

Field-oriented control of five-phase induction motor with open-end stator winding

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Abstract: The mathematical model of the five-phase squirrel-cage induction motor and the system of the dual five-phase voltage source inverter have been presented. The control methods and control systems of the field-oriented control of the five-phase induction motor with an open-end stator winding are described. The structures of the direct field-oriented control system (DFOC) and the Indirect Field-oriented control system (IFOC) with PI controllers in outer and inner control loops are analyzed. A method of space vector modulation used to control the system of the dual five-phase voltage source inverter has been discussed. The results of simulation studies of the field-oriented control methods are presented. Comparative analysis of the simulation results was carried out.

Key words: analysis, field-oriented control, five-phase induction motor, open-end winding, simulation studies, space-vector modulation

1. Introduction

Nowadays three-phase squirrel cage induction motors are widely used in the industrial drive systems. In recent years, there is a great interest in using the constructions of squirrel-cage induction motors with the number of phases of the stator winding greater than three. Motors of this design are called multi-phase motors [2, 4-9].

Multi-phase squirrel-cage induction motors have a lot of advantages in comparison to conventional three-phase induction motors [2, 4-9]. The nominal values of the phase currents in multi-phase systems are smaller than the nominal values of the phase currents in the three-phase systems with the same power ratings. Other beneficial properties of the multi-phase induction motors include: reduction of the amplitudes of pulsating components of the motor electromagnetic torque, reduction of losses caused by higher harmonics of motor currents and reduction of the amplitude of the current harmonics in the dc link of frequency converter. In addition, the multi-phase induction motors allow to ensure greater reliability of the drive

systems. Motors with a phase number greater than three may be operated conditionally at failure of one or more phases of the stator windings. Development of frequency converter control systems provides the possibility of industrial applications of these types of motors. Power frequency converters can be built for a larger number of phases during powering from the three phase mains.

Induction motors with an open-end stator winding with dual-inverter supply have been extensively investigated for various applications, for example series hybrid power vehicles and fault-tolerant drives. The topology is simple to realize while offering a higher number of switching states in comparison to standard converters and allows to increase the accuracy of control [1, 3, 10]. The control structures of the multi-phase induction motor with an open-end stator winding allow to generate voltage waveforms, which are comparable with voltage waveforms obtained from multilevel inverters.

In this paper the theoretical analysis and simulation research were performed for the control systems of the five-phase induction motor with an open-end stator winding. The open-end stator winding of the motor is fed and controlled by the system which consists of two voltage source inverters, connected to the beginnings and the ends of five-phase stator winding terminals.

2. Mathematical model of five-phase induction motor

The mathematical model of the five-phase squirrel-cage induction motor has been formulated on the basis of commonly used simplifying assumptions [2, 4, 8]: a multi-phase stator and rotor phase windings are considered as concentrated, a motor magnetic circuit is linear, the effects of eddy currents and iron losses are neglected, the values of parameters and variables of the rotor phase winding are converted to the stator winding side.

The mathematical model of the five-phase induction motor is described by differential equations with coefficients changing as a function of the angle of rotor rotation. Equations with constant coefficients can be obtained by the use of suitable power invariant transformations of the stator and rotor phase variables. The non-power-invariant forms of transformation matrices for stator and rotor phase variables are presented in detail in [4-9]. The stator and rotor phase variables of the five-phase induction motor can be transformed to new variables considered in the transformed coordinate systems: the x - y coordinate system, which rotates at arbitrary angular speed ω_k (in case $\omega_k = 0$ the stationary coordinate system is denoted as α - β), the additional coordinate system z_1 - z_2 and the system of zero components.

The equations of the five-phase induction motor after transformation take the following form [4-9]:

- the voltage equations of the stator and rotor in the x - y coordinate system, which rotates at arbitrary angular speed ω_k :

$$u_{sx} = R_s i_{sx} - \omega_k \psi_{sy} + p \psi_{sx}, \quad (1)$$

$$u_{sy} = R_s i_{sy} + \omega_k \psi_{sx} + p \psi_{sy}, \quad (2)$$

$$0 = R_r i_{rx} - (\omega_k - \omega_e) \psi_{ry} + p \psi_{rx}, \quad (3)$$

$$0 = R_r i_{ry} + (\omega_k - \omega_e) \psi_{rx} + p \psi_{ry}, \quad (4)$$

– the stator voltage equations in the additional coordinate systems $z1$ - $z2$:

$$u_{sz1} = R_s i_{sz1} + p \psi_{sz1}, \quad (5)$$

$$u_{sz2} = R_s i_{sz2} + p \psi_{sz2}, \quad (6)$$

– the equation of motor electromagnetic torque:

$$T_e = (5/2) p_b (\psi_{sy} i_{rx} - \psi_{sx} i_{ry}) = (5/2) p_b (\psi_{ry} i_{sx} - \psi_{rx} i_{sy}), \quad (7)$$

where: u_{sx} , u_{sy} , u_{sz1} , u_{sz2} are components of the stator voltage vectors in the x - y and $z1$ - $z2$ systems; i_{sx} , i_{sy} , i_{sz1} , i_{sz2} , i_{rx} , i_{ry} are components of the stator and rotor current vectors in the x - y and $z1$ - $z2$ systems; ψ_{sx} , ψ_{sy} , ψ_{sz1} , ψ_{sz2} , ψ_{rx} , ψ_{ry} are components of the stator and rotor flux linkage vectors in the x - y and $z1$ - $z2$ systems; ω_k is the arbitrary angular speed of the coordinate system relative to the stator; ω_e is the electrical angular speed of the motor; T_e is the motor electromagnetic torque; R_s , R_r are the stator and rotor phase resistances; p_b is the number of motor pole pairs; $p = d/dt$ is the derivative operator.

In the above system the equations for stator and rotor zero components and the rotor voltage equations in the additional coordinate systems $z1$ - $z2$ are omitted, because they are identically equal to zero.

3. Mathematical model of the system of dual five-phase voltage source inverter

The scheme of the five-phase squirrel-cage induction motor with the open-end stator winding supplied by the dual five-phase voltage source inverter is shown in Fig 1. The dual five-phase voltage source inverter consists of two conventional five-phase voltage source inverters. The individual inverters and their elements are marked by indices 1 and 2. The inverter legs are denoted with capital letters A , B , C , D , E and the neutral points of the two dc links are identified as $N1$ and $N2$. The machine stator phases are labeled as a , b , c , d and e [1, 3, 10]. It is assumed that the both inverters are supplied from separate ideal DC voltage sources and that the voltage values u_{d1} and u_{d2} are the same for the two inverters.

