TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE
ELECTRICAL ENGINEERING | ELEKTROTECHNIKA
2-E/2015

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SWITCHING LOSSES IN THREE-PHASE VOLTAGE SOURCE INVERTERS

STRATY PRZEŁĄCZANIA W TRÓJFAZOWYCH FALOWNIKACH NAPIĘCIA

Abstract

The efficiency of three-phase voltage source inverters depends mainly on power losses that occur in semi-conductor elements. Total losses in these elements are a sum of conduction losses and switching losses. The switching losses are dependent on the supply voltage, load current, operating frequency and on the dynamic parameters of the switching elements; these losses can be limited with the use of soft switching methods. This paper discusses the switching loss dependence on the above mentioned factors. An analysis was carried out on power losses in voltage source inverters which generate the output voltage in the form of a rectangular wave and losses in these inverters operating with pulse width modulation. A comparison of switching losses was performed for two voltage source inverters with different nominal power ratings.

Keywords: *pulse width modulation*, *switching losses*, *voltage source inverter*

Streszczenie

Sprawność trójfazowch falowników napięcia zależy głównie od strat mocy występujących w elementach półprzewodnikowych. Straty w tych elementach są sumą strat przewodzenia i strat przełączania. Straty przełączania zależą od napięcia zasilania, prądu odbiornika, częstotliwości pracy oraz od parametrów dynamicznych tranzystorów IGBT; straty te mogą być ograniczone przez zastosowanie układów wspomagających przełączanie elementów. W artykule omówiono zależność strat przełączania od wymienionych czynników. Przeprowadzono analizę strat w falowniku generującym na wyjściu napięcie w postaci fali prostokątnej oraz analizę strat przełączania w falowniku pracującym z modulacją szerokości impulsów. Porównania strat przełączania dokonano dla dwóch falowników napięcia o różnych mocach znamionowych.

Słowa kluczowe: *falownik napięcia*, *modulacja szerokości impulsów*, *straty przełączania*

DOI: 10.4467/2353737XCT.15.087.3919

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1. Introduction

The efficiency of power electronics devices is very high and is in the range from 97 to 99 percent. Despite this fact, many scientific centers still conduct studies which tend to improve this efficiency. This problem is significant, first of all, in three-phase voltage source inverters (VSI), which frequently operate with relatively high frequencies. Partially, this issue also concerns DC-DC converters, however, their application is much smaller than the use of the VSIs. Power losses in these inverters occur mainly in semi-conductor elements, first of all, in insulated gate bipolar transistors (IGBTs) and in their freewheeling diodes. Total power losses in semi-conductor elements are a sum of the conduction losses and the switching losses [1, 2]. The first kind of power losses depend mainly on a collector current and on the collector-emitter voltage of the given transistor. However, we do not have any influence on these losses because their reduction requires decreasing the collector-emitter voltage during a conduction state; this is only possible by technological procedures during the manufacture of IGBTs. It is worth underlining that the junction temperature can have a significant influence on the value of these losses.

The switching losses occur during both the transistor turn-on and turn-off processes and they depend on the following parameters: the voltage supplying the given three-phase VSI, the load current, and the dynamic parameters of the given IGBT; these parameters depend in varying degrees on the junction temperature and on the resistance in the gate-driver circuit. The switching losses can be reduced by use of soft switching methods [3, 4]. In these methods, the transistor current or the collector-emitter voltage should be close to zero during the turn-on and turn-off processes.

On the one hand, the pursuit of the reduced losses is to increase the efficiency of power electronic inverters; on the other hand, less switching losses should lead to an improvement of cooling conditions of IGBTs. Fulfillment of the second requirement is often more important than improvement of the efficiency, especially in medium and high power inverters – this has significant meaning when inverters operate with pulse width modulation (PWM). The determination of a transistor cooling method requires calculations, among others, the switching losses, which are one of the components of the heat source in any transistor thermal model.

2. Switching losses in insulated gate bipolar transistors

Total power losses in IGBTs are the sum of the conduction losses P_{con} and the switching losses P_{sw}. The first loss component is frequently described as follows:

$$P_{con} = \frac{1}{T_p} \int_0^{t_{con}} i_C(t)\, u_{CEsat}(t)\, dt \tag{1}$$

where:

T_p – switching period,
$i_C(t)$ – collector current,

$u_{CEsat}(t)$ – collector-emitter voltage during transistor conduction,
t_{con} – transistor conduction time.

