Soft-Switching System With Safe Connections of Capacitors and Inductors in Three-Phase Two-Level Voltage Source Inverter

Witold Mazgaj, Zbigniew Szular, and Bartosz Rozegnał

***Abstract*—This article presents a new soft-switching system for three-phase two-level voltage source inverters. In this system, capacitors are not connected in parallel to the main transistors, and inductors are not connected in series with the auxiliary transistors. Avoiding these types of connections protects the inverter transistors against damage in cases of disturbances in the inverter control system. The control algorithm of the main transistors of the inverter is the same as that of the transistors of an inverter operating with the hard-switching technique because the auxiliary transistors are switched depending on the operation state of the main transistors. The structure and operation principles of the new soft-switching solution are comprehensively described herein. Additionally, the control algorithm and the principles for selecting the elements of the new soft-switching circuits are discussed. The validity of the system operation was verified by performing laboratory tests with a three-phase voltage source inverter (3 kW, 250 V, 12 A, and 3 kHz) supplying an inductive-resistive load or a squirrel cage induction motor, whereas numerical calculations were performed for inverters with a higher rated power. The switching losses of the inverter operating with the proposed soft-switching solution were compared with those of an inverter operating with the hard-switching technique. The proposed soft-switching system increases the inverter efficiency, especially with medium- and high-rated powers.**

***Index Terms*—Soft-switching, switching losses, voltage source inverter (VSI), ZCZVS converter.**

I. Introduction

A. Losses in Inverter Transistors

INSULATED-GATE bipolar transistors (IGBTs) and their freewheeling diodes are the main components of voltage source inverters (VSIs). Accordingly, their losses have the most significant influence on the efficiency of such inverters. The power losses occurring in transistors can be classified into conduction and switching losses [1]–[4]. The conduction losses depend mainly on the current and voltage drop across a given transistor during its conduction. The estimation of the switching losses becomes particularly important when VSIs operate with pulsewidth modulation (PWM) at high power ratings because the switching losses often exceed the conduction losses at frequencies of several kilohertz. The losses occurring in the freewheeling diodes, similar to the transistor losses, can be classified into conduction and switching losses. The losses in the overvoltage protection systems and in the resistances of the transistor gate circuits have a significantly smaller impact on the inverter efficiency.

B. Soft-Switching Solutions in Three-Phase VSIs

The soft-switching systems cause the transistor current or voltage during the switching processes to become close to zero. This aim is generally achieved through the resonant phenomena occurring in the additional circuits included in the structure of the typical three-phase VSI. In most solutions, some connections between the transistors and capacitors or inductors can stop the inverter operation or even damage semiconductor elements when the control disturbances appear. The soft-switching solutions in the three-phase VSIs can be classified into group soft-switching systems and systems that support the switching of transistors individually in each phase. The first type includes solutions having a single soft-switching system for all inverter transistors [5]–[11]. A significant advantage of these systems is the requirement of a small number of additional elements, whereas the disadvantages are a rather complex control algorithm and a narrow range of frequency variations of the inverter output voltage.

In most phase soft-switching systems, each phase of a three-phase inverter is equipped with additional circuits containing two auxiliary transistors, one or two inductors, and two capacitors, usually connected in parallel to the main transistors of the inverter [12]–[18]. In case of disturbances in the control system of the inverter operating with a certain phase soft-switching solution, turning ON one of the main transistors at a nonzero voltage of the capacitor leads to a sudden discharge of this capacitor through the main transistor, which can also cause damage. However, one of the auxiliary transistors may be turned OFF at a nonzero current of the inductor connected in series with this transistor; consequently, an overvoltage appears, which may be dangerous to this transistor [13], [16].

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Magnetic couplings between circuits containing the main transistors or auxiliary transistors have been applied in some phase soft-switching methods [13]–[16], [18]. In these proposals, the control algorithm of the auxiliary transistors influences the control of the main transistors. Similarly, due to the parallel connections of the main transistors and capacitors, these transistors may be damaged by a sudden capacitor discharge when the disturbances occur in the control system.

It is necessary to mention the system presented in [12] and [13] while providing an overview of phase soft-switching solutions. There are neither parallel connections between the main transistors and capacitors nor series connections between the inductors and auxiliary transistors. However, the control algorithm of this proposal is complex because the switching processes of the main transistors depend on the operating states of the auxiliary transistors. For a correct operation, the instantaneous value of the load current has to be considered in the control algorithm, which becomes more complicated. Additionally, the time delays between the turn-ON signals of the individual main transistors depend on both the value and direction of the load current.

The inverters with the phase soft-switching solutions are characterized by an operation over a wide range of inverter output voltage frequencies. However, in most existing soft-switching systems, the capacitors are connected in parallel to the main transistors or the inductors are connected in series with the auxiliary transistors. This poses a risk of transistor damage when disturbances occur in the control system. An additional drawback of these systems is the complexity of the control algorithms. Before one of the main transistors is turned ON, the appropriate auxiliary transistor should generally be turned ON at a precisely determined time; however, this operation is very difficult when the inverter operates with PWM. Notably, all the existing phase soft-switching systems have at least six additional auxiliary transistors. However, the losses occurring in these transistors account for a small portion of the losses generated in the main transistors of VSIs operating without soft-switching solutions.

II. Soft-Switching System With Safe Connections of Capacitors and Inductors

A. Structure and Operation Principles

The new soft-switching solution proposed in this article is a phase soft-switching system applied in three-phase VSIs. This system does not have the above-mentioned drawbacks of the existing soft-switching solutions and the control algorithm of its transistors is significantly simpler in comparison with other control algorithms. It is assumed that the control signals of the auxiliary transistors depend on the operating states of the main transistors, not vice versa, which is the case in most phase soft-switching methods. The structure of the new soft-switching solution in the three-phase VSI is shown in Fig. 1 [19], [20].

The use of capacitors is intended to reduce the steepness of the increase in the main transistor voltage during the turn-OFF processes. The basic role of the inductors connecting the main transistors with the terminals of the voltage source is to limit the rate of the current rise of these transistors during their turn-ON

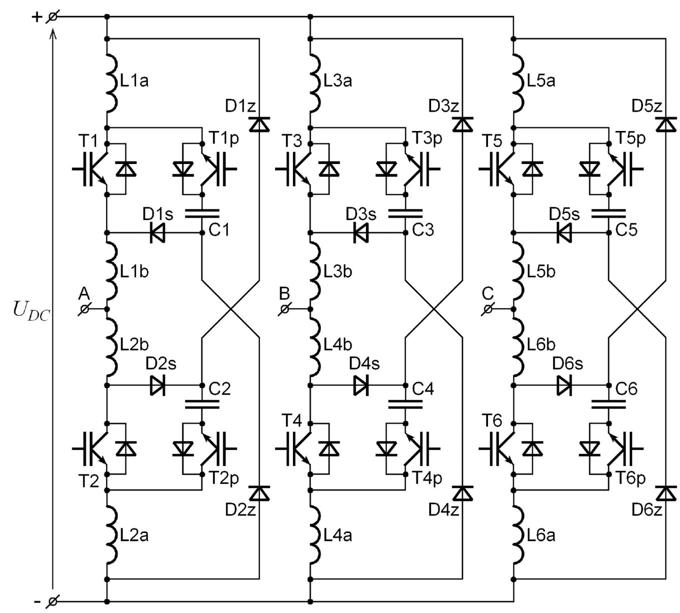


Fig. 1. Proposed soft-switching system with safe connections of the capacitors and inductors in a three-phase inverter [19], [20].

processes. The inductors connecting the main transistors with the load terminals prevent sudden capacitor discharge through both the voltage source and the main transistors after the auxiliary transistors are turned ON.

B. Working Stages

The operation principles of the new phase soft-switching solution are described for one working cycle. To simplify this description, the load current I_L is assumed to be constant in all the considered working states. Fig. 2 shows the simplified waveforms.

At the beginning of the discussed working cycle, transistor $T1$ conducts the load current and the other transistors are in a nonconduction state. Capacitor $C1$ is discharged, and the load current I_L flows from the positive terminal of the voltage source U_{DC} through inductor $L1a$, main transistor $T1$, and inductor $L1b$ to load phase A. The circuit with the current is denoted by a bold line in Fig. 3(a).

Stage t_1–t_2: As shown in Fig. 3(b), at time t_1, transistor $T1$ is turned OFF. Its current decreases to zero immediately, whereas its voltage increases slowly from zero due to the charging process of capacitor $C1$. The voltage of transistor $T1$ is close to zero during the turn-OFF process. Therefore, it can be stated that the main transistor $T1$ is turned OFF softly. A constant load current I_L (in a given operation cycle) flows through capacitor $C1$, causing it to charge

$$u_{C1}(t) = \frac{I_L(n)}{C_1}\, t \tag{1}$$

where $u_{C1}(t_1) = 0$ and n denotes the number of the given switching cycle. This operating stage lasts until the voltage of capacitor $C1$ reaches the supply voltage U_{DC}. The duration of this process depends on the load current $I_L(n)$.