In the case of a two-level voltage source inverter, each inverter branch consists of two power electronics keys operated alternately. Each branch of the inverter can be presented as a binary switch, assuming an ideal operation of the voltage source inverters keys.

The phase voltages of the stator winding can be described as:

$$u_{sa} = u_{A1N1} + u_{N1N2} - u_{A2N2}, \quad (8)$$

$$u_{sb} = u_{B1N1} + u_{N1N2} - u_{B2N2}, \quad (9)$$

$$u_{sc} = u_{C1N1} + u_{N1N2} - u_{C2N2}, \quad (10)$$

$$u_{sd} = u_{D1N1} + u_{N1N2} - u_{D2N2}, \quad (11)$$

$$u_{se} = u_{E1N1} + u_{N1N2} - u_{E2N2}. \quad (12)$$

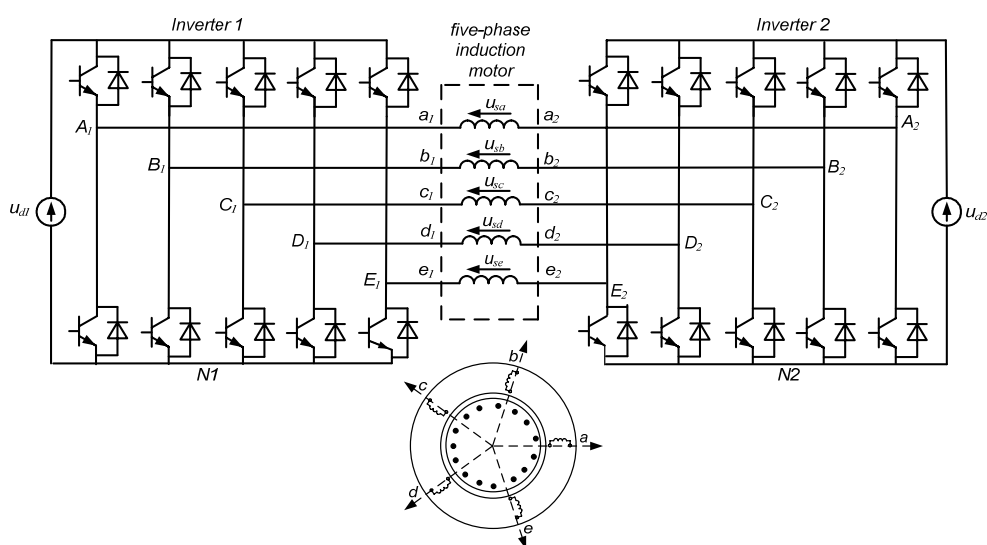


Fig. 1. Five-phase induction motor with open-end stator winding supplied by two voltage source inverters

The voltage space vectors generated by the inverter 1 and 2 expressed in the stationary rectangular coordinate systems α - β and in the system $z1$ - $z2$ can be determined in general form:

$$\underline{u}_{\alpha\beta i} = u_{\alpha i} + ju_{\beta i} = \frac{2}{5} \left(u_{A1N1} + \underline{a} u_{B1N1} + \underline{a}^2 u_{C1N1} + \underline{a}^3 u_{D1N1} + \underline{a}^4 u_{E1N1} \right), \quad (13)$$

$$\underline{u}_{z1z2 i} = u_{z1 i} + ju_{z2 i} = \frac{2}{5} \left(u_{A1N1} + \underline{a}^2 u_{B1N1} + \underline{a}^4 u_{C1N1} + \underline{a}^6 u_{D1N1} + \underline{a}^8 u_{E1N1} \right), \quad (14)$$

where: $i = 1, 2$; $\underline{a} = \exp(j2\pi/5)$.

The stator voltage space vectors of the five-phase induction motor with the open-end winding in the coordinate systems α - β and $z1$ - $z2$ are equal to the difference of the corresponding output voltage space vectors of individual inverters. This condition can be described by the following formulas:

$$\underline{u}_{s\alpha\beta} = \underline{u}_{\alpha\beta 1} - \underline{u}_{\alpha\beta 2}, \quad (15)$$

$$\underline{u}_{sz1z2} = \underline{u}_{z1z2 1} - \underline{u}_{z1z2 2}. \quad (16)$$

All output voltage vectors generated by individual five-phase voltage source inverters are presented in Fig. 2 [4]. Voltage vectors designated in coordinate system α - β are shown in Fig. 2a and voltage vectors designated in coordinate system $z1$ - $z2$ are shown in Fig. 2b.

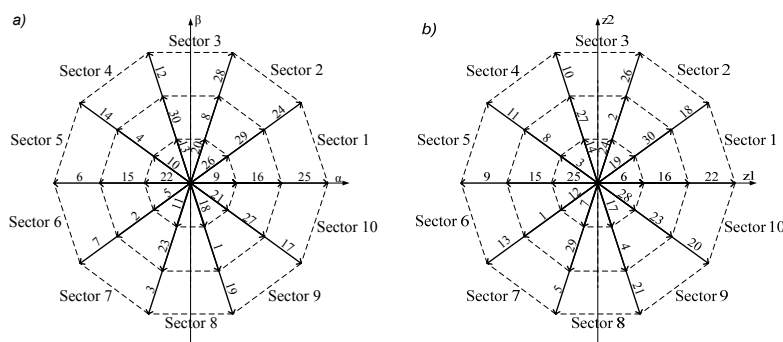


Fig. 2. Voltage space vectors generated by five-phase voltage source inverter: a) in coordinate system α - β ; b) in coordinate system $z1$ - $z2$

All output voltage space vectors generated by the five-phase voltage source inverter considered in coordinate systems α - β and $z1$ - $z2$ can be divided into thirty active vectors and two zero vectors. Thirty active voltage space vectors can be divided into three groups taking into account the length of the vector: 10 long vectors, 10 medium vectors and 10 short vectors. In Fig. 2 the zero voltage vectors were marked with the numbers 0 and 31 and the active voltage vectors were marked with the numbers from 1 to 30. The decimal number specifying the number of voltage vector can be converted into a 5-position number in the binary system. The binary bits determine states of the switches in the suitable legs of the five-phase voltage source inverter. Voltage vectors in coordinate system $z1$ - $z2$ are not involved in the generation of the motor electromagnetic torque, but they can cause enlargement of the amplitude of the stator phase currents and the power losses in the stator windings.