The transistor conduction time t_{con} depends on the applied control method of the given electronic power device. The collector-emitter voltage during transistor conduction is a non-linear function of the transistor current. On average, this voltage is within the range of 1.5 V to 2.5 V. Scientific research and technological attempts tend to decrease the collector-emitter voltage during transistor conduction. In recent years, constructing injection-enhanced gate transistors has succeeded in significantly reducing this voltage to 1.3 V. It is worth underlining that in some cases, integrated gate commutated thyristors (IGCTs) are used instead of the IGBTs [5]. The conduction losses occurring in the freewheeling diodes can be estimated similarly to the transistor losses, but in this case, the diode conduction time depends on the switching moments of the IGBTs. The diode voltage during conduction intervals is higher than the voltage of typical silicon diodes, and it can even be equal to 2.0 V.

Quite often, the problem of switching losses in IGBTs is considered on the basis of different test circuits without taking into account a specific power electronics device [6–8]. However, estimation of total switching losses in electronic power converters, especially in voltage source inverters, should be carried out whilst taking into account an applied circuit of overvoltage protection. Most frequently, this protection circuit consists of a capacitor, resistor, and fast diode, but these elements can be connected in two ways; both versions of the overvoltage protection circuit (RDC snubber) are shown in Figs. 1 and 2 [9–11]. It is necessary to stress that the chosen protection circuit can significantly influence the switching processes of the IGBTs and thereby affects the switching losses. Total switching losses in VSIs also depend on losses in resistors of the gate-driver circuits, and on losses relating to the occurrence of parasitic inductances in the DC supply circuit.

