Sławomir KARYŚ

Kielce University of Technology, Power Electronics Department

Mixed Commutation Techniques and their Influence on Loss in the Three-Phase Voltage-Feed Zero Current Switching Inverter

Streszczenie. *Niniejszy artykuł przedstawia wpływ zastosowania komutacji: twardej i miękkiej na straty w trójfazowym falownika typu ZCS, który może być zastosowany w układach napędowych pojazdów elektrycznych. Falownik tego rodzaju charakteryzuje się bardzo niskim poziomem strat przełączania dla prądów znamionowych. W zakresie prądów obciążenia o niewielkiej wartości, ograniczenie strat przełączania przez komutację miękką nie rekompensuje dodatkowych strat przewodzenia w łącznikach pomocniczych. Zatem w tym zakresie prądów obciążenia komutacja twarda zapewnia niższy poziom strat całkowitych. Przeprowadzono badania eksperymentalne trójfazowego falownika typu ZCS o mocy około 1,5kW. Przedstawiono zalety i wady zastosowanej metody sterowania.* ***(Mieszane metody komutacji i ich wpływ na straty w trójfazowym falowniku napięcia przełączanym w warunkach zerowego prądu).***

Abstract. *The paper presents the hard and soft commutation influence on loss in the three-phase ZCS inverter which can be implemented in the electric cars drive systems. A very low switching loss level, for nominal load current conditions is typical for this kind of inverter. In the range where load current has small value, loss reduction obtained thanks to soft-switching does not to compensate additional conduction loss in the auxiliary switches. Therefore in this load current range, the hard-switching warrants lower total loss level. The experimental research of the 3 kW three-phase ZCS inverter has been done. The merits and disadvantages of implemented control method were shown.*

Słowa kluczowe: falownik ZCS, komutacja miękka
Keywords: ZCS inverter, soft commutation

Introduction

The three-phase zero current switching inverter originates from McMurray thyristor based inverter [1] developed in 1960s. When the power transistors became popular, this idea has been adapted to new requirements [2]. Many control methods were proposed in the past [2,3,4]. The most popular one is described in [4]. A structure with reduced number of switches was also elaborated [5,6]. But simulation and experimental results [7,8] show that this structure has far greater total loss than 6 switch ZCS inverter. A diagram of the analyzed inverter is shown in Fig.1.

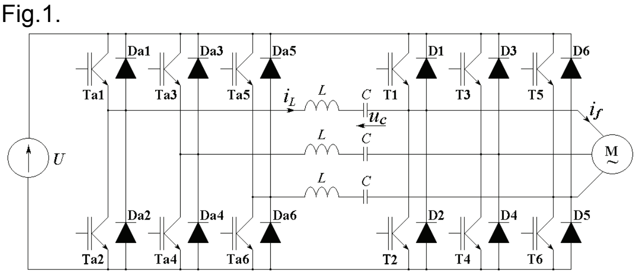

Fig. 1. Three-phase ZCS inverter

Both the main transistors T1÷T6 and auxiliary transistors Ta1÷Ta6 are switching in zero current conditions.

Detail operational principle were described in [4,9]. The control signals and characteristic waveforms in one phase for load current *I*>0 are shown in Fig. 2.