4. Space vector modulation method

Space vector modulation (SVM) is widely used for the control of voltage source inverters with three-phase induction motors. This modulation technique can be also implemented for the control of the dual system of the five-phase voltage source inverters, used for the five-phase induction motor with an open-end stator winding. But there are some difficulties in the application of the principle of the space vector modulation to multiphase inverters. For example, in the five-phase inverter there are $2^5 = 32$ voltage space vectors as illustrated in Fig. 2. Due to a great number of generated voltage space vectors it is not practical for using all these voltage vectors in the modulation technique. For this reason in the system of the dual five-phase voltage source inverter used for the five-phase induction motor with an open-end stator winding the modified concept of conventional modulation has been adopted.

The block diagram of the space vector modulation method used to control the system of the dual five-phase voltage source inverter is shown in Fig. 3 [1, 3]. Two space vector modulators: SVM 1 and SVM 2 are used in this control structure. The value of the reference stator voltage space vector \underline{u}_{sref} is multiplied by 0.5 and -0.5 . It means, that the reference stator voltage vector is divided into two reference voltage vectors \underline{u}_{1ref} , \underline{u}_{2ref} with opposite directions and two times smaller magnitudes. These two new reference voltage vectors are applied to individual space vector modulators and are synthesized by the selection of the appropriate voltage space vectors of individual inverters and the dwell times.

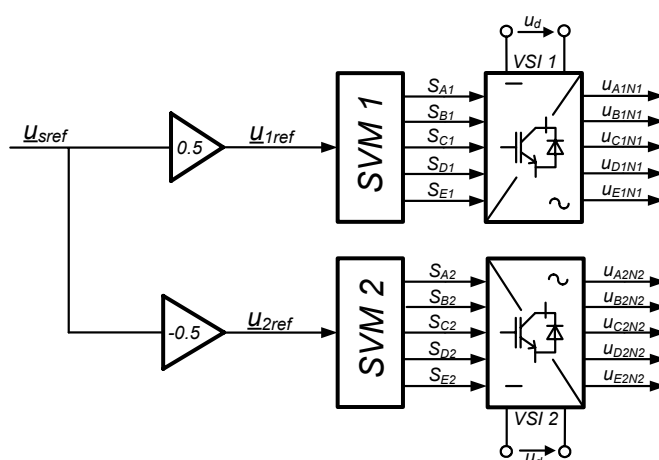


Fig. 3. Block diagram of the space vector modulation method used to control the system of the dual five-phase voltage source inverter

The space vector modulation of each inverter has been based on the synthesis of the reference voltage vector by using the appropriate switching times of two long and two medium inverter voltage vectors, chosen from the same sector in which the reference voltage vector is located and using additionally two zero voltage vectors. Graphical interpretation of the space vector modulation method used for SVM 1 and SVM 2 is shown in Fig. 4.

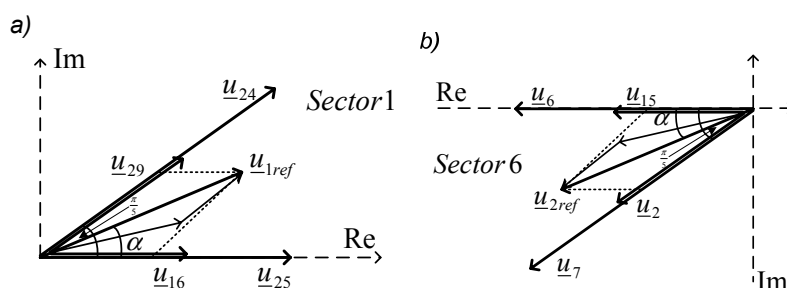


Fig. 4. The principle of determining the reference voltage vector with the choice of long and medium inverter voltage vectors: a) for SVM 1; b) for SVM 2

For example, when reference voltage vector \underline{u}_{1ref} falls into Sector 1, as shown in Fig. 4a it can be synthesized by four adjacent active vectors and two zero vectors. The two adjacent long voltage vectors: \underline{u}_{25} , \underline{u}_{24} , two adjacent medium voltage vectors: \underline{u}_{16} , \underline{u}_{29} and two zero voltage vectors: \underline{u}_0 , \underline{u}_{31} are selected for modulation. For the reference voltage vector \underline{u}_{2ref} situated in Sector 6, as shown in Fig. 4b it can be also synthesized by four adjacent active vectors and two zero vectors. The two adjacent long voltage vectors: \underline{u}_6 , \underline{u}_7 , two adjacent medium voltage vectors: \underline{u}_{15} , \underline{u}_2 and two zero voltage vectors: \underline{u}_0 , \underline{u}_{31} are selected for modulation.

For the case when the reference voltage vectors are located in sector 1 and 6, the principle of the space vector modulation method for SVM 1 and SVM 2 can be described by the equations:

a) for SVM 1:

$$\underline{u}_{1ref} \cdot T_s = \underline{u}_{25} \cdot t_{al} + \underline{u}_{24} \cdot t_{bl} + \underline{u}_{16} \cdot t_{am} + \underline{u}_{29} \cdot t_{bm} + \underline{u}_0 \cdot t_0/2 + \underline{u}_{31} \cdot t_0/2, \quad (17)$$

b) for SVM 2:

$$\underline{u}_{2ref} \cdot T_s = \underline{u}_6 \cdot t_{al} + \underline{u}_7 \cdot t_{bl} + \underline{u}_{15} \cdot t_{am} + \underline{u}_2 \cdot t_{bm} + \underline{u}_0 \cdot t_0/2 + \underline{u}_{31} \cdot t_0/2. \quad (18)$$

