

DTC-ST and DTC-SVM Control of Five-Phase Induction Motor with MRAS^{CC} estimator

Abstract. The paper presents the methods of the Direct Torque Control of five-phase squirrel-cage induction motor with MRAS^{CC} estimator. The mathematical models of the five-phase induction motor, voltage inverter and the MRAS^{CC} estimator have been described. The structures of Direct Torque Control with Switching Table (DTC-ST) and the Direct Torque Control with Space Vector Modulation (DTC-SVM) are analyzed. Results of simulation studies of the Direct Torque Control methods are presented.

Streszczenie. W artykule przedstawiono metody bezpośredniego sterowania momentem 5-fazowego silnika indukcyjnego klatkowego z zastosowaniem estymatora MRAS^{CC}. Opisano modele matematyczne 5-fazowego silnika indukcyjnego, falownika napięcia i estymatora MRAS^{CC}. Przeprowadzono analizę bezpośredniego sterowania momentem DTC z wykorzystaniem tablicy przełączeń (DTC-ST) oraz z zastosowaniem modulacji wektorowej (DTC-SVM). Przeprowadzono badania symulacyjne układów sterowania momentem oraz przedstawiono wyniki badań symulacyjnych. (Analiza sterowania DTC-ST i DTC-SVM 5-fazowym silnikiem indukcyjnym z wykorzystaniem estymatora MRAS^{CC})

Keywords: five-phase squirrel-cage induction motor, MRAS^{CC} estimator, sensorless drives, Direct Torque Control

Słowa kluczowe: 5-fazowy silnik indukcyjny klatkowy, estymator MRAS^{CC}, napędy bezczujnikowe, bezpośrednie sterowanie momentem

Introduction

In the industrial drive systems the conventional three-phase squirrel-cage induction motors are commonly used. Conventional three-phase motors do not have high reliability of operation because the break of only one stator phase eliminates the possibility of further motor operation. In addition during frequency control of a conventional three-phase induction motor the pulsations of the electromagnetic torque and the current in the DC link of frequency converter usually have large amplitudes. For these reasons, recently, there is a great interest in using the new constructions of squirrel-cage induction motors with the number of phases of the stator winding greater than three. Motors of this design are called as multiphase motors [1-5].

Multiphase squirrel-cage induction motors have many advantages in comparison to conventional three-phase induction motors [1-5]. The nominal values of the stator phase currents in multiphase systems are smaller than the nominal values of these currents in the three-phase systems with the same power ratings. This allows to reduce the requirements for the ampacity of the motor, semiconductor switches of the inverter and other elements. Multiphase induction motors allow to ensure greater reliability of the drive systems. Motors with number of stator phases greater than three may be operated conditionally at failure of one or more stator phases. Development of frequency converter systems provides the possibility of industrial applications of these types of motors. Power electronic frequency converters can be built for a large number of phases at the output during powering from the conventional three-phase mains.

Nowadays the reliability of the drive systems is very important and sensorless drives have been very popular, because the elimination of the mechanical sensors increases the reliability of the drive systems. The values of the motor angular speed and the values of the magnitude of the stator or rotor flux vector can be estimated by various techniques [6-9]. In the control systems considered in this article, the estimated stator flux and the estimated motor angular speed are calculated by the Stator-Current-Based Model Reference Adaptive System (MRAS^{CC}) estimator presented in detail in [6, 8]. This estimator is characterized by high robustness to the changes of motor parameter and it is insensitive to the disturbances in the current and

voltage waveforms. Detailed analysis of the MRAS^{CC} estimator proving its very good properties has been presented in [8].

In this paper the control of five-phase squirrel-cage induction motor based on Direct Torque Control method with Switching Table (DTC-ST) and with Space Vector Modulation (DTC-SVM) have been presented. In these both control methods the MRAS^{CC} estimator for estimation of motor angular speed has been applied.

