ZVZCS PWM CONVERTER USING SECONDARY ACTIVE CLAMP

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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 (t_0-t_1): The transistors T_1, T_2 are turned on with ZVS at t_0 because magnetizing current flows through diodes D_1, D_2 and rate of rise of the collector current is limited by the leakage inductance of the transformer. The collector current of the transistor T_S, which is turned on at t_0 too, starts to flow and the capacitor C_C is discharged. The rise of the capacitor discharging current is limited by the inductor L_S in the clamp circuit.

Mode 2 - interval (t_1-t_2): The transformer leakage inductance reflected to the primary side causes the primary current i_P to increase linearly while the secondary

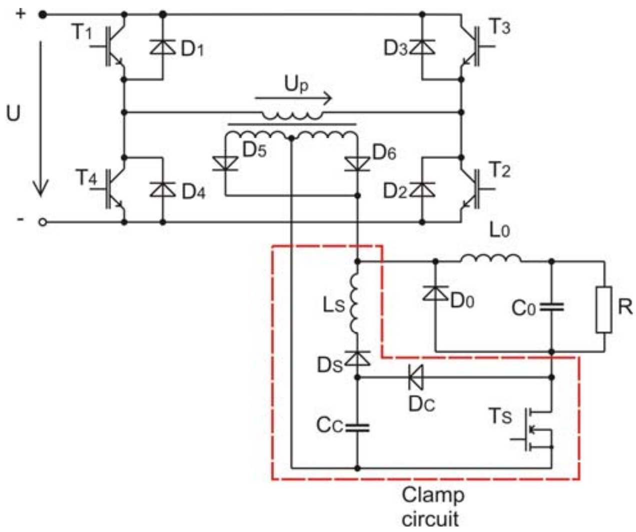

Fig. 1 Scheme of the proposed converter

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 ΔU_S appears on secondary voltage. This clamped overvoltage can be calculated by the formula:

$$\Delta U_S = I_{MAX}\sqrt{\frac{L_L}{C_C}} \tag{1}$$

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:

$$U_{CcMAX} = \Delta U_S + U\frac{N_S}{N_P} = I_{MAX}\sqrt{\frac{L_L}{C_C}} + U\frac{N_S}{N_P} \tag{2}$$

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.

