

Analysis and control of dual stator winding induction motor

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Abstract: The paper presents the mathematical models of dual stator squirrel-cage induction motor, formulated in phase coordinate system and in general transformed space vector form. The two types of models of dual stator induction motor are considered. The control systems of field-oriented control (IFOC and DFOC) and direct torque control (DTC) of the dual stator induction motor have been described and discussed.

Key words: dual stator induction motor, mathematical models, analysis, IFOC, DFOC and DTC control.

1. Introduction

Nowadays, the use of electrical drive systems with multiphase squirrel cage induction motors in various industrial applications is increasing. It is caused by the development of power electronic frequency converters that can generate multi-phase systems of voltages and currents. Multiphase squirrel cage induction motors are mainly used in high power electrical drives or drives with specific requirements for control. The main advantages of these types of motors are their higher torque density, higher efficiency, reduced torque pulsations, greater fault tolerant and a reduction in the required rating per inverter leg. The possibility of power distribution among a greater number of phases makes it possible to obtain a reduction of currents of motor circuits and power converter circuits.

Among the different multiphase drive solutions, one of the most interesting and widely applied is the dual three-phase stator winding squirrel cage induction motor. The dual stator induction motor (DSIM) has two separate three-phase stator windings, sharing the same machine core and the common squirrel cage rotor winding. According to the layout of the stator windings in the motor core the dual stator induction motors can be divided into two basic groups. The first one comprises the construction in which two separate three-phase stator windings are located sequentially along the stator core. In this case there is no magnetic coupling between the stator windings, but each of stator windings is magnetically coupled with the

rotor cage winding. The two stator windings can be supplied from the same or separate AC voltage sources of the same frequency. This type of motor construction was considered and described in many papers written by the author and others [4, 7]. The former type of dual stator construction comprises the motor with two stator windings, that are spatially shifted and are situated in the same stator core. The studies permit the statement that this is promising construction. The analysis of this type of motors has been performed in some papers [1-3, 5, 6, 8] and is the subject of this article.

This paper presents the general approach to the analysis and control of dual stator induction motors. The mathematical models of DSIM motors have been described and the principles and methods of vector control, using rotor field-oriented control (FOC) and direct torque control (DTC) have been discussed.

2. The models of dual stator induction motor

2.1. The simplified assumptions

In the mathematical description of dual stator induction motor it is assumed that the DSIM motor is considered as an electromechanical system consisting of two three-phase stator windings, denoted as stator 1 and stator 2 and the common squirrel-cage rotor winding. The cage rotor winding is replaced by an equivalent three-phase winding. Figure 1 shows the representation of the stator and rotor windings of dual stator induction motor.

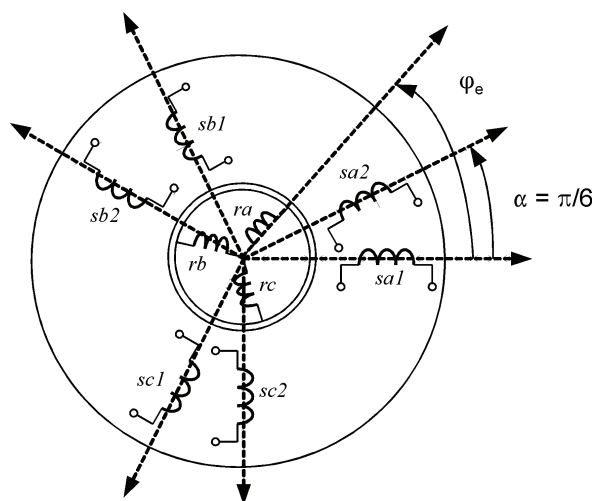


Fig. 1. Schematic representation of motor windings of dual stator induction motor (DSIM)

It is assumed that the motor windings are sinusoidally distributed around the air gap. The two sets of stator windings are designed with isolated neutral points and are spatially shifted by an electrical angle of $\pi/6$ degrees. The symmetry of the phase motor windings and the linearity of motor magnetic circuit are assumed. The hysteresis phenomena and eddy currents

are neglected. It was assumed that the magnetic coupling between stator windings 1 and 2 occurs only through the main flux, the coupling between these windings through the leakage flux is neglected. All the electromagnetic variables and parameters of equivalent three-phase rotor winding have been transferred to the stator side.

In this paper, two modeling approaches and general methods of analysis of dual stator squirrel-cage induction motor have been considered:

- Model I – the DSIM motor is treated as two independent three-phase motors coupled together by a common rotor winding. This approach is based on modeling principles used for classical three-phase induction machines.
- Model II – the DSIM motor is considered as a six-phase induction motor. This approach is based on modeling principles used for multi-phase induction machines.

The both mathematical models of DSIM will be first formulated in phase variable form. These models are then transformed to arbitrary common reference frame in order to obtain more useful general forms.

2.2. The equations for the Model I of the DSIM motor

General voltage and flux equations for stator and rotor circuits for Model I of the DSIM motor have the following matrix form:

$$\begin{aligned} [u_{s1}] &= [R_{s1}][i_{s1}] + p[\psi_{s1}] \\ [u_{s2}] &= [R_{s2}][i_{s2}] + p[\psi_{s2}] \\ 0 &= [R_r][i_r] + p[\psi_r], \end{aligned} \quad (1)$$

where:

$$\begin{aligned} [\psi_{s1}] &= [L_{s1}][i_{s1}] + [L_{s1,s2}][i_{s2}] + [L_{s1,r}][i_r] \\ [\psi_{s2}] &= [L_{s1,s2}]^T [i_{s1}] + [L_{s2}][i_{s2}] + [L_{s2,r}][i_r] \\ [\psi_r] &= [L_{s1,r}]^T [i_{s1}] + [L_{s2,r}]^T [i_{s2}] + [L_r][i_r]. \end{aligned} \quad (2)$$