The aim of the Direct Torque Control is the control of the motor angular speed, the magnitude of the stator flux vector and the motor electromagnetic torque [4]. The states of the switches of the Voltage Source Inverter (VSI) in the DTC-ST method are determined with the use of hysteresis controllers and in the DTC-SVM method are determined with the use of Space Vector Modulation. In the DTC-SVM control method constant switching frequency and constant value of switching losses can be achieved.

Mathematical model of five-phase induction motor

The scheme of the stator and rotor windings of five-phase squirrel-cage induction motor is shown in Figure 1. In this motor the spatial displacement between axes of two consecutive stator phase windings is equal to $\alpha = 2\pi/5$.

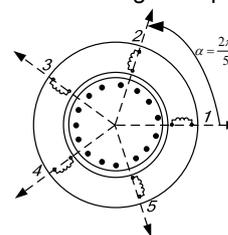


Fig.1. The scheme of the stator and rotor windings of five-phase squirrel-cage induction motor

Mathematical model of five-phase induction motor has been formulated on the basis of commonly used simplifying assumptions [2, 5]: five-phase stator and rotor windings are considered as concentrated and with symmetrical parameters, motor magnetic circuit is linear, the values of parameters and variables of the rotor concentrated winding are converted to the side of stator winding.

Differential equations which describe the mathematical model of the five-phase induction motor considered in the

natural phase coordinate system have the coefficients changing as a function of the angle of rotor rotation. Equations with constant coefficients can be obtained by the use of the suitable transformation matrices, which are presented in detail in [2, 5]. For the five-phase motor, the system of 5-dimensional stator and rotor phase variables can be transformed into a common reference frame x - y rotating at an arbitrary angular speed ω_k and $z1$ - $z2$ reference frame and a zero sequence variable. Since the rotor is short-circuited all rotor $z1$ - $z2$ components and zero sequence component are identically equal to zero. The same applies to the stator zero sequence component, because the star connection of stator phase windings is assumed. For these reasons the equations for these components are neglected in the further analysis.

The general equations of five-phase induction motor after transformations take the following form:

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

$$(1) \quad \begin{aligned} u_{sx} &= R_s i_{sx} - \omega_k \psi_{sy} + \frac{d}{dt} \psi_{sx} \\ u_{sy} &= R_s i_{sy} + \omega_k \psi_{sx} + \frac{d}{dt} \psi_{sy} \\ 0 &= R_r i_{rx} - (\omega_k - \omega_e) \psi_{ry} + \frac{d}{dt} \psi_{rx} \\ 0 &= R_r i_{ry} + (\omega_k - \omega_e) \psi_{rx} + \frac{d}{dt} \psi_{ry} \end{aligned}$$

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

$$(2) \quad \begin{aligned} u_{sz1} &= R_s i_{sz1} + \frac{d}{dt} \psi_{sz1} \\ u_{sz2} &= R_s i_{sz2} + \frac{d}{dt} \psi_{sz2} \end{aligned}$$

- the equation of the electromagnetic torque:

$$(3) \quad T_e = \frac{5}{2} p_b (\psi_{sx} i_{sy} - \psi_{sy} i_{sx}) = \frac{5}{2} p_b \frac{L_m}{L_r} (\psi_{rx} i_{sy} - \psi_{ry} i_{sx})$$

where: $u_{sx}, u_{sy}, u_{sz1}, u_{sz2}$ - components of the stator voltage vectors in the x - y and $z1$ - $z2$ coordinate systems; $i_{sx}, i_{sy}, i_{sz1}, i_{sz2}, i_{rx}, i_{ry}$ - components of the stator and rotor current vectors in the x - y and $z1$ - $z2$ coordinate systems; $\psi_{sx}, \psi_{sy}, \psi_{sz1}, \psi_{sz2}, \psi_{rx}, \psi_{ry}$ - components of the stator and rotor flux linkage vectors in the x - y and $z1$ - $z2$ coordinate systems; ω_k - arbitrary angular speed of the coordinate system relative to the stator; ω_e - the electrical angular speed of the motor; T_e - the motor electromagnetic torque; R_s, R_r - stator and rotor phase resistance; p_b - the number of motor pole pairs.