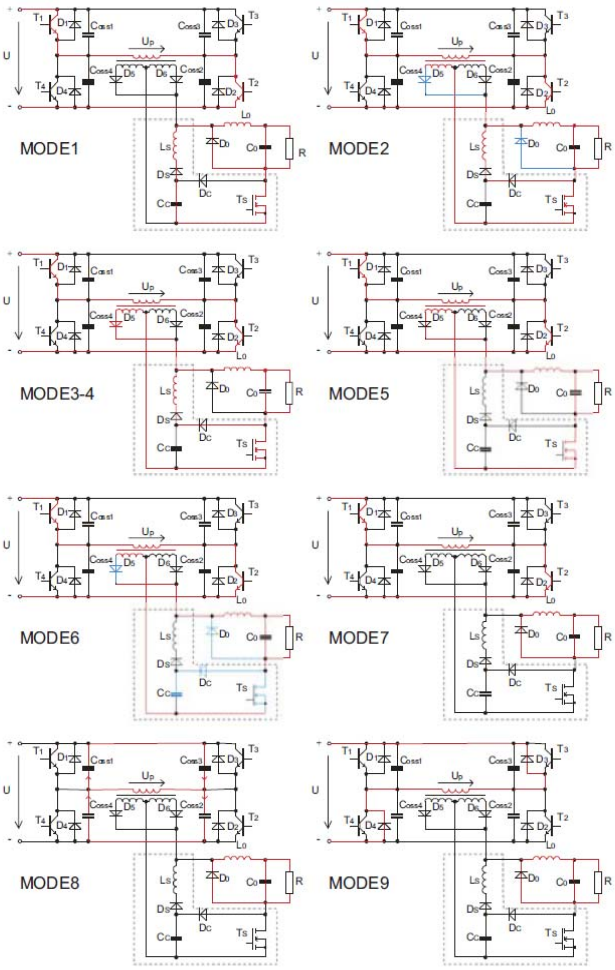

Fig. 2 Operation modes

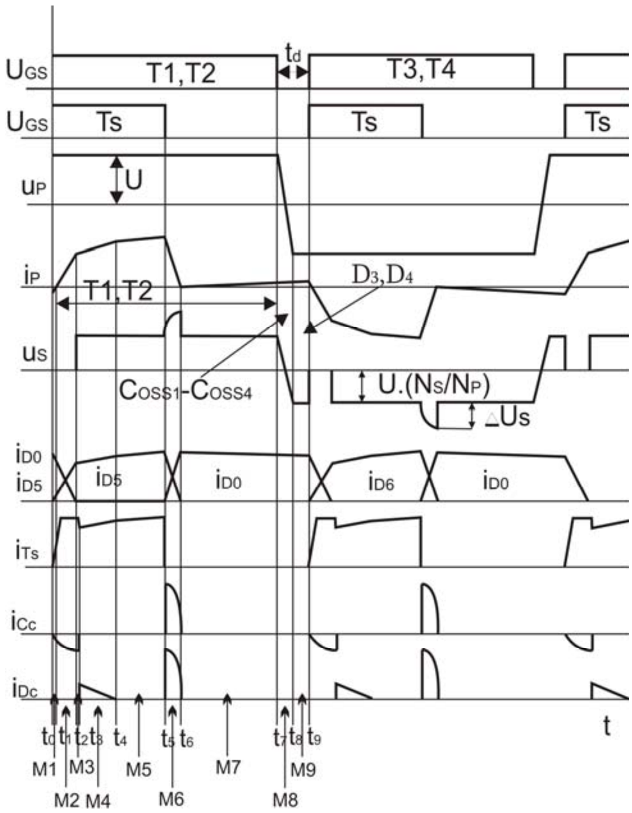

Fig. 3 Operation waveforms

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 this 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 μH and leakage inductance on the primary side is 18,5 μH. 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 1 Utilized components and parameters

T_1-T_4	IRGP35B60PD
T_S	IRFP4668
D_5, D_6	80EBU02
D_S, D_C	60EPU02
D_0	249NQ135
C_C	220 nF
L_S	7,4 μH
L_0	47 μH

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 value 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.

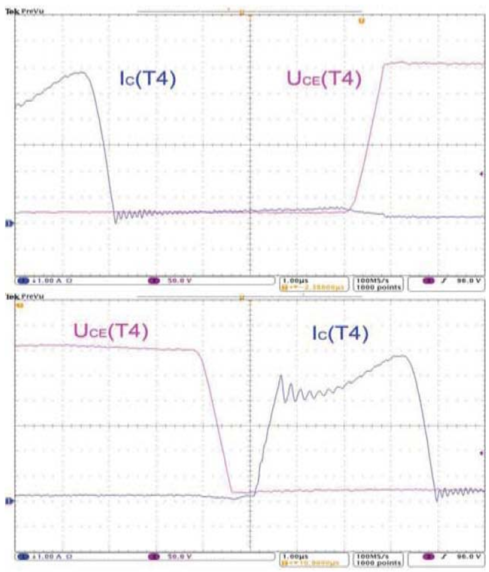

Fig. 5 Extended switch waveforms of the transistor T_4

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_S 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.