For the Model I the electromagnetic torque of the motor can be expressed as the sum of two components caused by the electromagnetic interaction between the stator 1 and the rotor and the interaction between the stator 2 and the rotor:

$$M_e = M_{e1} + M_{e2} = p_b [i_{s1}]^T \left(\frac{\partial}{\partial \varphi_e} [L_{s1,r}] \right) [i_r] + p_b [i_{s2}]^T \left(\frac{\partial}{\partial \varphi_e} [L_{s2,r}] \right) [i_r]. \quad (3)$$

The individual matrices of electromagnetic phase variables in Equations (1)-(3) have the following forms:

$$\begin{aligned} [w_{si}] &= [w_{sai}, w_{sbi}, w_{sci}]^T, \quad i = 1, 2 \\ [w_r] &= [w_{ra}, w_{rb}, w_{rc}]^T, \quad w = u, i, \psi. \end{aligned} \quad (4)$$

The symbols used in the above equations have the following meanings: subscripts s, r indicate the variables and parameters of stators and rotor, respectively; subscripts a, b, c indicate phase variables and parameters respectively and subscripts 1, 2 denote variables and parameters of stator 1 and 2 respectively; T – is the symbol of matrix transposition; u – voltage, i – current, ψ – flux linkage; $[R_{s1}], [R_{s2}], [R_r]$ and $[L_{s1}], [L_{s2}], [L_r]$ – resistance and inductance matrices of stator 1, stator 2 and rotor, respectively; $[L_{s1, s2}], [L_{s1, r}], [L_{s2, r}]$ – matrices of mutual inductances between stator 1 and 2, stator 1 and rotor, stator 2 and rotor, respectively; φ_e – electrical angle of rotor rotation; p_b – the number of motor pole pairs, $p = d/dt$ – the differential operator. The detailed form of matrices of phase resistances and inductances of considered dual stator motor is given in [3, 6, 8].

The mutual inductances between stator and rotor phase windings of DSIM have periodic variation with the change of the angle of rotor rotation. This causes that the coefficients in Equations (1)-(3) are time dependent and this makes the equations difficult for analysis. In order to obtain the constant coefficients the transformation of motor phase variables to the common, rectangular reference frame $(x, y, 0)$ is applied. It is assumed that this reference frame rotates relative to stator system with any arbitrary angular speed ω_k . The applied general form of transformation matrix denoted as $[T_i]$ makes the transformation of phase variables of 3-phase stator 1, 2 and rotor to the rectangular components in the system (x, y) and to the zero component:

$$[T_i] = [D_i] \cdot [T_3], \quad (5a)$$

where:

$$[D_i] = \begin{bmatrix} \cos \theta_i & \sin \theta_i & 0 \\ -\sin \theta_i & \cos \theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix}; \quad i = s1, s2, r; \quad [T_3] = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}, \quad (5b)$$

$$\theta_{s1} = \theta_k; \quad \theta_{s2} = \theta_k - \pi/6; \quad \theta_r = \theta_k - \varphi_e; \quad \theta_k = \int \omega_k \cdot dt. \quad (5c)$$

θ_{s1} – the angle between the x -axis of the common reference frame and the $a1$ -axis of stator 1; θ_{s2} – the angle between the x -axis of the common reference frame and the $a2$ -axis of stator 2; θ_r – the angle between the x -axis of the common reference frame and the a -axis of rotor. The form of transformation $[T_i]$ is dependent on whether this transformation is applied to the phase variables of stator 1, stator 2 and rotor, respectively.

The motor transformed variables can be treated as the projections of the electromagnetic space vectors on the axes of the common reference frame. Hence the Equation (1)-(3) can be expressed in the vector form. The vector voltage equations are:

$$\begin{aligned} \underline{u}_{s1} &= R_{s1} \cdot \underline{i}_{s1} + p \underline{\psi}_{s1} + j \omega_k \cdot \underline{\psi}_{s1} \\ \underline{u}_{s2} &= R_{s2} \cdot \underline{i}_{s2} + p \underline{\psi}_{s2} + j \omega_k \cdot \underline{\psi}_{s2} \\ 0 &= R_r \cdot \underline{i}_r + p \underline{\psi}_r + j(\omega_k - \omega_e) \cdot \underline{\psi}_r, \end{aligned} \quad (6)$$

The vector flux linkage equations are:

$$\begin{aligned}\underline{\psi}_{-s1} &= L_{s1} \cdot \underline{i}_{-s1} + L_m \cdot \underline{i}_{-s2} + L_m \cdot \underline{i}_{-r} \\ \underline{\psi}_{-s2} &= L_m \cdot \underline{i}_{-s1} + L_{s2} \cdot \underline{i}_{-s2} + L_m \cdot \underline{i}_{-r} \\ \underline{\psi}_{-r} &= L_m \cdot \underline{i}_{-s1} + L_m \cdot \underline{i}_{-s2} + L_r \cdot \underline{i}_{-r}.\end{aligned}\quad (7)$$

The electromagnetic torque can be expressed in the vector form as

$$M_e = M_{e1} + M_{e2} = p_b(L_m/L_r) \cdot \text{Im}\left(\underline{i}_{-s1} \cdot \underline{\psi}_{-r}^*\right) + p_b(L_m/L_r) \cdot \text{Im}\left(\underline{i}_{-s2} \cdot \underline{\psi}_{-r}^*\right).\quad (8)$$

The voltage equations for the zero components of the stator 1, stator 2 and rotor are:

$$\begin{aligned}u_{s01} &= R_{s1} \cdot i_{s01} + p \psi_{s01} = R_{s1} \cdot i_{s01} + p(L_{sl1} \cdot i_{s01}) \\ u_{s02} &= R_{s2} \cdot i_{s02} + p \psi_{s02} = R_{s2} \cdot i_{s02} + p(L_{sl2} \cdot i_{s02}) \\ 0 &= R_r \cdot i_{r0} + p \psi_{r0} = R_r \cdot i_{r0} + p(L_{rl} \cdot i_{r0}),\end{aligned}\quad (9)$$

where:

$$L_{s1} = L_{sl1} + L_m; \quad L_{s2} = L_{sl2} + L_m; \quad L_r = L_{rl} + L_m; \quad L_m = (3/2)L_\mu.\quad (10)$$

L_{s1} , L_{s2} , L_r – the total inductance of a stator 1, stator 2 and rotor respectively; L_{sl1} , L_{sl2} , L_{rl} – the leakage inductance of stator 1, stator 2 and rotor respectively; L_μ – the main magnetizing inductance; ω_e – electrical angular speed of the rotor.