Besides the generation of two above described reference voltage vectors in the α - β coordinate system, the reference voltage vectors which are equal to zero in the $z1$ - $z2$ coordinate system were also generated. Switching times of individual voltage vectors are calculated according to the equations [1]:

$$t_{al} = 2 \sin(2\pi/5) \cdot \sin(s \cdot \pi/5 - \alpha) \cdot (u_{sref}/u_d) \cdot T_s, \quad (19)$$

$$t_{bl} = 2 \sin(2\pi/5) \cdot \sin[\alpha - (s-1) \cdot \pi/5] \cdot (u_{sref}/u_d) \cdot T_s, \quad (20)$$

$$t_{am} = 2 \sin(\pi/5) \cdot \sin(s \cdot \pi/5 - \alpha) \cdot (u_{sref}/u_d) \cdot T_s, \quad (21)$$

$$t_{bm} = 2 \sin(\pi/5) \cdot \sin[\alpha - (s-1) \cdot \pi/5] \cdot (u_{sref}/u_d) \cdot T_s, \quad (22)$$

$$t_0 = T_s - t_{al} - t_{am} - t_{bl} - t_{bm}, \quad (23)$$

where: t_{al} , t_{bl} are switching times of long voltage vectors; t_{am} , t_{bm} are switching times of medium voltage vectors; t_0 is the switching time of zero voltage vectors; u_{sref} the magnitude of the reference voltage vector; T_s is a switching period; α is the angle position of reference voltage vector; s is a sector number ($s = 1, \dots, 10$).

5. Field-oriented control systems

In this paper the methods of rotor field oriented control of the five-phase induction motor with an open-end stator winding are considered. The rotor field oriented control systems can be generally classified into Direct Field-Oriented Control (DFOC) and Indirect Field-Oriented Control (IFOC).

The block diagram of the Direct Field-Oriented Control system of the five-phase induction motor with an open-end stator winding is shown in Fig. 5.

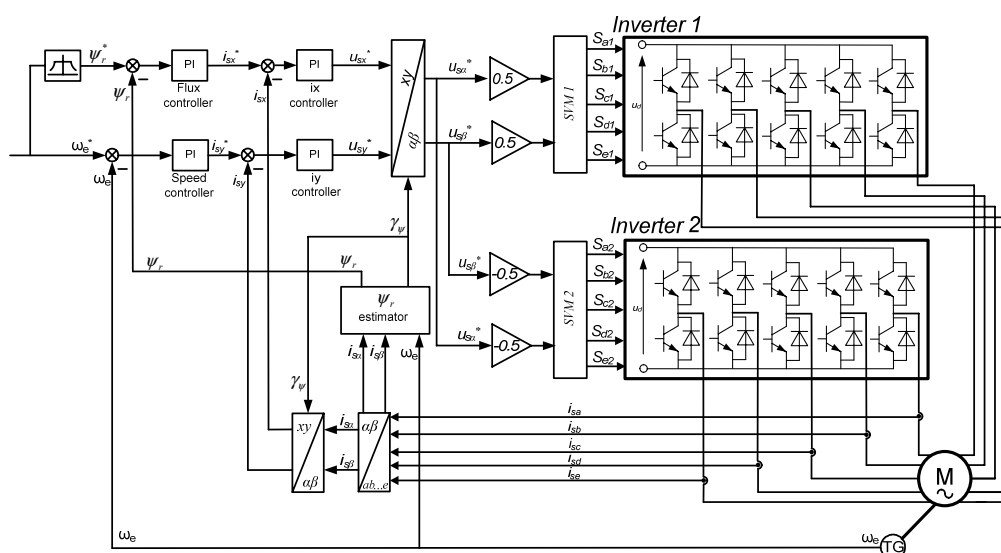


Fig. 5. The Direct Field-Oriented Control system of five-phase induction motor with open-end stator winding

To implement the DFOC scheme the estimator of the instantaneous magnitude of the rotor flux vector and the instantaneous angle of the rotor flux vector has been used. The estimator is based on the measured stator phase currents and motor angular speed. In the control scheme two outer control loops are applied: the control loop for motor angular speed and the control loop for magnitude of the rotor flux vector. In the speed control loop the reference motor speed is compared with the actual motor speed and the error signal is given to the PI controller. An output signal from the PI controller is the reference value of the y component of the stator current vector which is responsible for electromagnetic torque control. In the flux control loop the reference magnitude of rotor flux is compared with the estimated magnitude of rotor flux and the output signal is given to the PI flux controller. An output signal from this PI controller is the reference value of the x component of the stator current vector which is responsible for the rotor flux control. Then the reference values of x and y components of the stator current vector are compared with the transformed values of measured stator phase currents and the error signals are given to the inner PI controllers. Reference values of the stator voltage vector components determined by the PI controllers are transformed to the α - β coordinate system and afterwards given to the space vector modulators. Space voltage modulators set the switching states in the system of the dual five-phase voltage source inverter.

The Indirect Field-Oriented Control system of the five-phase induction motor with an open-end stator winding is shown in Fig. 6.

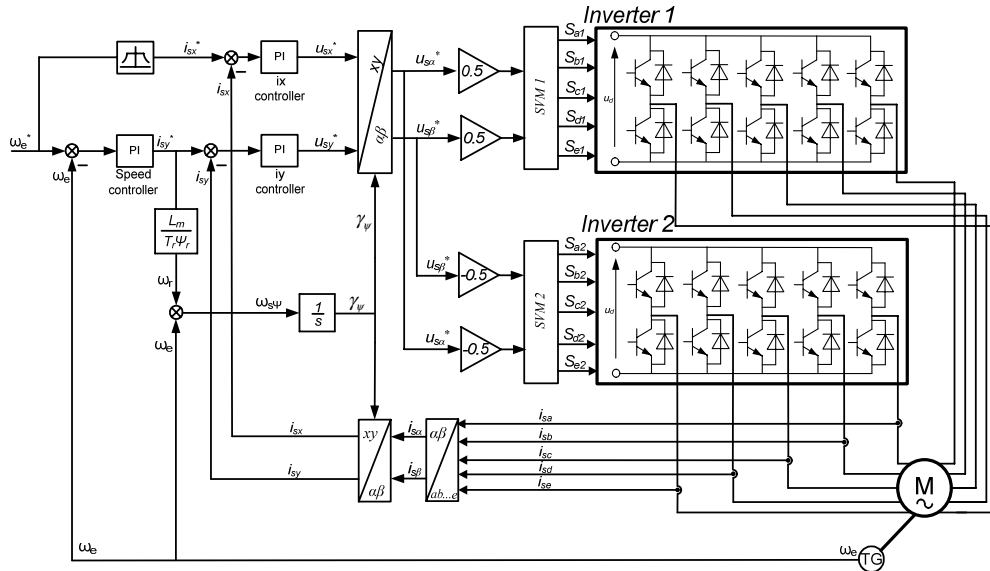


Fig. 6. The Indirect Field-Oriented Control system of the five-phase induction motor with an open-end stator winding

To implement the IFOC scheme the angle of the rotor flux vector for field orientation is obtained by measuring the motor speed and calculation of slip angular frequency. In this control system the rotor slip frequency is calculated. The slip angular frequency is added to the signal of the measured electrical angular speed of the motor and the output value is integrated in order to obtain the instantaneous angle position of the rotor flux vector.