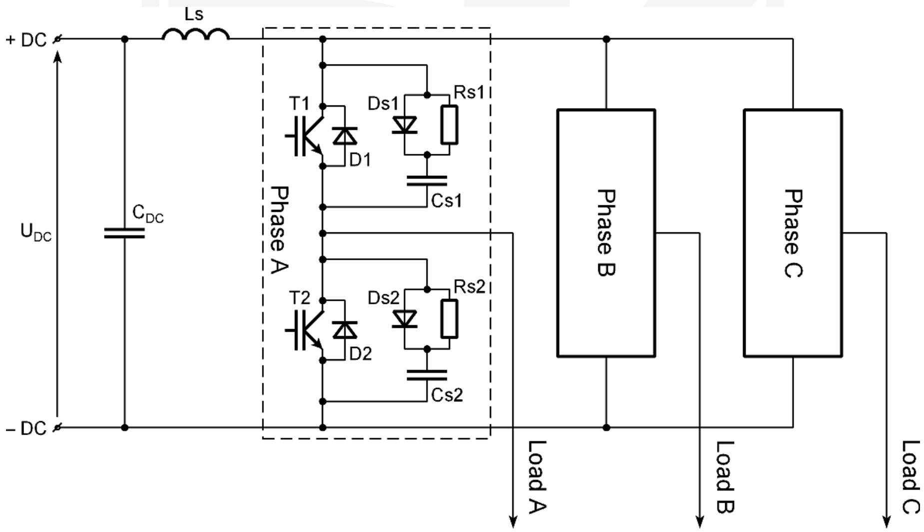

Fig. 1. The first type of RDC snubber in the three-phase VSI

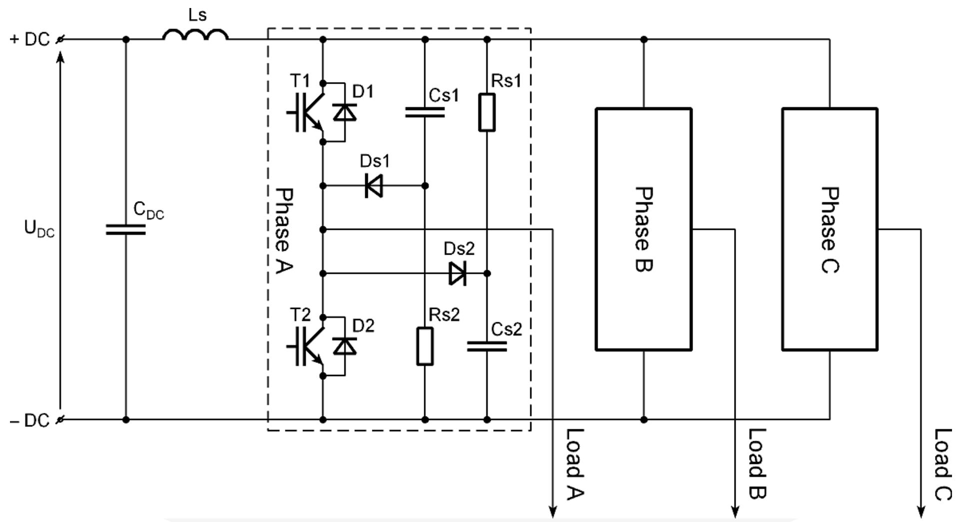

Fig. 2. The second type of RDC snubber in the three-phase VSI

The switching losses depend not only on the collector current and supplying voltage, but their value significantly depends on the change time of the transistor current and voltage during the turn-on and turn-off processes. In order to estimate switching losses, real waveforms of the transistor voltage and current should be approximated by appropriate time functions. In some papers [8, 12], these waveforms are heavily idealized, and the switching processes are considered in several time intervals. However, datasheets do not usually contain all of the required parameters, e.g. duration of individual intervals, values of currents or voltages in the border between some individual time intervals etc. In the presented paper, we assume that the simplified waveforms of transistor currents and voltages have shapes as is shown in Fig. 3. In this Figure, t_r denotes the so-called rise time – this is the time when the collector current rises to 10% of the maximum value at the IGBT turn-on process and when the collector-emitter voltage drops to 10% of the maximum value. The fall time t_f is the time when the collector current drops from 90% to 10% of the maximum value during the turn-off process. These times vary significantly with respect to the turn-on and turn-off times, denoted as t_{on}, and t_{off}, respectively.

It is necessary to stress that the rise time t_r depends significantly on the collector current, and this time increases as the collector current increases. In turn, we can assume that the fall time t_f has very little dependence upon the collector current. It is worth underlining that the resistance of the gate-driver circuit strongly influences the value of the rise time t_r, so the value of this resistance should be taken into account in the determination of this time.

As is shown in Fig. 3, a certain current overshoot appears during the transistor turn-on process. This overshoot is caused by the reverse recovery current of the freewheeling diode of the transistor T2 (Figs. 1 and 2) in the given phase branch [12]. This type of current overshoot also occurs when the overvoltage protection (snubber) presented in Fig. 1 is applied

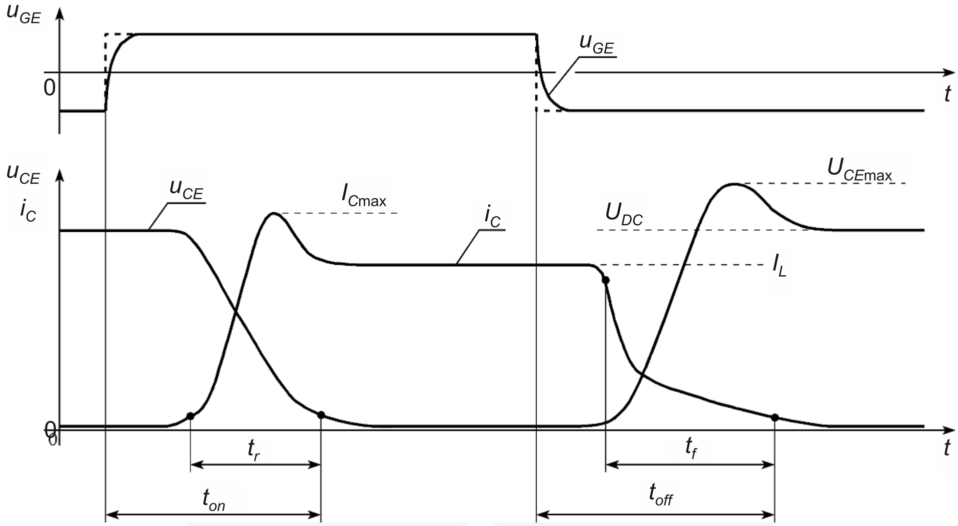

Fig. 3. Simplified waveforms of the transistor current i_C, the collector-emitter voltage u_{CE} during the turn-on and turn-off processes; u_{GE} denotes the gate-emitter voltage

in the given VSI. When the transistor T1 is turned-on, the capacitor Cs1 discharges by the resistor Rs1 and by the conducting transistor T1. Therefore, the current of this transistor during the turn-on process is the sum of the load current, the reverse recovery current of the second freewheeling diode D2, and the discharging current of the capacitor Cs1. In the turn-off process, a voltage overshoot occurs which is caused by occurring a certain parasitic inductance Ls in the DC supply circuit (Figs. 1 and 2) – this is further described in section 3.