Figure 2 presents the circuit representation of the transformed equations for the Model I of the DSIM. These circuits show the electromagnetic couplings between stator and rotor equivalent circuits and the principle of electromechanical energy conversion in the motor. The circuit in Fig.2a is an equivalent circuit, which shows the magnetic couplings between stator 1, stator 2 and rotor. Figure 2b presents the same circuit after elimination of magnetic couplings and introducing galvanic connections between circuits. In the Fig. 2c, 2d and 2e the equivalent circuits for zero components of stator 1, stator 2 and rotor, respectively. These circuits are not coupled with any other circuits.

From the consideration of the above equations and equivalent circuits it can be stated that the zero components are not involved in electromechanical energy conversion, but their presence can cause additional power losses in the motor. In typical cases of the motor design with phase winding connections in star without neutral these components are always equal to zero and can be neglected in further analysis.

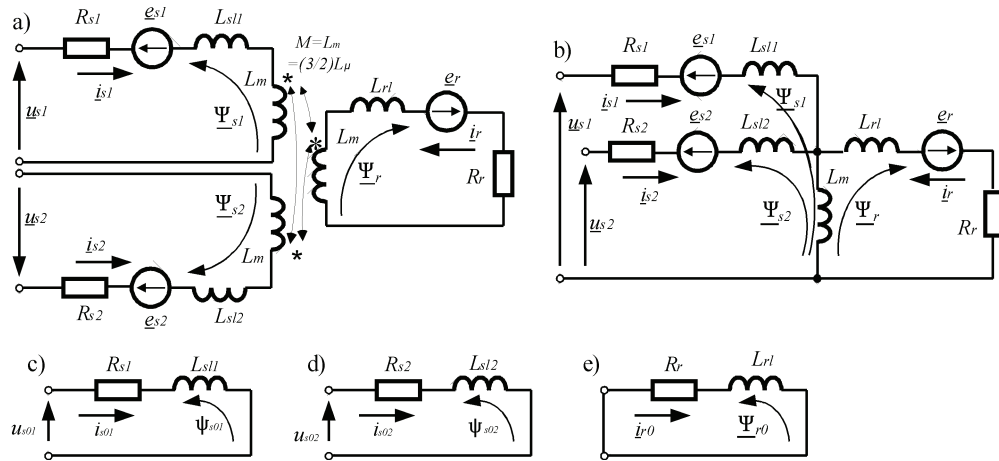


Fig. 2. The circuit representation of equations in arbitrary reference frame for Model I of dual stator induction motor

2.3. The equations for the Model II of the DSIM motor

The analysis of DSIM motor on the base of Model II requires an additional assumption of the phase symmetry of the both stator windings 1 and 2. The two three-phase stator windings can then be considered as a symmetrical six-phase system. In the modeling the rotor winding can be considered as six-phase or three-phase winding. Below the rotor winding is treated as an equivalent three-phase winding.

General voltage and flux equations for Model II expressed with application of stator and rotor phase variables have the following matrix form:

$$[u_s] = [R_s] [i_s] + p[\psi_s] \quad (11)$$

$$[0] = [R_r] [i_r] + p[\psi_r].$$

$$[\psi_s] = [L_s] [i_s] + [L_{s,r}] [i_r] \quad (12)$$

$$[\psi_r] = [L_{s,r}]^T [i_s] + [L_r] [i_r].$$

The equation of motor electromagnetic torque is:

$$M_e = p_b [i_s]^T \left(\frac{\partial}{\partial \varphi_e} [L_{s,r}] \right) [i_r], \quad (13)$$

where: $[R_s]$, $[L_s]$ – the matrices of phase resistances and inductances of six-phase stator windings respectively, $[R_r]$, $[L_r]$ – the matrices of phase resistances and inductances of three-phase rotor windings respectively, $[L_{s,r}]$ – the matrix of mutual inductances between the six-phase stator and three-phase rotor winding. The other designations used above are the same as for the Model I of DSIM.

The matrices of electromagnetic phase variables occurring in equations (11)-(13) have the following general forms:

$$\begin{aligned} [w_s] &= [w_{sa1}, w_{sb1}, w_{sc1}, w_{sa2}, w_{sb2}, w_{sc2}]^T \\ [w_r] &= [w_{ra}, w_{rb}, w_{rc}]^T \quad w = u, i, \psi. \end{aligned} \quad (14)$$

The Equations (11)-(13) constitute a system of differential-algebraic equations with some variable coefficients caused by mutual inductances between stator and rotor windings, which are sine functions of the angle rotation of the rotor. Thus, in order to obtain the simplified mathematical model the transformations of motor variables have been used. The transformation of rotor variables has been made by using the presented above transformation matrix $[T_3]$. The transformation matrix of six-phase stator variables, denoted as $[T_6]$ has been formulated on the theory of Vector Space Decomposition, which has been proposed in [8]. The transformation matrix $[T_6]$ has the following form:

$$[T_6] = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & \cos(\gamma) & \cos(2\gamma) & \cos(\alpha) & \cos(\alpha + \gamma) & \cos(\alpha + 2\gamma) \\ 0 & \sin(\gamma) & \sin(2\gamma) & \sin(\alpha) & \sin(\alpha + \gamma) & \sin(\alpha + 2\gamma) \\ 1 & \cos(2\gamma) & \cos(\gamma) & \cos(\alpha + \gamma) & \cos(\alpha) & \cos(\alpha + 2\gamma) \\ 0 & \sin(2\gamma) & \sin(\gamma) & \sin(\alpha + \gamma) & \sin(\alpha) & \sin(\alpha + 2\gamma) \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix} \quad (15)$$