It can be noted that equations in x - y reference frame of five-phase motor are similar to those of a three-phase motor. The variables represented in $z1$ - $z2$ system do not link the rotor side and consequently do not influence the machine dynamics but are just a source of copper losses in the motor [2, 5]. However, for these reasons these variables must be considered in the analysis and the amplitudes of these variables must be minimized.

Mathematical model of five-phase Voltage Source Inverter

The scheme of the five-phase two-level Voltage Source Inverter (VSI) is presented in Figure 2. In each inverter leg, the power switches are represented with the upper and lower switches which are complementary to each other. The

switching state S_i ($i=1, \dots, 5$) of an inverter leg indicates 1 when the upper switch of the inverter leg is ON and the lower switch is OFF and vice-versa.

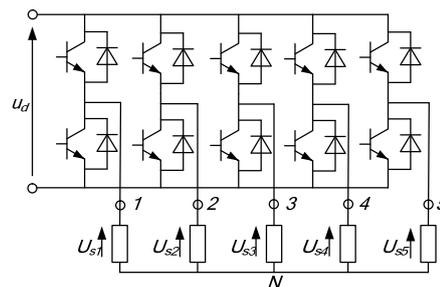


Fig.2. General scheme of the five-phase Voltage Source Inverter

Stator voltage space vectors generated by the five-phase Voltage Source Inverter expressed in the stationary rectangular coordinate system α - β ($\omega_k=0$) and $z1$ - $z2$ system can be determined in general form [2, 5]:

$$(4) \quad \begin{aligned} \underline{u}_{s\alpha\beta} &= u_{s\alpha} + ju_{s\beta} = \frac{2}{5} (S_1 + \underline{a}S_2 + \underline{a}^2S_3 + \underline{a}^3S_4 + \underline{a}^4S_5) \cdot u_d \\ \underline{u}_{sz1z2} &= u_{sz1} + ju_{sz2} = \frac{2}{5} (S_1 + \underline{a}^2S_2 + \underline{a}^4S_3 + \underline{a}^6S_4 + \underline{a}^8S_5) \cdot u_d \end{aligned}$$

where: $\underline{a} = \exp(j2\pi/5)$; S_1, \dots, S_5 - the states of the switches of the five-phase voltage source inverter ($S_i=0$ or 1, $i=1, \dots, 5$).

Stator voltage space vectors generated by the five-phase Voltage Source Inverter in the coordinate system α - β are presented in Figure 3a and in the coordinate system $z1$ - $z2$ are presented in Figure 3b.

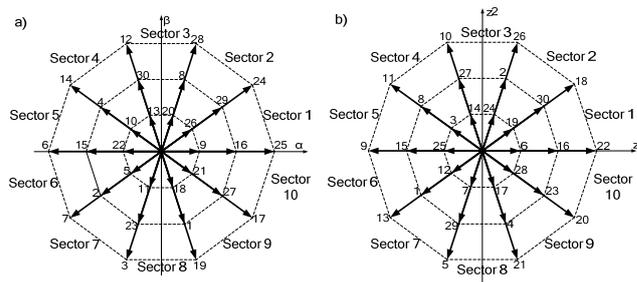


Fig.3. Voltage space vectors generated by the five-phase Voltage Source Inverter in coordinate systems: a) α - β and b) $z1$ - $z2$

For the five-phase Voltage Source Inverter the total number of the state combinations of inverter switches is equal to $2^5=32$. In the set of all generated voltage vectors, thirty active vectors and two zero vectors can be identified. The ten active voltage vectors have long magnitude, the ten active voltage vectors have medium magnitude and the ten active voltage vectors have small magnitude. The set of all active voltage vectors divide the surface of voltage vectors into ten sectors. Voltage vectors presented in Figure 3a and in Figure 3b have been described by the decimal numbers. These decimal numbers can be converted into 5-position binary numbers. The binary bits that represent the decimal number determine the states of the switches represented by the legs of the five-phase inverter.