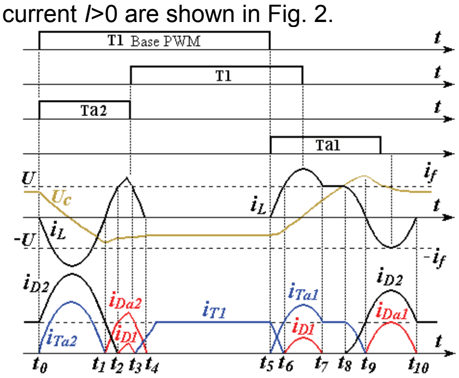

Fig. 2. Control signals and operational waveforms

It is assumed, that before time t_0, the whole load current is flowing through diode D2. Turning on the auxiliary transistor Ta2 at time t_0 starts the soft commutation process of the main transistor T1. Under the initial capacitor C voltage influence, the resonant current i_L flows through transistor Ta1, serially connected L, C resonant tank elements, diode D2 and voltage source U. At time period $t_{2\text{-}3}$ the resonant current i_L is greater than load current. As the diode D1 conducts, the main transistor T1 can be turned on and auxiliary transistor Ta1 is turned off in the zero-current conditions. The resonant current i_L decreases to zero and the turn on process ends at time t_4. The turn off process begins when the auxiliary transistor Ta1 is switched on at time t_5. The resonant current i_L increases and at time period $t_{6\text{-}7}$ its value exceeds the load current. The main transistor T1 can be turned-off at zero current-conditions because its anti-parallel diode D1 conducts the current. The Diode D2 has reverse bias as long as the resonant capacitor C voltage reaches the supply voltage U value (capacitor C is loaded then by the load current). At time t_8 the diode D1 starts to conduct and during time period $t_{9\text{-}10}$ the resonant current i_L changes its direction, the diode Da1 conducts. The auxiliary transistor Ta1 is turned off at zero current-conditions and commutation process ends at time t_{10}.

The experimental operational waveforms at turn-on and turn-off process of the T1 main transistor are shown in Fig. 3.

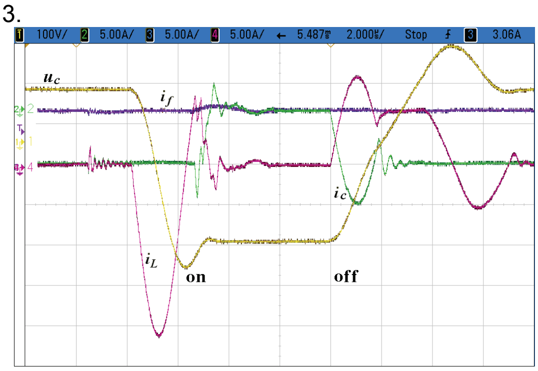

Fig. 3. Operational waveforms, i_f – load current, i_c collector current, i_L – resonant inductor current, u_c – capacitor voltage

Fig.3 shows, that during time periods t_{23} and t_{67}, resonant inductor current i_L is greater than load current i_f and the main diode D1 conducts current equal to i_L - i_f. Thanks that, the main transistor T1 can switch under zero-current conditions. Inside the regions, where the load current has small value, the resonant current has high value. Therefore, in this region high conduction loss in the auxiliary circuit is generated. Fig. 4. shows current in the resonant inductor i_L and sinusoidal shape load current i_f in one phase of the inverter.

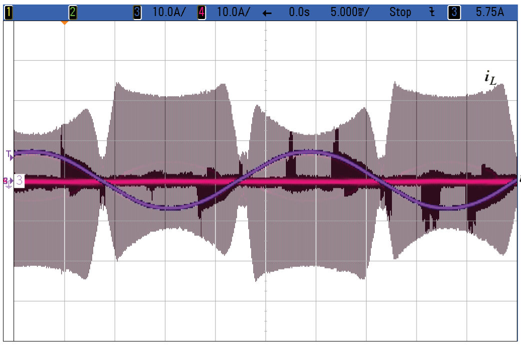

Fig. 4. Resonant inductor current i_L and load current i_f, soft commutation

Hence, when the load current has small value, dominant component of the total loss are conduction loss and for load current above border value I_{gr}, the switching loss becomes dominant component. The proposed regions where hard switching or soft switching should be used are shown in Fig. 5.

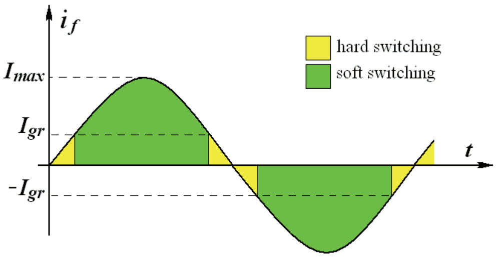

Fig. 5. Different types of modulation

The value of the current I_{gr} can be determinated experimentally or calculated numerically in the base of the simplified power switch loss model. The second method is described in [9].

To verify how the mixed commutation control influences the loss in ZCS inverter, the research station shown in Fig.6 was built.

