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Model of Multiphase Induction Motor

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Introduction

Multi-phase motor drives have been studied from more than thirty years. Since the last two years, the interest has grown so that some international power electronic conferences have hosted sessions on the multi-phase motor drives [1].

Generally, multi-phase machines drive has many advantages over conventional three-phase drive such as high power handling capability by dividing the required power between multiple phases, reduced torque pulsations and higher reliability. In particular, unlike in a three phase drive, the loss of stator phase does not prevent the machine from starting and running. Other advantages of multi-phase systems, are increased torque per ampere for the same volume machine, reduced stator copper losses and reduced rotor harmonic currents [2].

The main application areas of multiphase induction-motor drives are ship propulsion, traction (including electric and hybrid electric vehicles) and the concept of „more-electric“ aircraft [3]. Other suitable applications are locomotive traction [1], aerospace and high power applications [2].The six phase motor has some advantages against the other multiphase motors: the six phase motor, fed by frequency converter, has no the third of aliquot to three magnetic flux harmonics [4–6].

The main focus of this paper is developing dynamic model of six-phase induction motor, simulation and analysis of the dynamic characteristics of the motor.

Dynamic Model of Six-phase Induction Motor

It is evident that the six-phase induction machine has six phase windings in the stator. But regarding rotor, some arguments exist about how many phases should be used in the analysis and modeling. In the modeling some researches [7] used six rotor phase windings, while others adopted three rotor phase windings [8, 9, 10].

Dynamic model for motor with three-phase rotor winding and six-phase stator winding is developed. Assumption of different number of phases in the stator and the rotor corresponds to application of wound rotor induction motor. Using a three-phase rotor for modeling gives a clear concept of per phase equivalent circuit or arbitrary rotating reference frame equivalent circuit. Fig. 1 shows the representation of the motor stator windings as well as the set of three rotor phase windings and phasors.

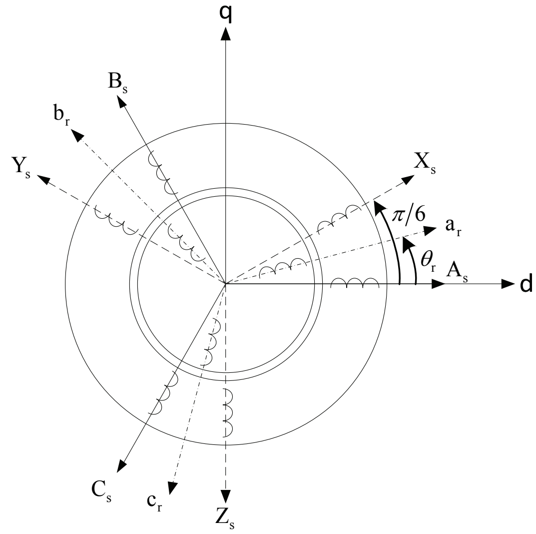

Fig. 1. Stator and rotor windings and phasors of the six-phase induction machine

In order to develop the six-phase induction machine model, the following assumptions are made:

- The air gap is uniform and the windings are sinusoidally distributed around the air gap.
- Magnetic saturation and core losses are neglected.

As for the three-phase induction motor, where the well-known dq rotating reference is used in analysis and control [11, 12] a dq reference frame is also used for the six-phase induction motor. The six-phase induction machine can be modeled with the following voltage equations in synchronous reference frame [9]:

$$
\begin{cases}
u_{qs1} = r_s i_{qs1} + s\psi_{qs1} + \omega\psi_{ds1}; \\
u_{ds1} = r_s i_{ds1} + s\psi_{ds1} - \omega\psi_{qs1}; \\
u_{qs2} = r_s i_{qs2} + s\psi_{qs2} + \omega\psi_{ds2}; \\
u_{ds2} = r_s i_{ds2} + s\psi_{ds2} - \omega\psi_{qs2}; \\
u'_{qr} = r'_r i'_{qr} + s\psi'_{qr} + (\omega - \omega_r)\psi'_{dr}; \\
u'_{dr} = r'_r i'_{dr} + s\psi'_{dr} - (\omega - \omega_r)\psi'_{qr};
\end{cases} \qquad (1)
$$

where the flux linkage expressed as:

