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# Modifications of the soft switching system resistant to disturbances in control systems of voltage sources inverters

# Modyfikacje układu łagodnego przełączania odpornego na zakłócenia w układach sterowania trójfazowych falowników napięcia

**Abstract**

Reduction of the switching losses in three-phase voltage source inverters can be achieved by using of soft switching systems that not only increase the efficiency of the inverters, but they also reduce the size of the semiconductor cooling circuits, that is especially important in traction vehicles. The majority of existing soft switching systems have some drawbacks that could be danger for inverter operation in the case of disturbances in control systems. The paper briefly describes the structure, operation principles and results of laboratory tests of the proposed soft switching system. Particular attention has been paid to the specific features of alternative versions of the proposed soft switching system, that allow to improve operating parameters of the basic system.

**Keywords:** soft switching, switching losses, voltage source inverters, ZCZVS converters

**Streszczenie**

Zmniejszenie strat przełączania w trójfazowych falownikach napięcia można uzyskać, stosując układy łagodnego przełączania, które nie tylko wpływają na zwiększenie sprawności falownika, ale również pozwalają ograniczyć gabaryty układów chłodzących elementy półprzewodnikowe, co w napędach trakcyjnych ma istotne znaczenie. Zdecydowana większość istniejących układów łagodnego przełączania ma pewne mankamenty mogące zagrozić bezawaryjnej pracy falowników w przypadku wystąpienia zakłóceń w układzie sterowania. W artykule skrótowo opisano strukturę, zasady działania oraz wyniki badań laboratoryjnych proponowanego układu łagodnego przełączania tranzystorów. Szczególną uwagę zwrócono na alternatywne wersje proponowanego układu, które pozwalają polepszyć parametry eksploatacyjne układu podstawowego.

**Słowa kluczowe:** falownik napięcia, łagodne przełączanie, straty przełączania, przekształtniki ZCZVS

## 1. Introduction

A squirrel-cage induction motor is the most common solution to convert electrical energy into kinetic energy. This type of motors has gained great popularity in traction vehicles because of high reliability and lower price compared to other solutions. Traction vehicles in Poland are supplied by the DC network. Therefore, in order to use a three-phase induction motor it is necessary to transform the direct voltage into the alternating voltage with the adjustable frequency and RMS value, and the voltage source inverter (VSI) seems to be an indispensable device. Modern constructions of the traction vehicles impose large size limitation on drive systems which refer also to the inverters. It is necessary to ensure the proper operating temperature of semiconductor elements, and the cooling system applied in inverter largely determines dimensions of this device.

Due to the extreme operating conditions of the inverter, caused by various loads and different weather conditions (especially high temperatures during the summer months), cooling systems of the inverters have important meaning. Therefore, it is advisable to make attempts which can allow us to reduce energy dissipation during the inverter operation. This aim can be achieved by power loss reduction in the inverter transistors, especially when the voltage source inverter operates with the pulse width modulation method. Power losses in transistors are a sum of the conduction losses and the switching losses. The first type of these losses depends on the transistor current and on the collector-emitter voltage during the conduction state of the given transistor; user of inverters do not have influence on the conduction losses. On the other hand, the switching losses depend on changes of the transistor current and voltage during both the turn-on and turn-off processes and these losses can be reduced by using VSIs which operate with the so-called soft switching systems [1–6]. Figure 1 shows an example of waveforms of the transistor current, voltage, and power losses of the Insulated Gate Bipolar Transistor (IGBT) type IRG4PH50KD (1200 V, 24 A) during the hard switching processes in the three-phase laboratory voltage source inverter. The transistor

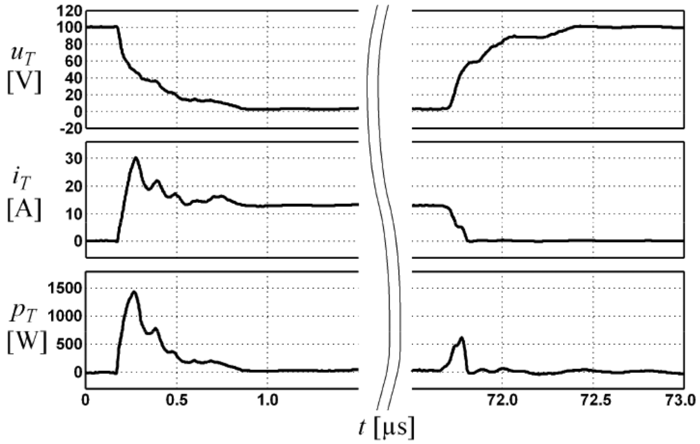


Fig. 1. Waveforms of the transistor current, voltage, and power losses during both the turn-on and turn-off processes in the three-phase voltage source inverter

