Model of Controled Six Phase Induction Motor

R. Rinkeviciene, B. Kundrotas, S. Lisauskas

***Abstract*—**In this paper, the authors take a look at advantages of multiphase induction motors comparing them with three phase ones and present the applications where six-phase induction motors are used. They elaborate the mathematical model of six-phase induction motor with two similar stator three phase winding, shifted by 30 degrees in space and three phase winding in rotor, in synchronous reference frame for soft starting and scalar control. The authors simulate and discuss results of speed and torque starting transients.

***Keywords*—**Model, scalar control, six-phase induction motor.

I. INTRODUCTION

THE roots of multiphase variable speed drives can be traced to the time when inverter-fed ac drives were in the initial development stage. Due to the six-step mode of three-phase inverter operation, one particular problem at that time was the low frequency torque ripple. As the best solution to the problem appeared an increase in the number of phase of the machine [1].

Over the years, many other beneficial features of multiphase machines and drives have become recognized. Some of them: improved reliability as the machine continues running with one of its many phases open or short-circuited and there is not much performance degradation, reduced iron loss leading to improved overall performance, lower current per phase without increase in per phase voltage, increased torque per rms ampere for the same machine volume. The most advantageous feature is increase in power rating of the machine on high phase order connection in the same frame [2].

Multiphase motor drives have been proposed for different applications. Some of the most suitable applications are the high current ones: ship propulsion, locomotive traction, electric vehicles, where the main advantage of multiphase drives consists of splitting the controlled current on more inverter legs, reducing the single switch current stress compared to the three-phase converters [3]. Improved reliability is advantageous in nuclear power plants for its circulation pumps and for other similar applications in process industries [2].

Control methods of multiphase motors generally are the same as for three-phase motors [4]. Scalar control produces interior dynamic performance of an induction motor compared to vector control but is simpler and cheaper to implement. In variable-speed applications in which loading are tolerable, a scalar control system can produce adequate performance. Because of these advantages many applications operate with this control technique in the industry.

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

II. COMPUTER MODEL OF SIX-PHASE INDUCTION MOTOR

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 shown in Fig. 1 and represent in [5].

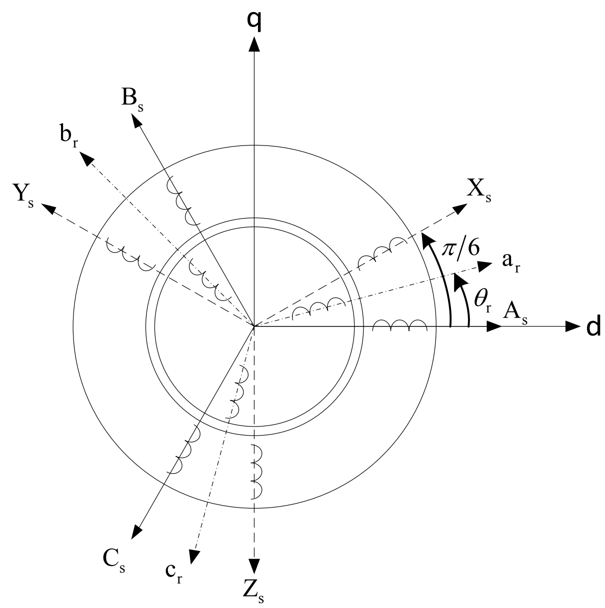

Fig. 1 Stator and rotor windings and phasors of the six-phase induction machine

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

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

As for the three-phase induction motor, where the well-known dq rotating reference frame is used in analysis and control, the same [6, 7, 8, 9] is also used for the six-phase induction motor. The equations of voltage, flux linkages, electromagnetic torque for dynamic model of six-phase induction motor in synchronous reference frame are presented in [10]. Referred equations are expressed in matrix form (1)

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as:

$$\mathbf{A} \cdot \mathbf{x} = \mathbf{F} \tag{1}$$

where matrix **A** is expressed as:

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & 0 & 0 & a_{15} & 0 & 0 \\ 0 & 0 & a_{23} & a_{24} & 0 & a_{26} & 0 \\ a_{31} & a_{32} & 0 & 0 & a_{35} & 0 & 0 \\ 0 & 0 & a_{43} & a_{44} & 0 & a_{46} & 0 \\ a_{51} & a_{52} & 0 & 0 & a_{55} & 0 & 0 \\ 0 & 0 & a_{63} & a_{64} & 0 & a_{66} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & a_{77} \end{bmatrix} \tag{2}$$

and $a_{11} = a_{23} = a_{32} = a_{44} = L_{ls} + L_{lm} + L_m$, $a_{12} = a_{24} = a_{31} = a_{43} = = L_{lm} + L_m$, $a_{15} = a_{26} = a_{35} = a_{46} = a_{51} = a_{52} = a_{63} = a_{73} = a_{74} = = L_m$, $a_{55} = a_{66} = a_{76} = L'_{lr} + L_m$, $a_{77} = J_r$, L_{ls} is stator leakage inductance, L_m is magnetizing inductance, L_{lm} is stator mutual leakage inductance, L'_{lr} is rotor leakage inductance, J_r is rotor inertia.

