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Vector control of squirrel-cage induction motor using voltage source inverter with soft-switching technique

Sterowanie wektorowe silnika indukcyjnego przez falownik napięcia z miękkim przełączaniem tranzystorów

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Abstract: The article presents the cooperation of a three-phase voltage inverter with a soft-switching system of transistors with a squirrel-cage induction motor with field-oriented control. The operation of a voltage source inverter with a soft-switching system is briefly described. The tests have shown stable operation of the drive system and no adverse effects from the inverter with the soft-switching system on the dynamics of the drive system. A significant advantage of the presented solution is a noticeable increase in the efficiency of the system.

Keywords: power loss, soft-switching, vector control, voltage source inverter

Streszczenie: W artykule przedstawiono współpracę trójfazowego falownika napięcia z układem łagodnego przełączania tranzystorów z silnikiem indukcyjnym klatkowym ze sterowaniem polowo zorientowanym. Opisano krótko działanie falownika napięcia z układem miękkiego przełączania tranzystorów. Przeprowadzone badania wykazały stabilną pracę układu napędowego oraz brak niekorzystnego oddziaływania ze strony falownika z miękkim przełączaniem na dynamikę układu napędowego. Istotną zaletą przedstawionego rozwiązania jest zauważalne zwiększenie sprawności układu napędowego.

Słowa kluczowe: falownik napięcia, miękkie przełączanie, sterowanie wektorowe, straty mocy

Introduction

Squirrel-cage induction motors are very often used in electric drives due to their simple construction, reliability and relatively low cost. In less demanding applications, where the angular velocity of the motor is not regulated or motor dynamics are not a priority, scalar control methods are mainly used. In these control methods, the set parameters are the frequency and the effective value of the voltage supplying the motor. In the case of high dynamics of angular velocity, control and rapidly changing external load torque, the field-oriented vector control becomes more appropriate [1-5]. This solution allows direct control of the electromagnetic torque and magnetic flux of the motor.

Controlling the torque generated by a squirrel-cage induction motor is one of the important issues in electric drives. However, an equally significant problem is efficiency of drive systems. This efficiency depends not only on the induction motor but also on the voltage source inverter (VSI) supplying this motor. The VSIs are characterized by relatively efficiency, that ranges from about 94 to 99 %. Transistors, which are main elements of the VSIs, are responsible for power losses first of all. These losses can be divided into conduction losses and switching losses. The switching losses occur during the switching-on and switching-off of the inverter transistors. The share of these losses in the total balance depends on the switching frequency. The power losses also occur in the freewheeling diodes of transistors. The soft-switching systems cause a reduction of the voltage or current of the switched element to a value close to zero [6,7]. In the existing soft-switching systems, uncontrolled discharge of the capacitor connected in parallel to the main transistor or interruption of the current of an inductor connected in series with an auxiliary transistor may occur.

Field-Oriented Vector Control

The vector control method, which is applied in drive systems with squirrel-cage induction motor, is widely known and well described [1-4]. Figure 1 shows an example structure of a field-oriented vector control system with signals v_{sx}^{rs}, v_{sy}^{rs} generated by the control system. These signals are transformed into phase components v_U^{rz}, v_V^{rz}, v_W^{rz}. The set signals are the relative rotor flux ψ_r^{rs} and the rotor angular velocity ω^{rs}.

The set relative values of the rotor flux and angular velocities are introduced into the control system. Based on the measured actual angular velocity and the calculated actual rotor flux, errors of these values are introduced into the inputs of appropriate controllers. The rotor flux controller $R\psi$ generates an output signal of the set x-axis current, which is compared with the calculated x-component of the actual stator current. The difference between these currents is introduced into the x-component input of the stator current controller Ri_x. The output signal v_{Rx}^{rs} of this controller, after taking into account the decoupling voltage e_x^r, constitutes the set x-component of the relative stator voltage v_{sx}^{rs}. The output signal of the angular velocity controller $R\omega$ refers to the y-component of the set relative stator current i_{sy}^r. After taking into account the calculated actual value of this current component, the control error is introduced in the input of the y-component of the stator current controller Ri_y. The signal obtained at the output of this controller, after decoupling the calculated voltage e_y^r, constitutes the set y-component of the relative stator voltage v_{sy}^{rs}. Both components of the set stator voltage are transformed into phase coordinates v_U^{rz}, v_V^{rz}, v_W^{rz}, which control the operation of the VSI.