current after the turn-on process was equal to 12 A, and the voltage at the end of the turn-off process reached a value of 100 V; the turn-on and the turn-off times of this transistor were equal to 72 ns and 390 ns, respectively. The transistor switching losses in a single cycle at the frequency of 3 kHz were approximately equal about 1.17 W for the assumed switching conditions. It is well known that the share of the switching losses in total power losses occurring in IGBTs rises with the switching frequency. In many cases, these losses are greater than the conduction losses at the switching frequency of a few kHz. An increase of these losses leads not only to a reduction of the inverter efficiency, but it can cause problems with proper cooling of IGBTs. It is worth underlining that the estimation of the total switching losses in VSIs needs to take into account the losses occurring in freewheeling diodes.

The pursuit of the reduction of the switching losses is to increase the efficiency of power electronic inverters; less switching losses lead to an improvement of cooling systems of IGBTs. The fulfilment of this requirement is often more important than an improvement of the efficiency, especially in inverters of medium and high power ratings. In order to reduce the switching losses, the voltage value or the current value of the switched transistor should be close to zero during the switching processes. A lot of soft switching solutions are described in scientific literature. Generally, these systems can be divided into two groups; the first one includes VSIs with one central auxiliary soft switching circuit [7–12] and the second group refers to the inverters with individual auxiliary soft switching circuit in each phase of the given inverter [13–19]. The majority advantages of the first group are small number of additional elements of the given soft switching circuit, and in result simple structure. However, control methods in these solutions of the transistor soft switching are quite complicated and the switching frequency can change in relatively narrow ranges. In the second group of the soft switching systems, each phase of the inverter has an own soft switching circuit. In this case the soft switching circuits have more complicated structures in comparison to the inverters with central auxiliary circuits, but the VSIs can operate with higher switching frequencies. In some individual solutions, the structure of auxiliary resonant circuits includes special transformers [20–22]. Figure 2 presents, for example, one of the most often soft switching system presented in literature [13, 16].

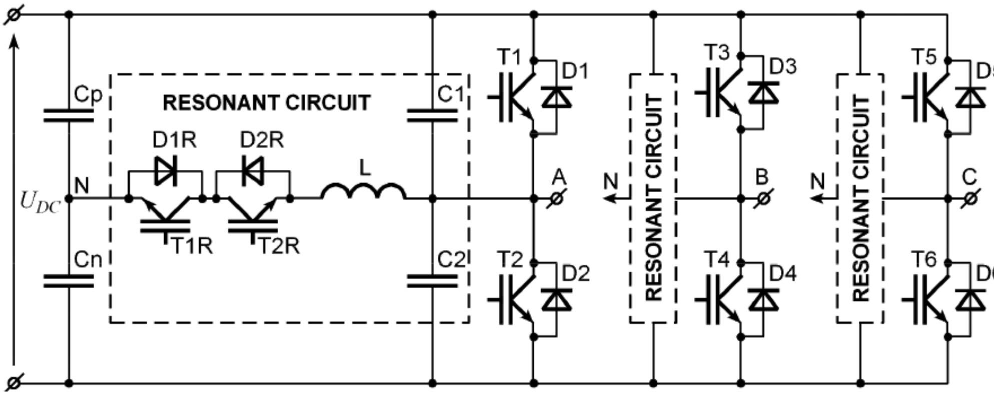


Fig. 2. Three-phase voltage source inverter with individual soft switching in each phase

In the majority of the existing soft switching systems, the auxiliary circuits consist of capacitors connected in parallel to the main transistors [8, 10, 20] and resonant coils which are connected in series to auxiliary transistors [7, 9, 10, 13, 16]. These connections are not recommended because the main or auxiliary transistor can be damaged during disturbances in control systems. For example, when the main transistor is turned on and the voltage of the capacitor connected in parallel to this transistor is higher than zero, then this capacitor discharges abruptly through the given main transistor; in second case when the auxiliary transistor is turned off at a non-zero current of the resonant coil then an overvoltage can appear in the given VSI. Due to these drawbacks the next part of this paper presents the patented solution, wherein the above disadvantages do not occur.

## 2. Basic soft switching system resistant to control disturbances

The basic soft switching system which is resistant to control disturbances is presented in Fig. 3 [23–25]. In this system do not occur previously mentioned connections which are characteristic properties of the majority soft switching systems existing up till now. The control method of the presented system is easier in comparison to other soft switching methods because the auxiliary transistors in the given VSI are switched with respect to the main transistors, not the other way round.