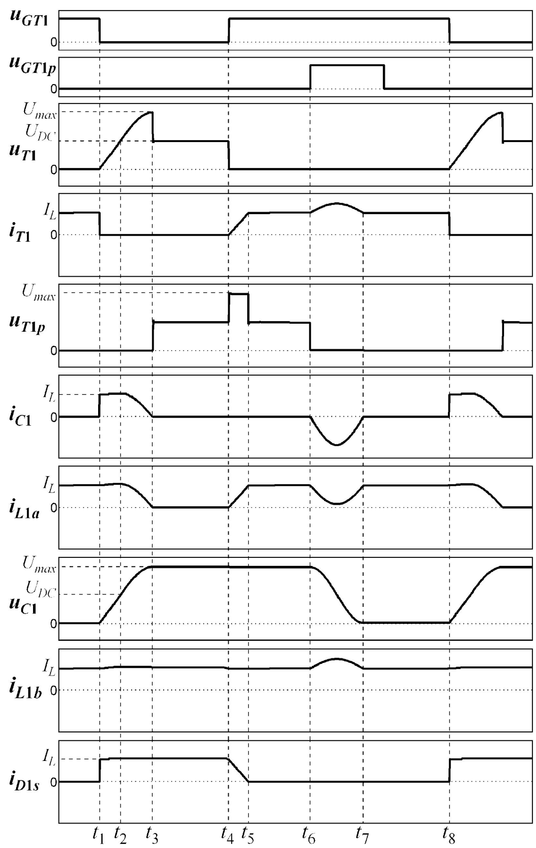


Fig. 2. Simplified waveforms in one phase of the new soft-switching solution: u_{GT1} and u_{GT1p} are the control signals of transistors $T1$ and $T1p$, respectively; i_{T1} and u_{T1} are the current and voltage of transistor $T1$, respectively; u_{T1p} is the voltage of transistor $T1p$; i_{C1} and u_{C1} are the current and voltage of capacitor $C1$, respectively; i_{L1a} and i_{L1b} are the currents of the inductors $L1a$ and $L1b$, respectively; i_{D1s} is the current of diode $D1s$; I_L is the load current.

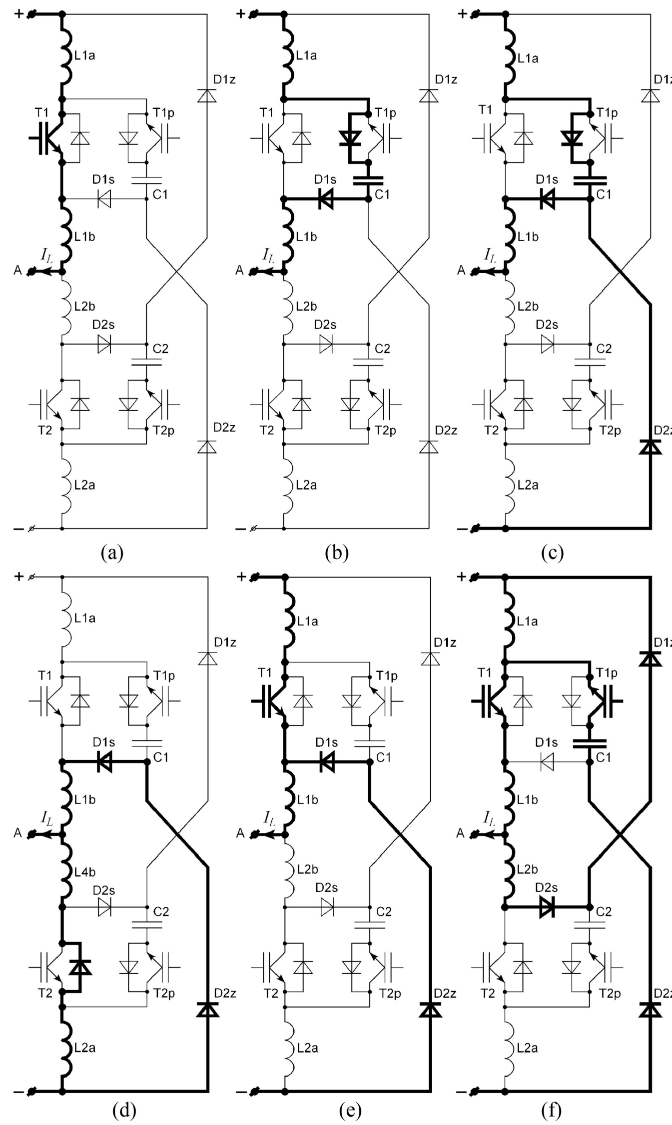


Fig. 3. Operation stages of the proposed soft-switching system; I_L is the load current.

When the load current is small relative to its rated value, the charging time of capacitor $C1$ until reaching the voltage U_{DC} may be longer than the assumed deadtime. However, at small load currents, capacitor $C1$ will not be discharged to zero. In some cases, after transistor $T1$ is turned OFF, a certain current may flow through $L2b$, $T2$, and $L2a$. This current decreases to zero because the load current during the nonconduction state of transistor $T1$ flows through diodes $D2z$ and $D1s$ and inductor $L1b$. Due to the occurrence of voltage drops across these elements, a certain current begins to flow from the minus clamp of the dc source through inductor $L2a$, the freewheeling diode of transistor $T2$, and inductor $L2b$ to the load phase A. To eliminate such operation cases, transistor $T2$ should not be turned ON for the assumed direction of the load current, and similarly, transistor $T1$ should not be turned ON for the opposite current direction. It is possible when both the main transistors $T1$ and $T2$ are switched if the load current I_L meets the condition $-w\ I_{L\max} < I_L < w\ I_{L\max}$, where w denotes the ratio of an individually selected threshold current value with respect to the maximum value $I_{L\max}$ of the load current; so, in this case, it would require measuring the phase load current. This threshold current can range from a few to several percent of the current $I_{L\max}$. However, the current flowing through $L2b$, $T2$, and $L2a$ is relatively small, so the power losses caused by the flow of this current do not significantly affect the efficiency of the inverter.

Stage t_2–t_3: As shown in Fig. 3(c), at time t_2, the voltage of capacitor $C1$ reaches the supply voltage U_{DC}. Then, the load current I_L starts to flow partially from the minus clamp of the voltage source through diode $D2z$, and simultaneously, the value of the capacitor current decreases. The capacitor is resonantly charged to a voltage higher than U_{DC}. The changes in the capacitor voltage are expressed by the following equation:

$$C_1 L_{1a} \frac{d^2 u_{C1}(t)}{dt^2} + u_{C1}(t) = U_{\mathrm{DC}} \tag{2}$$

where $u_{C1}(t_2) = U_{\mathrm{DC}}$ and $i_{C1}(t_2) = I_L(n)$. The duration of this process is equal to one-fourth of the oscillation period of the circuit containing capacitor $C1$ and inductor $L1a$. The changes in the voltage and current of capacitor $C1$ in this stage are expressed by the following relationships:

$$u_{C1}(t) = U_{\mathrm{DC}} + \sqrt{\frac{L_{1a}}{C_1}} I_L(n) \sin\left(\frac{t}{\sqrt{C_1 L_{1a}}}\right) \tag{3}$$

$$i_{C1}(t) = I_L(n) \cos\left(\frac{t}{\sqrt{C_1 L_{1a}}}\right). \tag{4}$$

The maximum voltage of capacitor $C1$ in the given switching cycle is

$$U_{C1\max}(n) = U_{\mathrm{DC}} + \sqrt{\frac{L_{1a}}{C_1}} I_L(n). \tag{5}$$

The current flowing through diode $D2z$ is the difference between the load current (constant in the switching cycle under consideration) and the current of capacitor $C1$. Notably, in the time interval t_1–t_3, the voltage of the main transistor $T1$ changes, as the voltage of capacitor $C1$ changes. At time t_3, both voltages reach the highest value in the analyzed switching cycle.

Stage t_3–t_4: As shown in Fig. 3(d), at time t_3, the freewheeling diode of the auxiliary transistor $T1p$ ceases to conduct. The voltage of capacitor $C1$ does not change and the voltage of transistor $T1$ decreases rapidly to the supply voltage U_{DC}. The total energy of the magnetic field of inductor $L1a$ is converted to the electric field energy in capacitor $C1$. The load current I_L flows from the minus clamp of the voltage source through the diodes $D2z$ and $D1s$ and inductor $L1b$. A small portion of the load current also flows through inductor $L2a$, the freewheeling diode of main transistor $T2$, and inductor $L2b$. At this stage, the flow of the currents depends on the inductance of the mentioned inductors and their resistances, and the diode conduction voltage drops. In the analyzed time interval, transistor $T1$ is in the nonconducting state. The voltages of the individual elements of the considered phase of the inverter do not change.

Stage t_4–t_5: As shown in Fig. 3(e), the subsequent stage begins at time t_4, when transistor $T1$ is turned ON again. The current of both inductor $L1a$ and transistor $T1$ begins to increase slowly to the load current value. In turn, the current flowing through the diodes $D1s$ and $D2z$ and the current flowing through inductor $L2a$, the freewheeling diode of the main transistor $T2$, and inductor $L2b$ both start to decrease slowly to zero. The changes in the current of the main transistor $T1$ are expressed in this stage by the following equation (neglecting the resistance of inductor $L1a$):

$$L_{1a}\frac{di_{T1}}{dt} = U_{\mathrm{DC}} \tag{6}$$

where $i_{T1}(t_4) = 0$.

The current of the main transistor $T1$ can be calculated using the following linear time function:

$$i_{T1}(t) = \frac{U_{\mathrm{DC}}}{L_{1a}} t. \tag{7}$$

The main transistor $T1$ is turned ON at a current close to zero. Hence, this transistor is considered to turn ON softly.

