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Analysis of Switching Conditions of IGBTs in Modified Sine Wave qZSIs Operated with Different Shoot-Through Control Methods

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Introduction

In 2009 researchers of the Department of Electrical Drives and Power Electronics of Tallinn University of Technology proposed a new type of an isolated step-up DC/DC converter - the quasi-Z-source (qZS) based DC/DC converter [1, 2]. The converter (Fig. 1) consists of the quasi-Z-source network (qZS-network) that includes two capacitors (C_1 and C_2), a diode (D_1), and two inductors (L_1 and L_2). The high-frequency step-up isolation transformer (Tr) is supplied by the IGBT based single-phase modified sine wave inverter (T_1...T_4). To reduce the turn ratio of the transformer a voltage doubler rectifier based on two capacitors (C_3 and C_4) and two diodes (D_2 and D_3) was implemented.

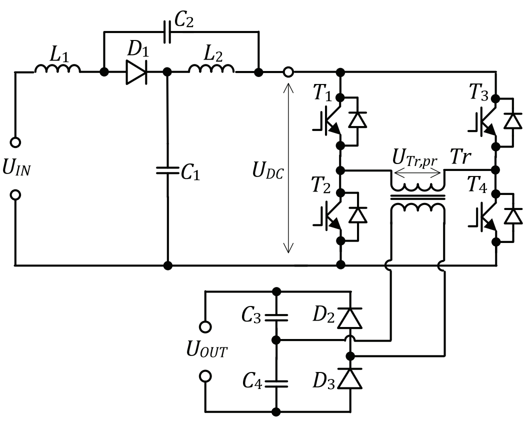


Fig. 1. Simplified power circuit diagram of the proposed converter

Since the proposed converter is intended for low voltage stepping up, high current values in the input side of the converter at high power ratings of the system are unavoidable. It means that serious attention should be paid to loss reduction not only in conductors but also in the semiconductor switches of the inverter. Losses in IGBT switches can be significantly reduced by proper control methods in order to reach soft switching. This paper discusses two novel shoot-through control methods specially developed for the modified sine wave qZSI. The operating conditions of IGBTs are experimentally examined in both control methods and the resulting advantages of each method are explained.

Generalized operation principle of the converter

The proposed converter is meant for applications with input voltage changing at a wide range, such as power conditioning systems for fuel cells and solar panels. To regulate the varying input voltage the front-end quasi-Z-source inverter (qZSI) has two different operation modes: non-shoot-through and shoot-through (Fig. 2).

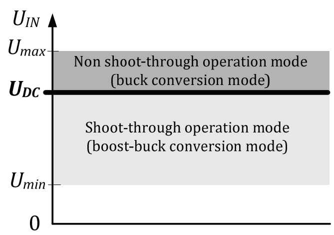


Fig. 2. Operation modes of the qZS based DC/DC converter

In the non-shoot-through mode the qZSI performs only the voltage buck function. This operation mode is typically used during light load conditions, when the output voltage of a fuel cell or a solar panel reaches its maximum. The inverter is controlled in the same manner as a traditional VSI utilizing only the active states, when one and only one switch in each phase leg conducts. The transistors in the full-bridge configuration are controlled alternately in pairs (T_1 and T_4 or T_2 and T_3) with 180^0 phase shifted control signals.

When the input voltage drops below a predefined value (i.e., U_{DC} in Fig. 2), the qZSI starts to operate in the shoot-through mode performing both the voltage boost and buck functions. Thus, the varying input voltage is first preregulated to some desired DC-link voltage level U_{DC} by adjusting the shoot-through duty cycle (shoot-through operating state). Afterwards the isolation transformer is being supplied with voltage at a constant amplitude value (active state). The shoot-through states (i.e., simultaneous conduction of both switches of the same phase leg) are used to boost the magnetic energy stored in the dc side inductors without short-circuiting the dc capacitors. This increase of inductive energy in turn provides the boost of voltage seen on the transformer primary winding during the traditional operating states of the inverter.