The transistor current and voltage do not abruptly change their values during switching processes. Therefore, in these processes, average power losses can be determined as an integral of the product of these values. Both the current and the voltage of the given transistor can vary differently during the switching processes. Therefore, switching losses in the turn-on process and losses in the turn-off process per one switching period should be determined separately:

$$P_{sw} = \frac{1}{T_p}\left(\int_0^{t_r} i_{Cr}(t)\, u_{CEr}(t)\, dt + \int_0^{t_f} i_{Cf}(t)\, u_{CEf}(t)\, dt\right) \tag{2}$$

where:

- $u_{CEr}(t)$ – collector-emitter voltage during the turn-on process,
- $u_{CEf}(t)$ – collector-emitter voltage during the turn-off process,
- $i_{Cr}(t)$ – collector current during the turn-on process,
- $i_{Cf}(t)$ – collector current during the turn-off process,
- t_r – current rise time in the turn-on process,
- t_f – current fall time in the turn-off process.

Switching losses in one period of the output voltage are the sum of the switching losses in the individual switching intervals. In most cases of turn-on processes, it can be assumed that the transistor current and voltage are linear time functions:

$$i_{Cr}(t) = \frac{I_{C\max}}{t_r} t, \quad u_{CEr}(t) = -\frac{U_{DC}}{t_r} t + U_{DC} \tag{3}$$

where:

$I_{C\max}$ – maximum value of the collector current,
U_{DC} – voltage of a power supply source.

The maximum value $I_{C\max}$ of the collector current in the turn-on process is the sum of the load current I_L and the reverse recovery current $I_{rr\max}$ of the freewheeling diode when the second transistor in the given phase of the VSI is turning-off. It is necessary to stress that the load current I_L is different in each switching interval. The discharge current of the snubber capacitor has a certain influence on the maximum value of the collector current, but it refers only to the case in which the snubber shown in Fig. 1 is applied. After integration, we obtain the last relationship describing the average losses in the turn-on process:

$$P_{\text{on}} = \frac{1}{6} f_p U_{DC} I_{C\max} t_r \tag{4}$$

where:

f_p – switching frequency.

In waveforms of the collector current in the turn-off process, we can observe two characteristic intervals [13, 14]. In the first, the collector current decreases quite rapidly. When this current reaches a value of about 30 percent of the initial current value, the collector current decreases to zero much slower. The most common datasheets do not contain the time value at which the collector current changes its derivative. Therefore, we propose to approximate the collector current changes by means of the exponential function in the form:

$$i_{Cf}(t) = I_L e^{-\frac{t}{\tau_f}} \tag{5}$$

where:

τ_f – time constant of the collector current decrease during the turn-off process.

On the basis of the definition of the fall time t_f, we can write the following relationship:

$$0.1 I_L = 0.9 I_L e^{-\frac{t_f}{\tau_f}} \tag{6}$$

hence the time constant τ_f is equal to 0.46 t_f.

The maximum value of the collector-emitter voltage $U_{CE\max}$ in the turn-off process is equal to the voltage of the snubber capacitor Cs1 (Figs. 1 and 2), thus, the voltage $U_{CE\max}$ can be written as the sum $U_{DC} + U_{ad}$, wherein the latter voltage is approximately equal to $I_L \sqrt{\text{Ls}/\text{Cs1}}$. When we take into account formula (5) and we assume that the collector--emitter voltage is a linear time function in the turn-off process, the switching losses can be estimated with the use of the formula:

$$P_{\text{off}} = 0.135 f_p I_L U_{CE\max} t_f \tag{7}$$

Relationships (4) and (7) allow us to estimate the switching losses of one transistor in one switching period.