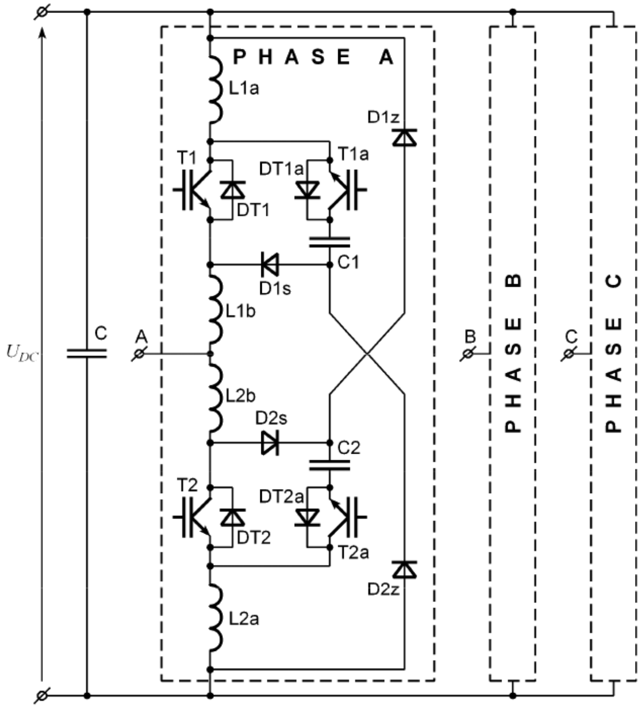


Fig. 3. Three-phase VSI with soft switching system resistant to control disturbances

In the presented solution, to the given main transistor *T*1 following elements are added: one auxiliary transistor *T*1*a*, two resonant coils *L*1*a*, *L*1*b*, one capacitor C1 and two diodes. So, the auxiliary circuit of one phase of the VSI includes six additional elements, what is typical of other VSIs equipped in individual soft switching systems. The key role of the additional coil *L*1*a* is certain limitation of the increase of the main transistor current during the turn-on process. In turn, the capacitor *C*1 is applied to reduce the increase of the main transistor voltage during the turn-off process. Two additional diodes *D*1*s* and *D*2*z* should keep linearity of the load current when the main transistor is turned off. The coils *L*1*b* and *L*2*b* protect the VSI against short circuits when accidentally two main transistor in one phase may be turned on. The auxiliary transistors are turned on with a certain delays with respect to the main transistors and they are turned off after the end of the capacitor resonant discharge process, but not later than the corresponding main transistor is turned off. In the proposed solution the capacitors are not connected in parallel to the main transistors and the coils are not connected in series to the auxiliary transistors. These are significant advantages in comparison to the soft switching systems existing up till now. Simplified waveforms of chosen currents and voltages of the proposed soft switching system are shown in Fig. 4. The whole switching process has only six stages, unlike to many other proposals of the soft switching [12]. The operation principles and determination of the parameters of the proposed soft switching system are described in detail in [24, 25].

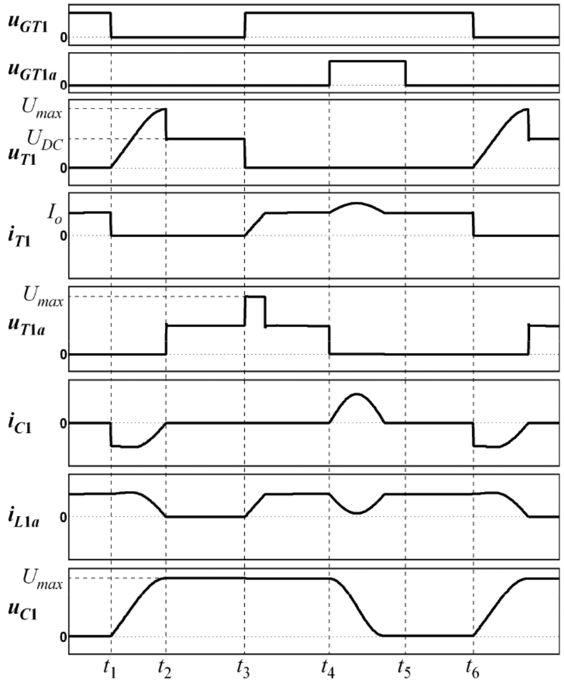


Fig. 4. Simplified waveforms in the proposed soft switching system: $u_{GT1}$, $u_{GT1a}$ – control signals of the main transistor *T*1, and auxiliary transistor *T*1a, $u_{T1}$, $i_{T1}$ – voltage and current of the transistor *T*1, $u_{T1a}$ – voltage of the auxiliary transistor *T*1*a*, $i_{C1}$, $u_{C1}$ – current and voltage of the capacitor *C*1, $i_{L1a}$ – current of the coil *L*1*a*

Validation of the described soft switching system was performed with the use of the voltage source inverter with the power rating of about 3 kW. The value of the DC supply voltage was equal to 100 V and the maximum load current was not higher than 14 A. Figures 5 and 6 show waveforms of laboratory measurements for previously described full switching process.