Three control loops are applied in this control system: the loop of motor speed control and the loops of x and y components of the stator current vector. In the loop of speed control the reference speed is compared with the actual speed of the five-phase induction motor and the error signal is given to the PI controller. The output signal from the PI controller is the reference value of y component of the stator current vector which is responsible for electromagnetic torque control. The reference value of x component of the stator current vector is specified in accordance with the equation: $i_{sx}^* = \psi_r / L_m$. The reference values of x and y components of the stator current vector are compared with the transformed values of measured stator phase currents and the error signals are given to the PI controllers. Reference values of the stator voltage components determined by the PI controllers are transformed to the α - β coordinate system and afterwards given to the space vector modulators. Space voltage modulators set the switching states in the system of the dual five-phase voltage source inverter.

6. Simulation results

Simulation studies were carried out for the 5-phase squirrel-cage induction motor with an open-end stator winding with the data and parameters: $P_N = 3 \text{ kW}$, $U_{fN} = 230 \text{ V}$, $f_N = 50 \text{ Hz}$, p_b

$= 2$, $R_s = 10 \Omega$, $R_r = 6.3 \Omega$, $L_{ls} = 0.04 \text{ H}$, $L_{lr} = 0.04 \text{ H}$, $L_m = 0.42 \text{ H}$. Simulation studies were carried out for two field-oriented control methods: Indirect Field Oriented Control (IFOC) and Direct Field Oriented Control (DFOC).

The studies of the induction motor with an open-end stator winding and dual converter system were performed for the assumed trapezoidal form of time changes of reference motor electrical speed. The step changes of load torque were applied after transition to steady-state operation. The time waveforms of reference speed and electrical speed of the motor are shown in Fig. 7.

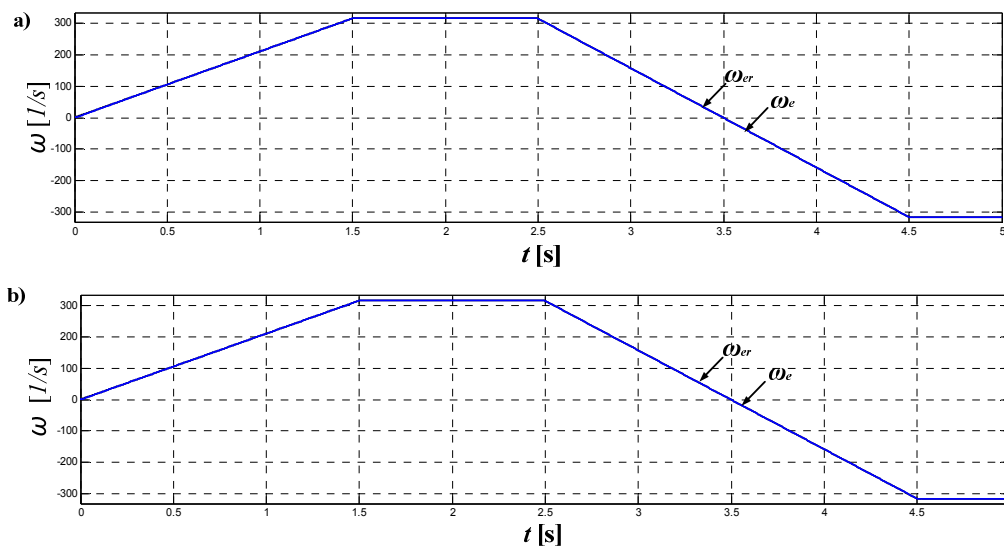


Fig. 7. The waveforms of reference electrical speed ω_{er} and electrical speed ω_e of the five-phase induction motor with an open-end stator winding for field-oriented control methods: a) IFOC and b) DFOC

It can be stated that for the considered operation the motor electrical speed ω_e follows the reference electrical speed ω_{er} with great accuracy.

The waveforms of the motor electromagnetic torque and the load torque for the two considered field-oriented control methods are presented in Fig. 8. The electromagnetic torque of the induction motor has the values equal to the dynamic torques during start-up. In other operating states of the drive system the values of the electromagnetic torque are equal to the load torque.

The waveforms of the flux component i_{sx} and the torque component i_{sy} of the stator current vector of the five-phase induction motor with an open-end stator winding for the Indirect Field-Oriented Control method are presented in Fig. 9 and for the Direct Field-Oriented Control method in Fig. 10. It can be stated for both control methods that the flux component i_{sx} of stator current vector is regulated at the nominal value and that the torque component i_{sy} of the stator current vector has the values proportional to the values of the motor electromagnetic torque.

Fig. 11 shows the trajectories of the reference and the estimated values of the magnitude of the rotor flux vector during operation of the motor in the Direct Field Oriented Control structure. It can be stated that the magnitude of the rotor flux vector is regulated at the nominal value.