Stage t_5–t_6: As shown in Fig. 3(a), when the current of transistor $T1$ reaches the load current $I_L(n)$, the current flowing through the diodes $D1s$ and $D2z$, the current flowing through inductor $L2a$, the freewheeling diode of transistor $T2$, and inductor $L2b$ to phase A (of a three-phase load) both reach zero. The flow of the load current is similar to that during the initial operation state but capacitor $C1$ is charged to the highest voltage value in the considered operating cycle. Notably, for the correct operation of the discussed soft-switching solution, the time interval between the turn-ON signals of transistors $T1$ and $T1p$ should not be shorter than the rise time of the current of transistor $T1$ to the load current.

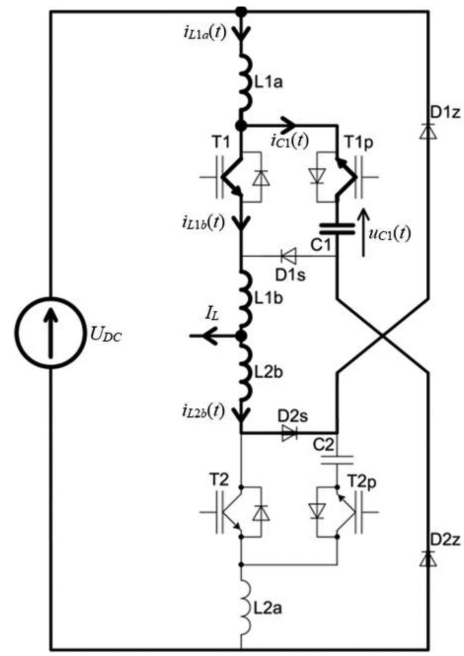


Fig. 4. Distribution of currents in the stage t_6–t_7.

Stage t_6–t_7: As shown in Fig. 3(f), at time t_6, the auxiliary transistor $T1p$ is turned ON. Consequently, capacitor $C1$ starts to discharge resonantly. The capacitor discharges partly through the circuit consisting of the auxiliary transistor $T1p$, inductor $L1a$, the voltage source, and diode $D2z$ and partly through transistors $T1p$ and $T1$, inductors $L1b$ and $L2b$, diodes $D2s$ and $D1z$, the voltage source, and diode $D2z$. During the resonant capacitor discharge, the current of inductor $L1a$ is the difference between the load current I_L and the discharge current flowing through this inductor. On the other hand, the current of inductor $L1b$ is the sum of the load current and the discharge current flowing through this inductor. The distribution of currents in this stage is shown in Fig. 4. The changes in the capacitor voltage and current can be calculated using the following equation:

$$\begin{cases} L_{1a}\frac{di_{L1a}(t)}{dt} + u_{C1}(t) = U_{\mathrm{DC}} \\ L_{1a}\frac{di_{L1a}(t)}{dt} + L_{1b}\frac{di_{L1b}(t)}{dt} + L_{2b}\frac{di_{L2b}(t)}{dt} = 0 \\ i_{L1a}(t) - i_{C1}(t) - i_{L1b}(t) = 0. \end{cases} \tag{8}$$

By solving this system of equations and assuming that $C_1 = C_2 = C, L_{1\,a} = L_{2\,a} = L_a$, and $L_{1\,b} = L_{2\mathrm{b}} = L_b$, the voltage and current of capacitor $C1$ in this stage can be expressed as the following time functions:

$$u_{C1}(t) = U_{\mathrm{DC}}\left(1 + (k-1)\cos(\omega t)\right) \tag{9}$$

$$i_{C1}(t) = -(k-1)U_{\mathrm{DC}}\sqrt{\frac{C(L_a+2L_b)}{2L_aL_b}}\sin(\omega t) \quad (10)$$

where k is the ratio of the maximum capacitor voltage in the chosen switching cycle relative to the voltage U_{DC} and

$$\omega = \sqrt{\frac{L_a+2L_b}{2L_aL_bC}}.$$

The minus sign in relationship (10) indicates that the direction of the capacitor current during its resonant discharge is opposite to the direction marked in Fig. 4.

The maximum values of the auxiliary and main transistor currents are

$$I_{Tp\max} = (k-1)U_{\mathrm{DC}}\sqrt{\frac{C(L_a+2L_b)}{2L_aL_b}} \quad (11)$$

$$I_{T\max} = I_{L\max} + I_{Tp\max}\left(\frac{L_a}{L_a+2L_b}\right) \quad (12)$$

respectively, where $I_{L\max}$ denotes the maximum load current.

The energy stored in capacitor $C1$ is returned to the voltage source. This process ends when capacitor $C1$ is completely discharged. However, at small load currents, the voltage of the capacitor $C1$ during the discharge process decreases to a constant value higher than zero in the given switching cycle, and the mentioned process is finished when the current of the capacitor $C1$ drops to zero. Transistor $T1p$ is turned ON softly due to the resonant nature of its current. When the capacitor voltage decreases to zero, the current of inductor $L1a$ increases linearly to the load current. On the other hand, the current of inductor $L1b$ decreases to the load current and the current of inductor $L2b$ decreases linearly to zero; such current changes occur if $k > 2$.

As capacitor $C1$ is fully discharged, the auxiliary transistor $T1p$ can be turned OFF because its current is zero. Notably, capacitor $C1$ is completely discharged only if its voltage is not less than twice the voltage U_{DC}.

Stage t_7–t_8*:* As shown in Fig. 3(a), the auxiliary transistor $T1p$ is turned OFF after the resonant capacitor discharge. In the considered stage, the current flows through the same circuit as in the initial state. Capacitor $C1$ is discharged to zero. This state lasts until transistor $T1$ is turned OFF again. Notably, the auxiliary transistor $T1p$ has to be turned OFF while the corresponding main transistor $T1$ is turned ON. At time t_8, the main transistor $T1$ is turned OFF again and the subsequent operating cycle begins. The second main transistor $T2$ and the second auxiliary transistor $T2p$ of the considered phase are switched similarly when the load current flows in the opposite direction.

C. Switching Algorithm

It was assumed that the switching of the auxiliary transistors cannot influence the control method of the main transistors. The switching signals of the auxiliary transistors should depend on the operating states of the main transistors, unlike in the existing soft-switching systems. It is worth emphasizing that the control signals of the main transistors are unchanged in relation to the control signals of the VSIs operating without any soft-switching system. Fig. 5 shows the control signals of main transistors $T1$, $T3$, and $T5$ and the signals of the auxiliary transistors $T1p$, $T3p$, and $T5p$.

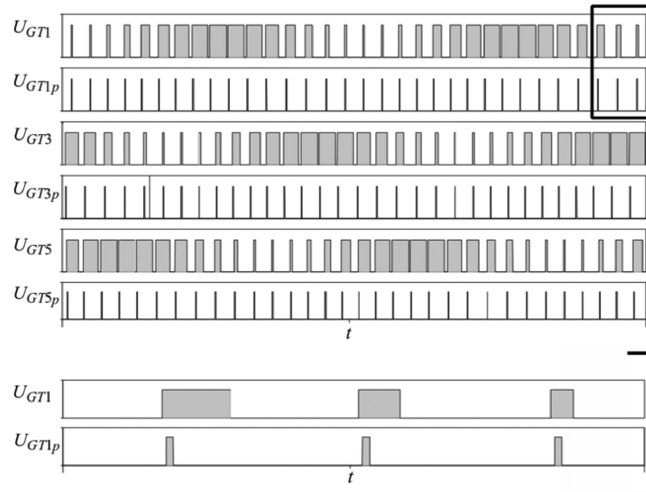


Fig. 5. Switching signals of the transistors $T1$, $T3$, and $T5$ and the corresponding transistors $T1p$, $T3p$, and $T5p$.

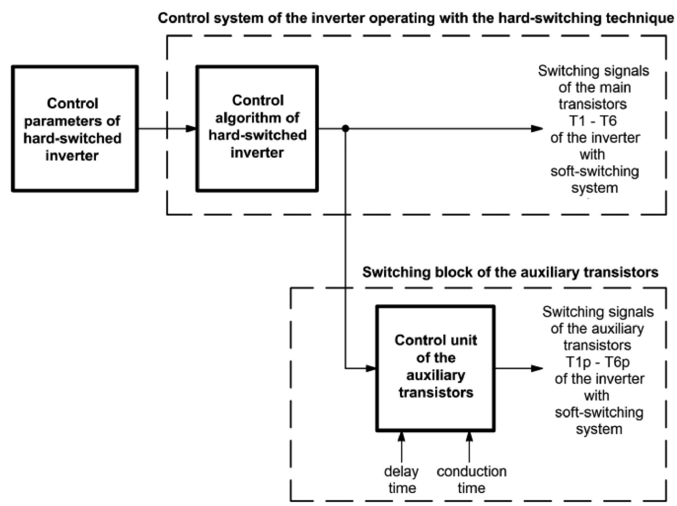


Fig. 6. Block diagram of the control system of the auxiliary transistors.

The auxiliary transistors are turned ON with a slight time delay relative to the turn-ON moments of the corresponding main transistors and can be turned OFF when the capacitors are completely discharged; then, their currents are equal to zero. The signals that turn OFF the auxiliary transistors should be generated no later than the turn-OFF signals of the corresponding main transistors. The correct operation of the given VSI with the discussed soft-switching solution is also possible when the auxiliary transistors are turned OFF at the same time as with the corresponding main transistors. It should be noted, the main transistors of the inverter with the proposed soft-switching system are controlled in the same manner as in the inverter operating with the hard-switching technique, i.e., the structure of the controllers and their parameters remain unchanged for a given load**.** Only the control signals of the auxiliary transistors are additionally generated. Fig. 6 shows a block diagram of the control system with an additional switching block of the auxiliary transistors. Eventual changes in the control parameters, e.g., the modulation depth factor, which depends on the assumed switching frequency, can be introduced in the first block of the control system.