Space Vector Modulation method

The Space Vector Modulation method has been used in the DTC-SVM control system. Graphical interpretation of the applied Space Vector Modulation method used for control of the five-phase Voltage Source Inverter is presented in Figure 4.

In the applied Space Vector Modulation method the reference voltage vector lying in the considered sector is

synthesized by using the appropriate switching times of two long and two medium voltage vectors, chosen from the same sector and of two zero voltage vectors. The case when the reference voltage vector \underline{u}_{sref} is situated in Sector 1 has been presented in Figure 4. In this case the reference voltage vector is synthesized with using: two long voltage vectors: \underline{u}_{25} , \underline{u}_{24} , two medium voltage vectors: \underline{u}_{16} , \underline{u}_{29} and two zero voltage vectors: \underline{u}_0 , \underline{u}_{31} .

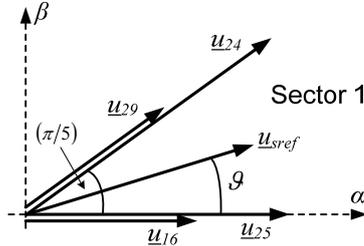


Fig.4. The principle of Space Vector Modulation of 5-phase VSI

Switching times of individual voltage vectors are calculated according to the below general equations (these formulas allow to ensure the average values of voltage in $z1-z2$ coordinate system equal to zero) [1]:

$$\begin{aligned}
 t_{al} &= 2 \sin(2\pi/5) \cdot \sin(s \cdot \pi/5 - \vartheta) \cdot \frac{u_{sref}}{u_d} \cdot T_s \\
 t_{am} &= 2 \sin(\pi/5) \cdot \sin(s \cdot \pi/5 - \vartheta) \cdot \frac{u_{sref}}{u_d} \cdot T_s \\
 t_{bl} &= 2 \sin(2\pi/5) \cdot \sin[\vartheta - (s-1) \cdot \pi/5] \cdot \frac{u_{sref}}{u_d} \cdot T_s \\
 t_{bm} &= 2 \sin(\pi/5) \cdot \sin[\vartheta - (s-1) \cdot \pi/5] \cdot \frac{u_{sref}}{u_d} \cdot T_s \\
 t_0 &= T_s - (t_{al} + t_{am} + t_{bl} + t_{bm})
 \end{aligned}
 \tag{5}$$

where: t_{al} , t_{bl} - switching times of long voltage vectors; t_{am} , t_{bm} - switching times of medium voltage vectors; t_0 - switching time of zero voltage vectors; u_{sref} - magnitude of the reference voltage vector; T_s - switching period; ϑ - the angle of position of reference voltage vector; s - number of sector.

Mathematical model of the MRAS^{CC} estimator

The scheme of the Stator-Current-Based Model Reference Adaptive System (MRAS^{CC}) estimator is presented in Figure 5 [6, 8].

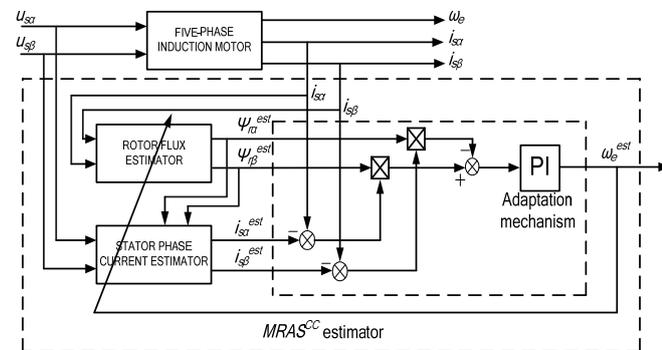


Fig.5. The scheme of the MRAS^{CC} estimator

The MRAS^{CC} estimator contains two mathematical models: a rotor-flux-model based on measured stator

currents and a stator-current model based on measured stator voltages.