$$
\begin{cases}
\psi_{qs1} = L_{ls} i_{qs1} + L_{lm}\left(i_{qs1} + i_{qs2}\right) + L_m\left(i_{qs1} + i_{qs2} + i'_{qr}\right); \\
\psi_{ds1} = L_{ls} i_{ds1} + L_{lm}\left(i_{ds1} + i_{ds2}\right) + L_m\left(i_{ds1} + i_{ds2} + i'_{dr}\right); \\
\psi_{qs2} = L_{ls} i_{qs2} + L_{lm}\left(i_{qs1} + i_{qs2}\right) + L_m\left(i_{qs1} + i_{qs2} + i'_{qr}\right); \\
\psi_{ds2} = L_{ls} i_{ds2} + L_{lm}\left(i_{ds1} + i_{ds2}\right) + L_m\left(i_{ds1} + i_{ds2} + i'_{dr}\right); \\
\psi'_{qr} = L'_{lr} i'_{qr} + L_m\left(i_{qs1} + i_{qs2} + i'_{qr}\right); \\
\psi'_{dr} = L'_{lr} i'_{dr} + L_m\left(i_{ds1} + i_{ds2} + i'_{dr}\right);
\end{cases} \qquad (2)
$$

where ψ_{qs1}, ψ_{qs2} are stator q-axis flux linkages components, ψ_{ds1}, ψ_{ds2} are stator d-axis flux linkages components, ψ'_{qr}, ψ'_{dr} are rotor q-axis and d-axis flux-linkage component, i_{qs1}, i_{qs2} are stator q-axis currents components, i_{ds1}, i_{ds2} are stator d-axis currents components, i'_{qr}, i'_{dr} are rotor q-axis and d-axis current components, L_{ls} is stator leakage inductance, L_m is air gap inductance, L_{lm} is stator mutual leakage inductance, L'_{lr} is rotor leakage inductance, s is Laplace operator, □ is synchronous speed of one pole induction motor the same as speed of rotating magnetic field, r_s is stator resistance u_{ds1}, u_{ds2}, u_{qs1}, u_{qs2} and u'_{dr}, u'_{qr} are voltages of stator windings and rotor windings correspondingly.

The voltage and flux linkage equations corresponds the equivalent circuits, shown in Fig. 2.

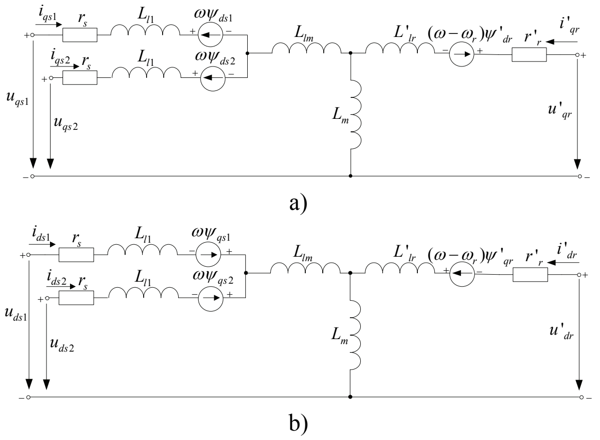

Fig. 2. Dynamic equivalent per phase circuits of six-phase induction motor

The electromagnetic torque can be expressed in the synchronous dq reference frame as

$$
T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\frac{L_m}{L'_r}\right)\left[\psi'_{dr}\left(i_{qs1} + i_{qs2}\right) - \psi'_{qr}\left(i_{ds1} + i_{ds2}\right)\right]; \quad (3)
$$

where P is number of pole pairs.

The equation of drive movement is written as

$$
\frac{d\omega_r}{dt} = \frac{1}{J_r}\left(T_e - T_L\right); \qquad (4)
$$

where T_L is load torque.

Computer model of six-phase induction machine

Equations (1, 2, 3, 4) are represented in matrix form (5) as

$$
A \cdot x = F; \qquad (5)
$$

where matrix A is expressed as:

$$
A = \begin{bmatrix}
a_{11} & a_{12} & 0 & 0 & a_{15} & 0 & 0 \\
0 & 0 & a_{23} & a_{24} & 0 & a_{26} & 0 \\
a_{31} & a_{32} & 0 & 0 & a_{35} & 0 & 0 \\
0 & 0 & a_{43} & a_{44} & 0 & a_{46} & 0 \\
a_{51} & a_{52} & 0 & 0 & a_{55} & 0 & 0 \\
0 & 0 & a_{63} & a_{64} & 0 & a_{66} & 0 \\
0 & 0 & a_{73} & a_{74} & 0 & a_{76} & a_{77}
\end{bmatrix}; \qquad (6)
$$

where $a_{11} = a_{23} = a_{32} = a_{44} = L_{ls} + L_{lm} + L_m$, $a_{12} = a_{24} = = a_{31} = a_{43} = L_{lm} + L_m$, $a_{15} = a_{26} = a_{35} = a_{46} = a_{51} =$, $= a_{52} = a_{63} = a_{73} = a_{74} = L_m$ $a_{55} = a_{66} = a_{76} = L'_{lr} + L_m$, $a_{77} = J_r$.