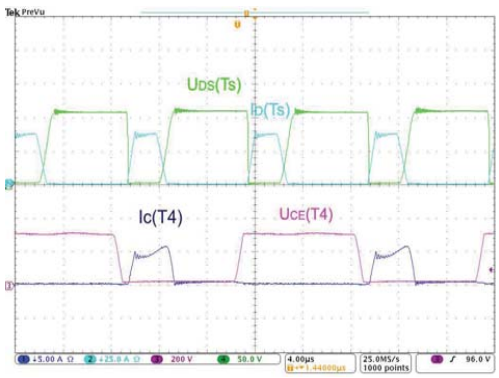

Fig. 4 Voltage and current of the secondary transistor T_S and primary transistor T_4

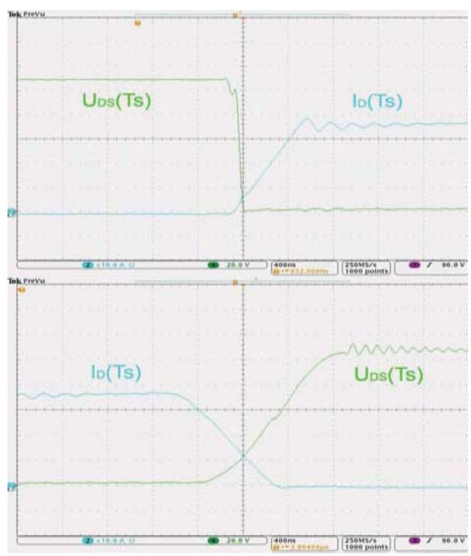

Fig. 6 Extended switch waveforms of the secondary transistor T_S

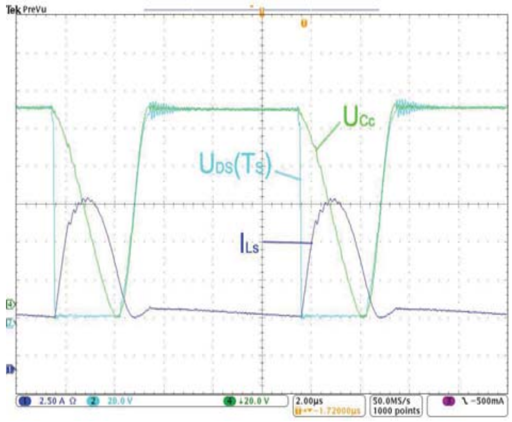

Fig. 7 Transistor T_S voltage in comparison with clamp capacitor voltage and inductance L_S current

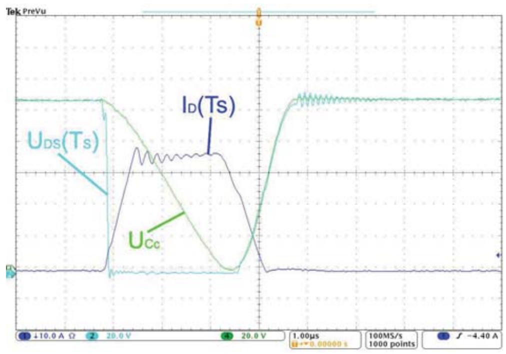

Fig. 8 Transistor T_S switching waveforms in comparison with clamp capacitor voltage

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 T_1 -T_4 in the inverter are achieved.

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

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REFERENCES

[1] CHOI, H.-S. – KIM, J.-W. – CHO, B. H.: Novel zero-voltage and zero-current-switching (ZVZCS) full-bridge PWM converter using coupled output inductor, *IEEE Transactions on Power Electronics*, Sep. 2002, Vol. 17, No. 5, pp. 641–648.

[2] CHO, J. G. – BAEK, J. W. – YOO, D. W. – LEE, H. S. – RIM, G. H.: Novel zero-voltage and zero-current-switching (ZVZCS) full bridge PWM converter using transformer auxiliary winding, *Power Electronics Specialists Conference, 1997. PESC '97 Record., 28th Annual IEEE*, June 22–27, 1997, Vol. 1, pp. 227–232.

[3] CHEN, T.-F. – CHENG, S.: A Novel Zero-Voltage Zero-Current Switching Full-Bridge PWM Converter Using Improved Secondary Active Clamp, *2006 IEEE International Symposium on Industrial Electronics*, July 9–13, 2006, Vol. 3, pp. 1683–1687.