The rotor-flux model is described by the following equations [7]:

$$\begin{aligned}
 \frac{d}{dt} \psi_{ra}^{est} &= \frac{R_r}{L_r} (L_m i_{sa}^{est} - \psi_{ra}^{est}) - \omega_e^{est} \psi_{r\beta}^{est} \\
 \frac{d}{dt} \psi_{r\beta}^{est} &= \frac{R_r}{L_r} (L_m i_{s\beta}^{est} - \psi_{r\beta}^{est}) + \omega_e^{est} \psi_{ra}^{est}
 \end{aligned}
 \tag{6}$$

The stator-current model is described by the following equations [6, 8]:

$$\begin{aligned}
 \frac{d i_{s\alpha}^{est}}{dt} &= -i_{s\alpha}^{est} \frac{R_r L_m^2 + L_r^2 R_s}{\sigma L_s L_r^2} + \frac{L_m R_r}{\sigma L_s L_r^2} \psi_{ra}^{est} + \frac{L_m}{\sigma L_s L_r} \omega_e^{est} \psi_{r\beta}^{est} + \frac{1}{\sigma L_s} u_{s\alpha} \\
 \frac{d i_{s\beta}^{est}}{dt} &= -i_{s\beta}^{est} \frac{R_r L_m^2 + L_r^2 R_s}{\sigma L_s L_r^2} + \frac{L_m R_r}{\sigma L_s L_r^2} \psi_{r\beta}^{est} - \frac{L_m}{\sigma L_s L_r} \omega_e^{est} \psi_{ra}^{est} + \frac{1}{\sigma L_s} u_{s\beta}
 \end{aligned}
 \tag{7}$$

where: i_{sa}^{est} , $i_{s\beta}^{est}$ - the estimated values of the components of the stator phase current vector in the α - β coordinate system; L_m - motor magnetizing inductance; L_s , L_r - stator and rotor inductance; $\sigma = 1 - L_m^2 / L_s L_r$ - total leakage factor; ψ_{ra}^{est} , $\psi_{r\beta}^{est}$ - the estimated values of the components of the rotor flux vector in the α - β coordinate system; ω_e^{est} - the estimated value of the electrical motor speed.

In the considered estimator the mathematical model of induction motor is treated as the reference model. The values of the components of the stator phase current vector in the reference system α - β , obtained from the mathematical model of the five-phase induction motor are compared with the estimated values of the components of the stator phase current vector. The error signals are sent to the adaptation mechanism together with the estimated values of the components of the rotor flux vector. In the adaptation mechanism the PI controller is applied. The output signal from PI controller is the estimated value of the motor speed ω_e^{est} .

The estimated value of the motor speed ω_e^{est} is calculated according to the equation [6, 8]:

$$\omega_e^{est} = K_p (e_{i_{s\alpha}} \psi_{r\beta}^{est} - e_{i_{s\beta}} \psi_{ra}^{est}) + \frac{1}{T_i} \int_0^t (e_{i_{s\alpha}} \psi_{r\beta}^{est} - e_{i_{s\beta}} \psi_{ra}^{est}) dt
 \tag{8}$$

where - $e_{i_{s\alpha,\beta}} = i_{s\alpha,\beta} - i_{s\alpha,\beta}^{est}$ - the error between the measured and estimated values of the components of the stator phase current vector in the α - β coordinate system.

The value of the estimated speed returns the estimator of the components of the rotor flux vector and the estimator of the components of the stator phase current vector.

Direct Torque Control with Switching Table

The block diagram of the Direct Torque Control with Switching Table (DTC-ST) of five-phase induction motor is shown in Figure 6. To implement the DTC-ST control system the MRAS^{CC} estimator has been used. The estimation block determines the estimated value of motor angular speed ω_e^{est} , the instantaneous magnitude of the stator flux vector ψ_s , the estimated value of the electromagnetic torque T_e and the number of sector N .