It is worth emphasizing that the switching of the main transistors is independent of the operating states of the auxiliary transistors. This may be significant in electrical drives operating with different vector control methods, where the switching times of the inverter transistors constantly change depending on the current state of the given drive system.

III. Selection of the Soft-Switching Elements

A. Selection of Transistors

Due to the occurrence of the resonant processes, the transistors should be selected for rated voltages higher than the supply voltage U_{DC}. This condition results from the condition of correct system operation. The capacitors of the discussed solution charge to a voltage higher than the U_{DC} after the respective main transistors are turned OFF. The maximum voltage value of the capacitors in a given switching cycle depends on the energy of the magnetic field generated by the inductors $L1a$ and $L2a$. This voltage value appears across the main transistors when the capacitor resonant charging processes are completed. The same voltage value also appears across the auxiliary transistors when the main transistor current is increasing to the load current value.

To obtain a soft turn-OFF process of the main transistors, the maximum capacitor voltage should not be less than twice the voltage U_{DC}. It should be noted that IGBTs with a rated voltage of 6.5 kV and a rated current of 1 kA are currently produced in series. The necessity of selecting transistors for the maximum voltage appearing across the capacitors may be considered an inconvenience to the proposed system.

The maximum current values of the inverter transistors are determined using relationships (11) and (12). The highest current value of the auxiliary transistor does not usually exceed the maximum load current. Moreover, these transistors conduct for a much shorter duration than the main transistors, and hence, their conduction losses are significantly smaller than the analogous losses of the main transistors. It is worth emphasizing that the maximum transistor current in the three-phase VSIs with the hard-switching technique is the sum of the load current and the reverse recovery current of the freewheeling diode of the second transistor of the given phase.

B. Reactive Elements

The key role of the inductors connecting the main transistors with the voltage source terminals is to reduce the steepness of the increase of the main transistor current during the turn-ON process. After the main transistor is turned ON, its current increases from zero linearly with time (7). If the current of this transistor after the end of its turn-ON process cannot be higher than the assumed value $I_{T\mathrm{on}}$, the inductance L_a of the inductors $L1a$ and $L2a$ is determined as follows:

$$L_a = \frac{U_{\mathrm{DC}}}{I_{T\mathrm{on}}} t_r \tag{13}$$

where t_r denotes the time interval during the turn-ON process between the moment at which the main transistor current increases from 10% of its maximum value and the moment at which the main transistor voltage decreases to 10% of the maximum value of this voltage.

It should be noted that the current value $I_{T\mathrm{on}}$ is the only parameter assumed during the selection of the inductance L_a. The time t_r is determined based on the datasheets of the IGBTs. The current value $I_{T\mathrm{on}}$ directly influences the switching losses of the main transistors. Thus, the current $I_{T\mathrm{on}}$ should be decreased to reduce these losses. The turn-ON process can be considered as a soft process when the value $I_{T\mathrm{on}}$ is not higher than 10% of the maximum load current I_L.

Inductors $L1b$ and $L2b$ prevent a sudden discharge of the capacitors through both the main transistors and the voltage source when the auxiliary transistors are turned ON. After transistor $T1p$ is turned ON, the resonant discharge of capacitor $C1$ begins; this is described in detail in the stage t_6–t_7 [see Figs. 3(f) and 4]. The inductances of these inductors depend on the maximum values of both the current $I_{T\max}$ of the main transistors and the load current $I_{L\max}$. The current $I_{T\max}$ is higher than the current $I_{L\max}$. Hence, based on (11) and (12), the inductance of the inductors $L1b$ and $L2b$ is

$$L_b = \frac{1}{4}\left(\sqrt{4\frac{CL_a(U_{\mathrm{DC}}(k-1))^2}{(I_{T\max}-I_{L\max})^2}+L_a^2}-L_a\right). \tag{14}$$

On the other hand, the inductors $L1b$ and $L2b$ should limit the steepness of the increase of the current of the auxiliary transistors at the beginning of the resonant discharging processes of the capacitors. The duration of the turn-ON process of the auxiliary transistor is much shorter than the resonant discharge time. Hence, it can be assumed that, in the initial phase of this process, the current flowing through the auxiliary transistor changes linearly with time, and the changes of the capacitor voltage can be neglected. Due to the aforementioned simplifications, the current of the auxiliary transistor $T1p$ during its turn-ON process can be expressed as follows:

$$i_{T1p} = U_{\mathrm{DC}}(k-1)\left(\frac{1}{L_a}+\frac{1}{2L_b}\right) t. \tag{15}$$

Let t_{Tpr} be the time interval in the turn-ON process between the moment at which the auxiliary transistor current increases from 10% of its maximum value and the moment at which the voltage of the auxiliary transistor decreases to 10% of its maximum voltage. Assuming that the auxiliary transistor current should not be higher than the maximum value I_{Tpon} at time t_{Tpr}, the inductance L_b can be determined as follows:

$$L_b = \frac{t_{Tpr}L_aU_{\mathrm{DC}}(k-1)}{2\left(L_aI_{Tpon}-t_{Tpr}U_{\mathrm{DC}}(k-1)\right)}. \tag{16}$$

The higher value of inductance L_b determined based on (14) and (16) should be selected.

Until the capacitor voltage reaches the supply voltage U_{DC}, the constant load current flows through this capacitor and its voltage increases linearly with time. Assuming that the maximum capacitor voltage is $U_{C\mathrm{off}}$ at the end of the turn-OFF process of the main transistor, the capacitance can be determined as follows:

$$C = \frac{I_{T\max}}{U_{C\mathrm{off}}} t_f \tag{17}$$

where t_f is the time interval during the turn-OFF process of the main transistor when the current of this main transistor decreases from 90% of its maximum value to 10% of this value, and $I_{T\max}$ denotes the maximum transistor current. It was assumed that the value of $U_{C\mathrm{off}}$ cannot be higher than 10% of the maximum supply voltage U_{DC}.

The main transistors are turned OFF softly if the capacitors are completely discharged before these transistors are turned OFF. This condition is satisfied if the maximum capacitor voltage is not less than twice the voltage U_{DC}. Otherwise, the capacitor voltage will be higher than zero at the next turn-OFF process of the given main transistor. Based on (5) and assuming that the maximum capacitor voltage is equal to $k_{\max} U_{\mathrm{DC}}$, an additional condition concerning the capacitance C is given as follows:

$$C = L_a \left(\frac{I_{L\max}}{(k_{\max} - 1)\, U_{\mathrm{DC}}} \right)^2 \tag{18}$$

where $k_{\max}$ is the ratio of the maximum capacitor voltage relative to the supply voltage U_{DC}.

The maximum capacitor voltage cannot be arbitrarily large due to the selection of the rated voltage of the inverter transistors. The first step in the determination of the capacitance is to calculate the maximum permissible voltage $U_{C\mathrm{off}}$, which should not be higher than 10% of the supply voltage U_{DC}. Then, based on (18), the minimum value of capacitance C should be determined for the assumed parameter $U_{C\mathrm{off}}$. Considering an assumed value of the coefficient $k_{\max}$, the capacitance C can be calculated based on the condition in (18). However, if the capacitance resulting from the condition in (18) is higher than the value obtained from condition (17), then the first capacitance value is accepted. Otherwise, the inductance L_a should be increased to the value at which the capacitance C determined from (18) is equal to that determined from the dependence (17). The selected parameters C and L_a affect the duration of the resonant processes in the discussed VSI.

IV. Laboratory Research

To confirm the correct operation of the described soft-switching method, a three-phase laboratory VSI with a rated power of 3 kW was built using the IGBT type IRG4PH50KD (see Table I).

The control system of the laboratory inverter is based on the board Altera DE-2 (FPGA CYCLONE II 2C35). Using this device it is possible to set the operating parameters, such as the modulation depth factor, the switching frequency and the frequency of the output voltage, deadtimes of the main transistors, the conduction time, and the turn-ON time delay of the auxiliary transistors. The control system does not allow to switch the transistors when an incorrect operation of the inverter occurs (e.g., short circuit and overvoltage).