Shoot-through control methods for modified sine wave qzsi

Two shoot-through control methods for a modified sine wave qZSI were recently proposed: the pulse width modulation (PWM) and phase shift modulation (PSM) [3–6]. The shoot-through in both cases is generated during zero states. The zero and shoot-through states are spread over the switching period so that the number of higher harmonics in the transformer primary could be reduced. To reduce switching losses of the transistors, the number of shoot-through states per period was limited by two. Moreover, in order to decrease the conduction losses of the transistors, shoot-through current is distributed between both inverter legs.

In both of the proposed shoot-through control methods the switching period consists of three states: active, zero and shoot-through state

$$T = t_A + t_S + t_Z \,. \qquad (1)$$

Equation (1) could also be represented as

$$\frac{t_A}{T} + \frac{t_S}{T} + \frac{t_Z}{T} = D_A + D_S + D_Z = 1 \,, \qquad (2)$$

where D_A is the duty cycle of an active state, D_S is the duty cycle of a shoot-through state and D_Z is the duty cycle of a zero state. The duty cycle of the shoot-through states can never exceed 0.5.

In the active state only one switch in each phase leg conducts. In the zero state the primary winding of the isolation transformer is shorted through either the top- (T_1 and T_3) or bottom-side (T_2 and T_4) inverter switches. To provide a sufficient regulation margin, the zero state time t_Z should always exceed the maximum duration of the shoot-through states per one switching period.

PWM shoot-through control. Fig. 3a shows the PWM control principle of a single-phase modified sine wave qZSI where shoot-through is generated during zero states. Zero states in the case of PWM are always generated by the same switches either the top (T_1 and T_3) or the bottom (T_2 and T_4) inverter switches. Two shoot-through states are generated by simultaneous conduction of all inverter switches. During this operating mode the voltage across the inverter bridge (U_{DC}) drops to zero and the resulting primary winding voltage waveform ($U_{Tr,pr}$) of the isolation transformer is indicated in Fig. 3a.

Regarding to this methodology the switching states sequence is shown in Table 1. The states are shown for one switching period of the isolation transformer. As it can be seen, the transistors work with different switching frequencies, thus they have unequal switching losses. T_1 and T_3 are working with the same frequency as the isolation transformer while T_2 and T_4 have three times higher operating frequency.

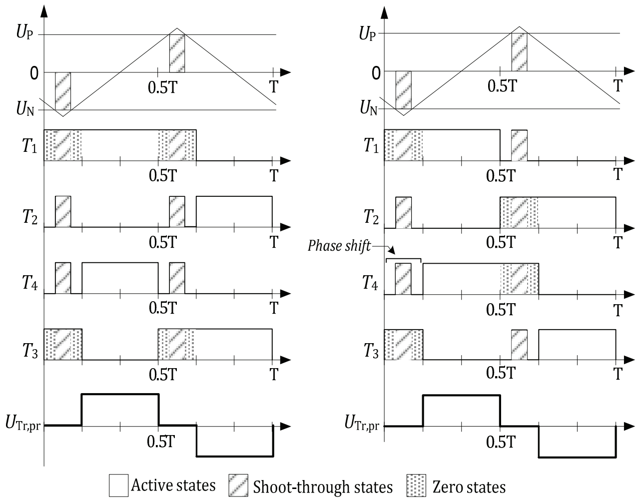


Fig. 3. Shoot-through control methods for the modified sine wave qZSI: (a) pulse width modulation (PWM) and (b) phase shift modulation (PSM)

Table 1. PWM switching states sequence per one period

	T_1	T_2	T_3	T_4
Zero state	1	0	1	0
Shoot-through	1	1	1	1
Zero state	1	0	1	0
Active state	1	0	0	1
Zero state	1	0	1	0
Shoot-through	1	1	1	1
Zero state	1	0	1	0
Active state	0	1	1	0

Gating signals of this control method are shown in Fig. 4. The signals are recorded with the following parameters: maximal shoot-through D_S=0.25, duty cycle of active states D_A=0.5 and duty cycle of zero states D_Z=0.25. As can be seen, the zero states are produced by the simultaneous conduction of top-side transistors (T_1 and T_3). The switching frequency of the top-side transistors in the shoot-through mode is equal to the operating frequency of the isolation transformer, while the switching frequency of the bottom-side transistors (T_2 and T_4) is three times higher. In the case of maximal input voltage when shoot-through states are eliminated, all transistors operate with the same frequency as the isolation transformer.

