ZVZCS PWM CONVERTER USING SECONDARY ACTIVE CLAMP

Marcel BODOR*, Jaroslav DUDRIK*, Ján PERDULÁK**

*Department of Electrical Engineering and Mechatronics, Faculty of Electrical Engineering and Informatics, Technical University of Košice, Letná 9, 042 00 Košice, Slovak Republic, tel.: +421 55 602 2276, e-mail: jaroslav.dudrik@tuke.sk
**Department of Theoretical and Experimental Electrical Engineering, Faculty of Electrical Engineering and Informatics, Technical University of Košice, Letná 9, 042 00 Košice, Slovak Republic, tel.: +421 55 602 2592, e-mail: jan.perdulak@tuke.sk

ABSTRACT

A novel zero-voltage and zero-current switching (ZVZCS) pulse-width modulation (PWM) converter is presented in this paper. An active energy recovery clamp in the secondary side provides conditions for zero-current switching (ZCS) of the transistors in the primary side of the DC/DC converter. Zero-voltage switching (ZVS) of the primary switches is achieved by the magnetizing current of the transformer. The active energy recovery clamp provides soft switching of the transistor located on the secondary side of the transformer. The principle of converter operation is explained and analyzed and experimental results obtained on the laboratory model are presented.

Keywords: DC/DC converter, zero voltage switching, zero current switching, soft switching, clamp circuit

1. INTRODUCTION

In recent days, there is an increasing demand for high performance load converters. This has resulted in an extra emphasis towards increasing the switching frequencies of the power devices in the circuit. While the reduction in the size and weight of the converters are the direct implications of this trend. However, the other side of the coin are issues like increased switching loss in the devices and electromagnetic compatibility problems.

MOSFETs are mainly used as switching devices in ZCZVS FB (full bridge) PWM converters. In spite of their several advantages, including very short switching times, they are not suitable for high power applications owing to an increased conduction loss with rise in voltage.

These days, IGBTs are replacing MOSFETs for high voltage, high power applications, since IGBTs have higher voltage rating, higher power density, and lower cost compared to MOSFETs [1]. On the other hand, the use of IGBTs is significantly reduced by their frequency switching, usually limited to 20-30 kHz because of their tail current characteristic at turn-off [2]. To operate IGBTs at higher switching frequencies it is required to significantly reduce turn off switching losses.

Many topologies have been developed to solve this problem [1]-[15]. This topology uses an auxiliary circuit on the secondary side of the transformer to achieve ZCZVS and hence reduces the switching loss to zero. Generally, the ZVS of the leading-leg switches is achieved in a manner similar to that of ZVS FB PWM converters [3]-[4], [6] while ZCS of lagging-leg switches is achieved by resetting the primary current during the freewheeling period. The technical realization of the auxiliary circuit which provides reset of primary current is realized in different ways. The converter proposed in [3] has a simple auxiliary circuit which contains neither loss components nor active switches. Resetting of the primary current is achieved by using the energy of leakage inductance and clamp capacitor placed on the secondary side. The converter used in both [2] and [3] contains neither loss components nor active switches. Resetting of the primary current is achieved using transformer auxiliary winding inserted into the secondary side which makes this auxiliary circuit more complex. The converter [7] contains an active switch on the secondary side. This switch is used to control the clamping circuit. The clamp switch induces switching losses due to its hard switching, and the maximum output current is limited by the capacitance of the holding capacitor [3]. The blocking capacitor on the primary side of the transformer winding is used in the converter [5]. The auxiliary circuit contains an active switch and the transformer auxiliary winding which makes this circuit considerably complex and its parameter design is complicated [2].

The new energy recovery clamp presented in this paper clamps the collector-emitter voltage of the secondary switch at turn-off and recycles all the energy stored in the transformer leakage inductance. This energy is consequently transferred to the load. Furthermore, because the transformer leakage inductance energy is fully recovered, the efficiency of the converter is increased.

2. OPERATION PRINCIPLE

Fig. 1 shows the proposed converter with novel energy recovery clamp (patent pending) arranged for the use during the turn-off process of the secondary active switch. The proposed converter has nine operating modes within each operating half cycle. Operational analysis is shown in Fig. 2 and the corresponding operation waveforms are shown in Fig. 3. The detail description of the converter is presented in [6].