where $\alpha = \pi/6$ – electrical angle of shift between the a-phase axis of the stator 1 and 2; $\gamma = 2\pi/3$. Applying the transformation $[T_6]$ to the stator voltage and flux equations, the original six-dimensional stator system can be decomposed into three two-dimensional decoupled systems: the basic system (α, β) and the systems (z_1, z_2) and $(0_1, 0_2)$. The variables transformed to the system (α, β) can be considered as the electromagnetic components determined in a stationary coordinate system fixed to the stator, with the α -axis aligned with the a -axis of the stator 1. To obtain the general analysis the electromagnetic components (α, β) have been further transformed to the reference frame (x, y) , rotating relative to the stator with arbitrary angular speed ω_k . After these manipulations the general motor equations can be represented in vector form given below:

- the vector equations for the transformed variables expressed in the general system (x, y) :

$$\underline{u}_{-s} = R_s \cdot \underline{i}_{-s} + p \underline{\psi}_{-s} + j\omega_k \cdot \underline{\psi}_{-s} \quad (16)$$

$$0 = R_r \cdot \underline{i}_{-r} + p \underline{\psi}_{-r} + j(\omega_k - \omega_e) \cdot \underline{\psi}_{-r},$$

$$\underline{\psi}_{-s} = L_s \cdot \underline{i}_{-s} + L_m \cdot \underline{i}_{-r} \quad (17)$$

$$\underline{\psi}_{-r} = L_m \cdot \underline{i}_{-s} + L_r \cdot \underline{i}_{-r},$$

$$M_e = 3p_b(L_m/L_r) \cdot \text{Im} \left(\underline{i}_{-s} \cdot \underline{\psi}_{-r}^* \right), \quad (18)$$

where:

$$L_s = L_{sl} + L_m; \quad L_r = L_{rl} + L_m; \quad L_m = 3L_\mu, \quad (19)$$

- the vector equations for the stator variables expressed in the system (z_1, z_2) :

$$\underline{u}_{-sz} = R_s \underline{i}_{-sz} + p \underline{\psi}_{-sz} \quad \underline{\psi}_{-sz} = L_{sl} \cdot \underline{i}_{-sz}, \quad (20)$$

- the vector equations for the stator variables expressed in the system $(0_1, 0_2)$:

$$\underline{u}_{-s0} = R_s \underline{i}_{-s0} + p \underline{\psi}_{-s0}, \quad \underline{\psi}_{-s0} = L_{sl} \cdot \underline{i}_{-s0}. \quad (21)$$

The vector equation for the zero rotor components is the same as for Model I. Figure 3 presents the circuit representation of the transformed equations for the Model II of the DSIM. These circuits describe the electromagnetic couplings between stator and rotor equivalent circuits and the principle of electromechanical energy conversion in the motor. The circuit in Fig.3a is an equivalent circuit, which shows the magnetic couplings between stator and rotor. Figure 3b presents the same circuit after elimination of magnetic couplings and introducing galvanic connections between circuits. Fig.3c presents the equivalent circuit for stator (z_1, z_2) components, Figure 3d and 3e present the equivalent circuits for zero components of six-phase stator and three-phase rotor, respectively. These circuits are not coupled with any other circuits.

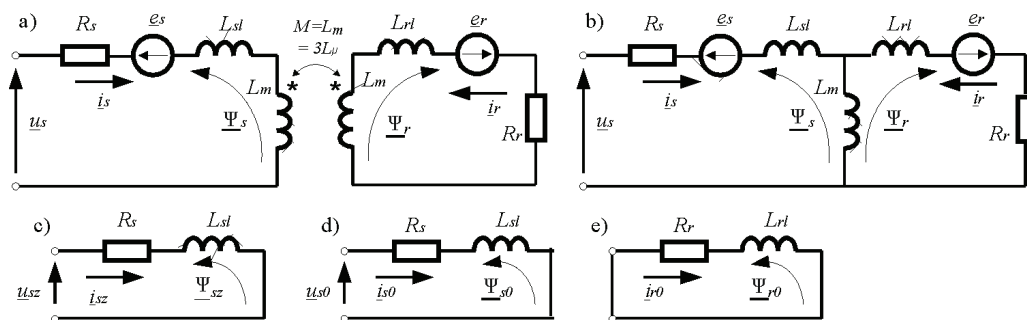


Fig. 3. The circuit representations of vector equations for Model II of dual stator induction motor

The analysis of Equations (16)-(21) and circuits from Figure 3 show that only the vector electromagnetic variables expressed in the basic system (x, y) or (α, β) are associated with the generation of the main flux linkage and contribute to the electromechanical energy conversion in the motor. Hence it follows that although the dual stator induction motor is represented as a six-phase motor, only these two vector components can be used for control of magnetic flux and electromagnetic torque of the motor.

If the stator windings of the DSIM are designed in the form of two three-phase systems with isolated neutral points then the $(0_1, 0_2)$ -components of the stator electromagnetic vari-

ables are always equal to zero and can be omitted in further analysis. In contrast, the specific feature of the DSIM is the possibility of occurrence of electromagnetic components in the system (z_1, z_2) [2, 8]. The harmonic voltages of order $k = 6n \pm 1$, ($n = 1, 3, 5, \dots$) are transformed to these components, so in result the harmonics of order $k = 5, 7, 17, 19, \dots$ can exist. Harmonics of these numbers can be generated by the voltage vectors of power electronics inverters used for the control of the motor. The stator currents forced by these harmonics can reach large values, because they are limited only by the low motor impedance determined by the phase resistance and the phase leakage inductance of the stator winding. Thus, during the control of dual stator induction motor by six-phase power electronics inverter from a large number of voltage vectors generated by an inverter, only the such voltage vectors should be chosen, which do not generate large values of the components defined in the system (z_1, z_2) .