VSI with soft-switching system

One phase of the VSI with the proposed soft-switching technique is shown in Figure 2 [8,9]. The capacitors C1, C2 reduce the steepness of the voltage increase in the main transistors T1, T2 during the turn-off processes. The inductors L1b, L2b, which connect the main transistors to the load terminal A, limit the rate of current increase in these transistors during their turn-on processes. The resonant discharge current of the capacitors C1, C2 is limited by the inductors L1a, L2a, connected in series with the diodes D1z, D2z, respectively. The negative magnetic coupling M between the inductors L1b, L2b to zero after they are turned off.

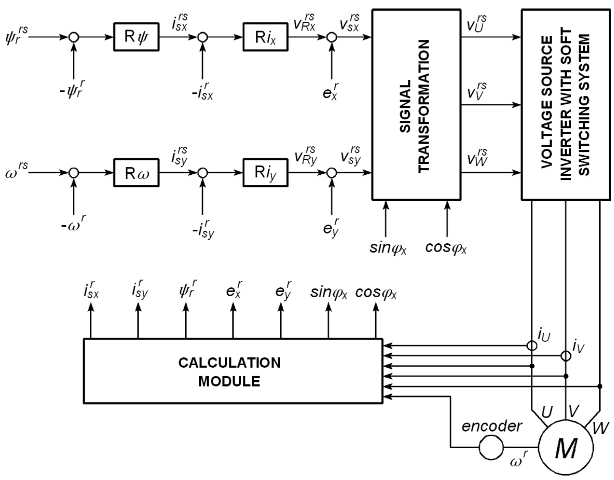

Fig. 1. Structure of control system with field-oriented vector control of squirrel-cage induction motor

Simplified waveforms of control signals and selected voltages and currents in the VSI with the modified soft-switching system are shown in Figure 3.

The detailed description of the soft-switching of transistors and the selection of transistors and reactive elements are discussed in detail in [8]. These papers present, among others, the waveforms of the voltages and currents of transistors during their switching in the VSI with the presented soft-switching system of transistors.

To verify the functionality of the described soft-switching method, a three-phase laboratory VSI with the rated power of 10 kW was constructed. It utilized an IGBT-type SKM100GB176D and a diode-type DSEP30-12A. The inverter was supplied with a voltage of 400 V, and the permissible load current was 12 A. Measurements were conducted using a laboratory inverter with a squirrel-cage induction motor (P_N = 3 kW, V_N = 230/400 V Δ/Y). The inverter operated with sinusoidal pulse width modulation.

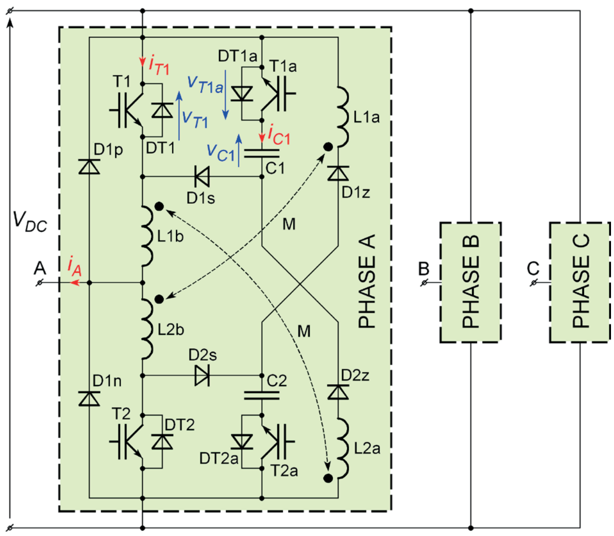

Fig. 2. One phase of soft-switching system in three-phase VSI; M represents a magnetic coupling

The waveforms of the phase-to-phase voltage, phase voltage, phase current of the induction motor, and the current of the main transistor T1 in the soft-switching system are shown in Figure 3. Analogous waveforms are depicted in Figure 4 during the regenerative braking of the induction motor.

In the VSI with the described soft-switching system, capacitors are not connected in parallel with the main transistors or inductors in series with the auxiliary transistors. Consequently, capacitor discharges through the main transistors, and abrupt interruptions in the inductor currents are eliminated.

The soft-switching processes do not affect the shape of the phase-to-phase voltage or the phase voltage of the load, which is crucial for protecting the windings of the motor and insulation from exceeding their rated voltage.