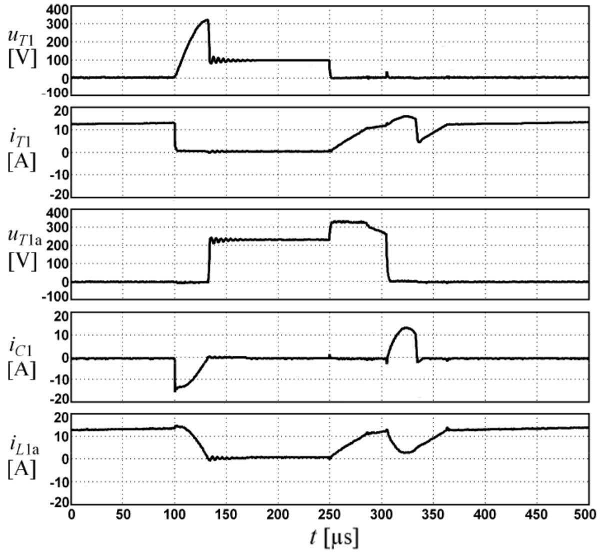

Fig. 5. Waveforms measured in the laboratory voltage source inverter with the proposed soft switching system: $u_{T1}$, $i_{T1}$ – voltage and current of the transistor $T1$, $u_{T1a}$ – voltage of the auxiliary transistor $T1a$, $i_{C1}$ – current of the capacitor $C1$, $i_{L1a}$ – current of the coil $L1a$, the capacity of the capacitors – 1 μF, inductance of all coils – 300 μH

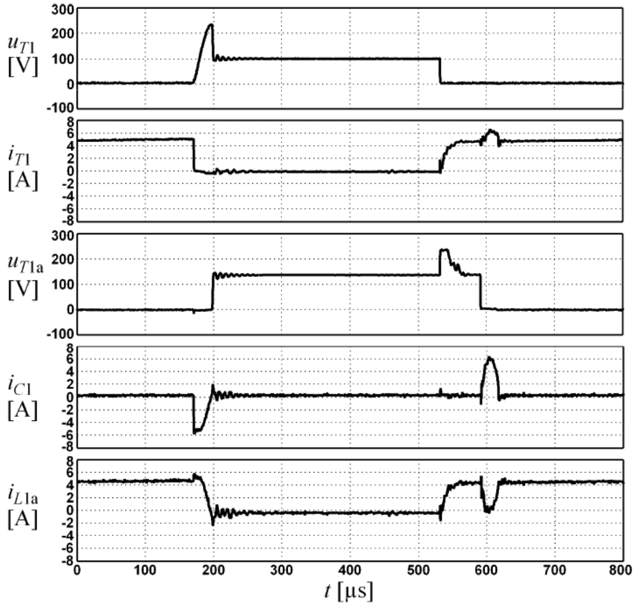

Fig. 6. Analogous waveforms as in Fig. 5 measured for inductance 100 μH of the coils $L1b$, $L2b$

The switching processes of both the main and auxiliary transistors have soft character. It allows us to reduce the switching losses even up to 70–80 per cent with respect to these losses occurring in the VSIs which operate without soft switching systems. The control method is simple because the control algorithm should determine only the value of the time delay between switching signals of the main and the auxiliary transistors.

It is worth underlining that the decrease of the inductance $L_{1a}$, $L_{2a}$ leads to a certain reduction of the maximum value of the capacitor voltage that is equal to the maximum value of the voltage of the main transistor T1. However, for the correct operation of the proposed soft switching system, this voltage should be at least twice the voltage of the DC supply source.