Matrix F is written as:

$$
F = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \\ F_7 \end{bmatrix}; \qquad (7)
$$

where $F_1 = u_{qs1} - i_{qs1} r_s - \omega \cdot i_{ds1}(L_{ls} + L_{lm} + L_m) - -\omega \cdot i_{ds2}(L_{lm} + L_m) - \omega \cdot i'_{dr} L_m;$ $F_2 = u_{ds1} - i_{ds1} r_s + +\omega \cdot i_{qs1}(L_{ls} + L_{lm} + L_m) + \omega \cdot i_{qs2}(L_{lm} + L_m) + \omega \cdot i'_{qr} L_m;$ $F_3 = u_{qs2} - i_{qs2} r_s - \omega \cdot i_{ds2}(L_{ls} + L_{lm} + L_m) - -\omega \cdot i_{ds1}(L_{lm} + L_m) - \omega \cdot i'_{dr} L_m;$ $F_4 = u_{ds2} - i_{ds2} r_s + +\omega \cdot i_{qs2}(L_{ls} + L_{lm} + L_m) + \omega \cdot i_{qs1}(L_{lm} + L_m) + \omega \cdot i'_{qr} L_m;$ $F_5 = u_{qr} - i'_{qr} r'_r - (\omega - \omega_r) \cdot i_{ds1} L_m - (\omega - \omega_r) \cdot i_{ds2} L_m - -(\omega - \omega_r) \cdot i_{ds1} L_m - (\omega - \omega_r) \cdot i'_{dr}(L'_{lr} + L_m);$

$$F_6 = u_{dr} - i_{dr}^{'} r_r^{'} + (\omega - \omega_r)\cdot i_{qs1} L_m + (\omega - \omega_r)\cdot i_{qs2} L_m +$$
$$+(\omega - \omega_r)\cdot i_{ds1} L_m + (\omega - \omega_r)\cdot i_{qr}^{'} (L_{lr}^{'} + L_m);$$
$$F_7 = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_{lr}^{'}}\left(\psi_{dr}^{'}\left(i_{qs1}+i_{qs2}\right) - \psi_{qr}^{'}\left(i_{ds1}+i_{ds2}\right)\right).$$

Matrix of variables x is expressed as

$$x = \begin{bmatrix} \frac{di_{qs1}}{dt} \\ \frac{di_{ds1}}{dt} \\ \frac{di_{qs2}}{dt} \\ \frac{di_{ds2}}{dt} \\ \frac{di_{qr}^{'}}{dt} \\ \frac{di_{dr}^{'}}{dt} \\ \frac{d\omega_r}{dt} \end{bmatrix}. \quad (8)$$

According to Eq. 5 the MATLAB model was elaborated. Dormand-Prince method (ode45) was used to solve the set of discussed equations.

Results of simulation

Parameters of the modeled motor are presented in Table 1.

Table 1. Motor parameters

R_s, Ω	$R_r^{'}$, Ω	L_{ls}, mH	$L_{lr}^{'}$, mH	L_m, H	L_{lm}, H	U, V	ω rad/s	J_r, $kg\cdot m^2$	P
3.55	1.04	5.2	9.3	0.3	0.035	220	314	0.07	1

Fig. 3 shows starting transients of six-phase motor at no load. The settling time is 0.45 s. Due to torque oscillations in the beginning of process, oscillation of speed also are seen.

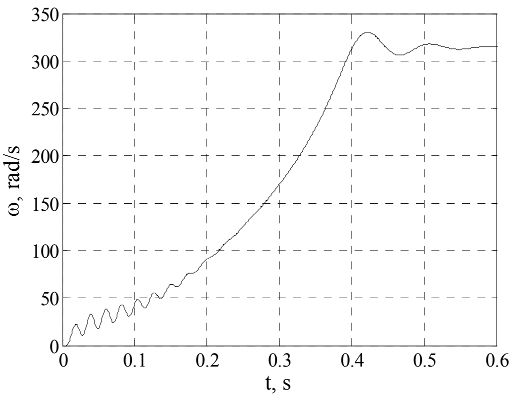

Fig. 3. Speed response of six-phase induction motor

Response of torque, developed by motor is presented in Fig. 4. The greatest value of torque is equal to 175 N·m. The steady-state of torque is equal to zero while motor is starting at no load.