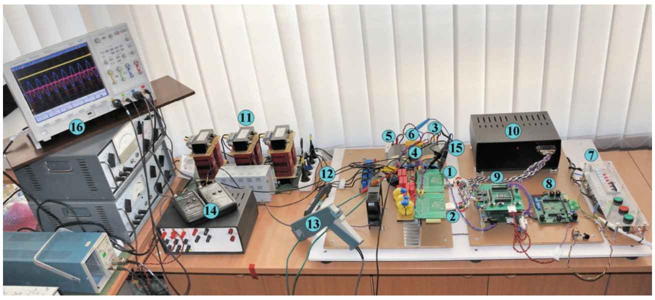

Fig. 6. Research station

The station consists of the following components:

1. Main inverter
2. Auxiliary inverter
3. Three-phase diode bridge rectifier
4. DC-link capacitor set C1, C2
5. Auxiliary two-phase diode rectifier
6. Pre-load resistor - R
7. Contactor set S1, S2
8. Superior modulator system SVM
9. Control unit of the ZCS inverter
10. Voltage supply
11. Load inductors
12. Phase load current probe, Agilent N2783A
13. DC-link current probe, Tektronix A6303
14. Rogowski stripe for the resonant current measure, CWT15B
15. DC-link voltage probe, Tektronix P5120
16. Oscilloscope Agilent MSO7034A

The diagram of the research station is shown in Fig. 7.

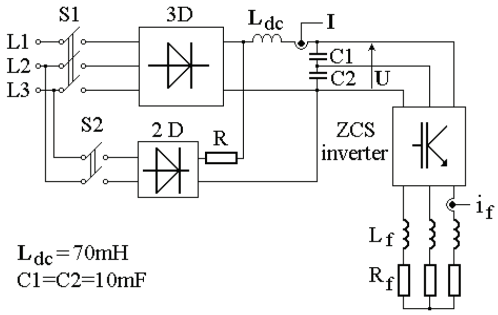

Fig. 7. The diagram of the research station

The ZCS inverter is fed from power net through three-phase 3 diodes star rectifier. Consequently, the DC-link voltage is equal to 270V. This solution makes it possible to limit the maximum value of the resonant capacitors voltage that is twice higher than DC-link voltage. The output power of the inverter is equal about 1,5 kW. This power range is sufficient to verify how different types of modulation influence power loss in the low load current regions of the ZCS inverter. Fig. 8 shows resonant inductor current i_L and load current i_f. for control with mixed modulation type.

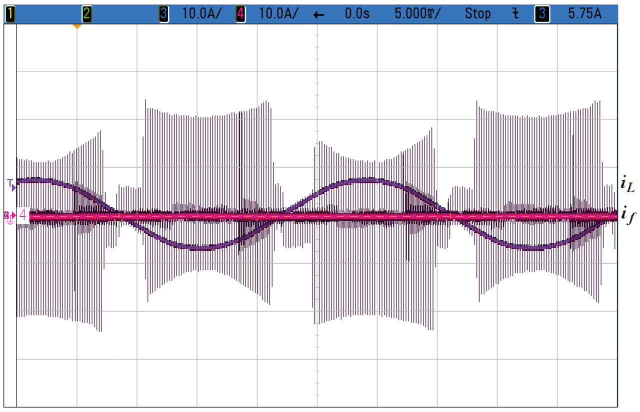

Fig. 8. Resonant inductor current i_L and load current i_f, hard and soft commutation

The comparison to currents shown in Fig. 4 shows that the introduction of hard switching in the regions where load current has small value, effectively limits amplitude of resonant current i_L.

Inverter efficiency has been calculated from following equation

(1) $$\eta = \frac{P_O}{P_{IN}}$$

where: $P_O = 3I_{fRMS}^2 R_f$, $P_{IN} = I_{AV} U_{AV}$, I_{fRMS} – RMS value of the load current, R_f – load resistance, I_{AV} – average value of the input current, U_{AV} - average value of the DC-link voltage

Experimental plots of the inverter efficiency for switching frequency f_S =5kH and f_S =10kH are shown in Fig. 9 and 10 respectively.