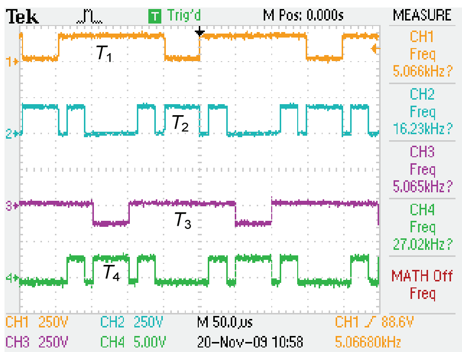


Fig. 4. Gating signals of transistors $T_1 \ldots T_4$ in the PWM control

PSM shoot-through control. An alternative to PWM is the PSM shoot-through control, which also involves two parts: the active and the shoot-through state control. Fig. 3b shows the PSM control principle of a single-phase qZSI where shoot-through is generated during zero states. Active states are controlled with a phase shift between PWM control signals. Unlike the PWM control where the zero state is always generated by the same pair of transistors (T_1 and T_3 or T_2 and T_4), here the pairs are alternating twice in each period. As a result, the transistors are equally loaded.

The switching states sequence of the transistors is shown in Table 2. As compared to the PWM method, differences can be seen. All transistors work with the same frequency, which is twice the transformer operating frequency. Thus, the transistors have also equal switching losses.

Table 2. PSM switching states sequence per one period

	T_1	T_2	T_3	T_4
Zero state	1	0	1	0
Shoot-through	1	1	1	1
Zero state	1	0	1	0
Active state	1	0	0	1
Zero state	0	1	0	1
Shoot-through	1	1	1	1
Zero state	0	1	0	1
Active state	0	1	1	0

Gating signals of the PSM shoot-through control method are shown in Fig. 5. The signals are recorded with the following parameters: maximal shoot-through D_S=0.25, duty cycle of active states D_A=0.5 and duty cycle of zero states D_Z=0.25. The operating frequency of the power transistors is twice the frequency of the isolation transformer. In the case of maximal input voltage when shoot-through states are eliminated, all the transistors operate with the same frequency as the isolation transformer.

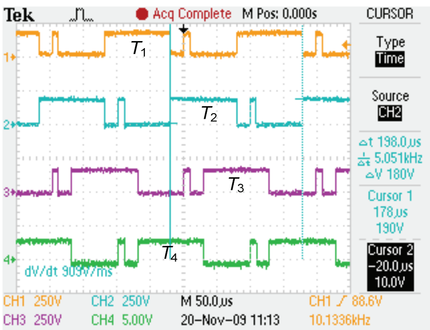


Fig. 5. Gating signals of transistors $T_1 \ldots T_4$ in the PSM control

Analysis of switching conditions of igbts operated with different shoot-through control methods

To analyze switching conditions of IGBTs with different shoot-through control methods an experimental setup of the qZSI-based single-phase DC/DC converter shown in Fig. 1 was developed. Operating parameters of the investigated converter (see Table 3) were selected for the case of maximal voltage boost when the maximal current in the input side of the converter appears.

Collector-emitter voltage U_{CE} and collector current I_C waveforms were measured with a digital oscilloscope *Tektronix TPS2024*, a differential voltage probe *Tektronix P5205* and a current probe LEM HEME PR 30. Measured data were acquired in the tabular form and later processed in MS Excel.