The instantaneous magnitude of the stator flux vector ψ_s is calculated according to the equation:

$$\psi_s = \frac{L_m}{L_r} \psi_r + \sigma L_s i_s
 \tag{9}$$

In DTC-ST control structure three control loops are applied: the control loop for motor angular speed with PI controller, the control loop for magnitude of the stator flux

vector with hysteresis controller and the control loop for electromagnetic torque with hysteresis controller.

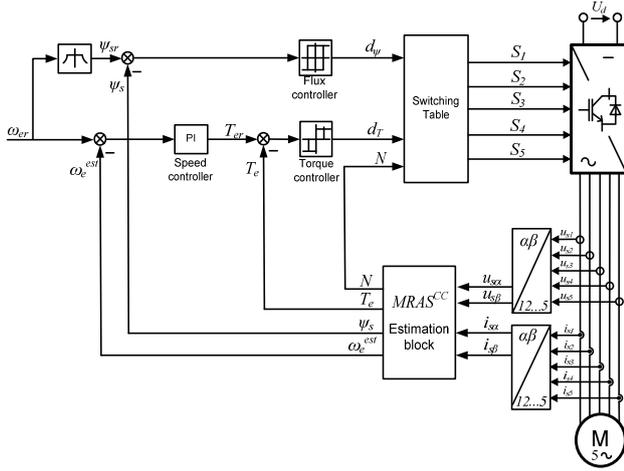


Fig.6. DTC-ST control system of five-phase induction motor

In the speed control loop the reference speed ω_{er} is compared with the estimated value of the actual speed ω_e^{est} of the five-phase induction motor and the error signal is sent to the PI speed controller. The output signal from PI speed controller is the reference value of the electromagnetic torque T_{er} . The reference value of the electromagnetic torque T_{er} is compared with the value of the electromagnetic torque T_e and the error signal is sent to the three-position hysteresis controller, which may achieve only control values $d_T = -1, 0$ or 1 . The reference values of the magnitude of the stator flux vector ψ_{sr} are compared with the values of the magnitude of the stator flux vector ψ_s and the error signal is sent to the two-position hysteresis controller, which may achieve only control values $d_\psi = 0$ or 1 . The voltage vectors are selected with hysteresis controllers according to the errors of the magnitude of the stator flux vector, according to the errors of the electromagnetic torque and the information about the sector number N . The appropriate stator voltage vectors are chosen from the switching table which is presented in Table 1. In this control system only the long voltage vectors have been used.

Table 1. Switching table

		$N=1$	$N=2$	$N=3$	$N=4$	$N=5$
$d_\psi=1$	$d_T=1$	11000	11100	01100	01110	00110
	$d_T=0$	00000	11111	00000	11111	00000
	$d_T=-1$	10001	11001	11000	11100	01100
$d_\psi=0$	$d_T=1$	00111	00011	10011	10001	11001
	$d_T=0$	11111	00000	11111	00000	11111
	$d_T=-1$	01110	00110	00111	00011	10011
		$N=6$	$N=7$	$N=8$	$N=9$	$N=10$
$d_\psi=1$	$d_T=1$	01110	00110	00111	00011	10011
	$d_T=0$	11111	00000	11111	00000	11111
	$d_T=-1$	00111	00011	10011	10001	11001
$d_\psi=0$	$d_T=1$	10001	11001	11000	11100	01100
	$d_T=0$	00000	11111	00000	11111	00000
	$d_T=-1$	11000	11100	01100	01110	00110

Direct Torque Control with Space Vector Modulation

The block diagram of the Direct Torque Control with Space Vector Modulation (DTC-SVM) of five-phase induction motor is shown in Figure 7. To implement the DTC-SVM control system the MRAS^{CC} estimator has been used. The estimation block determines the same values which have been presented for estimation block used in control structure DTC-ST (with the exception of the number of sector).