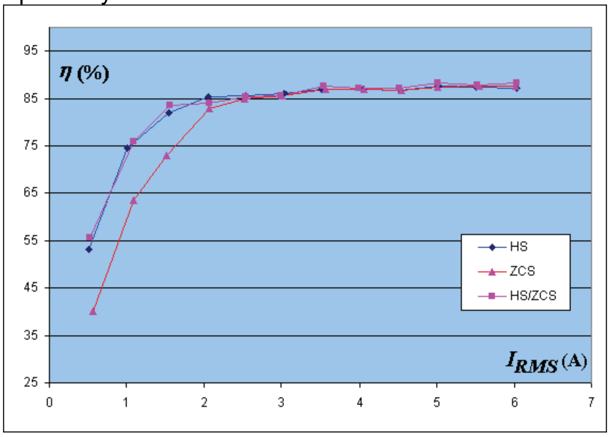

Fig. 9. Inverter efficiency, f=5kHz

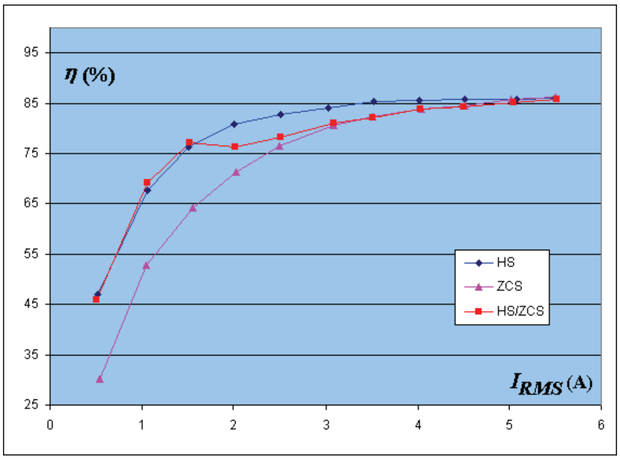

Fig. 10. Inverter efficiency, f=10kHz

Conclusions

Experimental results show, that in the regions where the load current has small value (I_{fRMS}<2A), introducing hard switching significantly increases efficiency of ZCS inverter - about 7% in the analyzed case. For greater load currents (I_{fRMS}>4A) benefit is marginal. If the higher load currents could be obtained, the soft switched ZCS inverter would show considerably better efficiency than classic hard switched one. In practice, mixed modulation mode can get important loss reduction if load current in ZCS inverter changes in a wide range. Such conditions are typical for electric car drive system where an electric motor is often in an idle mode. The main disadvantage of this solution is generation of low frequency noise (heard from auxiliary circuit) that has four times greater frequency then the first harmonic of the load current i_L. This inconvenience can be considerably reduced if electric components of the inverter are placed in the hermetic case settled on the radiator. Another one is the high amplitude of the voltage u_c that demands to use an expensive resonant capacitors. In spite of the above disadvantages, the proposed mixed modulation control makes ZCT inverter a very good solution for electric car applications.

REFERENCES

[1] McMurray W.: SRC Inverter Commutated by Auxiliary Impulse. IEEE Transactions on Communications and Electronics, Vol. 8-75 Nov/Dec., 1964, pp. 824-829.

[2] Hua G., Yang E., Jiang Y., Lee F. C.: Novel Zero-Current-Transition PWM Converters for High Power Applications. In Proceedings of IEEE-PESC, 1993, pp. 538-544.

[3] Mao H., Lee F. C., Zhou X., Boroyevich D.: Improved Zero-Current –Transition Converters for High Power Applications. In Proceedings of IEEE-IAS, 1996, pp. 1145-1152.

[4] Li Y., Lee F. C.: Design Considerations for a 50-kW Soft-Transition Inverter with Zero-Current and Near-Zero-Voltage Switching. In Proceedings of IEEE-APEC, 2001, pp. 931-937.

[5] Li Y., Lee F. C., Lai J., Boroyevich D.: A Low-Cost Three-phase Zero-Current-Transition Inverter with Three Auxiliary Switches. In Proceedings of IEEE-PESC , Vol 1, 2000, pp. 527-532.

[6] Li Y., Lee F. C., Katsis D., Mao Y.: Design of 50-kW Three-Phase Zero-Current-Transition Inverter with Three Auxiliary Switches for Electric Propulsion Drives. In Proceedings of IEEE-PESC 2001, pp. 311-318.

[7] Li Y., Lee F. C.: Design Methodologies for High-Power Three-Phase Zero-Current-Transition Inverters. In Proceedings of IEEE-PESC 2001, pp. 1217-1223.

[8] Li Y.P., Lee F.C, Boroyevich D.: A simplified three-phase zero-current-transition inverter with three auxiliary switches, In Proceedings of IEEE Transaction Power Electronics, vol. 18, no. 3, may 2003, pp. 803-813.

[9] Karyś S.: Analiza strat trójfazowego falownika o komutacji miękkiej ZCS sterowanego metodą PWM, Elektronika, konstrukcje, technologie zastosowania, Warszawa 2009, nr 9, pp. 152-156.

dr inż. Sławomir Karyś, Politechnika Świętokrzyska w Kielcach, WEA i I, Katedra Energoelektroniki
e-mail: enesk@tu.kielce.pl