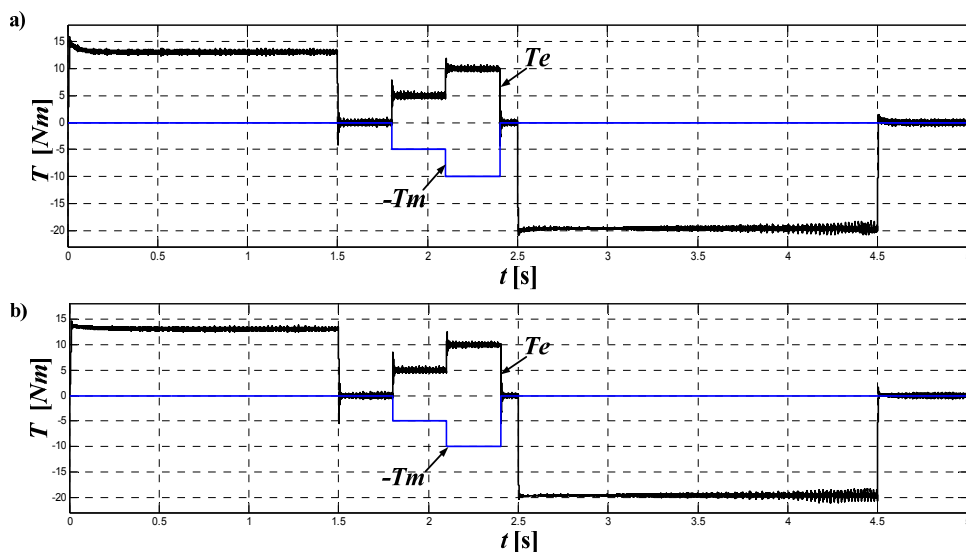


Fig. 8. The waveforms of the motor electromagnetic torque T_e and the load torque T_m of the five-phase induction motor with an open-end stator winding for field-oriented control methods: a) IFOC and b) DFOC

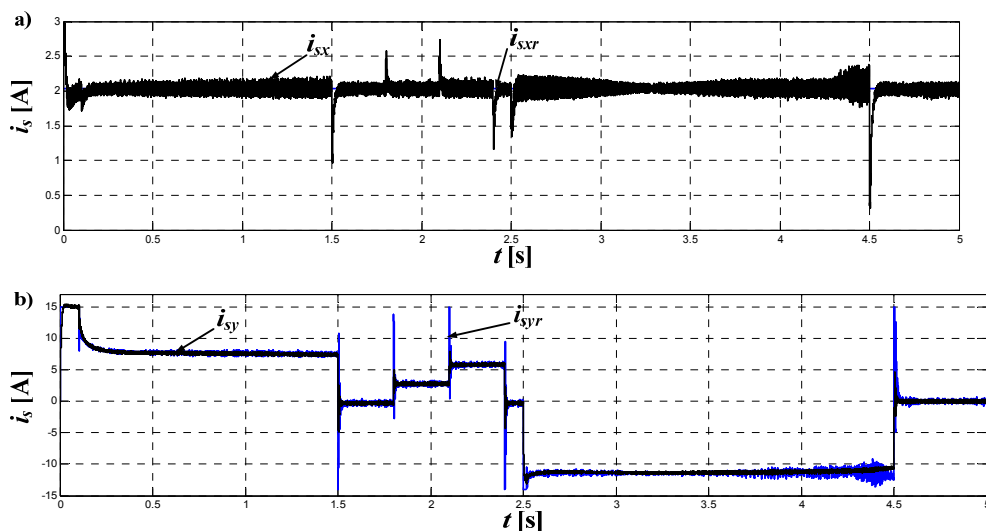


Fig. 9. The waveforms of the components of stator current vector of the five-phase induction motor with an open-end stator winding for Indirect Field-Oriented Control: a) the reference i_{sxr} and the actual i_{sx} flux component; b) the reference i_{syr} and the actual i_{sy} torque component

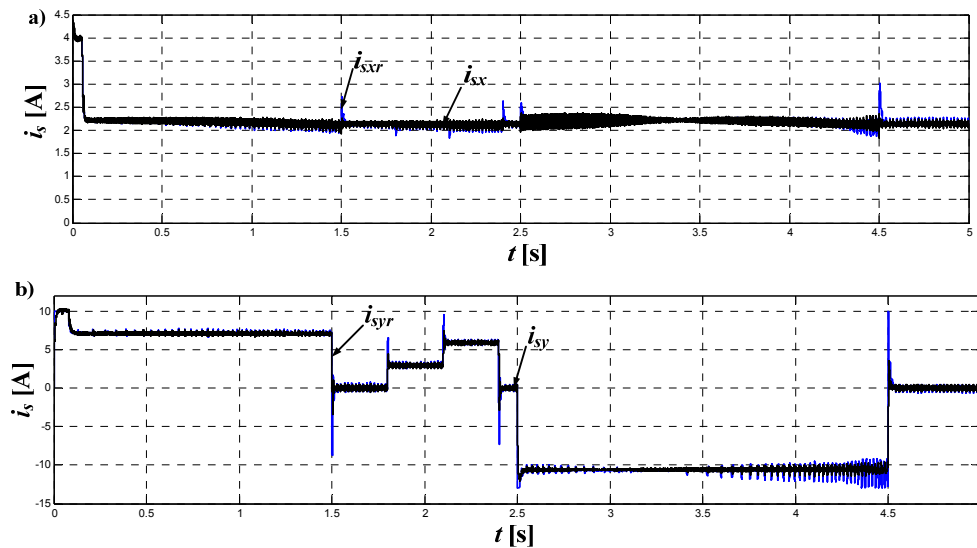


Fig. 10. The waveforms of the components of stator current vector of the five-phase induction motor with an open-end stator winding for Direct Field-Oriented Control: a) the reference i_{sxr} and the actual i_{sx} flux component; b) the reference i_{syr} and the actual i_{sy} torque component

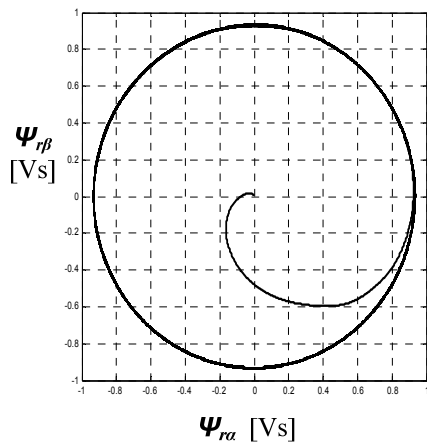


Fig. 11. Trajectory of the reference and the estimated magnitude of the rotor flux vector for Direct Field-Oriented Control of the five-phase induction motor with an open-end stator winding

Fig. 12 shows the waveforms of stator phase voltage of the five-phase induction motor with an open-end stator winding. It has been observed that for the Indirect Field Oriented Control structure and the Direct Field Oriented Control structure the stator phase voltage have similar amplitude values and time shapes.