Additionally, the control system is significantly simplified because the auxiliary transistors are controlled by the same signal as the main transistors, enhancing the reliability of VSIs operating with the soft-switching system. Laboratory tests confirmed that both the main and auxiliary transistors switched softly, significantly reducing the switching losses and improving the efficiency of the VSIs.

Analysis of vector control of induction motor supplied by inverter with soft-switching technique

The use of soft-switching system is recommended for VSIs with a rated power of at least 1 MW, because then VSIs are built based on IGBTs. These inverters with lower power ratings are constructed using SiC-MOSFETs, which have shorter switching times compared to IGBTs. Therefore, such inverters can operate at higher switching frequencies and with lower switching losses.

Control methods with the field vector orientation are already used in drive systems with a rated power of about a dozen or so kW. To show the possibilities and effects of the described soft-switching system in the vector control of an induction motor, the analysis of the operation of the drive system with the vector control method was performed for a squirrel-cage induction motor with a rated power of 1 MW (model: Y2-500L2-6, $V_N = 660$ V, $I_N = 1002$ A, $n_N = 995$ r/min, $cos\varphi_N = 0.86$, $\eta_N = 96.8$ %, $J = 72.3$ kgm^2). In the linear model of the squirrel-cage induction motor, only the fundamental harmonic of the magnetic field was taken into account. It was assumed that the inverter was made on the basis of Insulated-gate bipolar transistors (IGBTs) type CM1500HC-90XA (4500 V, 1500 A).

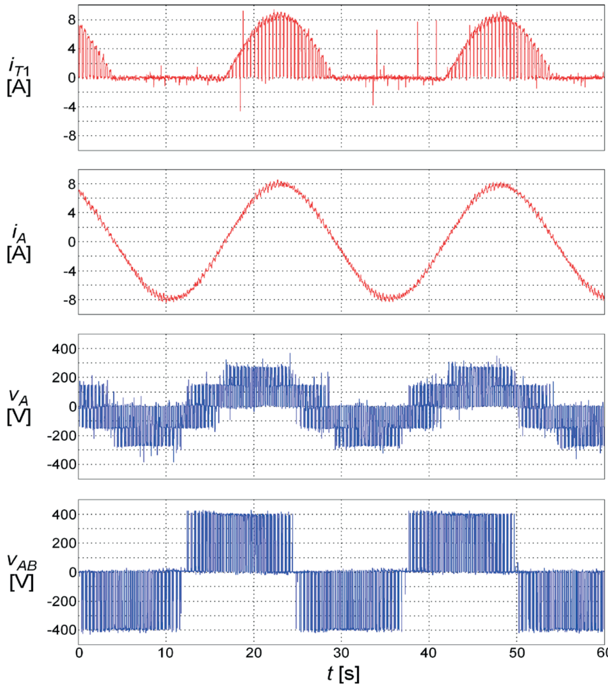

Fig. 3. Waveforms in two output-voltage periods while motor was supplied: i_{T1} – current of transistor T1; i_A and v_A – phase current and voltage of induction motor, respectively; and v_{AB} – phase-to-phase output voltage of inverter

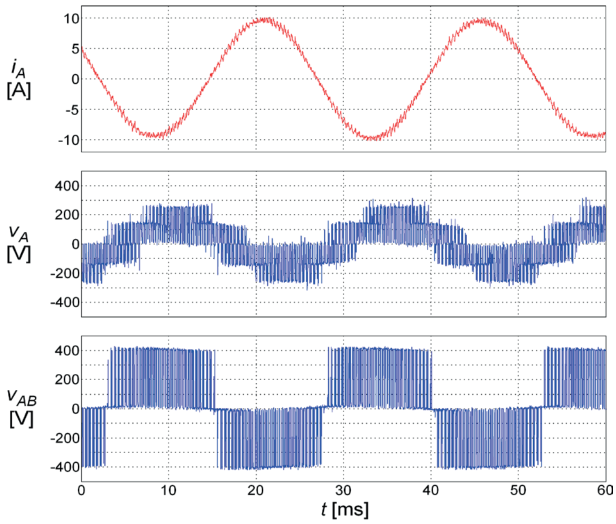

Fig. 4. Waveforms in two output-voltage periods while motor was braked to provide energy to DC voltage source: i_A and v_A – phase current and voltage of induction motor, respectively; and v_{AB} – phase-to-phase output voltage of inverter

The conduction voltage drop of IGBTs, and processes related to their switching were considered. The capacitors were modeled as ideal elements, having only capacitance. The winding resistance of the inductors was also taken into account. The parameters of the passive components for $k_{max} = 2.0$ were as follows: $C = 3.9$ µF, $L_a = 5.1$ µH, $L_b = 2.2$ µH, M = 2.2 µH; k_{max} denotes the ratio of the permissible voltage value on the main transistors and capacitors in relation to the supply voltage V_{DC}. Numerical calculations were performed using Isspice software.