Mode 1 - interval (t0-t1): The transistors T1, T2 are turned on with ZVS at t0 because magnetizing current flows through diodes D1, D2 and rate of rise of the collector current is limited by the leakage inductance of the transformer. The collector current of the transistor T3, which is turned on at t0 too, starts to flow and the capacitor Cc is discharged. The rise of the capacitor discharging current is limited by the inductor Ls in the clamp circuit.

Mode 2 - interval (t1-t2): The transformer leakage inductance reflected to the primary side causes the primary current Ip to increase linearly while the secondary
voltage $u_S$ is zero as a result of commutation between output freewheeling diode $D_0$ and rectifier diode $D_5$.

**Mode 3 - interval** $(t_2-t_3)$: The commutation between diode $D_5$ and output freewheeling diode $D_0$ is finished and the end of this interval the clamp capacitor current commutates to clamp diode $D_C$.

**Mode 4 - interval** $(t_3-t_4)$: The energy is delivered from the source to the load through transistors $T_1$ and $T_2$ which are conducting and from and the inductance $L_S$ as well. The smoothing inductance current is a sum of the secondary current and clamp inductance $L_S$ current.

**Mode 5 - interval** $(t_4-t_5)$: The energy is delivered from the source to the load.

**Mode 6 - interval** $(t_5-t_6)$: At $t_5$ the secondary transistor $T_S$ turns off. At this moment the commutation between transistor $T_S$ and clamp diode $D_C$ occurs and charging of the clamp capacitor $C_C$ starts. Afterwards, the commutation between $D_C$, $D_5$ and output freewheeling diode $D_0$ starts.

During the commutation, the energy stored in the leakage inductance is transferred to the clamp capacitor $C_C$ and consequently an overvoltage $\Delta U_S$ appears on secondary voltage. This clamped overvoltage can be calculated by the formula:

$$\Delta U_S = I_{MAX} \frac{L_L}{C_C}$$  \hspace{1cm} (1)

where: $I_{MAX}$ – current flowing through transistor $T_S$ at time $t_5$, $L_L$ – transformer leakage inductance, $C_C$ – clamp capacitor capacitance

Maximum clamped voltage on the clamp capacitor and transistor $T_S$ is:

$$U_{C_{MAX}} = \Delta U_S + U \frac{N_S}{N_P} = I_{MAX} \frac{L_L}{C_C} + U \frac{N_S}{N_P}$$  \hspace{1cm} (2)

where: $U$ – converter supply voltage, $N_S$ – transformer secondary turns, $N_P$ – transformer primary turns

**Mode 7 - interval** $(t_6-t_7)$: Only a small magnetizing current flows through the primary winding of transformer. The output current flows through the output freewheeling diode $D_0$. 

---

**Fig. 1** Scheme of the proposed converter

**Fig. 2** Operation modes

**Fig. 3** Operation waveforms
Mode 8 - interval \((t_7-t_8)\): In interval, the transistors \(T_1\) and \(T_2\) are turned off with ZCS. Only a small magnetizing current is switched off by transistors \(T_1\) and \(T_2\). The magnetizing current charges or discharges the internal output capacitances \(C_{OSS1}\) - \(C_{OSS4}\) of the IBGT transistors \(T_1\) - \(T_4\) respectively.

Mode 9 - interval \((t_8-t_9)\): At \(t_8\), the antiparallel diodes \(D_3\) and \(D_4\) of the transistors \(T_3\) and \(T_4\) starts to lead the primary current and thus conditions for the ZVS for these transistors are ensured.

3. EXPERIMENTAL RESULTS

A prototype of the proposed ZVZCS PWM converter with active secondary energy recovery clamp has been built and tested to verify the principle of operation. The coaxial transformer used has been laboratory built with turn ratio \(n = 6\). The magnetizing inductance of the transformer is 981.5 \(\mu\)H and leakage inductance on the primary side is 18.5 \(\mu\)H. The prototype of the converter was supplied by 300 \(V_{DC}\) and the switching frequency of IGBT’s were 50 kHz. The main parameters are summarized in Table 1.