TABLE I
Parameters of the IGBT Type IRG4PH50KD

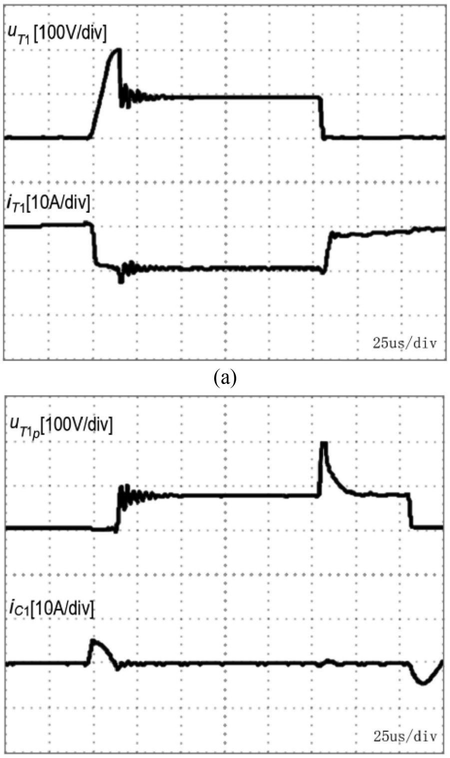
V_{CC} [V]	I_C [A]	t_{on} [ns]	t_r [ns]	t_{off} [ns]	t_f [ns]	t_{rr} [ns]	I_{rrm} [A]	V_{CE} [V]
1200	24.0	139	72.0	700	390	164	8.30	2.77

The voltage of the dc source was 100 V and the admissible current of the load was 12 A. Measurements were performed for the operation of the laboratory inverter with the star-connected inductive–resistive *RL* load and with a squirrel cage induction motor. To qualify the switching processes as soft, it was assumed that the transistor current during the turn-ON processes could not exceed 10% of the maximum current value of the load, and the transistor voltage during the turn-OFF processes could not exceed 10% of the inverter supply voltage U_{DC}. Assuming that the times t_r and t_f of a hypothetical transistor are equal to 1 μs, the parameters of the inductors and capacitors are $C = 1$ μF, $L_a = 100$ μH, and $L_b = 100$ μH. Notably, the times t_r and t_f of the transistors used in the laboratory inverter are smaller than 1 μs and are equal to 72 ns and 390 ns, respectively. For comparative purposes, laboratory research was also performed for $C = 0.5$ μF, $L_a = 100$ μH, and $L_b = 100$ μH. Laboratory research was performed for the following control parameter values: switching frequencies of 1 and 3 kHz; a modulation depth factor of 0.75; and an output frequency of 50 Hz.

Fig. 7 presents the current and voltage waveforms of the transistors $T1$ and $T1p$ for the case when the capacitance and inductance were 0.5 μF and 100 μH, respectively. At approximately 50 μs, transistor $T1$ is turned OFF, and the charging process of capacitor $C1$ begins. Thereafter, the voltage of this transistor increases slowly from zero and becomes approximately 9 V (9% of the inverter supply voltage) when the turn-OFF process is completed. The capacitor voltage at the end of the charging process is more than twice the value of the supply voltage U_{DC} (210 V); the voltage of transistor $T1$ changes similarly. This transistor is turned ON at approximately 177 μs. The voltage of transistor $T1$ immediately decreases to zero, whereas its current increases linearly from zero and it reaches 0.8 A at the end of the turn-ON process. Approximately 50 μs after transistor $T1$ is turned ON, the auxiliary transistor $T1p$ is turned ON, and the resonant capacitor discharge begins. The current waveform of auxiliary transistor $T1p$ has the same shape as the waveform of the discharge current of capacitor $C1$. The current of auxiliary transistor $T1p$ increases slowly and reaches 0.6 A after the turn-ON process.

The capacitor $C1$ discharges partly through inductor $L1a$, the voltage source, and diode $D2z$ and partly through transistor $T1$, inductors $L1b$ and $L2b$, diodes $D2s$ and $D1z$, the voltage source, and diode $D2z$. The turn-OFF of transistor $T1p$ proceeds when its current and voltage equal zero.

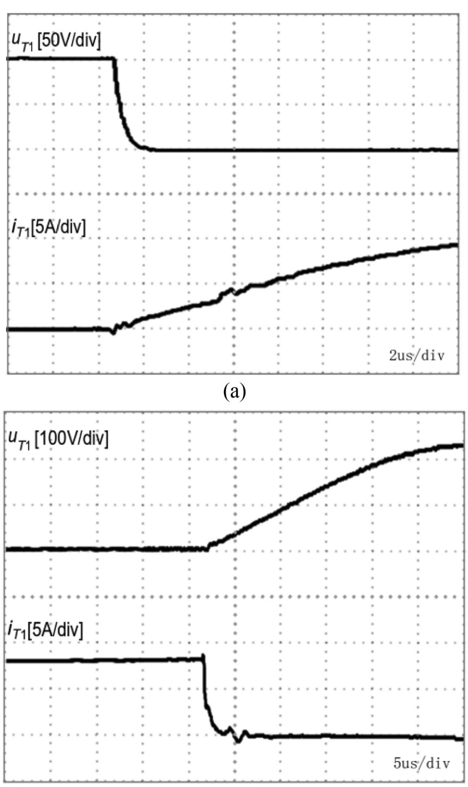
The waveforms of the main transistor $T1$ measured during a switching cycle are shown in Fig. 8. Approximately 1 μs after



(a)

(b)

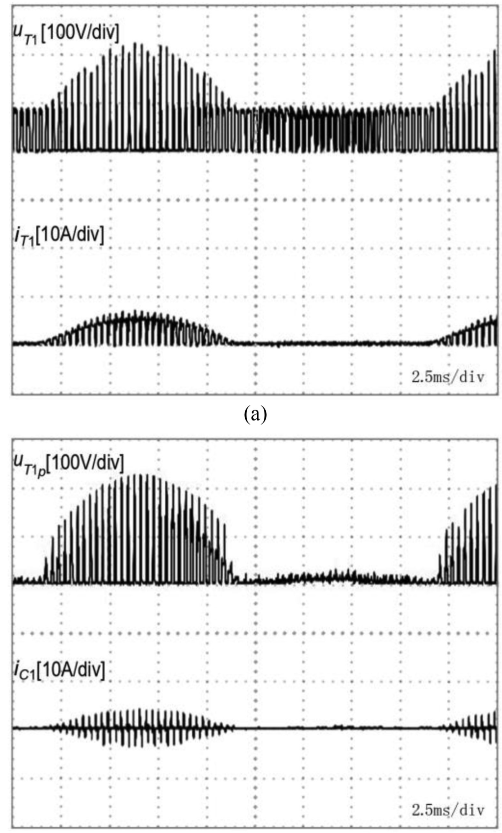
Fig. 7. Waveforms in one switching cycle of (a) transistor $T1$ and (b) transistor $T1p$ and its freewheeling diode when the laboratory inverter supplies the *RL* load (3.9 Ω and 3.7 mH), $C = 0.5$ μF, and $L_a = L_b = 100$ μH.



(a)

(b)

Fig. 8. Voltage u_{T1} and current i_{T1} of transistor $T1$ during the (a) turn-ON process and (b) turn-OFF process.



(a)

(b)

Fig. 9. Current and voltage waveforms in one output voltage period; $C =$ 0.5 μF, $L_a = L_b = 100$ μH, and switching frequency = 3 kHz.

transistor $T1$ is turned ON, its voltage is close to zero; simultaneously, the current of this transistor increases slowly from zero to the load current, which is reached after approximately 15 μs [see Fig. 8(a)]. From the moment the main transistor $T1$ is turned OFF, its current reaches a value close to zero after approximately 1 μs, whereas its voltage increases slowly; this voltage reaches a maximum value of approximately 230 V in the given switching cycle [see Fig. 8(b)]. This allows stating that both the switching processes of the main transistor $T1$ proceed softly.

Fig. 9 shows the waveforms measured in one output voltage period at the switching frequency of 3 kHz. It should be noted that the maximum values of the capacitor discharge current flowing through the auxiliary transistor $T1p$ do not exceed one-half of the current value of the load in any switching cycle. The capacitor discharge current has a small influence on the current of transistor $T1$.

Fig. 10 presents the waveforms of the currents of the inductors $L1b$ and $L2b$, and the waveforms of the voltage and current of the *RL* load for the inductance 100 μH and capacitance 0.5 μF.

These waveforms show the impact of the described soft-switching system on the shapes of both the load current and voltage. The discharge processes of capacitor $C1$ have a small influence on the current of the inductors $L1b$ and $L2b$. The load current at the frequency of 3 kHz is only slightly distorted with respect to the sinusoidal shape.

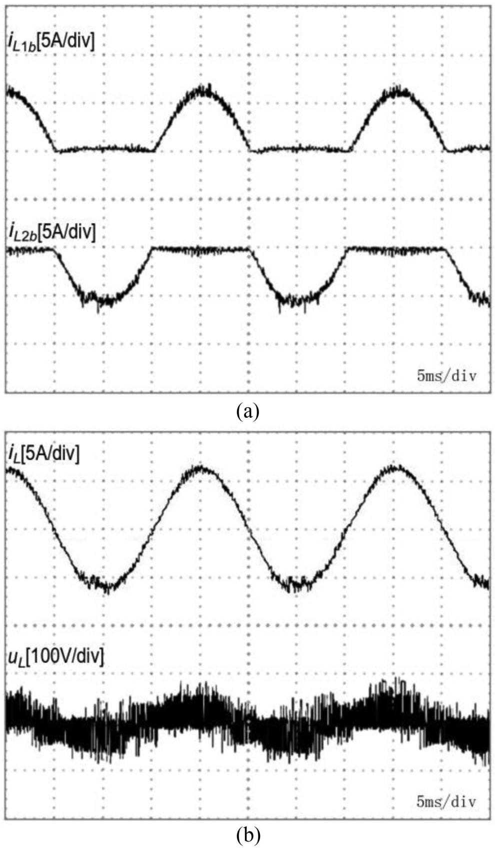


Fig. 10. Waveforms of (a) current of the inductors $L1b$ and $L2b$, and (b) phase current and voltage of the *RL* load; $C = 0.5\ \mu$F, $L_a = L_b = 100\ \mu$H, switching frequency = 3 kHz, and modulation depth factor = 0.75.