In DTC-SVM control structure three control loops with PI controllers are applied: the control loop for motor angular speed ω_e , the control loop for magnitude of the stator flux vector ψ_s and the control loop for electromagnetic torque T_e .

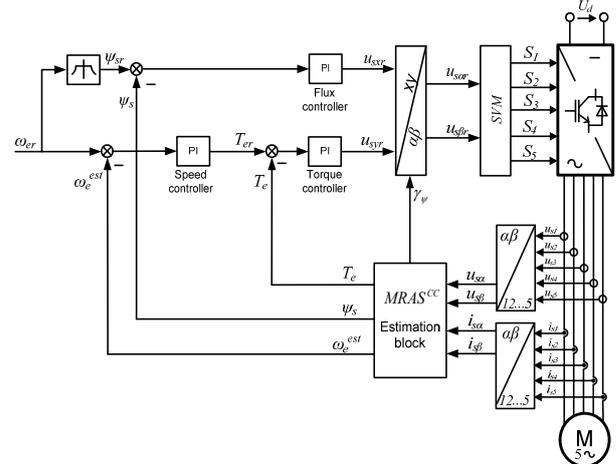


Fig.7. DTC-SVM control system of five-phase induction motor

The output signal from speed controller is the reference value of the motor electromagnetic torque T_{er} . The output signal from the electromagnetic torque controller is the reference value of y component of the stator voltage vector u_{syrr} and output signal from stator flux vector controller is the reference value of x component of the stator voltage vector u_{sxrr} . In the considered control method the x - y reference frame is chosen as the system where the x -axis is aligned with the direction of the stator flux vector. The reference values of x and y components of the stator voltage vector are transformed to the α - β coordinate system and afterwards given to the space vector modulator which sets the switching states of the five-phase VSI.

Simulation results

The simulation models of considered DTC systems have been implemented in MATLAB/Simulink. Simulation studies were carried out for the system with five-phase squirrel-cage induction motor with the data: $R_s=7.48\Omega$, $R_r=3.68\Omega$, $L_{ls}=L_{lr}=0.0221H$, $L_m=0.411H$, $f_N=50Hz$, $p_b=2$, $u_d=600V$.

The simulation studies of DTC-ST and DTC-SVM control of five-phase induction motor were performed for the same trajectories of the reference speed. After reaching the nominal value of reference speed the drive system has been loaded with a certain time delay. The waveforms of reference speed, estimated speed and measured electrical speed of the five-phase induction motor have been presented in Figure 8. It can be stated that the estimated and measured motor speeds follow the reference speed with great accuracy during every selected states of the drive systems and for two considered Direct Torque Control methods.

The waveforms of the load torque and the electromagnetic torque of the five-phase induction motor for Direct Torque Control methods are presented in Figure 9. The values of the electromagnetic torque depend on the working states of the drive systems. The two considered Direct Torque Control methods provide rapid responses of electromagnetic torque during the changes of motor speed and during the changes of the load torque.

The waveforms of the stator phase current of the five-phase induction motor for the Direct Torque Control methods are presented in Figure 10. 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.

The trajectory of the estimated magnitude of the stator flux vector for Direct Torque Control methods are presented in Figure 11. It can be noticed that the magnitude of the stator flux vector is regulated at the nominal value for both considered control methods.