<table>
<thead>
<tr>
<th>Utilized components and parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_1-T_4)</td>
<td>IRGP35B60PD</td>
</tr>
<tr>
<td>(T_S)</td>
<td>IRFP4668</td>
</tr>
<tr>
<td>(D_3, D_6)</td>
<td>80EBU02</td>
</tr>
<tr>
<td>(D_5, D_C)</td>
<td>60EP0U02</td>
</tr>
<tr>
<td>(D_0)</td>
<td>249NQ135</td>
</tr>
<tr>
<td>(C_C)</td>
<td>220 nF</td>
</tr>
<tr>
<td>(L_S)</td>
<td>7.4 (\mu)H</td>
</tr>
<tr>
<td>(L_0)</td>
<td>47 (\mu)H</td>
</tr>
</tbody>
</table>

The voltage and current of the primary switch \(T_4\) and the transistor \(T_S\) situated on the secondary side are shown in Fig. 4. Fig. 5 shows extended waveforms of the transistor \(T_4\). The voltage of the primary current decreases to the value of magnetizing current after turn off of the transistor \(T_S\). This small magnetizing current is subsequently turned-off by the transistor \(T_4\) and as can be observed, turn off losses are negligible. The turn on of the transistor \(T_4\) is implemented under zero-voltage because its internal output capacitance is discharged before and only a small magnetizing current flows through its antiparallel diode \(D_4\) and thus the condition for ZVS is fulfilled. The rise of the collector current is limited by the leakage inductance of the transformer, therefore also ZCS is achieved.

The voltage and the collector current of the transistor \(T_S\) are shown in Fig. 6. At the turn on of the transistor \(T_S\) the collector-emitter voltage decreases to zero immediately. The rise of the collector current is significantly limited by the transformer's leakage inductance (reflected to the secondary side) and the clamp inductance \(L_S\). So, the turn on losses are neglected.

From Fig. 7 it is evident that the voltage of the clamp capacitor rises at the same rate as the voltage of the transistor \(T_S\). At the turn on moment of the transistor \(T_S\) the energy stored in the clamp capacitor is delivered to the load through the diode \(D_5\) and inductance \(L_S\). The rate of the current rise is limited by the clamp inductance \(L_S\).

For completeness, comparing waveforms of the clamp capacitor voltage with the voltage and the collector current of the transistor \(T_S\) are provided in Fig. 8.
4. CONCLUSIONS

The paper describes a ZVZCS PWM converter with a new active energy recovery clamp. The operating principle of the proposed converter is presented together with experimental results achieved on the laboratory model of the converter. This prototype of the converter was constructed by using IGBT’s and it was successfully tested at 50 kHz switching frequency. The experimental results obtained confirm the appropriateness of using the proposed topology of the converter with secondary energy recovery clamp and thus the zero-voltage turn-on and zero-current turn-off for all of the transistors T1-T4 in the inverter are achieved.

It is shown that experimental results are in very good accordance with the theoretical assumptions.

ACKNOWLEDGMENT

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-0185-10 and by Scientific Grant Agency of the Ministry of Education of Slovak Republic under the contract VEGA No. 1/0099/09. The authors also wish to thank for the support to the R&D operational program Centre of excellence of power electronics systems and materials for their components. The project is funded by European Community, ERDF – European Regional Development Fund.

REFERENCES


Received June 22, 2011, accepted September 16, 2011

**BIOGRAPHIES**

Marcel Bodor was born on 14.11.1984 in Lučenec (Slovakia). He received the M.Sc. degree in electrical engineering from the Technical University of Košice, Slovakia, in 2009. He is currently Ph.D. student at the Department of Electrical Engineering and Mechatronics, Technical University of Košice, where he is engaged in research. His primary interest is power electronics.

Jaroslav Dudrik received the M.S. and Ph.D. degrees in electrical engineering from the Technical University of Košice, Slovakia, in 1976 and 1987, respectively. He is currently full professor of Electrical Engineering at the Department of Electrical Engineering and Mechatronics, Technical University of Košice, where he is engaged in teaching and research. His primary interest is power electronics. His field of research includes dc-to-dc converters, high power soft switching converters, converters for renewable energy sources and control theory of converters.

Ján Perduľak received the M.Sc. degrees in electrical engineering from the Technical University of Košice, Slovakia, in 2010. He is currently Ph.D. student of Theoretical Engineering at the Department of Theoretical Electrical Engineering and Electrical Measurement, Technical University of Košice, where he is engaged in research. His primary interest is power electronics. His field of research includes dc-to-dc converters, converters for renewable energy sources and control theory of converters.