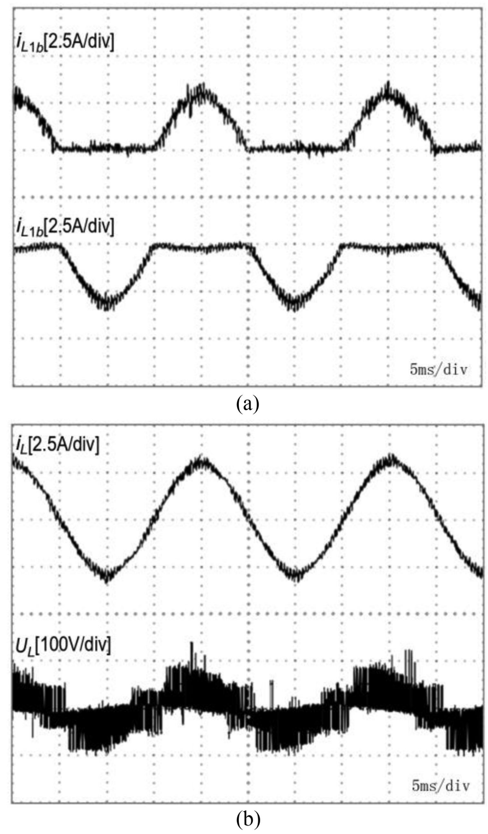


Fig. 11. Current and voltage waveforms of the squirrel cage induction motor for two inverter output voltage periods; $C = 0.5\ \mu$F, $L_a = L_b = 100\ \mu$H, and switching frequency = 3 kHz.

The voltages and currents were also measured for the operation of the laboratory VSI supplying a squirrel cage induction motor designed for a low-voltage supply (3 kW and 3 × 87 V). Some waveforms for this case are shown in Fig. 11.

The performed measurements show that for correctly selected inductances and capacitances, all transistors of the inverter with the proposed system are softly switched; the switching processes do not influence the current waveforms of the load. Additionally, it should be emphasized that the load type does not affect the switching processes of the transistors.

V. Power Losses in Inverter With the Proposed Soft-Switching System

A. Numerical Calculations

The total losses in the VSIs depend on their rated power and the types of applied transistors. At the initial stage of research, it is unreasonable to construct a laboratory VSI with medium and high-rated powers with the proposed soft-switching system. Therefore, the total losses of the inverter equipped with the proposed solution were estimated based on the numerical calculations. Accordingly, the simulation program PSpice, which enables the analysis of the behavior of power electronics systems, was used. The model of the IGBT described in [21] was used in the numerical calculations. It is a circuital model that allows considering the basic static and dynamic properties of IGBTs. It is especially recommended for modeling high-voltage and high-current transistors. All the inductors were replaced with *RL* branches and the capacitors were assumed to be ideal because both the resistance and inductance of the capacitors have no significant influence on the inverter operation. The correctness of the numerical model of the considered inverter with the new soft-switching method was verified by comparing selected calculated waveforms with analogous measured waveforms for different operation conditions. For example, Fig. 12 shows both the current and voltage waveforms of transistor $T1$ during its switching processes. Furthermore, the changes in the voltage of the auxiliary transistor $T1p$ and the current of capacitor $C1$ are presented in Fig. 13. Fig. 14 shows the analogous waveforms calculated and measured for one period of the inverter output voltage.

The individual losses were determined as the integral of the product of the current and voltage on a given inverter element. The calculated energy losses during the switching processes of the main transistor, determined on the basis of the simulation model, are 6.64 μJ, and the corresponding losses estimated based on the measurements are 6.33 μJ. In turn, the turn-ON energy losses of the auxiliary transistor based on the simulation and measurement are equal to 3.83 μJ and 3.67 μJ, respectively. Notably, the power losses during the turn-OFF process of this

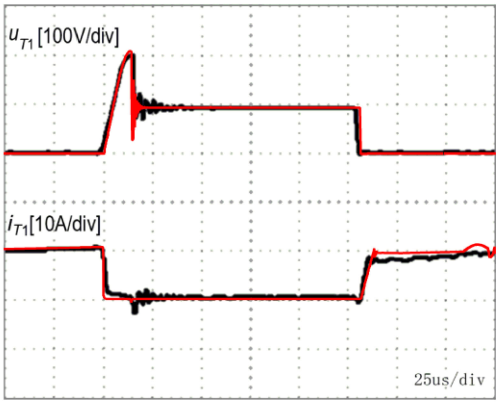


Fig. 12. Comparison of the calculated and measured voltage and current of the main transistor $T1$ during its switching processes. The black and red lines denote the measured and calculated waveforms, respectively.

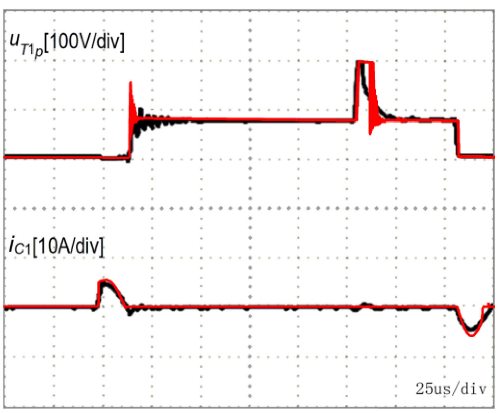


Fig. 13. Comparison of the calculated and measured voltages and currents of the auxiliary transistor $T1p$.

TABLE II
PARAMETERS OF THE IGBTs

Transistor Type	V_{CC} [V]	I_C [A]	t_{on} [µs]	t_r [µs]	t_{off} [µs]	t_f [µs]	t_{rr} [µs]	I_{rrm} [A]	V_{CE} [V]
CM1500HC-90XA	4500	1500	0.80	0.25	7.70	0.50	1.60	2100	2.80
SKM450GB33F	3300	450	0.44	0.12	1.47	0.29	1.49	493	2.86
FZ1500R33HE3	3300	1500	0.76	0.38	3.55	0.35	1.73	1850	3.15
CM300DY-34A	1700	300	0.80	0.20	1.20	0.35	0.45	300	2.45

transistor do not occur. The difference in energy losses is less than 5% relative to the losses from the measurements.

According to the authors, the proposed soft-switching solution is intended for medium- and high-rated-power inverters. Hence, the individual and total power losses were estimated for two inverters with the rated powers of 100 kW (120 A and 1 kV) and 1 MW (1200 A and 1 kV).

It was assumed that IGBTs with the rated voltage of 3.3 kV and current of 450 A (SKM450GB33F) were used in the inverter of 100 kW, and the transistors of 4.5 kV and 1500 A (CM1500HC-90XA) were used in the inverter of 1 MW. The parameters of these transistors are presented in Table II.

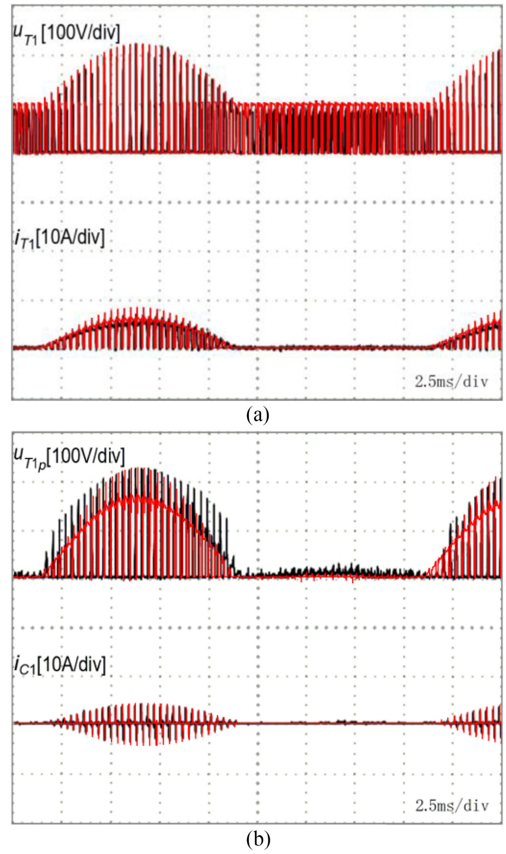


Fig. 14. Calculated and measured waveforms for one period of the inverter output voltage.

The power losses estimated for the inverter equipped with the new soft-switching solution were compared with the losses of the inverter operating with the hard-switching technique. In this case, the IGBTs used in this inverter have a lower rated voltage and their conduction drop voltage is lower than the analogous voltage of the aforementioned transistors (see Table II).

It was assumed that the 100-kW and 1-MW inverters supplied the Y2-315L1-6 squirrel cage induction motor ($P_N = 110$ kW, $U_N = 400$ V, and $I_N = 196$ A) and the Y2-500L2-6 motor ($P_N = 1$ MW, $U_N = 690$ V, $I_N = 1002$ A), respectively. The equivalent circuit of the squirrel cage induction presented in [22] was applied. Numerical calculations were performed for three switching frequencies. The values of the calculated parameters of the inductors and capacitors for the assumed values of the coefficient $k_{\max}$ are given in Table III.

The chosen waveforms of the currents and voltages calculated for the 1-MW inverter are presented in Figs. 15 and 16. Analogous waveforms calculated for the 100-kW inverter have similar shapes.