## 3. Application of auxiliary thyristors in proposed soft switching system

The auxiliary transistors in the proposed basic soft switching system can be replaced by appropriate selected thyristors (Fig. 7) [26]. This proposal refers first of all to the voltage source inverters with high power rating. Operation principles of the system with thyristors are analogous as in the basic version and the waveforms of currents and voltages are similar to the analogous waveforms in the basic soft switching system. However, the control method is simpler because thyristor (e.g. Ty1) requires only turn-on signal and this thyristor turns off when the resonant discharging of the capacitor C1 ends. So, we do not have to determine the conduction time of the auxiliary transistor as in the basic solution.

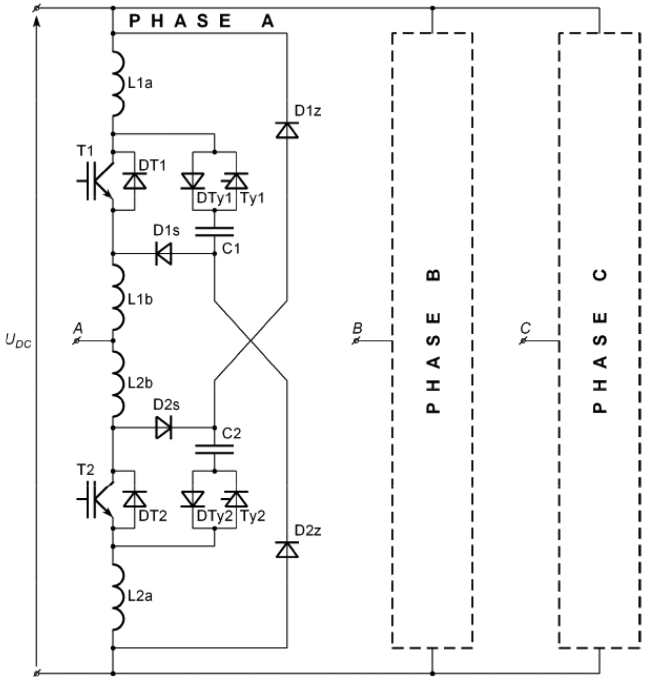


Fig. 7. Basic soft switching system with the auxiliary thyristors

The auxiliary transistor as in the basic solution. It is worth underlining that thyristors are more resistant to overvoltages and overloads.

Due to the relatively high switching frequency (several kHz), in this proposal the so-called pulse thyristors should be applied, which have significantly shorter turn-off times with respect to "classical" rectifier thyristors. However, even the pulse thyristors have significantly longer turn-off times in comparison to IGBTs. For example, the turn-off time of the IGBTs applied in the laboratory soft switching system is equal to 0,39 μs, whereas these times of the pulse thyristors with the similar operation parameters have these values in the range from 15 μs to 25 μs, so it should be taken in the control algorithm of the soft switching of the given three-phase VSI with auxiliary thyristors. Figure 8 presents simplified waveforms of the transistor current $i_{T1}$ and the capacitor current $i_{C1}$ in the case when the auxiliary transistors are replaced by the pulse thyristors. The correct operation of the modified soft switching system occurs when the auxiliary thyristor regains forward blocking capacity before the next turn-on process of the main transistor. Therefore, the minimum time interval $t_{Ton}$ between two successive turn-on processes of the main transistor should fulfil the following condition (Fig. 8):

$$t_{Ton} \geq t_{rise} + t_{dis} + t_q \tag{1}$$

where

$t_{rise}$ – time, when the transistor current reaches the maximum value of the load current,
$t_{dis}$ – time of the resonant discharge of the capacitor,
$t_q$ – turn-off time of thyristor.

The value $t_{Ton}$ can be shorter by the time $t_{char}$ which refers to the charge process of the capacitor after the turn-off process of the main transistor. If the relationship (1) is not fulfilled then the capacitor begins to discharge during the non-conduction state of the main transistor.

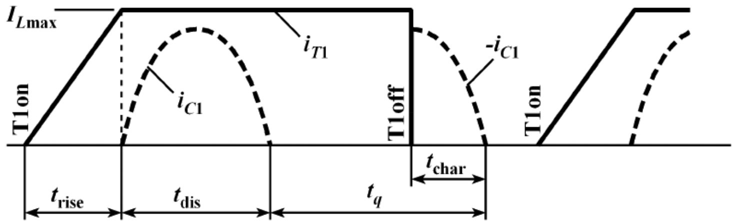


Fig. 8. Simplified waveforms of the transistor current $i_{T1}$ and the capacitor current $i_{C1}$ in the soft switching system with the auxiliary transistor: $t_{rise}$ – time when the transistor current reaches the maximum value of the load current $I_{Lmax}$, $t_{dis}$ – time of the resonant discharge of the capacitor, $t_q$ – time when the thyristor regains forward blocking capacity, $t_{char}$ – time of the charge of the capacitor

The minimum value of the time $t_{Ton}$, which describes a required time interval of the conduction state of the main transistor, influences the maximum admissible value of the amplitude modulation ratio $m_{amax}$:

$$m_{a\max} = 1 - 2 f_i \, t_{\min} \tag{2}$$

where:

$f_i$ – switching frequency.