3. Other switching losses in three-phase voltage source inverters

The total switching losses in VSIs also include losses relating to the turn-off process of the freewheeling diodes, losses occurring in the resistors of the gate-drive circuits and losses which concern magnetic energy related to the parasitic inductances of the DC supply circuit.

Switching losses which occur in the freewheeling diodes during their turn-off processes cannot be neglected in estimation of the total switching losses in VSIs. When the collector current of the turning-on transistor (T1 in Fig. 1 or in Fig. 2) reaches the value of the loads current, the turn-off process of the freewheeling diode D2 begins. The reverse recovery current of the diode D2 flows though the transistor T1; additionally, it increases the switching losses in this transistor. Simplified waveforms of the current and voltage of the freewheeling diode are shown in Fig. 4 [1, 12, 13].

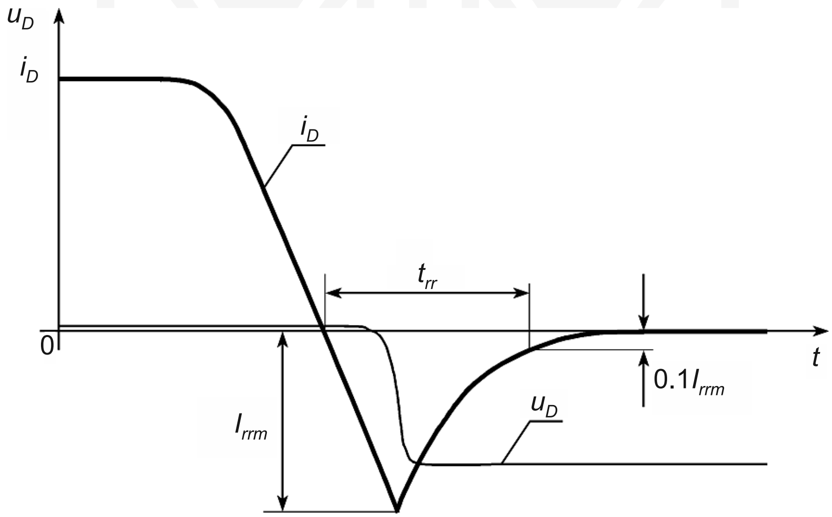

Fig. 4. Simplified waveforms of the current and voltage of the freewheeling diode

Manufacturers of IGBTs do not specify time intervals when the reverse recovery current decreases from the maximum value I_{rrm} to zero. Assuming that this time interval is approximately equal to half of the time t_{rr}, the switching losses in the freewheeling diode can be estimated with the use of the formula:

$$P_{Drr} = \frac{1}{4} f_P I_{rrm} U_{DC} t_{rr} \tag{8}$$

where:

I_{rrm} – maximum value of the reverse recovery current,
t_{rr} – reverse recovery time.

When any transistor, e.g. T1, is turning-off, the magnetic energy related to the parasitic inductance Ls of the DC supply circuit is stored in the snubber capacitor C1, and its voltage rises above the DC voltage. Next, this capacitor discharges through the snubber resistance Rs1 and the DC source to the DC voltage. A certain part of the energy stored in the capacitor C1 is returned to the DC source, and a certain energy part is dissipated in the snubber resistance Rs1. Estimation of the energy stored in the snubber capacitor is not easy because the accurate determination of the parasitic inductance is a quite difficult task. Some authors have assumed that this inductance, which depends strongly on the construction of the given converter, is equal to a few dozen of nH [1, 8], but this value can be even equal to a few hundred of nH. Approximate calculations carried out for the parasitic inductance 100 nH have shown that the switching losses related to the parasitic inductance of the DC circuit are less than 0.2% with respect to the total switching losses.

Power losses related to the switching processes also occur in resistances of the transistor gate-drive circuits. Due to the existence of the parasitic capacitances in IGBTs, especially the capacitance between the transistor gate and its emitter, short current pulses occur during transistor switching processes. The current in the gate-drive circuit decreases aperiodic to zero due to the resistive-capacitive character of this circuit, so the switching losses in the gate resistance can be estimated by using the following formula (two switching processes occur in one switching period):

$$P_{RG} = 4 f_P U_G^2 C_{GE} \tag{9}$$

where:

U_G – output voltage of IGBT drivers (usually ± 15 V),
C_{GE} – gate-emitter parasitic capacitance.