3. Field-oriented control (FOC) of dual stator induction motor

The main goal of a field-oriented control (FOC) is to obtain decoupled control of electromagnetic torque and rotor flux of the motor. It is considered the FOC control system of DSIM with application of the rotor flux vector orientation. The algorithm of FOC control is based on the mathematical equations of DSIM formulated in the common reference frame (x, y) with the x -axis aligned with the vector of rotor flux linkage.

For the rotor flux orientation the following conditions are met:

$$\underline{\psi}_r = \psi_{rx} = \psi_r; \quad \psi_{ry} = 0; \quad \omega_k = \omega_{s\psi}. \quad (22)$$

Including the conditions (22) in the system of equations for Model I of DSIM we obtain:

$$p\psi_r + \frac{1}{T_r} \psi_r = \frac{L_m}{T_r} (i_{s1x} + i_{s2x}), \quad (23)$$

$$M_e = p_b (L_m/L_r) \cdot \psi_r \cdot (i_{s1y} + i_{s2y}), \quad (24)$$

$$\omega_{sl} = \omega_{s\psi} - \omega_e = \frac{L_m}{T_r \psi_r} \cdot (i_{s1y} + i_{s2y}), \quad (25)$$

where: T_r – rotor time constant; ω_{sl} – rotor slip speed, $\omega_{s\psi}$ – angular speed of rotor flux vector, x, y – subscripts denoting vector components in field-oriented reference frame (x, y) .

The Equations (23)-(25) present the principle of FOC control of DSIM based on Model I of the motor. This principle is additionally graphically illustrated in Figure 4.

Including the conditions (22) in the equations of Model II of DSIM it is obtained:

$$p\psi_r + \frac{1}{T_r} \psi_r = \frac{L_m}{T_r} i_{sx}, \quad (26)$$

$$M_e = 3p_b (L_m/L_r) \cdot \psi_r \cdot i_{sy}, \quad (27)$$

$$\omega_{sl} = \omega_{s\psi} - \omega_e = \frac{L_m}{T_r \psi_r} \cdot i_{sy} \cdot \quad (28)$$

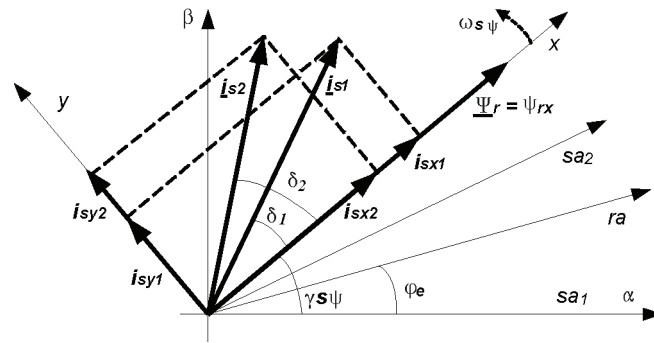


Fig. 4. Space vector diagram of FOC control based on Model I of DSIM

The Equations (26)-(28) present the principle of FOC control of DSIM based on Model II of the motor. This principle is additionally graphically illustrated in Figure 5.

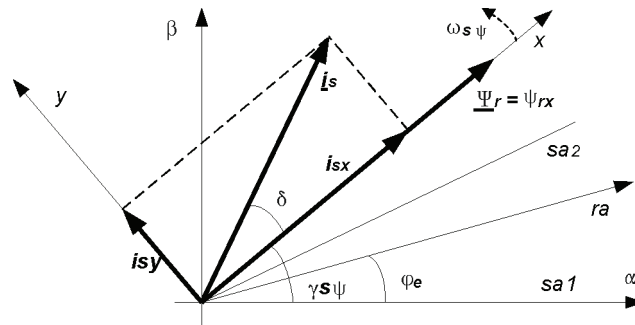


Fig. 5. Space vector diagram of FOC control based on Model II of DSIM

The above equations and Figures show that when the field-oriented control is used there is a possibility of independent control of the rotor flux and the electromagnetic torque of the motor. The following conclusions can be stated from presented considerations:

- 1) When the FOC algorithm is based on the Model I of the motor two stator current vectors i_{s1} and i_{s2} must be separately controlled in the control system. For this aim the individual stators of DSIM should be controlled by two separate three-phase converters.
- 2) When the FOC algorithm is based on the Model II of the motor only a resultant stator current vector i_s must be controlled in a similar manner as in conventional three-phase motor. For this aim the both stators of DSIM can be controlled by single six-phase converter.

FOC schemes can be classified according to the method on how the position of rotor flux vector is determined. The indirect IFOC method and direct DFOC method are distinguished. In the IFOC method only the value of angle position of the rotor flux vector is estimated. The

estimation is based on calculation of the integral of angular speed of rotor flux vector defined as the sum of the measured rotor angular speed and calculated rotor slip speed. In the DFOC method both the magnitude and angle position of the rotor flux vector are determined. These values can be obtained through estimation with using the appropriate current or voltage model of the rotor or by using the rotor flux observer based on direct measurements of rotor flux.

The block scheme of IFOC control based on Model I of DSIM is presented in Figure 4.