It is necessary to stress that the values $m_{amax}$ of the VSI operating with the auxiliary thyristors are smaller in comparison to these values concerning the VSI with the soft switching system based on the auxiliary transistors, and differences between these values depend strongly on the switching frequency. However, it should be noted that the switching times of IGBTs operating at a voltage of several kV are of the order a few μs, so the application of the auxiliary thyristors seems worthy of consideration, especially in VSIs of high power rating.

## 4. Alternative configuration of the basic soft switching system

In the proposed basic soft switching system, the signals turning on the auxiliary transistors have to be delayed with respect to the turn-on signals of the main transistors and this is a certain inconvenience in the control algorithm. Therefore, by way of further research it has been developed an alternative version of the basic soft switching system [27]. In the alternative proposal, the roles of the all coils differ in comparison to their roles in the basic system and the appropriate coils are coupled magnetically (Fig. 9). Numerical calculations have shown that the application of the magnetic couplings improves the basic system operation and allows us to simplify the control algorithm.

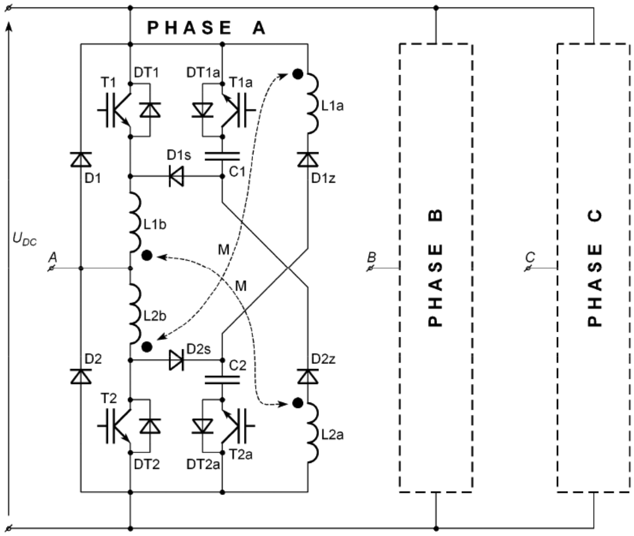


Fig. 9. Alternative configuration with magnetically coupled coils of the basic soft switching system

As previously mentioned, in the basic soft switching system it is necessary to set a certain time-delay between the turn-on signals of the auxiliary transistors with respect to the main transistors. Moreover, it is necessary to determine the conduction time of the auxiliary transistors. So, the control algorithm of the basic system has to generate two additional signals for the auxiliary transistors. Appropriately chosen negative magnetic couplings between the coils $L1a$, $L2b$ and between $L2a$, $L1b$ allow us to eliminate the two extra signals of the auxiliary transistors. These negative couplings are designed to reduce to zero the currents of the coils $L1b$ and $L2b$ (connected to the load terminal) when the main transistors are turned off. Consequently, the auxiliary transistors can be switched using the same control signals as the main transistors.

The operation of the proposed alternative solution is described with the assumption that the cycle begins when the main transistor $T1$ and the auxiliary transistor $T1a$ are turned off. From this moment the current of the transistor $T1$ drops abruptly to zero whereas the current of the auxiliary transistor $T1a$ is equal to zero; the load current flows through the diode $DT1$a, capacitor $C1$ and coil $L1b$ and the capacitor $C1$ charges itself resonantly. When the resonant charging process of the capacitor $C1$ is finished, the load current flows from negative terminal of the DC source through diode $D2$. In the next stage of the considered cycle both the main and auxiliary transistors $T1$, $T1$a are turned on simultaneously. The current of the main transistor $T1$ begins to increase with limited steepness to the value of the load current and also the capacitor $C1$ begins to discharge resonantly through transistor $T1a$, DC source, coil $L2a$ and diode $D2z$. Due to the occurrence of the coils $L1b$ and $L2a$ the turn-on processes of both the main and auxiliary transistors have soft character. In next time interval the current of the coil $L1b$ increases due to the negative magnetic coupling M between coil $L1b$ and $L2a$.