4. Switching losses in three-phase voltage source inverters

The character of switching process depends, first of all, on the inverter control method and on the additional circuit which protects IGBTs against overvoltages. When the snubber presented in Figure 1 is applied in the VSI, then the capacitor voltage is equal to zero when the given transistor is in the conduction state. Therefore, the turn-off process has a soft character because the capacitor voltage cannot change its value abruptly. Thus, this process occurs at almost zero voltage. In cases when the second RDC snubber is applied, the capacitor voltage is always higher than zero.

4.1. Losses in inverters generating output voltage in the form of a rectangular wave

When the given VSI operates with the use of the so-called six-step modulation, each transistor is controlled for the conduction state through one half of the period of the output voltage. In this case, the phase-to-phase output voltage has a rectangular shape. After the turn-off process of the transistor T2, the turn-on process of the T1 transistor occurs. At the same time, a discharging process of the C1 capacitor begins. The load current of phase A flows through the diode D1 in a certain time interval. If the capacitor discharging the current is less than the load current in phase A, then the discharging current flows through the D1 diode, the resultant current of which is the difference of the load current and the capacitor discharging current. When the load current reaches a value of zero, the transistor T1 begins to conduct the load current of phase A – this means that the turn-on process of the transistor T1 has a soft character because this process occurs with the zero current of this transistor.

In three-phase VSIs with the first type of protection circuit, both switching processes have a soft character. Thus, the switching losses in IGBTs can be neglected. Losses associated with the switching processes refer to dissipation of the capacitor energy in the snubber resistance R_s, and they can be described by the following relationship:

$$P_{Rs} = \frac{1}{2} f_{\mathrm{out}} C_s U_{DC}^2 \tag{10}$$

where:

C_s – capacitance of the snubber capacitor,
f_{out} – frequency of the output voltage.

In some VSIs, the overvoltage protection circuit has the form as is presented in Fig. 2. The capacitor voltages are equal to the supplying voltage, independently on the transistor operation state. As previously, the turn-on process has a soft character, but due to the capacitor voltage, the transistor turn-off process is hard. In this case, power losses in the transistor depend on the current value I_{Coff} at the beginning of the turn-off process and they can be estimated with the use of the formula:

$$P_{\mathrm{off}} = \frac{1}{6} f_{\mathrm{out}} U_{DC} I_{C_{\max}} t_f \tag{11}$$

The power losses calculated for the whole VSI should be multiplied by 6. It is necessary to underline that in this control method, each transistor is turned-on and turned-off only once in the period of the VSI output voltage. Therefore, switching losses are relatively small in respect to the conduction losses, so the switching losses can be neglected in the calculation of the inverter efficiency. For example, power losses were calculated for two chosen VSIs with the assumption that these inverters generated an output voltage in the form of the rectangular wave and that they have the first type of RDC snubber (Fig. 1). Nominal parameters of these inverters are presented in Table 1 – I_{LRMS} denotes the root mean square value of the load current.

Table 1

Parameters of two chosen voltage source inverters

P_N [kW]	U_{DC} [V]	I_{Cmax} [A]	I_{LRMS} [A]	R_G [Ω]	t_{on} [μs]	t_r [μs]	t_{off} [μs]	t_f [μs]	t_{rr} [μs]	I_{rr} [A]	C_{GE} [nF]
11.0	490	24.0	9.90	6.30	0.073	0.023	0.71	0.50	0.12	4	10
100	480	600	106	0.52	0.60	0.17	1.20	0.11	0.20	300	41
				5	1.00	0.50	1.60	0.11	0.19	260	

The capacitances of the RDC snubbers of these inverters were respectively equal to 86, and 68 nF. In the considered case of the inverter control method, power losses occurred mainly in the resistance of the snubber, and for a frequency of 50 Hz, these losses were about 0.03 W for the first inverter and 0.78 W for the second.

4.2. Switching losses in VSIs with the Pulse Width Modulation

The switching losses have a significant value in VSIs, which are controlled with the use of pulse width modulation (PWM), especially when the switching frequency equals a dozen or so kHz. It is understood that the greater the inverter nominal power is, the lower the switching frequency, but the inverter nominal current rises. This case occurs, first of all, in inverters of medium and high nominal power. As previously, the switching losses strongly depend on the type of RDC snubber. When the given VSI is protected by means of the snubber presented in Fig. 1, the transistor turn-off process has a soft character, but keeping in mind that the snubber capacitor should itself discharge to zero before the next transistor turn-off process begins. Figure 5 shows, for example, the waveforms of the transistor voltage, transistor current, and actual value of the power losses which were measured in a laboratory voltage source inverter.