The analysis was performed for the case when the induction motor was supplied by a VSI with hard-switching technique, and for the same operating conditions, when this motor was supplied by the VSI with soft-switching technique. Attention was paid to the dynamics of the motor operation with the vector control, checking whether the supplying from a VSI with the soft-switching did not deteriorate the dynamic parameters. The efficiency of the VSI with both switching techniques of transistors was analyzed. The individual losses were determined as the integral of the product of the current and voltage on a given inverter element. A comparison of the higher harmonic content in the induction motor currents was also made. The switching frequency was 4 kHz. For comparison, Figure 5 shows the voltage and current waveforms of the transistor T1 with hard- and soft-switching technique, respectively.

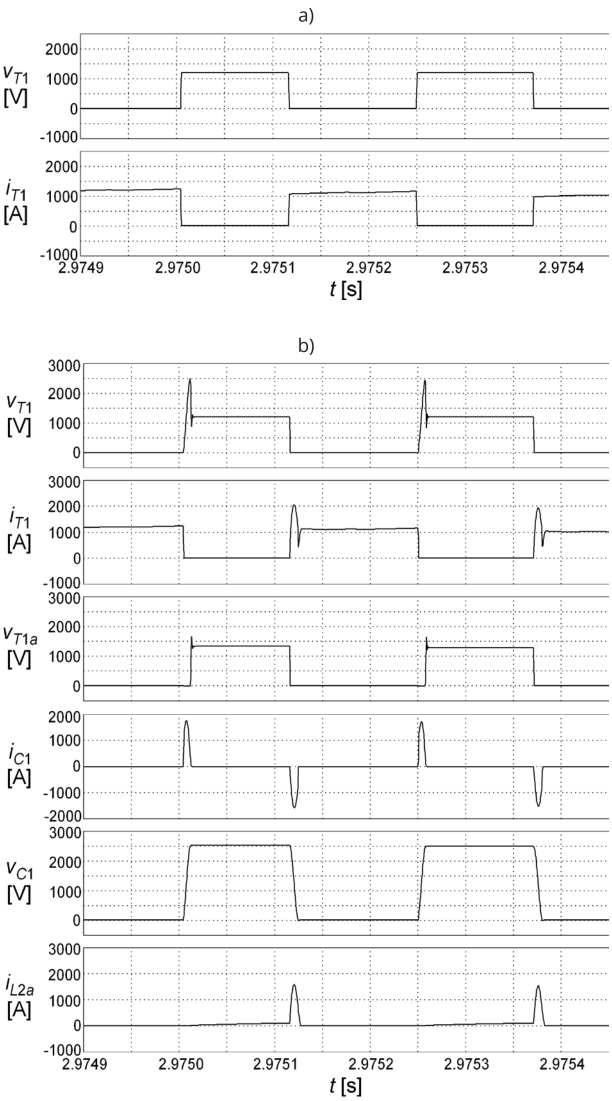

Fig. 5. Waveforms of voltage and current of transistor T1 of the VSI with: a) hard-switching technique, b) soft-switching technique; v_{T1}, i_{T1} – voltage and current of transistor T1, respectively, v_{T1a} – voltage of transistor T1a, i_{C1}, v_{C1} – current and voltage of capacitor C1, respectively, i_{L2a} – current of inductor L2a

It should be emphasized that the relatively short voltage increases on transistor T1 are not overvoltages, but the effect of the resonance processes related to the soft-switching of transistors. To ensure a soft turn-on process of the transistor T1, the voltage across capacitor C1 should be approximately twice as high as the supply voltage V_{DC}. This condition is included when selecting transistors and capacitors. Note that drive systems with an induction motor with rated voltage above 6 kV often have a transformer between the VSI and the induction motor. Therefore, the VSI can operate at lower voltage.