Table 3. Operating parameters of the experimental converter

Parameter	**Value**
Input voltage, U_{IN}	40 V
Desired DC-link voltage, U_{DC}	80 V
System power rating	1 kW
Operating frequency of qZS-network, f_{qZS}	10 kHz
Operating frequency of transformer, f_{Tr}	5 kHz
Shoot-through duty cycle, D_S	0.25
Active state duty cycle, D_A	0.5
Zero state duty cycle, D_Z	0.25
Type of IGBTs	IXGH 32N60BU1

PWM shoot-through control. Since the operation of top (T_1 and T_3) and bottom (T_2, T_4) transistors is different, each group was analyzed separately. Because both inverter legs are operating identically, measurements were made on one transistor leg (T_1 and T_2 in Fig. 1). Fig. 6 shows the experimental waveforms of top transistor T_1: collector-emitter voltage U_{CE}, collector current I_C, and power loss P_{Loss}. All the turn-on/off and conduction intervals are separated by dashed lines. It can be seen that the transients in both shoot-through states (S1 and S2) are identical in terms of voltage (U_{CE}) and current (I_C), thus in the further discussion only one shoot-through state is analyzed.

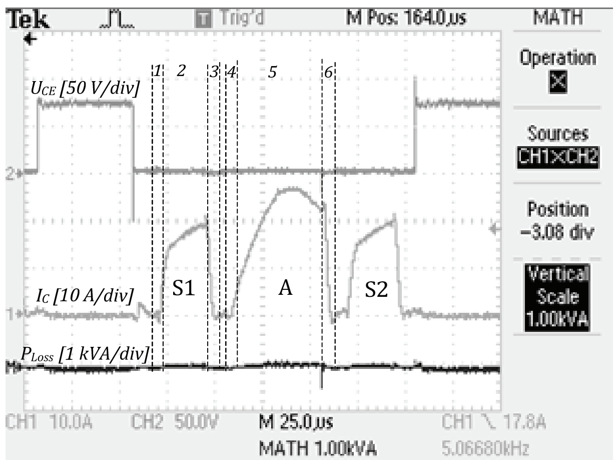


Fig. 6. Experimental waveforms of one switching period of top transistors in the PWM shoot-through control method

Generally, it can be seen that because of the inherent properties of the PWM shoot-through control algorithm the top transistors are soft-switched over the whole period, but for reasons of clarity, a detailed examination of turn-on/off intervals will be made.

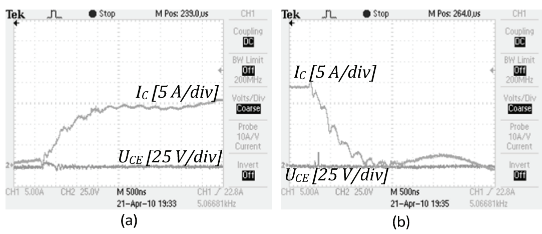
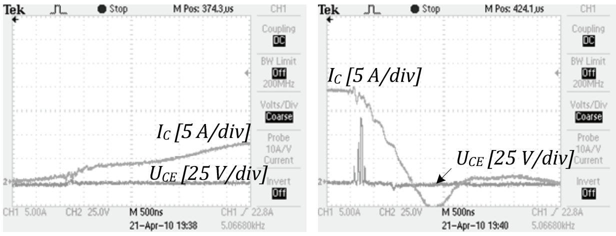


Fig. 7. Shoot-through state turn-on (a) and turn-off (b) intervals of top transistors

Fig. 7*a* and 7*b* show the turn-on and turn-off intervals (1 and 3) of the shoot-through state according to Fig. 6. It is obvious that both shoot-through states are soft switched.

Fig. 8*a* and 8*b* show the turn-on and turn-off intervals (4 and 6) of the active state according to Fig. 6. It is seen that during both intervals the top transistors are soft switched.



(a) (b)

Fig. 8. Active state turn-on (a) and turn-off (b) intervals of top transistors

Fig. 9 shows the experimental waveforms of bottom transistor T_2: collector-emitter voltage U_{CE}, collector current I_C, and power loss P_{Loss}. It can be seen that the waveforms of both shoot-through states (S1 and S2) are identical in terms of voltage (U_{CE}) and current (I_C), thus in our further discussion only one shoot-through state is analyzed. All the turn-on, turn-off and conduction intervals are outlined with dashed lines. Power loss P_{Loss} waveform already shows that shoot-through and active state turn-offs (intervals 3 and 6) are hard switched.