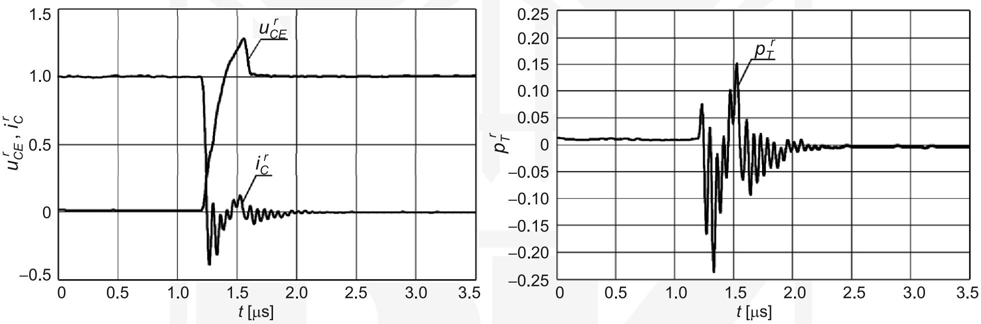

Fig. 5. Waveforms of relative values of transistor voltage, the transistor current and power losses during the turn-off process; reference voltage – 150 V; reference current – 16 A; and reference power – 2.5 kW

The turn-on processes of the IGBTs in inverters have a hard character. In turn, Figure 6 shows waveforms of the transistor voltage, the transistor current and power losses during the turn-on process. When the transistor is turning-on, then its current is equal to the sum of the load current, the current of the capacitor discharging, and of the freewheeling diode reverse recovery current of the second transistor in the given phase of the VSI.

Power losses occurring in the turn-on process depend strongly on the load current. For simplicity, it was assumed that the load current has a sinusoidal shape. Assuming that switching moments occur at equal time intervals, the value of the transistor switching current in the k-th switching interval can be determined as follows:

$$i_L(k) = I_{L\max} \sin\left(k \frac{2\pi}{m_f}\right) \tag{12}$$

where:

k – switching number in a half period of the output voltage,

$I_{L\max}$ – amplitude of the first harmonic of the load current.

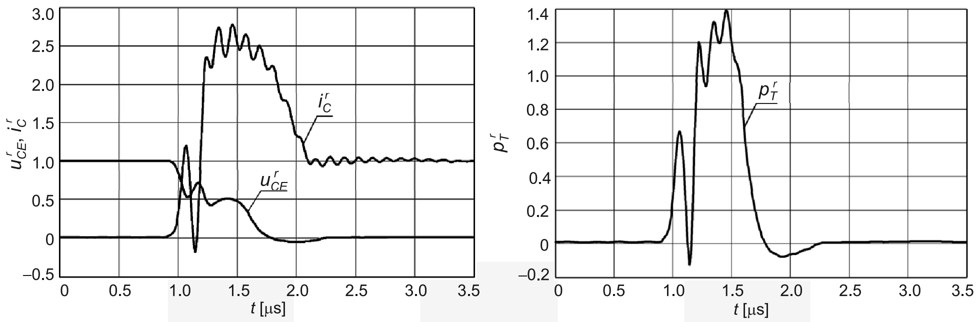

Fig. 6. Waveforms of relative values of the transistor voltage, the transistor current and power losses during turn-on process: reference voltage – 150 V; reference current – 16 A; reference power – 2.5 kW

Thus, the turn-on losses in IGBTs which are caused by the load current can be estimated with the use of the formula:

$$P_{\text{on}} = \frac{1}{6} f_{\text{out}} U_{DC} t_r I_{L\max} \sum_{k=1}^{\frac{m_f}{2}} \sin\left(k\frac{2\pi}{m_f}\right) \tag{13}$$

In the case when the snubber shown in Fig. 1 is applied in the given VSI, these losses are a little higher due to the capacitor discharge current flowing through turning-on transistor.