Figure 6 shows results of numerical calculations regarding the dynamics of the squirrel-cage induction motor supplied by the VSI with the hard-switching technique. At the beginning, the magnetic flux was induced in the motor to the assumed relative value of 1. The induction motor starts in 0.8 s to 1.8 s. In the time interval from 2.5 s to 3.0 s, the motor is loaded with the rated torque. At 3.5 s, the motor starts to reverse which lasts up to 5.5 s. In the range from 6 s to 6.5 s, the motor is loaded with the rated torque of the opposite sign.

The calculated factor of the Total Harmonic Distortion (THD) of the stator current for the motor supplied by the inverter with hard-switching technique and loaded with a positive rated external torque is 2.47%. For the induction motor operating under the

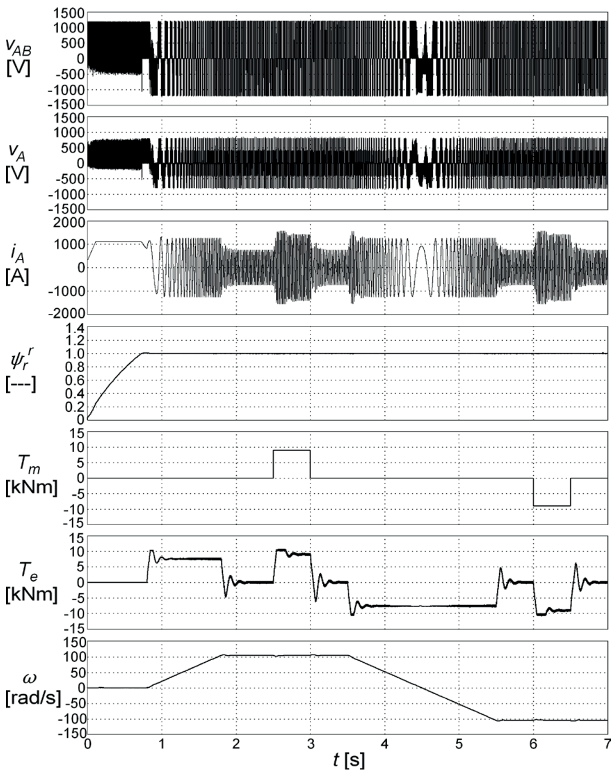

Fig. 6. Calculated waveforms of electrical and mechanical variables when the induction motor was supplied by VSI with hard-switching technique: v_{AB} – phase to phase voltage, v_A – phase voltage, i_A –motor phase current, ψ_r^r – relative rotor flux, T_m – load torque, T_e – electromagnetic torque, ω – rotational velocity of the rotor

same conditions and supplied by the VSI with the soft-switching system, the stator current THD is 2.42 %. Both values are very close, and they are within the limits of accuracy. This indicates that the use of the proposed soft-switching system does not adversely affect motor operation.

Table 1 shows the inverter efficiency for several load power values and three assumed values of the k_{max}.

The efficiency of the VSIs depends not only on the switching frequency but also on the switching technique of transistors. The efficiency of the 1 MW VSI with the soft-switching system is about 4 % higher than the efficiency of the VSI with the hard-switching technique at the rated load power. Notably that the efficiency of drive systems is the product of the efficiency of both the inverter and induction motor.

Table 1. Efficiency of the VSI with hard- and soft-switching technique; switching frequency 4 kHz

Switching technique	$0.25P_N$ [%]	$0.5P_N$ [%]	$0.75P_N$ [%]	P_N [%]
hard-switching	92.79	93.60	94.42	94.80
soft-switching $k_{max} = 1.5$	95.18	97.03	97.84	98.29
soft-switching $k_{max} = 2.0$	96.44	97.81	98.42	98.72
soft-switching $k_{max} = 2.5$	97.31	92.22	98.69	98.95

The resonant processes concerning the soft-switching technique do not affect the shape of the voltage supplying the squirrel-cage induction motor. The content of the higher harmonics of the motor currents is similar to that which are generated by inverter with hard-switching system.

Conclusions

Supplying squirrel-cage induction motors from voltage source inverters with the soft-switching technique does not degrade the dynamics of the motor. The speed changes are the same as when the induction motor was supplied by the inverter with the hard-switching technique. The drive system operates correctly for both directions of energy flow between the inverter and the induction motor.

It is important to emphasize that the efficiency of inverter with soft-switching system can be approximately 4 % higher than that of the inverter with the hard-switching technique. As a result, using voltage source inverters with the soft-switching system can significantly lead to increased efficiency of the drive system.

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