the proposed converter will have a resonant peak so that the converter's peak switch current will be higher than that of a switch in a ZVS-PWM converter.
3) The light load efficiency of the converter is worse when the active auxiliary circuit is implemented than when it is not. This is because the turn-off losses of the leading leg switches to which the active auxiliary circuit is at-tached are fewer than the losses of the active auxiliary circuit when the converter is operating under light load conditions. The opposite becomes true at heavier loads.

It should be noted that all the aforementioned drawbacks are common to ZCS-PWM converters in general.

IV. Design Guidelines

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A procedure for the design of the two auxiliary circuits for the converter—the active circuit at the primary side and the passive circuit at the secondary side—is presented in this section and is demonstrated with an example. For the example, the auxiliary circuits are to be designed for a full-bridge converter operating with output voltage V_O = 380 V, input voltage V_{in} = 400 V, maximum output power P_O = 3 kW, leakage inductance L_{lk} = 3.2 μH, transformer ratio is 6:7, and switching frequency f_{sw} = 80 kHz. The design procedure that is presented here is iterative and requires several iterations before the final design can be completed. Only the final iteration will be shown in the example that follows.

The following design objectives should be considered:

1) The auxiliary circuit is attached to the leading converter leg, which is the leg with switches that would normally turn on and off with ZVS in a ZVZCS-PWM full-bridge converter. The auxiliary circuit must be such that its peak current is greater than the maximum peak current that flows through the main switches in the leg in order for the switches to turn off with ZCS. If this is not the case, then the auxiliary circuit will not be able to divert sufficient current away from the bottom switch of the leg that it is

attached to and have it flow in its circuit. It will also not be able to divert the current away from the top switch of the leg by reversing the flow of current through the switch so that its body diode conducts.

2) It has been determined from previous iterations that an auxiliary switch peak current that is about two times the maximum peak switch current allows current to be trans-ferred away from a main switch at a rate that is neither too sudden nor too gradual. If the peak auxiliary circuit is very high, however, say four times the maximum peak current for the main switches in the leg, then the transfer of current away from a main switch is too sudden and the IGBT device will still turn off with a current tail and thus with switching losses. The ratio of peak auxiliary circuit current to maximum peak switch current should not be too high or too low, which would make the transfer of current away from a main switch too gradual and would increase the length of time that the auxiliary circuit is active in the converter.

3) An appropriate "ZCS time window" needs to be consid-ered in the design of the auxiliary circuit. The ZCS time window is the amount of time during which a main switch in the leading converter leg can turn on with ZCS. If a main switch is turn off before this window of time, then an insufficient amount of time will have been given to the auxiliary circuit to divert current away from a main switch. If a main switch is turned off after this window of time, current that has been diverted away from a main switch will reappear in the same switch due to the res-onant nature of the auxiliary circuit. As with the rate of current transfer, the width of the ZCS time window is de-pendent on the ratio of peak auxiliary circuit current to maximum peak switch current. If this ratio is too high, then the time window is too narrow; if it is too low, then the time window is too wide and the auxiliary circuit will be on for a considerable fraction of the switching cycle. This should be avoided as it increases the average and rms current stresses of the auxiliary circuit components and may place limits on the duty cycle of the converter as time is needed to reset the auxiliary circuit in preparation for the next switching cycle.

4) It would be preferable if the voltage across resonant ca-pacitor C_a in the auxiliary circuit does not exceed 400 V so that standard 450 V capacitors can be used with some voltage margin. This places a constraint on the impedance of the resonant circuit in the auxiliary circuit as it must be such that it allows the peak auxiliary circuit current to be

sufficiently high so that the main power switches in the leg can turn off with ZCS. A voltage of C_a that is low may result in values of L_a and C_a that are such that the transfer of current away from the main switches in the leg is too sudden for the current tail in the IGBT to be eliminated.

5) The switches in the lagging converter leg turn off with

ZCS due to the secondary side auxiliary circuit. The key component in this circuit is capacitor C_c as it is the volt-age across C_c that gets reflected to the transformer primary

that is the basis of the counter voltage that extinguishes the current that circulates in the converter when it is in a freewheeling mode of operation. The value of this capaci-tor should be sufficiently high so that it does not discharge too quickly, before the freewheeling current in the primary side can be extinguished. If the value of this capacitor is too high, however, then C_c will not discharge and this may interfere with the operation of the converter. Higher values of C_c require smaller duty cycles during light load conditions to make sure that the C_c completely discharges during the freewheeling period.

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The design of the converter's auxiliary circuit can be done with the following steps.

A. *Step 1: Active Auxiliary Circuit Component Values*

In this step, preliminary values of C_a and L_a are determined based the voltage across C_a . As stated above, it is desired that this voltage be high, but not so high that it exceeds 400 V. Once these preliminary values have been selected, the suitability of these component values based on whether they allow the auxiliary circuit to divert current away from the main switches at a suitable rate can be confirmed in a later step of the procedure.