B. Estimation of Power Losses

The power losses were estimated by performing numerical calculations using the previously mentioned IGBT model. This allowed considering, among others, the nonlinear properties of the IGBTs, variable values of the transistor, and diode conduction drop voltages, and above all, to consider the switching

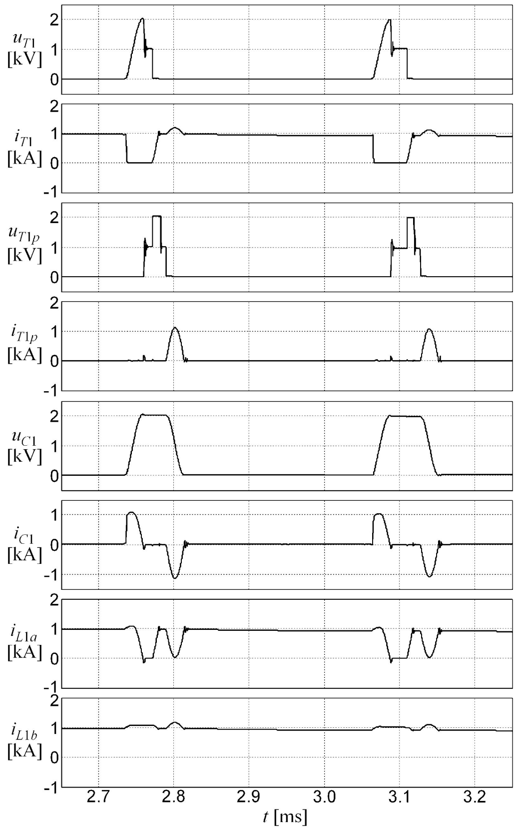


Fig. 15. Waveforms in two switching cycles of the chosen voltages and currents of the inverter that supplies the induction motor. The switching frequency is 3 kHz.

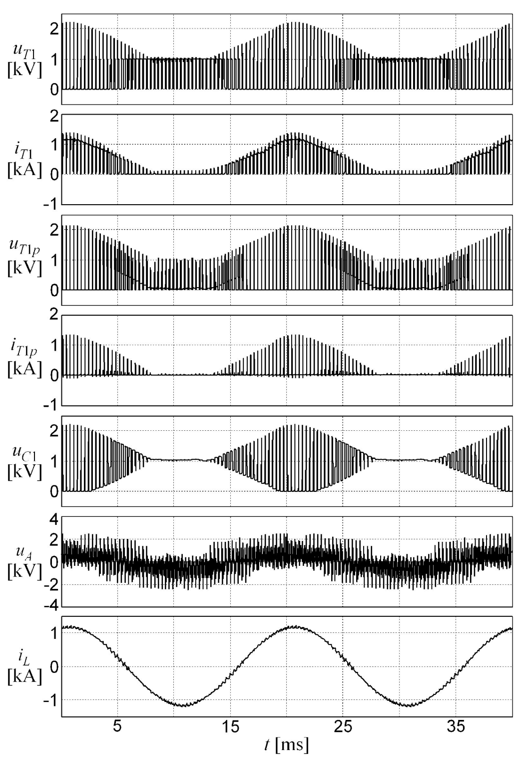


Fig. 16. Voltages and currents during two output frequency periods; u_A and i_L are the phase voltage and phase current of the induction motor, respectively.

TABLE III
ASSUMED PARAMETERS OF THE INDUCTORS AND CAPACITORS OF THE SOFT-SWITCHING SYSTEM

	100 kW			1 MW		
k_{max}	2.0	2.5	3.0	2.0	2.5	3.0
L_a [μH]	110	110	110	26.5	26.5	26.5
R_a [mΩ]	1.48	1.48	1.48	0.73	0.73	0.73
L_b [μH]	131	160	166	32.3	36.6	40.8
R_b [mΩ]	1.62	1.79	1.82	0.80	0.86	0.90
C [μF]	0.8	0.5	0.3	20.0	11.0	7.5

processes without the need to linearize the current and voltage waveforms, as it is in the cases of analytical calculations.

The power losses were calculated separately for each inverter element as the integral of the product of the current and voltage on the considered inverter element. Regardless of the type of soft switching, the power losses occurring in the transistor switching processes are not equal to zero and should be considered in the calculations of the inverter power losses. The switching losses of the main transistors depend on their currents and voltages during the switching processes and on the duration of these processes. Additionally, the conduction losses of the freewheeling and other diodes should be included in the estimation of the total power losses. However, unlike VSIs operating with the hard-switching technique, the turn-OFF losses are not generated in the diodes of the presented soft-switching solution. Notably, the losses occurring in the inductors may account for a significant proportion of the total power losses.

The turn-ON losses of the main transistors depend on the assumed inductance L_a [see formula (13)], which limits the steepness of the increase of the current of these transistors. The given main transistor is turned OFF when the corresponding capacitor is completely discharged. However, for small values of the load current, this capacitor is not discharged to zero, and the coefficient k [see formulas (9) and (10)] is less than two. Thus, in these cases, relatively small power losses occur during the turn-OFF process of the main transistor.

It is necessary to stress that power losses occur also in the additional elements of the soft-switching circuits, such as the auxiliary transistors and their freewheeling diodes and inductors, and these losses should be taken into account in the estimation of the total power losses. The conduction time of the given auxiliary transistor, which is equal to the time of resonant capacitor discharge in a given switching cycle, and the resonant discharge current should be determined. Owing to the resonant character of the capacitor discharge current, the turn-ON losses of these transistors are close to zero.

The conduction losses in the freewheeling diodes of the auxiliary transistors occur during the capacitor charge processes when the corresponding main transistors are turned OFF. Due to the presence of inductors, the turn-OFF processes of these diodes occur without power losses. It is worth emphasizing that in power electronics systems, power losses during the turn-ON processes of diodes can be neglected [23]. To estimate the total power losses in the considered VSI, the power losses in other diodes

TABLE IV
POWER LOSSES OF THE INVERTER WITH THE PROPOSED SOFT-SWITCHING SYSTEM

k_{max}	100 kW			1 MW		
	3 kHz	6 kHz	9 kHz	1 kHz	2 kHz	4 kHz
Switching losses of the main transistors [W]						
3.0	11.8	22.6	37.1	186	281	456
2.5	19.3	39.1	60.3	251	384	629
2.0	47.7	96.5	147.0	349	626	1192
Switching losses of the auxiliary transistors [W]						
3.0	0.65	1.44	2.36	13.3	27.5	61.5
2.5	1.08	2.26	3.67	20.1	41.2	86.5
2.0	2.23	4.61	6.98	14.8	30.2	67.6
Total switching losses of the inverter [W]						
3.0	**12.4**	**24.1**	**39.5**	**200**	**309**	**517**
2.5	**20.4**	**41.4**	**64.0**	**271**	**425**	**716**
2.0	**49.9**	**101.1**	**154.0**	**364**	**657**	**1260**
Conduction losses of the main transistors [W]						
3.0	602	657	712	6077	6177	6670
2.5	588	616	637	5891	5899	6104
2.0	567	593	599	5819	5809	5962
Conduction losses of the freewheeling diodes of the main transistors can be neglected						
Conduction losses of the auxiliary transistors [W]						
3.0	33.9	55.3	78.5	168	302	570
2.5	25.4	41.1	58.1	131	240	461
2.0	16.4	28.1	39.5	154	293	573
Conduction losses of the freewheeling diodes of the auxiliary transistors [W]						
3.0	16.4	36.0	60.1	138	275	605
2.5	12.9	27.1	42.8	109	211	439
2.0	9.4	19.3	29.6	137	264	540
Conduction losses of additional diodes [W]						
3.0	246	302	373	3038	3207	3974
2.5	220	248	280	2777	2773	3059
2.0	204	220	234	2684	2623	2783
Conduction losses of inductors [W]						
3.0	865	1046	1158	5463	5623	6226
2.5	681	715	752	3907	3942	4130
2.0	446	460	470	3291	3301	3405
Total power losses of the inverter with the proposed solution [W]						
3.0	**1777**	**2129**	**2445**	**15087**	**15916**	**18602**
2.5	**1548**	**1691**	**1841**	**13085**	**13492**	**14941**
2.0	**1293**	**1421**	**1526**	**12448**	**12943**	**14534**
Efficiency [%]						
3.0	**98.16**	**97.93**	**97.64**	**98.54**	**98.44**	**98.19**
2.5	**98.48**	**98.35**	**98.21**	**98.72**	**98.69**	**98.55**
2.0	**98.72**	**98.62**	**98.52**	**98.79**	**98.74**	**98.59**

should be considered. Accordingly, the conduction time and the currents of these diodes were determined. The power losses in the inductors depend on the internal resistance of the inductors, their conduction times, and their currents. The total power losses occurring in the considered inverter are given in Table IV and they are graphically represented in Figs. 17 and 18. These losses were compared with the power losses of the VSI operating with the hard-switching technique (see Table V and Fig. 19).

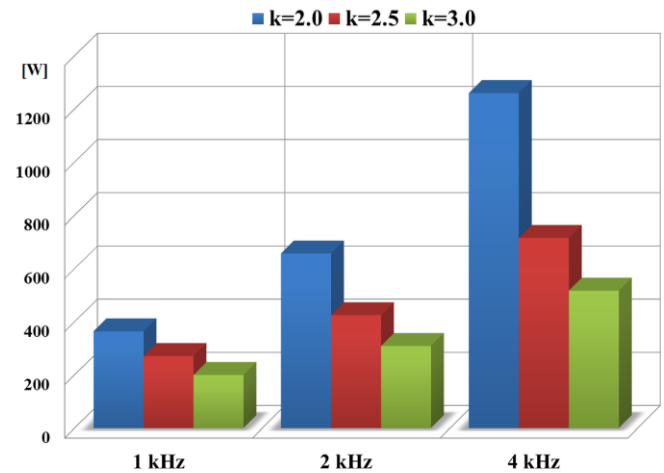


Fig. 17. Switching losses of the proposed soft-switching system.