In the next stage the discharge current of the capacitor $C1$ and the current of the coil $L2a$ start to decrease; the voltage of the coil $L1b$ changes its sign. This causes that the current of the coil $L1b$ is reduced to the value of the load current. In the end stage of the operation cycle, the current of the auxiliary transistor T1a decreases instantly to zero, whereas the collector-emitter voltage of this transistor is close to zero; so, the turn-off process of the auxiliary transistor $T1$a has the soft character. The second transistors $T2$, $T2a$ of the given phase are switched similarly as the transistors $T1$, $T1a$.

The coils $L1b$, $L2b$ (Fig. 9) should reduce the current steepness of the main transistors $T1$, $T2$ during turn-on processes; inductance of these coils can be determined as follows:

$$L_{1,2b} = \frac{U_{DC}\, t_r}{m_r\, I_{T\max}} \tag{3}$$

where:

- $t_r$ – time when the current of the main transistor increases from 10% to 90% of its maximum value,
- $m_r$ – ratio of the transistor current at time $t_r$ to the $I_{T\max}$ value $(m_r \le 1)$.

As previously mentioned, the resonant discharging process of the capacitor $C1$ occurs in the circuit $T1a$, DC source, $L2a$, $D2z$. Assuming that in the initial stage of this process the current of the coil $L1b$ rises linearly and the voltage change of the capacitor $C1$ is not significant, the inductance of the coils $L1a$, $L2a$ can be determined using the formula:

$$L_{1,2a} = \frac{U_{DC}\left(m_C - 1\right)t_r}{m_r\, I_{T\max}} \tag{4}$$

where:

$m_C$ – ratio of the maximum capacitor voltage with respect to the UDC supply voltage.

The current of the coil $L1b$ flows through diode $DT1a$ after the turn-off process of the transistor $T1$ (Fig. 9); so the magnetic field energy associated with the coil $L1b$ is converted into energy of the electric field in the capacitor $C1$. Hence, the capacitance of the capacitors $C1$, $C2$ can be determined using the following formula:

$$C_{1,2} = L_{1,2b} \frac{I_{T\max}^2}{(m_C U_{DC})^2}. \tag{5}$$

The value of the coefficient $m_C$ depends on the DC supply voltage and on the maximum load current. It is necessary to stress that all IGBTs should be selected with respect to the maximum voltage that can occur on the capacitors, and the determination of the inductances $L_{1,2a}$, $L_{1,2b}$ is a bit simplified, because in reality the negative magnetic coupling between coils also should be taken into considerations.

As a result of the application of the negative magnetic couplings between appropriate coils, the current of the coil $L1b$ decreases to zero after the turn-off processes of both the main and auxiliary transistors. The current of the coil $L1b$ decreases to zero when the diode $D2z$ is in the reverse region; at the end of this process, the whole load current flows only through the diode $D2$. An equivalent circuit diagram of the given soft switching system for the considered process is shown in Fig. 10. It is assumed that the load current does not change its value, so this current can be replaced by a current source. On the basis of the second Kirchhoff's law we can write the following equation for the mesh consisting of the coils $L1b$, $L2a$, conducting diodes $D1s$, $D2$ and non-conducting diode $D2z$ (voltage drops on the diodes $D1s$, $D2$ are neglected):

$$L_{1b} \frac{di_{L1b}}{dt} + u_{D2z} - M \frac{di_{L1b}}{dt} = 0 \tag{6}$$

where:

$u_{D2z}$ – voltage on the diode D2z,

$M$ – mutual inductance $M = k\sqrt{L_{1b} L_{2a}}$,

$k$ – mutual inductance ratio.

In the considered process the diode $D2z$ should be in the reverse region, so the voltage $u_{D2z}$ on this diode has not to be higher than zero, and the derivative of the current $i_{L1b}$ has negative values. By using the mentioned conditions and the equation (6) we can determinate the value of the mutual inductance ratio $k$:

$$k \geq \sqrt{\frac{L_{1b}}{L_{2a}}} \tag{7}$$

If this condition is fulfilled, the current of the coil $L1b$ decreases to zero after the turn-off processes of both the main and auxiliary transistors. The value of the mutual inductance ratio $k$ depends on the previously determined inductances of the coils $L1a$, $L2a$ and $L1b$, $L2b$.