The waveforms of the stator phase current of the five-phase induction motor with an open-end stator winding are shown in Fig. 13. The amplitudes of the stator phase current depend on the operation conditions of the drive system. The amplitudes have great values in the dynamic states and fixed small values at the steady-state operation.

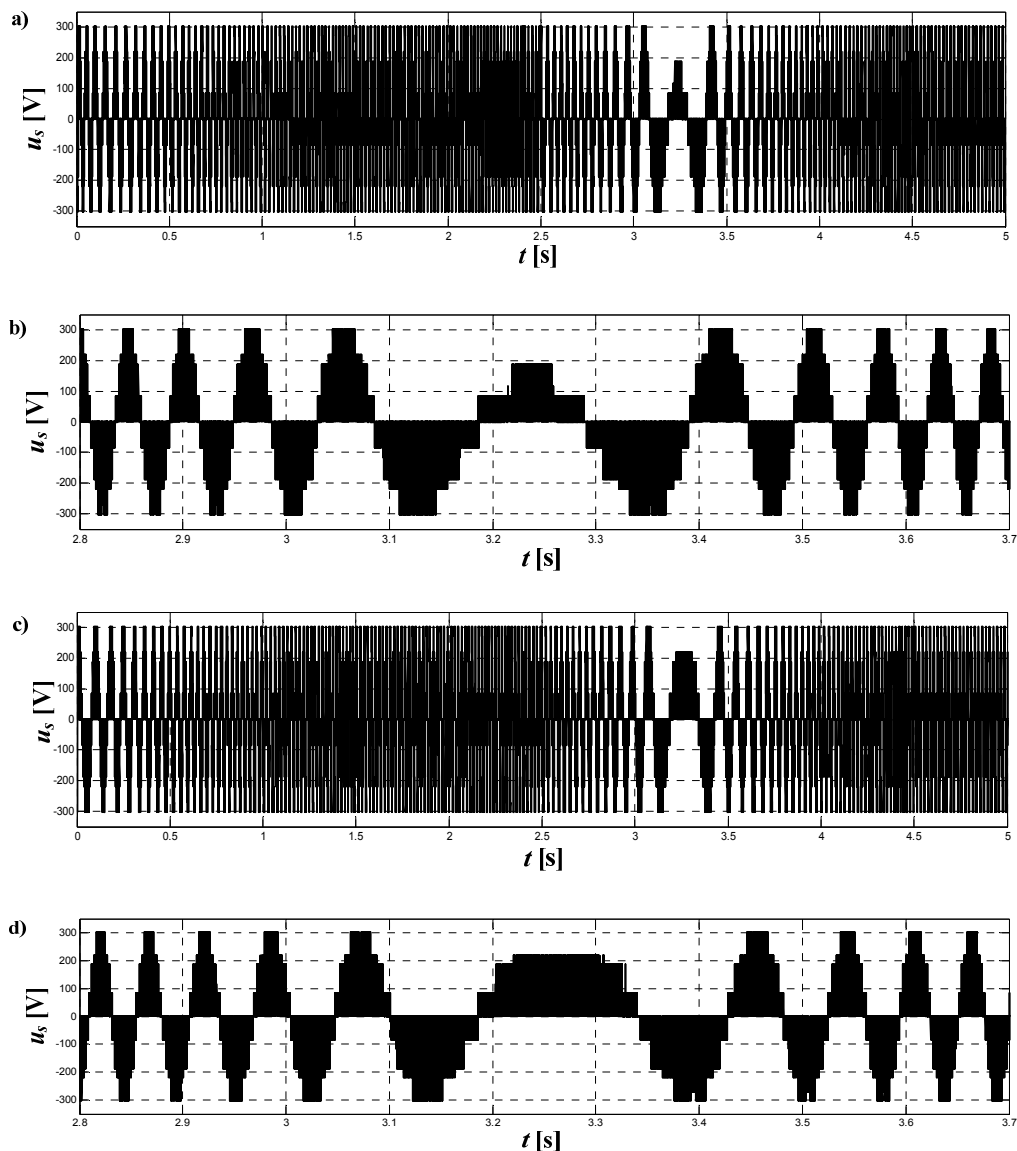


Fig. 12. The time waveforms of the stator phase voltage of the five-phase induction motor with an open-end stator winding: a) IFOC and c) DFOC – for the entire time of control system operation; b) IFOC and d) DFOC – for the selected time period of control system operation

The state variables obtained in the $z1$ - $z2$ coordinate system do not contribute to the electromagnetic torque at all. A five-phase machine presents low impedance to this variables and it is therefore mandatory that the supply does not generate current components in the $z1$ - $z2$ coordinate system. This has been verified via simulation.