[4] CHO, J.-G. – BAEK, J.-W. – JEONG, Ch.-Y. – RIM, G.-H.: Novel zero-voltage and zero-current-switching full-bridge PWM converter using a simple auxiliary circuit, *IEEE Transactions on Industry Applications*, Jan./Feb. 1999, Vol. 35, No. 1, pp. 15–20.

[5] JANGWANITLERT, A. – OLEJNICZAK, K. J. – BALDA, J. C.: "An improved zero-voltage and zero-current-switching PWM full-bridge DC-DC converter," *Industrial Electronics Society, 2003. IECON '03. The 29th Annual Conference of the IEEE*, Nov. 2–6, 2003, Vol. 2, pp. 1685–1690.

[6] DUDRIK, J. – RUŠČIN, V.: Voltage fed zero-voltage zero-current switching PWM DC-DC converter, *13th International Power Electronics and Motion Control Conference, 2008, (EPE-PEMC 2008)*, Sep. 1–3, 2008, pp. 295–300.

[7] CHO J.-G. – JEONG, Ch.-Y. – LEE, F. C. Y.: "Zero-voltage and zero-current-switching full-bridge PWM converter using secondary active clamp," *IEEE Transactions on Power Electronics,* July 1998, Vol. 13, No. 4, pp. 601–607.

[8] DUDRIK, J. – OETTER, J.: Soft-Switching PWM DC-DC Converter for High Power Applications, *12th International Power Electronics and Motion Control Conference, 2006, (EPE-PEMC 2006)*, Aug. 30, 2006–Sept. 1, 2006, pp.739–744.

[9] PETROV, S.: Prospective Topologies of the Welding Inverters. Sovremennaja Elektronika, 2009, No. 1, pp. 36–45. (in Russian)

[10] TRIP, N. D.: A new active snubber for dc-dc boost converters, *8th International Conference on Engineering of Modern Electric System, Proceedings, (EMES´05), Section Electronical Engineering*, Oradea, Romania, May 2005, pp. 124–127.

[11] HAMAR, J. – NAGY, I. – STUMP, P. – OHSAKI, H. – MASADA, E.: New Dual Channel Quasi Resonant DC-DC Converter Topologies for

Distributed Energy Utilization, *13th International Power Electronics and Motion Control Conference (EPE-PEMC 2008)*, Sep. 1–3, 2008, Poznan, Poland, 2008, pp. 1778–1785, ISBN 978-1-4244-1742-1.

[12] CHLEBIŠ, P.: Soft Switching Converters, VŠB Ostrava, 2004, p. 148, ISBN 80-248-0643-6. (in Czech)

[13] LEUCHTER, J. – BAUER, P. – ZOBAA, A. F.: Power Electronics and Energy Management of Hybrid Power Sources with Supercapacitors, *Proceedings of the 5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010)*, Brighton UK, 2010, pp. 1–6, ISBN 978-1-84919-231-6.

[14] STUMPF, P. – BARTAL, P. – VARGA, Z. – SEPSI, T. D. – JARDAN, R. K. – NAGY, I.: Comparison of Two Approaches in PWM Technique, *15th International Conference on Electrical Drives and Power Electronics (EDPE 2009): 4th Joint Croatia-Slovakia Conference,* Oct. 12–14, 2009, Dubrovnik, Croatia, Zagreb: KoREMA, 2009. pp. 1–10, ISBN 978-953-6037-56-8.

[15] ŠPÁNIK, P. – DOBRUCKÝ, B. – FRÍVALDSKÝ, M. – DRGOŇA, P. – KURYTNIK, I.: Measurement of Switching Losses in Power Transistor Structure. Magazine of Electronics & Electrical Engineering, Litva, Kaunas, 2008, No. 2, pp. 75–78, ISSN 1392-1215.

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