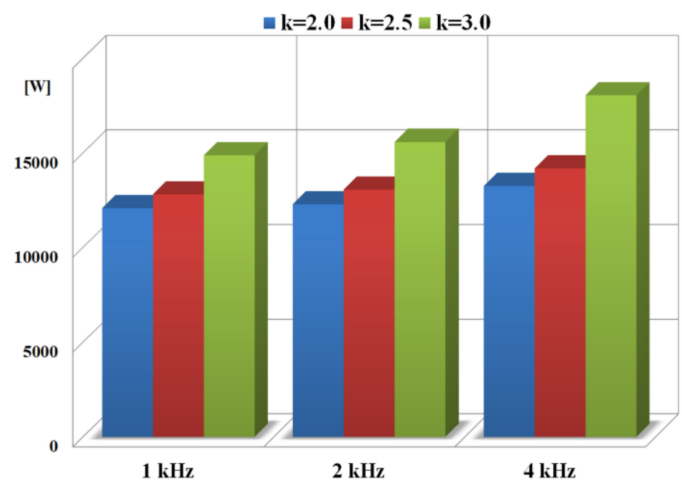


Fig. 18. Conduction losses of the proposed soft-switching system.

TABLE V
POWER LOSSES OF THE INVERTER WITH THE HARD-SWITCHING TECHNIQUE

100 kW			1 MW		
3 kHz	6 kHz	9 kHz	1 kHz	2 kHz	4 kHz
Switching losses of the transistors [W]					
411	823	1240	5696	11545	23771
Switching losses of the freewheeling diodes [W]					
344	690	1039	1083	2211	4554
Total switching losses of the inverter [W]					
754	**1513**	**2279**	**6779**	**13756**	**28326**
Conduction losses of the transistors [W]					
560	560	560	5537	5578	5663
Conduction losses of the freewheeling diodes [W]					
90.2	90.6	91.0	1090	1113	1187
Total power losses of the inverter with "hard" switching technique [W]					
1404	**2164**	**2930**	**13406**	**20447**	**35176**
Efficiency [%]					
98.62	**97.88**	**97.15**	**98.68**	**98.00**	**96.60**

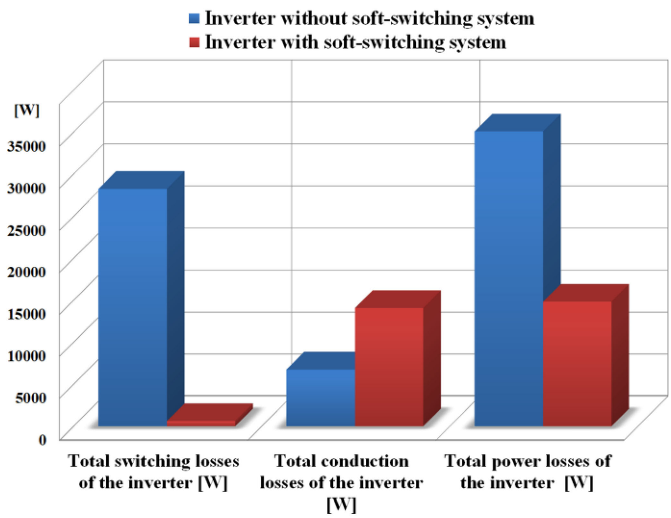


Fig. 19. Comparison of losses occurring in the soft-switching and hard-switching systems.

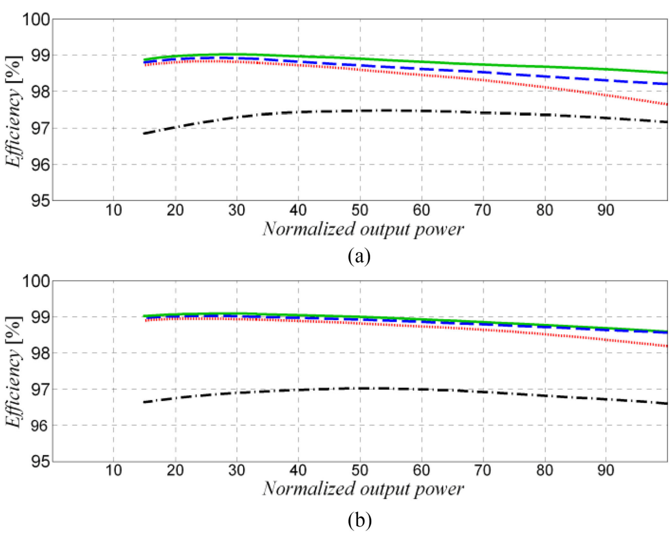


Fig. 20. Efficiency as the function of the normalized output load power. (a) 100-kW inverter. (b) 1-MW inverter. Green (continuous) lines denote $k = 2.0$, blue (dashed) lines denote $k = 2.5$, red (dotted) lines denote $k = 3.0$, and black (dashed-dotted) lines denote VSI with the hard-switching technique.

The VSI with the proposed soft-switching solution has the highest efficiency when the coefficient $k = 2$. For the lowest assumed switching frequencies, the efficiency of this inverter is comparable with the inverters operating with the hard-switching technique. Notably, due to the higher operating voltage, IGBTs with a higher rated voltage drop have to be applied in the inverter with the proposed soft-switching system. The difference between the efficiencies of the inverters operating with different switching techniques increases with the switching frequency. Fig. 20 shows the efficiencies of the 100-kW and 1-MW inverters as the function of the output load power for the switching frequency 9 and 4 kHz, respectively.

These dependences are similar to those presented in [8], [15], [24], and [25], although the latter ones were determined for other inverter parameters and other rated load powers. The influence of the switching frequency on the inverter efficiency is shown in Fig. 21 for the 1-MW inverter.

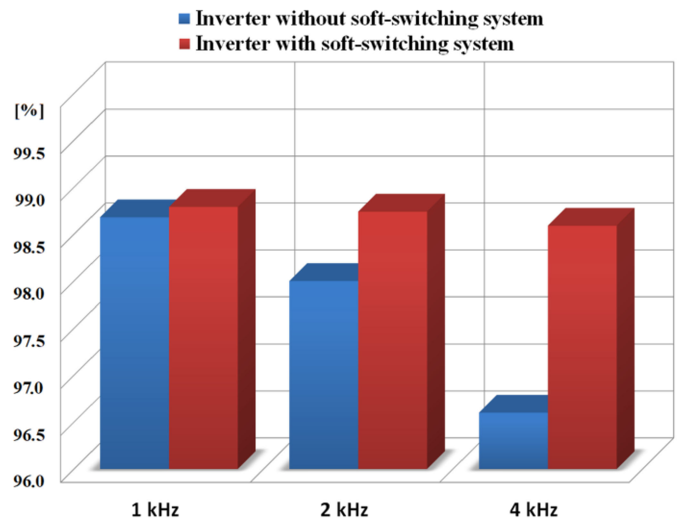


Fig. 21. Efficiency comparison for 1 MW inverters, where $k_{\max} = 2.0$.

TABLE VI
VALUES OF THE TOTAL HARMONIC DISTORTION FOR 200 HARMONICS (IN %)

	100 kW		1 MW	
	soft	hard	soft	hard
load current i_L	2.64	2.51	2.46	2.56
phase voltage u_A	76.61	80.19	78.28	80.69
phase-to-phase voltage u_{AB}	76.82	79.96	80.69	80.69

It should be noted that the resistance of the gate circuit, the semiconductor operating temperature, and also the inverter supply voltage may affect the total power losses of the inverter. Additionally, to compare both switching techniques, the total harmonic distortion was estimated for the soft- and hard-switching inverters (see Table VI). The modulation depth factor was 0.8 and the switching frequency was 3 kHz ($k_{\max} = 2.5$).

The results presented in Table VI show that the proposed solution reduces slightly a content of the higher harmonics in comparison with the hard-switched inverter.

VI. CONCLUSION

In the presented soft-switching system in the three-phase VSI, the capacitors are not connected in parallel to the main transistors and the inductors are not connected in series with the auxiliary transistors. Therefore, the discharges of the capacitors through the main transistors and the sudden interruption of the inductor currents are not possible; this enhances the reliability of the VSIs operating with the proposed soft-switching system.

The auxiliary transistors are switched in dependence on the working states of the main transistors, and as a result of this, the control system is relatively simple. When the control signals of the auxiliary transistors are not synchronized with the main transistors, these transistors will be hard switched; however, device failures will not occur.

Laboratory research confirmed that the switching processes of all the transistors of the VSIs operating with the new soft-switching method occur at transistor currents or voltages that are close to zero. This significantly reduces the switching power losses despite the occurrence of power losses in the additional diodes and inductors of the described soft-switching system. The reduction of the switching losses may simplify the cooling system of the given inverter.

It should be mentioned that the proposed soft-switching systems have certain limitations on the operating parameters. This mainly concerns the switching frequency and the maximum value of the amplitude modulation ratio, which depends on the minimum admissible value of the conduction times of the main transistors, among other factors. However, this feature concerns all soft-switching solutions.

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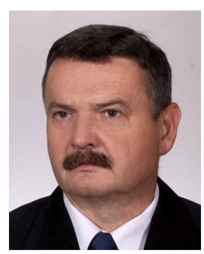

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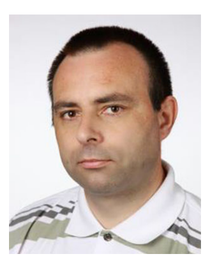

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