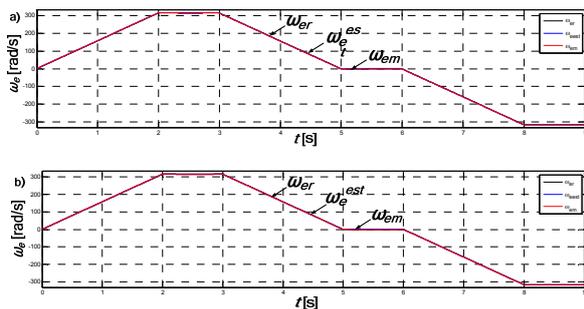


Fig.8. The waveforms of electrical speeds of five-phase induction motor for: a) DTC-ST; b) DTC-SVM

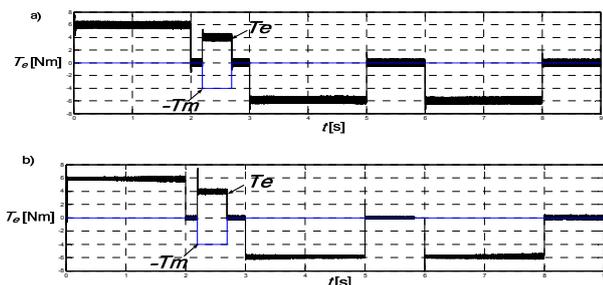


Fig.9. The waveforms of the load torque and the electromagnetic torque of five-phase induction motor for: a) DTC-ST; b) DTC-SVM

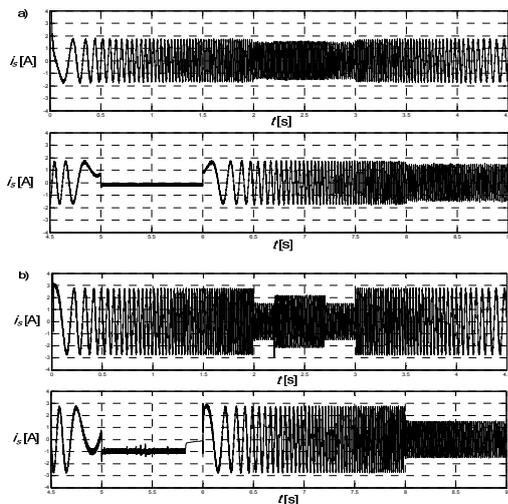


Fig.10. The waveforms of stator phase current of the five-phase induction motor for two time intervals: a) DTC-ST; b) DTC-SVM

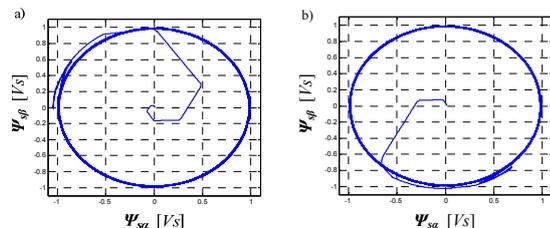


Fig.11. Trajectory of the estimated magnitude of the stator flux vector for: a) DTC-ST; b) DTC-SVM

Conclusions

The mathematical model of the five-phase squirrel-cage induction motor, five-phase Voltage Source Inverter

and MRAS^{CC} estimator has been presented and analyzed.

The structures of Direct Torque Control method with Switching Table (DTC-ST) and Direct Torque Control method with Space Vector Modulation (DTC-SVM) with five-phase induction motor are presented and described. The chosen concept of Space Vector Modulation method has been applied for control of the five-phase Voltage Source Inverter. In this Space Vector Modulation method the long and the medium voltage space vectors have been used.

Simulation studies were carried out for two control methods: DTC-ST and DTC-SVM. Selected results of simulation studies are presented and discussed. Simulation investigations confirmed the great accuracy of control of the given waveforms. The comparative analysis of DTC-ST and DTC-SVM leads to the conclusions, that the DTC-SVM control method has greater complexity, but it provides the better accuracy of the control and ensures more gentle waveforms of electromagnetic variables. For the certain constructions of multi-phase motors it may be necessary to take into account in the analysis the influence of the distribution of higher harmonics of the magnetic field in the motor air-gap [10].

The Direct Torque Control method with Switching Table and Direct Torque Control method with Space Vector Modulation provide rapid responses of electromagnetic torque during the changes of motor speed and during the changes of the load torque. The magnitudes of the stator flux vector are constantly regulated at the nominal value.

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