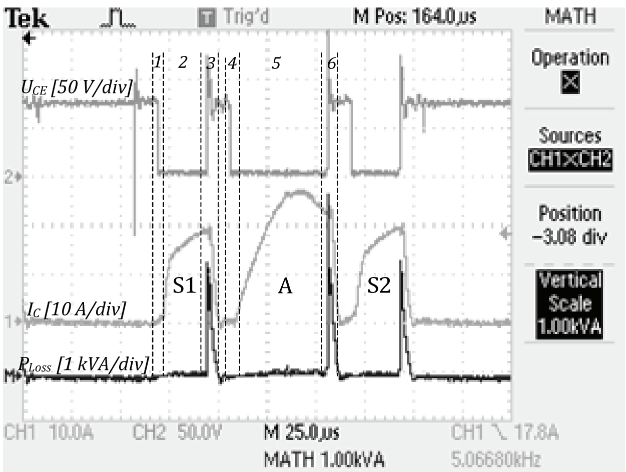
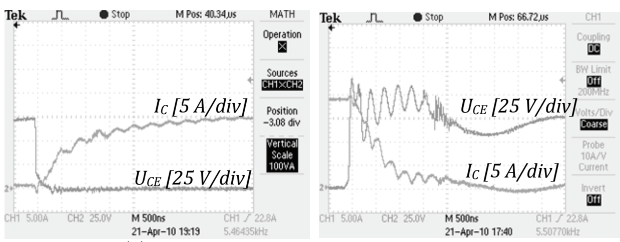


Fig. 9. Experimental waveforms of one switching period of bottom transistors in the PWM shoot-through control method

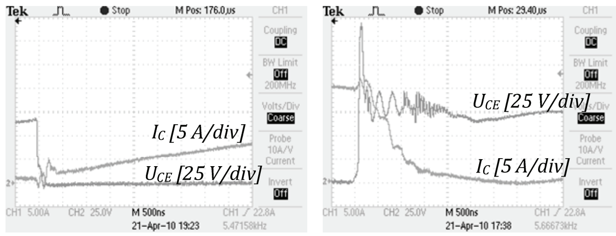
Fig. 10*a* and 10*b* show the turn-on and turn-off intervals (1 and 3) of the shoot-through state according to Fig. 9. It is seen that during the turn-on of the shoot-through state the bottom transistors are soft switched (Fig. 10*a*), but during the turn-off of the shoot-through state the transistors are hard switched (Fig. 10*b*).



(a) (b)

Fig. 10. Shoot-through state turn-on (a) and turn-off (b) intervals of bottom transistors in the PWM shoot-through control method

Fig. 11*a* and 11*b* show the turn-on and turn-off intervals (4 and 6) of the active state according to Fig. 9. It is seen that during the turn-on of the active state the bottom transistors are soft switched (Fig. 11*a*), but during the turn-off of the active state the transistors are hard switched (Fig. 11*b*).



(a) (b)

Fig. 11. Active state turn-on (a) and turn-off (b) intervals of bottom transistors in the PWM shoot-through control method

PSM Shoot-Through Control. Since the operation of all transistors in the PSM method is identical (Fig. 5), only the switching transients of the transistor T_1 were examined and analyzed. Fig. 12 shows the experimental waveforms of collector-emitter voltage U_{CE}, collector current I_C and power loss P_{Loss} of transistor T_1. All the turn-on/off and conduction intervals are separated by the dashed lines.

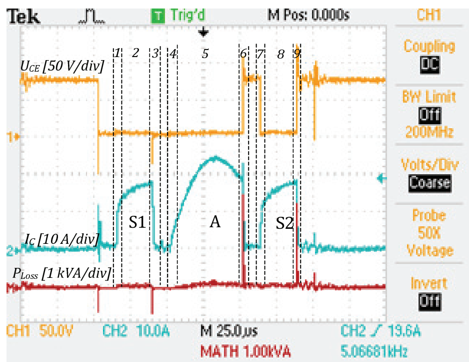
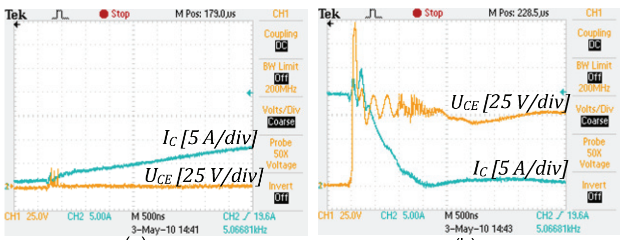