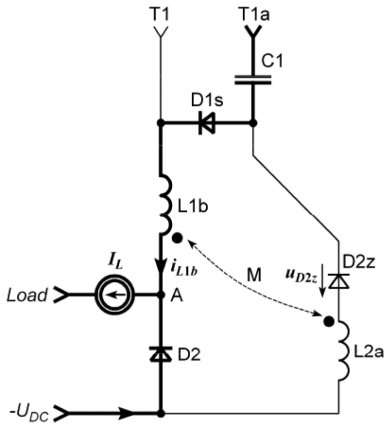

Fig. 10. An equivalent circuit diagram of the given soft switching system for the case when the current of the coil L1b decreases to zero; diode *D2z* is in the reverse region

Numerical calculated waveforms of the currents and voltages in the alternative configuration of the proposed soft switching system for different value of the coupling coefficient *k* are presented in Figs. 11 and 12. The first figure shows the waveforms for the correct selection of the ratio *k*. In turn, the next figure presents analogous waveforms for the case when the coils are not coupled magnetically; however, it does not lead to inverter failure, only transistors are switched "hard".

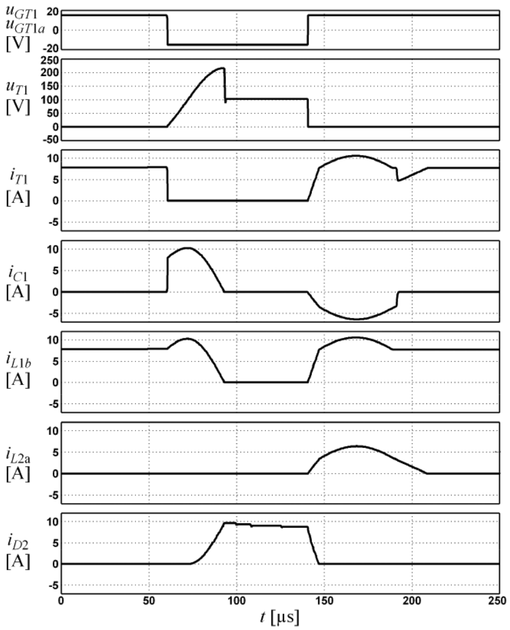

Fig. 11. Numerical calculated waveforms in the system presented in Figure 9: ($U_{DC}$ – 100 V, $I_{max}$ – 8 A, frequency – 3 kHz, C1, C2 – 0.7 µF, *L1b*, *L2b* – 550 µH, *L1a*, *L2a* – 150 µH, negative coefficient of mutual inductance – 0.52; waveform description as in Fig. 4

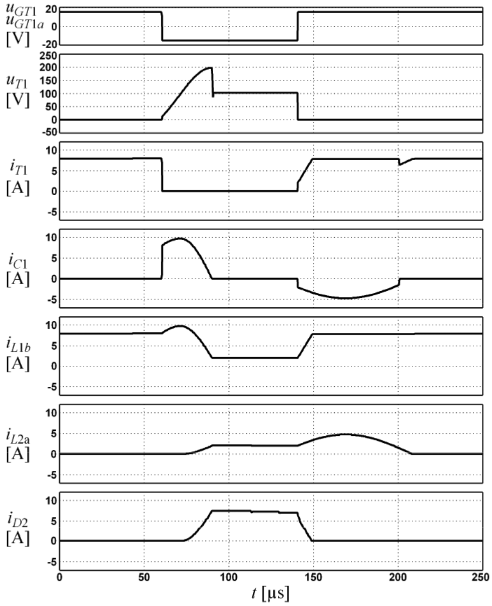


Fig. 12. Analogous waveforms as in Fig. 11 calculated for the case when the coils are not coupled magnetically

The presented research shows that for properly selected value of the mutual inductance ratio, the current of the coil $L1b$ reached zero before turn-on of the main and auxiliary transistors (Fig. 11), and in this case all transistors are soft switched using the simplest possible control algorithm; otherwise, the turn-on processes of the main transistors take place with increased losses because the turn-on process of this transistor begins at non-zero current (Fig. 12).

## 5. Conclusions

In the soft switching system, proposed in this paper, the capacitors cannot discharge rapidly through the main transistors and also it is impossible to interrupt the current of the coils when different control distortions appear. The control algorithm of the transistor switching is simple because the auxiliary transistors are turned on with a small time-delay with respect to the main transistors and the auxiliary transistors can be turned off at the same time as the main transistors. Laboratory research proofs that all transistors in the proposed soft switching system are switched softly.

The alternative solutions have several advantages with respect to the basic soft switching system. The application of the thyristors instead of the auxiliary transistors simplifies the control method, however, due to relatively long times of the thyristor turn-off process, the maximum switching frequency is lower in comparison to analogous value of the basic soft switching system. In turn, negative magnetic couplings between the appropriate coils allow us to use the same control signals for both the main and auxiliary transistors.

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