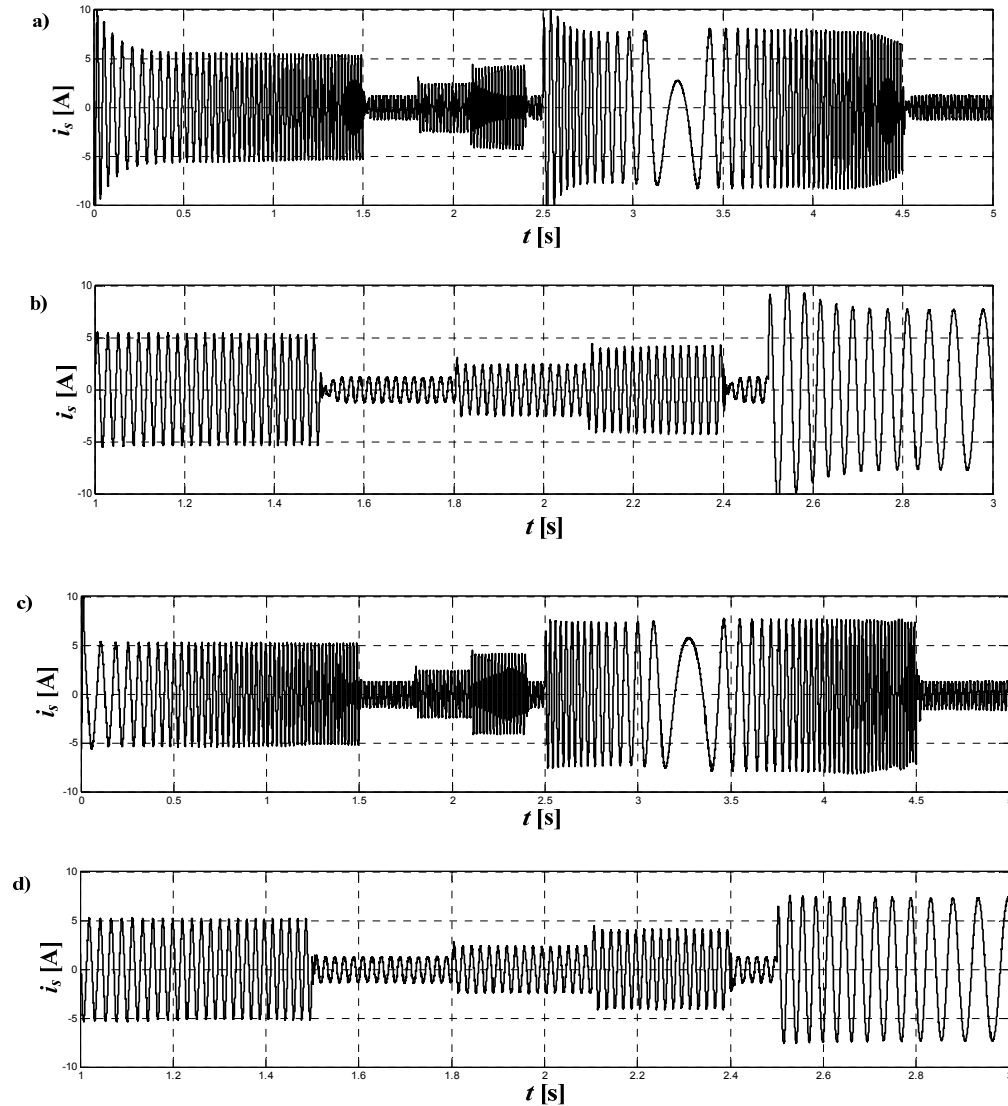


Fig. 13. The waveforms of the stator phase current of the five-phase induction motor with an open-end stator winding: a) IFOC and c) DFOC – for the entire time of control system operation; b) IFOC and d) DFOC – for the selected time period of control system operation

The waveforms of the stator current components in $z1$ - $z2$ system are shown in Fig. 14 for Indirect Field-Oriented Control of the five-phase induction motor with an open-end stator winding. The similar results were obtained for Direct Field-Oriented Control. As a result of the applied SVM strategy the amplitudes of the current vector components in the $z1$ - $z2$ coordinate system are very small and do not contribute to the performance of the motor.

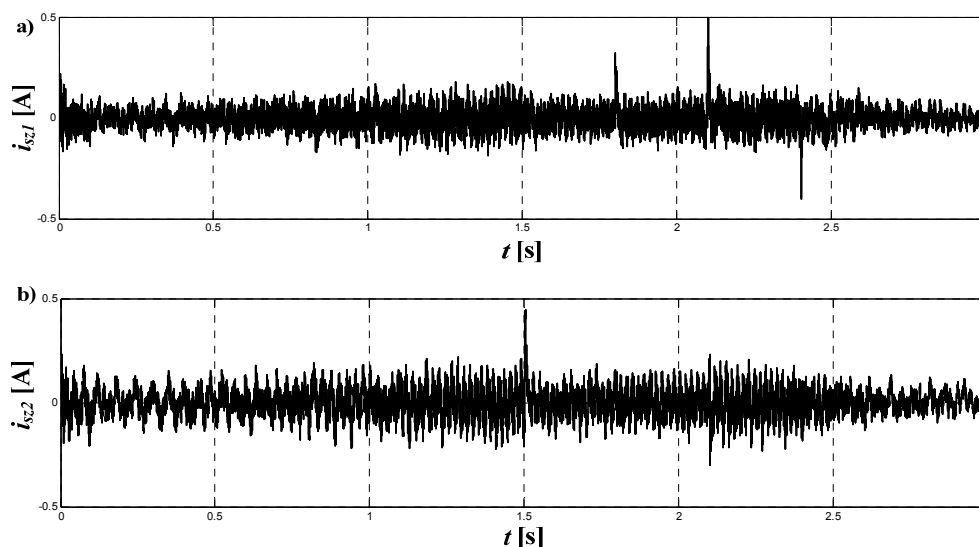


Fig. 14. The waveforms of the components of the stator current vector in the z_1 - z_2 coordinate system for Indirect Field-Oriented Control of the five-phase induction motor with an open-end stator winding:
a) i_{sz1} and b) i_{sz2}

In the article the system of the five-phase induction motor with an open-end stator winding with two isolated DC power supplies was considered. The common mode voltage is of non-zero value but the flow of zero sequence stator currents is avoided. The simulation results confirmed also that the zero sequence stator current is equal to zero.

7. Conclusions

The mathematical models of the five-phase squirrel-cage induction motor and the system of the dual five-phase voltage source inverter have been presented.

The modified concept of space vector modulation has been applied for the control of the dual inverter system. In the space vector modulation system the long and middle inverter voltage vectors have been chosen for synthesizing of the reference voltage vector.

The methods and control systems of Indirect Field-Oriented Control (IFOC) and Direct Field-Oriented Control (DFOC) of the five-phase induction motor with an open-end stator winding are described. Simulation studies were carried out for two field-oriented control methods: Indirect Field-Oriented Control Method and Direct Field-Oriented Control Method. The selected simulation results of the field-oriented control methods of the considered motor have been presented.

The induction motor drive was tested for different load torque conditions. The step changes of load torque were applied after transition to steady-state operation. The measured motor speed follows the reference speed with great accuracy. The electromagnetic torque of

the induction motor has a value equal to dynamic torque during start-up. In other operating states of the drive system the electromagnetic torque is equal to the load torque. It has been observed that there was a rapid torque response to mechanical load changes by using the both field-oriented control methods. The amplitudes of stator phase currents depend on the condition of the drive system: they have great values in dynamic states and fixed small values at the steady-state operation.

It has been stated for the both control methods that the flux component i_{sx} of stator current vector is regulated at the nominal value and that the torque component i_{sy} of the stator current vector has the values proportional to the values of the motor electromagnetic torque.

The components of the stator phase current vector determined in the $z1$ - $z2$ coordinate systems have small amplitudes in the studied states of the drive and these amplitudes are not dependent on the control structure and have only a small contribution to the performance of the studied drive system.

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