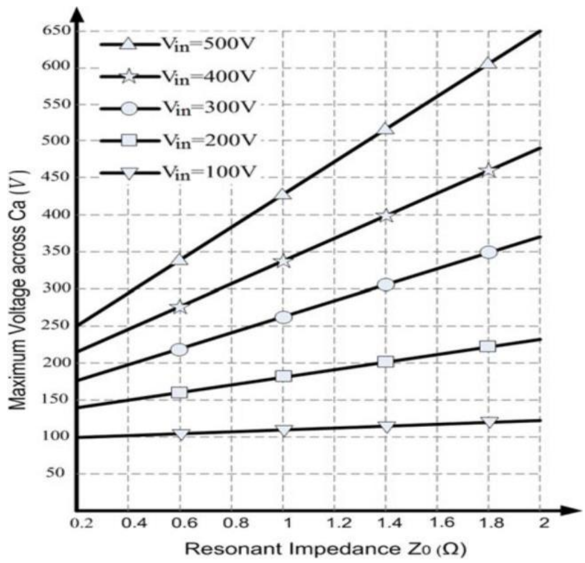
The maximum voltage across the resonant capacitor C_a can be calculated from the following equation:

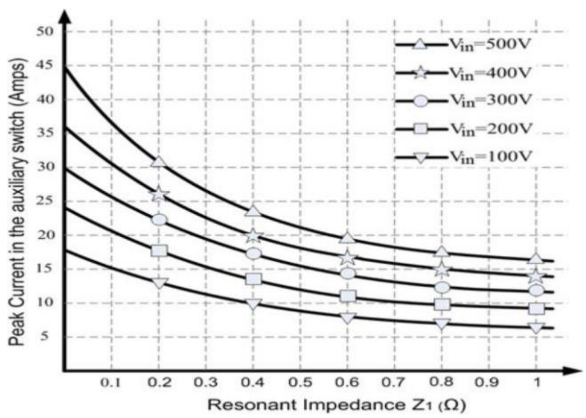
Equation (20) is derived using Kirchhoff's current law in Mode 3 by considering the reflected voltage source from the secondary side V_o/n and the transformer leakage inductance. Fig. 5 is plotted from (20) for different values of Z_0 versus the maximum voltage across C_a for different values of input voltage, when n = 21/18 and I_{in} = 7.5 A (the maximum input current considering 100% efficiency for a 3 kW prototype when input voltage is 400 V).

It can be found from this graph that by choosing a larger impedance, the voltage across C_a will increase. If a smaller impedance is chosen, a larger capacitor must be used for C_a as there must be enough energy stored in the capacitor at the end of this mode to force the current into the full bridge to reverse direction and create an opportunity for the ZCS turn off of switches. Since V_{in} = 400 V and it is desired that the voltage across C_a , V_{C_a} , be 400 V as well, the corresponding impedance value from the graph in Fig. 5 is Z_0 = 1.4 Ω

B. *Step 2: Characteristic Impedance of the Active Auxiliary Circuit*

The characteristic impedance of the auxiliary circuit





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that affects the peak current stress of the auxiliary circuit com-ponents and the window of time within the leading leg switches can be turned off with ZCS. It should be noted that the peak cur-rent in the auxiliary switch must be greater than the full-bridge input current so the bridge current can reverse, reduce to zero, and flow in the opposite direction through the body diodes of the bridge switches, which can then be turned off with ZCS.

C. Step 3: ZCS Range of Leading Leg Switches

With the auxiliary circuit values of L_a and C_a known, the next step is to confirm whether the auxiliary circuit can allow the converter's leading leg switches to operate with ZCS and the auxiliary switch to operate with ZCS. Fig. 7 is a graph of curves of the main switch (S_1) current versus time that are plotted by using (5) for different values of $V_{C\,a}$ and the values of L_a , C_a , and $L_{l\,k}$ that are defined earlier. The negative portion of each curve indicates the amount of time (ZCS time window) during which the switch can be turned off with ZCS after the current in S_1 has dropped to zero. For $V_{C\,a}$ = 400 V, the width of the ZCS time window is about 0.9 μs. It should be noted that the auxiliary switch S_a can be turned off softly when S_1 is turned off as current in S_a is flowing through its body diode when current is flowing through the body diode of S_1 .

D. Step 4: ZCS Turn-Off of Lagging Leg Switches

A very simple passive auxiliary circuit without any additional switch is applied in the secondary side of the converter to achieve ZCS for the lagging leg switches, by resetting the primary cur-rent with the energy stored in C_c . At the end of Mode 8 when C_c is charged completely, the voltage across C_c reaches the output voltage V_o . The voltage across C_c can be expressed according

VI. Conclusion

A new ZCS-PWM full-bridge converter is proposed in this paper. The outstanding feature of the new converter is that it allows its main power switches to operate with ZCS and with fewer conduction losses than conventional full-bridge convert-ers. This is achieved by using a very simple active auxiliary circuit and a ZVZCS technique so that the converter has all the advantageous features of ZVZCS converters but with ZCS operation for all the converter switches so that they can all be IGBT devices, which helps reduce component cost. The pro-posed converter does not have the drawbacks of previously proposed techniques for higher power dc–dc full-bridge con-verters with IGBTs, including resonant techniques, ZCS-PWM techniques with active auxiliary circuits, passive techniques, ZVZCS techniques, and techniques that require the use of re-verse blocking diodes.

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