Fig. 12. Experimental waveforms of one switching period of top transistors in the PSM shoot-through control method

It is seen from Fig. 12 that due to the inherent properties of the PSM control algorithm the transistor is fully soft switched during first shoot-through state S1. The turn-on and turn-off intervals (1 and 3) of the first shoot-through state are the same as in Fig. 7. However, during S2 (7 and 9) the transistor is partially soft switched and the turn-on/off transients are identical to those presented in Fig. 10.



(a) (b)

Fig. 13. Active state turn-on (a) and turn-off (b) intervals of transistors in the PSM shoot-through control method

Fig. 13*a* and 13*b* show the turn-on and turn-off intervals (4 and 6) of the active state according to Fig. 12.

It is seen that during turn-on the transistor is soft switched but during turn-off it is hard switched.

Comparison of losses of single-phase qzsi operated with different shoot-through control methods

To compare power losses of IGBTs in a single-phase qZSI operated with different shoot-through control methods numerical calculations were done by help of Eqs. (3) to (7). The turn-on losses of the transistor can be calculated as

$$P_{ON} = f \cdot \int_{t_1}^{t_2} I_C \cdot U_{CE} \cdot dt, \tag{3}$$

where f is the operating frequency and $t_1 - t_2$ is the rise time (time required for the collector current to increase from 10% to 90% from its final value). The turn-off losses of a transistor can be found as

$$P_{OFF} = f \cdot \int_{t_3}^{t_4} I_C \cdot U_{CE} \cdot dt, \tag{4}$$

where $t_3 - t_4$ is the fall time (time required for the collector current to drop from 90% to 10% from its initial value). The total switching losses of a transistor can be found as

$$P_{SW} = P_{ON} + P_{OFF}. \tag{5}$$

Conduction losses of a transistor can be found as

$$P_{COND} = f \cdot \int_{t_2}^{t_3} U_{CE} \cdot I_C \cdot dt. \tag{6}$$

The total losses in a transistor can be found as

$$P_{TOTAL} = P_{SW} + P_{COND}. \tag{7}$$

Table 4 summarizes comparisons made between the conduction and switching losses for one top transistor for one operating period of the PWM shoot-through control method.

Table 5. Comparison of top transistor losses in the pwm control method

Losses / State	P_{ON} (W)	P_{OFF} (W)	P_{COND} (W)
Shoot-through	0.28	0.5	11.67
Active	0.014	0.57	10

It can be concluded that conduction losses comprise 94% of total losses in one transistor (Fig. 14*a*). In addition, Table 4 shows that conduction losses in the active state and in both shoot-through states are almost equal.

Table 5 summarizes comparisons made between the conduction and switching losses for one bottom transistor for one operating period of the PWM shoot-through control method. It is obvious that the major part of switching losses is composed of hard-switched turn-off losses (96%). Moreover, the switching losses make up 52% of the total power dissipation of bottom group transistors in the PWM shoot-through control method (Fig. 14*b*).

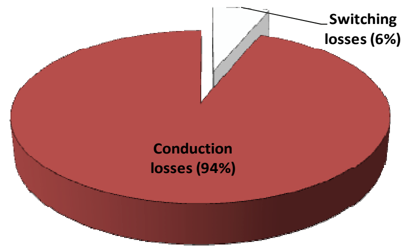
Table 6 summarizes the comparison made between the conduction and switching losses of one transistor for one operating period of the PSM shoot-through control method. It can be concluded that conduction losses comprise 59% of total losses in one transistor (Fig. 15).