The turn-off losses in IGBTs depend on the type of snubber. These losses are close to zero when the snubber presented in Fig. 1 is applied. In the case when the second snubber is applied, the turn-off losses in IGBTs can be estimated by means of the following relationship (using the formula (7) and (12)):

$$P_{\text{off}} = 0.135 f_{\text{out}} t_f I_{L\max} \sum_{k=1}^{\frac{m_f}{2}} \left[\sin\left(k\frac{2\pi}{m_f}\right)\left(U_{DC} + \sqrt{\frac{L_S}{C_S}} I_{L\max} \sin\left(k\frac{2\pi}{m_f}\right)\right)\right] \tag{14}$$

A comparison of the switching losses was carried out for two previously selected voltage source inverters. Calculations of switching losses were performed for two switching frequencies which were equal to 3 kHz and 6 kHz. It was assumed that the parasitic inductance of the DC supply circuit was equal to 100 nH. Individual types of switching power losses are presented in Table 2 and in Table 3. In the first case, the switching losses in IGBTs are equal to the losses occurring in the turn-on process because the turn-off losses are close to zero due to the applying of the snubber which is shown in Fig. 1. The switching losses related to the parasitic inductance of the DC circuit are less than 0.002 W and 0.25 W for the 11 kW and 100 kW VSI, respectively.

Table 2

Switching power losses in voltage source inverters in W Snubber shown in Fig. 1

Switching frequency	3 kHz			6 kHz		
VSI nominal power	11 kW	100 kW		11 kW	100 kW	
Gate resistance	6.3	0.52	5	6.3	0.52	5
Total switching losses in IGBTs	0.19	35.03	93.88	0.39	70.11	187.89
Total switching losses in freewheeling diodes	1.06	129.6	106.70	2.11	259.2	213.41
Total losses in all snubbers	64.82	62.20	62.20	129.66	124.42	124.42
Losses in resistances of gate-driver circuits	0.162	0.66	0.66	0.32	1.33	1.33
Total other losses in inverter	66.05	192.57	169.68	132.10	385.15	339.36
Total switching losses in inverter	66.24	227.61	263.56	132.49	455.27	527.25

Table 3

Switching power losses in voltage source inverters in W Snubber shown in Fig. 2

Switching frequency	3 kHz			6 kHz		
VSI nominal power	11 kW	100 kW		11 kW	100 kW	
Gate resistance	6.3	0.52	5	6.3	0.52	5
Turn-on losses in all IGBTs	0.19	35.03	93.88	0.39	70.11	187.89
Turn-off losses in all IGBTs	2.57	8.29	8.29	5.01	16.13	16.13
Total switching losses in IGBTs	2.73	43.32	102.17	5.40	86.25	204.02
Total switching losses in freewheeling diodes	1.06	129.60	106.70	2.12	259.20	213.41
Total losses in all snubbers	0.047	5.40	5.40	0.0911	10.46	10.46
Losses in resistances of gate-driver circuits	0.162	0.66	0.66	0.32	1.33	1.33
Total other losses in inverter	1.27	135.77	112.88	2.53	271.20	225.41
Total switching losses in inverter	4.03	179.09	215.04	7.93	357.45	429.42

5. Conclusions

In total switching losses in VSIs, the switching losses occurring in IGBTs have a significant share, but the amount of these losses depends strongly on the applied type of the overvoltage protection circuit. However, the influence of this circuit on the switching losses in IGBTs decreases with increases in the VSI nominal power. When the first type of overvoltage protection is applied, the switching losses in IGBTs are less than in the case when the second type of the protection circuit is used, especially for VSIs of relatively small nominal power ratings.

It is necessary to stress that power losses occurring in freewheeling diodes should be taken into consideration, because the reverse recovery time of these diodes is comparable to the switching times of IGBTs and the amount of these losses is comparable to losses in IGBTs. On the other hand, the switching losses occurring in gate resistances and losses related to the parasitic inductance of the DC supply circuit can be neglected because their share in the total switching losses are less than 1 per cent.

Switching losses in inverters generating output voltage in the form of the rectangular wave depend directly proportional on the frequency of the output voltage; in this case, the output voltage frequency is the same as the switching frequency of IGBTs. When inverters operate with the pulse width modulation, the total switching losses do not practically depend on the frequency of the output voltage and these losses depend directly on the switching frequency (usually frequency of a saw-tooth wave), which should be many times higher than the output voltage frequency.

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