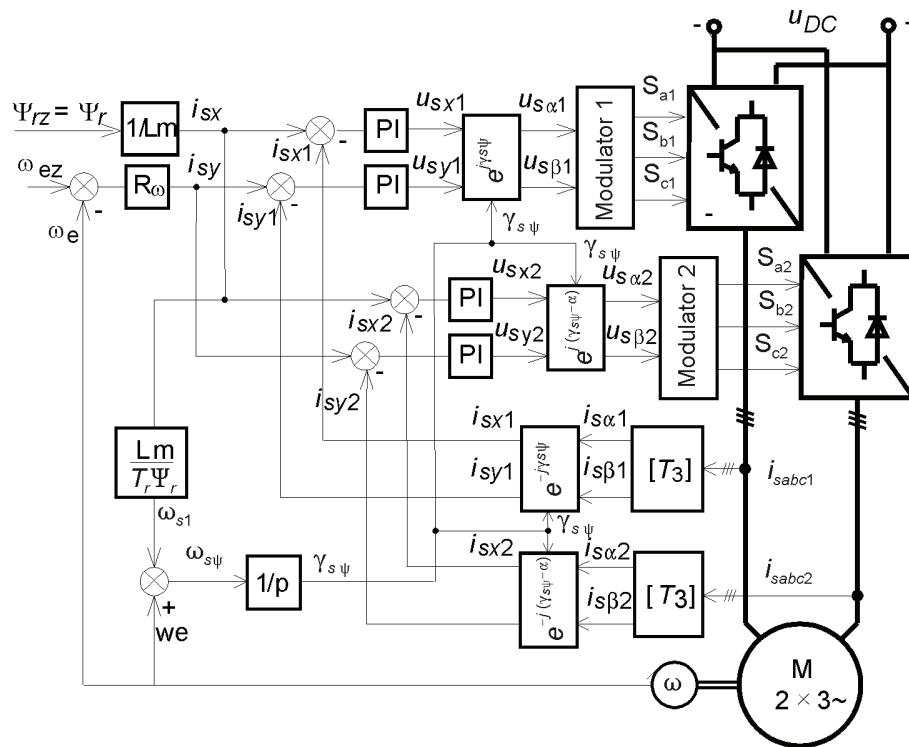


Fig. 6. Scheme of IFOC control of DSIM based on Model I of the motor

There are two main command signals in the control system: electric angular rotor speed ω_{ez} and magnitude of rotor flux vector Ψ_{rz} . The speed controller $R\omega$ determines the sum of command components of stator current vectors $i_{sy} = i_{sy1} + i_{sy2}$ which is proportional to the resultant electromagnetic motor torque. The flux producing command component of stator current vectors $i_{sx} = i_{sx1} + i_{sx2}$ is determined on the base on reference of rotor flux. The estimated instantaneous value of the angle position γ_ψ of the rotor flux vector is used in transformation blocks for suitable transformations of motor variables. Command current components in the control system are compared with the respective current components generated by transformation block on the base of measured values of motor variables of stator 1 and 2. The respective control errors generate through PI controllers two sets of reference components of stator voltage vectors determined in field oriented coordinate system. These voltage commands are then transformed into two stationary reference frames, spatially shifted by 30 electrical de-

grees and related to stator 1 and 2. These values are then converted by Modulator 1 and 2 in order to generate the switch trigger signals of individual three-phase inverters.

The block scheme of DFOC control based on Model II of DSIM is presented in Figure 7.

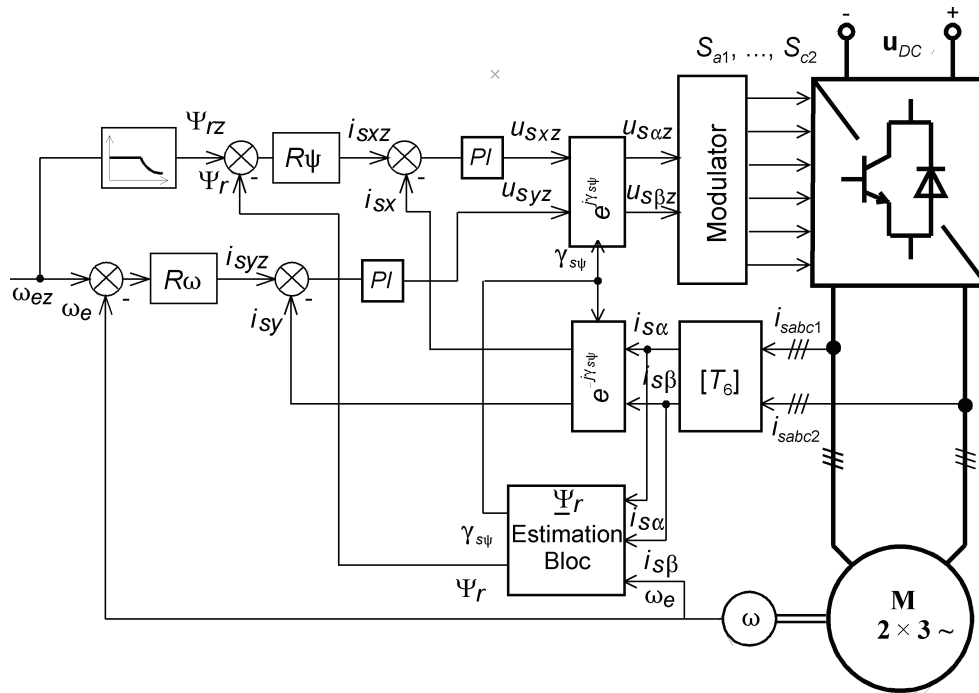


Fig. 7. Scheme of DFOC control of DSIM based on Model II of the motor

The system of DFOC control of DSIM consists of two overriding control loops for flux and speed regulation. The actual magnitude and angle position of rotor flux vector are determined through an estimation block or observer block. The flux controller $R\psi$ generates the reference of flux component i_{sx} of stator current vector and the speed controller $R\omega$ generates the reference of torque component i_{sy} of stator current vector. Command components of stator current vector are compared with the respective actual components of stator current vector obtained by transformation blocks on the base of measured values of motor variables. The subordinate PI controllers generate the reference components of stator voltage vector determined in field oriented system. These voltage commands are then transformed into stationary reference frame and send to PWM Modulator, which generates the switch trigger signals for six-phase inverter.

4. Direct torque control (DTC) of dual stator induction motor

Direct torque control (DTC) is an alternative to the field-oriented control (FOC) of induction motors. The principle of DTC is direct control of magnitude of stator flux vector and the

value of electromagnetic torque of induction motor. The main features of DTC control are: there are no current control loops, coordinate transformation is not required, there is no separate voltage PWM modulator. The DTC method of control can be applied to dual stator induction motors.