Table 5. Comparison of bottom transistor losses in the pwm control method

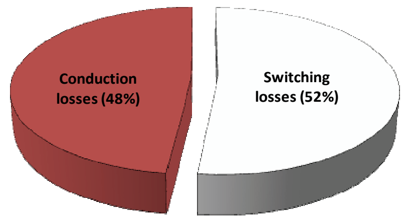
Losses / State	P_{ON} (W)	P_{OFF} (W)	P_{COND} (W)
Shoot-through	0.55	18.6	13.5
Active	0.35	5.1	9.4

Table 6. Comparison of transistor losses in the psm control method

Losses / State	P_{ON} (W)	P_{OFF} (W)	P_{COND} (W)
Shoot-through	0.15	9.77	12.6
Active	0.05	5.75	9.7



a)



b)

Fig. 14. Breakdown of power losses in IGBTs operated with PWM shoot-through control method: top transistors (a) and bottom transistors (b)

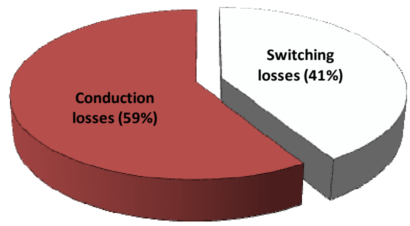


Fig. 15. Breakdown of power losses in IGBTs operated with PSM shoot-through control method

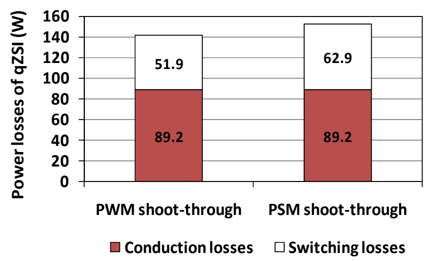


Fig. 16. Comparison of total losses of a single-phase qZSI operated with different shoot-through control methods

In Fig. 16 total losses of a 1 kW single-phase qZSI operated with different shoot-through control methods are compared. It is noticeable that both methods are fairly identical in terms of conduction losses since the number of conduction states and their duration remain unchanged. However, due to an increased number of hard-switched commutations in the case of the PSM shoot-through control method (8 vs. 6 for one operating period) switching losses were increased by more than 20%. It finally means that the PWM shoot-through control method enables the operating efficiency of a 1 kW single-phase qZSI to be increased by 1%.

Conclusions

This paper presents and evaluates two novel shoot-through control methods for the modified sine wave qZSI. The operating principles of the proposed PWM and PSM modulation methods were explained with the help of the switching diagrams and state tables. The practical part of the paper covers the analysis of operating conditions and power losses of IGBTs in a single-phase qZSI operated with different shoot-through control methods.

Results obtained from comparisons of both control methods lead to the following generalizations:

- the PSM shoot-through control method features equal operating conditions for all transistors in a qZSI, however, the PWM shoot-through control imposes unequal operating frequencies of the transistors.
- Both of the shoot-through control methods are fairly identical in terms of conduction losses since the number of conduction states and their duration remain unchanged.
- Due to the increased number of hard-switched commutations in the case of the PSM shoot-through control method (8 vs. 6 for one operating period) switching losses were more than 20% higher than with the PWM shoot-through control.

Acknowledgment

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This paper discusses two novel shoot-through control methods specially developed for the modified sine wave qZSI –the pulse width and phase shift modulation. The operating conditions of IGBTs are experimentally examined in both control methods and the resulting advantages of each method are explained. Ill. 16, bibl. 6, tabl. 6 (in English; abstracts in English and Lithuanian).

D. Vinnikov, I. Roasto, J. Zakis, S. Ott, T. Jalakas. Skirtingų valdymo metodų taikymas IGBT tipo tranzistorių persijungimo režimu // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 5(111). – P. 45–50.

Aptariami du nauji modifikuoto sinusinio signalo valdymo metodai, sąlygojami pločio ir fazės moduliacijų IGBT tranzistoriuose. Kiekvienas metodas yra patikrintas eksperimentiškai, atitinkamai nustatytos metodų teigiamybės. Il. 16, bibl. 6, lent. 6 (anglų kalba; santraukos anglų ir lietuvių k.).