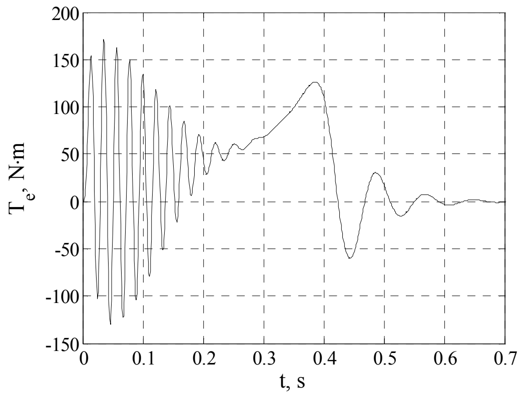

Fig. 4. Response of torque

Direct and quadrature components of stator currents are presented in Fig. 5 and Fig. 6.

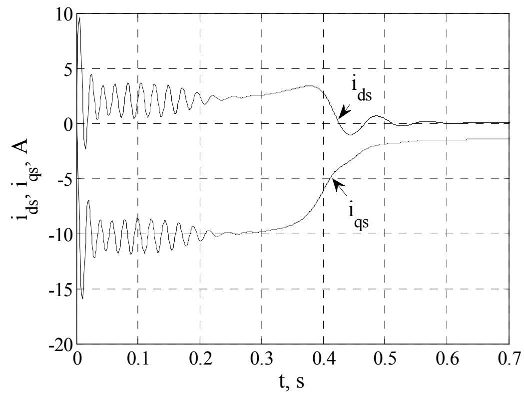

Fig. 5. Components of stator currents in synchronous reference frame

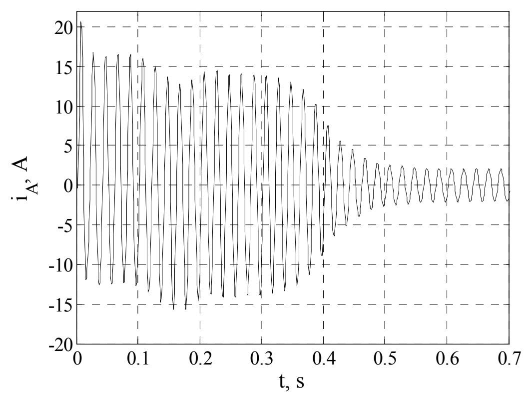

Fig. 6. Transient of stator A phase current at no load

Conclusions

Mathematical and computer model of multiphase motor with six-phase stator winding and three phase rotor winding in the synchronous reference frame is elaborated.

Equivalent circuits per phase of motor for direct and quadrature axis are presented.

Starting transients of torque, speed and current obtained by solving of differential equations of the motor are qualitatively close to that of three phase induction motor.

Electromagnetic transients last about 0.2 s causing torque oscillations of great amplitude and torque ripples.

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B. Kundrotas, S. Lisauskas, R. Rinkeviciene. Model of Multiphase Induction Motor // Electronics and Electrical Engineering. – Kaunas: Technologija, 2011. – No. 5(111). – P. 111–114.

The six-phase induction motor with two similar stator three phase windings, shifted by 30 degrees in space and three phase winding in rotor is considered. Differential equations of this motor are presented and transformed to dq synchronous reference frame. Dynamic equivalent circuits for each component are presented. Transformed equations are expressed in matrix form and are solved by MATLAB software using Dormand-Prince (ode45) method. Transient characteristics of torque, speed and current of six-phase induction motor are calculated and discussed. Ill. 6, bibl. 12, tabl. 1 (in English; abstracts in English and Lithuanian).

B. Kundrotas, S. Lisauskas, R. Rinkevičienė. Daugiafazio asinchroninio variklio modelis // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 5(111). – P. 111–114.

Nagrinėjamas šešiafazis asinchroninis variklis, kurio statoriuje yra dvi vienodos trifazės apvijos, kurių magnetinės ašys skiriasi 30 erdvinių laipsnių kampu, o rotoriuje yra trifazė apvija. Pateiktos tokio variklio dinamikos lygtys, transformuotos į sinchroniškai besisukančią koordinačių sistemą dq ir sudarytos variklio dinaminės ekvivalentinės schemos kiekvienai ašiai. Transformuotos lygtys užrašytos matricos pavidalu ir išspręstos Dormand – Prince (ode45) metodu naudojant MATLAB programų paketą. Gautos ir ištirtos šešiafazio asinchroninio variklio greičio, momento ir srovių dinaminės charakteristikos. Il. 6, bibl. 12, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).