The methods of DTC control of DSIM can be divided into two basic types, depending on which model of DSIM is included in control algorithm:

- 1) DTC method with individual stator fluxes control of the motor – the method is based on Model I of DSIM motor;
- 2) DTC method with resultant stator flux control of the motor – the method is based on Model II of DSIM motor;

On the base of equations of Model I of DSIM we obtain the following set of vector equations defined in the common stationary reference frame:

$$\underline{\psi}_{-s1} = \int_0^t \begin{pmatrix} u_{-s1} - R_{s1} \cdot i_{-s1} \\ -s1 \end{pmatrix} dt, \quad (29)$$

$$\underline{\psi}_{-s2} = \int_0^t \begin{pmatrix} u_{-s2} - R_{s2} \cdot i_{-s2} \\ -s2 \end{pmatrix} dt, \quad (30)$$

$$M_e = M_{e1} + M_{e2} = p_b \frac{L_m}{L_r} K \cdot \psi_{s1} \psi_r \sin \delta_{\psi 1} + p_b \frac{L_m}{L_r} K \cdot \psi_{s2} \psi_r \sin \delta_{\psi 2}, \quad (31)$$

where: ψ_{s1} , ψ_{s2} , ψ_r – the magnitudes of flux vector of stator 1, stator 2 and rotor, respectively, K – motor constant, $\delta_{\psi 1}$, $\delta_{\psi 2}$ – the angles between stator 1, stator 2 and rotor flux vector respectively.

The Equations (29)-(31) present the theoretical principle of DTC method with individual stator fluxes control of DSIM motor. This principle is additionally illustrated graphically in Figure 8.

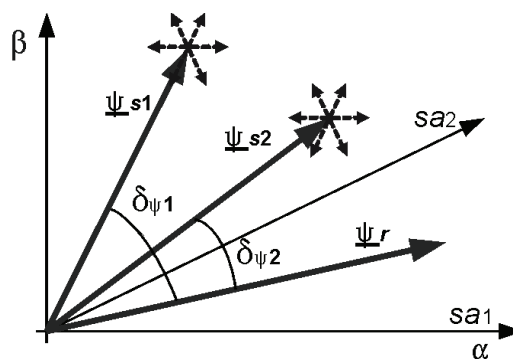


Fig. 8. Space vector diagram of DTC control based on Model I of DSIM

In order to apply this method of DTC control the two stators of DSIM should be supplied by two separate Voltage Source Inverters. Decoupled control of stator flux vectors and com-

ponents of electromagnetic torque is achieved by forcing relevant voltage vectors from separate inverters, acting on individual stator windings.

The block scheme of DTC control of DSIM with individual stator fluxes control of the motor is shown in Figure 9.

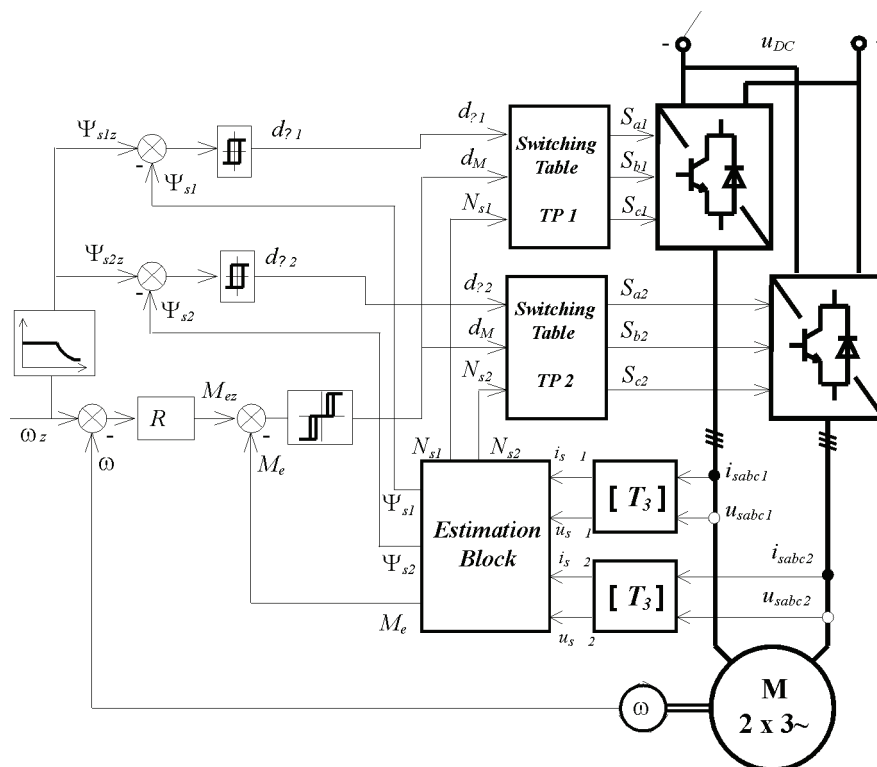


Fig. 9. The scheme of DTC control of DSIM with individual stator fluxes control

The control system uses nonlinear hysteresis controllers: the two-state hysteresis controllers of flux magnitude of stator 1 and stator 2 and the three-state hysteresis controller of electromagnetic torque of the motor. In the system phase voltages and currents of individual stator windings are measured. The measured values are transformed to rectangular coordinate systems (α_1, β_1) and (α_2, β_2) stationary relative to the stator windings. Transformed values are used in estimation block in order to determine the instantaneous value of electromagnetic torque, the instantaneous values of magnitudes of flux vectors of stator 1 and stator 2 and the sector numbers of instantaneous positions of stator flux vectors on the planes (α_1, β_1) and (α_2, β_2) . The reference values of electromagnetic torque and magnitudes of stator flux vectors are compared with actual values obtained from estimation block. Output signals from hysteresis controllers of torque and fluxes with signals specifying the sector numbers determine through switching tables TP1 and TP2 optimal control signals for control of individual 3-phase inverters.

On the base of equations of Model II of DSIM we obtain the following set of vector equations defined in the common stationary reference frame:

$$\underline{\psi}_{-s} = \int_0^t \left(\underline{u}_{-s} - R_s \cdot \underline{i}_{-s} \right) dt, \quad (32)$$

$$M_e = 3p_b \frac{L_m}{\sigma L_s L_r} \cdot \psi_s \psi_r \sin \delta_\psi, \quad (33)$$

where: ψ_s – magnitude of stator flux vector, σ – motor total leakage factor; δ_ψ – the angle between stator and rotor flux vector.

The Equations (32)-(33) present the theoretical principle of DTC method with resultant stator flux control of DSIM motor. This principle is additionally illustrated graphically in Figure 10.

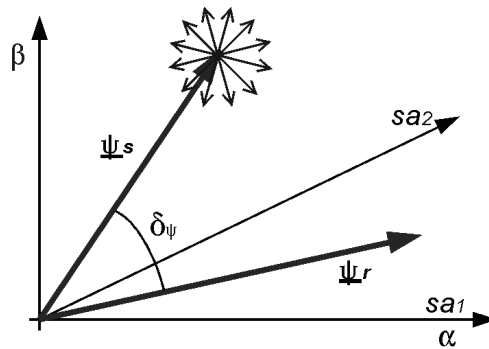


Fig. 10. Space vector diagram of DTC control based on Model II of DSIM

In order to apply this method of DTC control the two stators of DSIM should be supplied by single six-phase Voltage Source Inverter. Decoupled control of stator flux vector and electromagnetic torque is achieved by forcing relevant voltage vectors from inverter, acting on individual stator windings, considered as six-phase system.

The block scheme of DTC control of DSIM with resultant stator flux control of the motor is shown in Figure 11. The control system uses two nonlinear hysteresis controllers: the two-state controller of resultant stator flux and the three-state controller of electromagnetic torque. In the system phase voltages and phase currents of motor stators are measured, regarded as a 6-phase system. The measured values are transformed to the stationary rectangular coordinate system (α, β) . The transformed values are used in estimation block to calculate the instantaneous value of electromagnetic torque, magnitude of resultant flux vector and the sector number of angle position of the resultant stator flux vector. The set signals of electromagnetic torque and stator resultant flux are compared with actual values obtained from the estimation block. Output signals from hysteresis controllers, and signal with information of sector number of current position of stator resultant flux vector through the switch table deter-

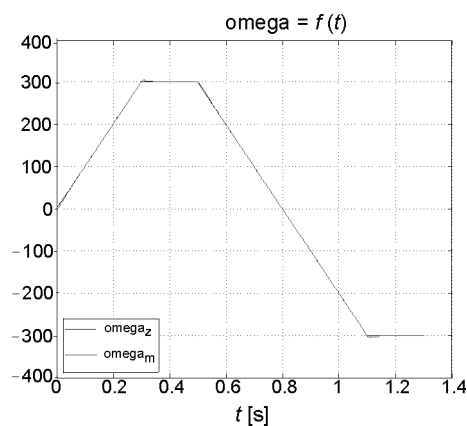


Fig. 12. The time waveforms of reference angular speed (ω_{z}) and actual angular speed (ω_{m}) of the DSIM motor for DTC control with individual stator fluxes control

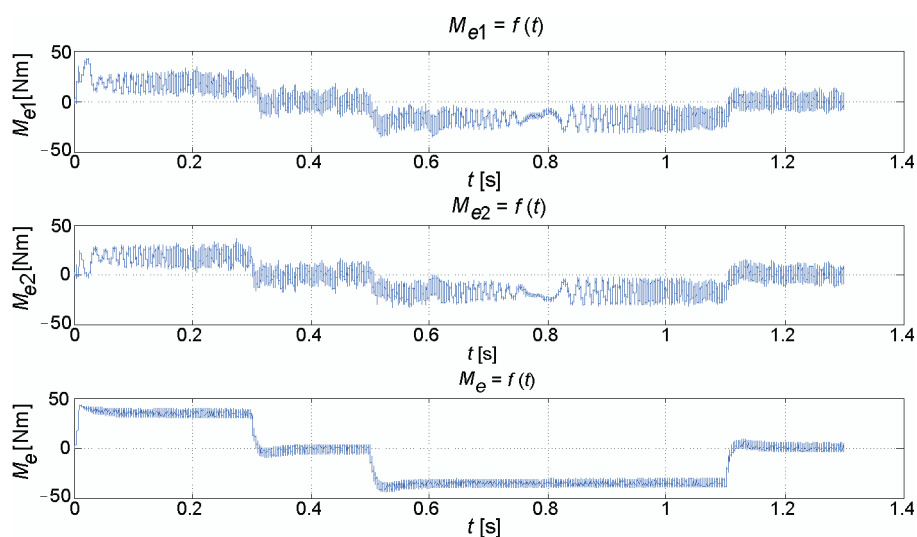


Fig. 13. The time waveforms of torque components and the resultant electromagnetic torque for DTC control of DSIM with individual stator fluxes control (From top to the bottom: electromagnetic torque components M_{e1} and M_{e2} , resultant electromagnetic torque M_e)

6. Summary

Analysis of dual stator induction motors may be performed on the basis of two equivalent mathematical models of the motor.

The Model I of the motor is considered as a system of two 3-phase motors with a common rotor. The advantage of this model is the ability to analyze motors with possible asymmetries of electromagnetic parameters of two stator windings.

The Model II of the motor is considered as a 6-phase system. A limitation of this method of analysis is the possibility of its application only to the motor with two identical stator windings. The advantage of this method is the possibility of rational choice vectors of the inverter output voltages for reducing excessive values of stator currents and power losses in the motor.

The conducted analysis allow to draw the conclusion that, depending on the choice of motor model different algorithms and control schemes are obtained. The DSIM motors can be controlled by application FOC or DTC methods of control. Control algorithms and control schemes based on the Model I are to some extent more complex and require a larger number of signal processing blocks and control blocks in comparison to schemes based on Model II.

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