Matrix of variables **x** is expressed in this way:

$$\mathbf{x} = \begin{bmatrix} \frac{di_{qs1}}{dt} \\ \frac{di_{ds1}}{dt} \\ \frac{di_{qs2}}{dt} \\ \frac{di_{ds2}}{dt} \\ \frac{di'_{qr}}{dt} \\ \frac{di'_{dr}}{dt} \\ \frac{d\omega_r}{dt} \end{bmatrix}, \tag{3}$$

Matrix **F** is written as:

$$\mathbf{F} = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \\ F_7 \end{bmatrix}, \tag{4}$$

where:

$$F_1 = u_{qs1} - i_{qs1} r_s - \omega \cdot i_{ds1}(L_{ls} + L_{lm} + L_m) - \omega \cdot i_{ds2}(L_{lm} + L_m) - -\omega \cdot i'_{dr} L_m,$$

$$F_2 = u_{ds1} - i_{ds1} r_s + \omega \cdot i_{qs1}(L_{ls} + L_{lm} + L_m) + \omega \cdot i_{qs2}(L_{lm} + L_m) + +\omega \cdot i'_{qr} L_m,$$

$$F_3 = u_{qs2} - i_{qs2} r_s - \omega \cdot i_{ds2}(L_{ls} + L_{lm} + L_m) - \omega \cdot i_{ds1}(L_{lm} + L_m) - -\omega \cdot i'_{dr} L_m,$$

$$F_4 = u_{ds2} - i_{ds2} r_s + \omega \cdot i_{qs2}(L_{ls} + L_{lm} + L_m) + \omega \cdot i_{qs1}(L_{lm} + L_m) + +\omega \cdot i'_{qr} L_m,$$

$$F_5 = u_{qr} - i'_{qr} r'_r - (\omega - \omega_r) \cdot i_{ds1} L_m - (\omega - \omega_r) \cdot i_{ds2} L_m - -(\omega - \omega_r) \cdot i'_{dr}(L'_{lr} + L_m),$$

$$F_6 = u_{dr} - i'_{dr} r'_r + (\omega - \omega_r) \cdot i_{qs1} L_m + (\omega - \omega_r) \cdot i_{qs2} L_m + +(\omega - \omega_r) \cdot i'_{qr}(L'_{lr} + L_m),$$

and ψ_{qs1}, ψ_{qs2} are stator q-axis flux linkages, ψ_{ds1}, ψ_{ds2} are stator d-axis flux linkages, ψ'_{qr}, ψ'_{dr} are rotor q-axis and d-axis flux-linkage, i_{qs1}, i_{qs2} are stator q-axis currents, i_{ds1}, i_{ds2} are stator d-axis currents, i'_{qr}, i'_{dr} are rotor q-axis and d-axis current.

The torque, developed by motor is calculated as:

$$F_7 = \frac{3}{2}\frac{P}{2}\frac{L_m}{L'_{lr}}\left(\psi'_{dr}\left(i_{qs1} + i_{qs2}\right) - \psi'_{qr}\left(i_{ds1} + i_{ds2}\right)\right), \tag{5}$$

where P is number of pole pairs.

III. Results of Simulation

Parameters of the modeled motor are presented in Table I.

TABLE I
MOTOR PARAMETERS

Symbol	Quantity	Value
R_S	stator inductance	3.5 Ω
R'_r	rotor inductance	1.04 Ω
L_{ls}	stator leakage inductance	5.2 mH
L'_{lr}	rotor leakage inductance	9.3 mH
L_m	air gap inductance	0.3 H
L_{lm}	stator mutual leakage inductance	0.035 H
U	voltage	220 V
ω	frequency	314 rad/s
J_r	rotor inertia	0.07 kg·m^2
P	number of pole pairs	1

According to equations 1-5 the MATLAB model was elaborated. Dormand-Prince method (ode45) was used to solve the set of discussed equations.

In Fig. 2 solid line (1) shows speed starting transients of induction motor when motor is starting up to reference speed. Maximum speed value is 330 rad/s; overshoot reaches 5 % and steady state speed reduces up to 314 rad/s. Settling time is equal to 0.64 s. Dashed line (2) indicates starting transients at 1.25 times reduced reference speed. It is evident that speed overshoot is 17.5 rad/s, or 7 % and steady state speed value is 251 rad/s. Settling time is equal to 0.52 s. The dashed-dotted line (3) and the dotted line (4) shows rotor speed starting transients respectively at 1.5 and 2 times reduced reference speed. Maximum speed value is 225 rad/s; at the first case, overshoot reaches 7.6 %, steady state speed reduces up to 209 rad/s and settling time is equal to 0.42 s. Maximum speed value is 175 rad/s; at reference speed 2 times reduced, overshoot reaches 11.5 % and steady state speed reduces up to 157 rad/s. Settling time is equal to 0.34 s.

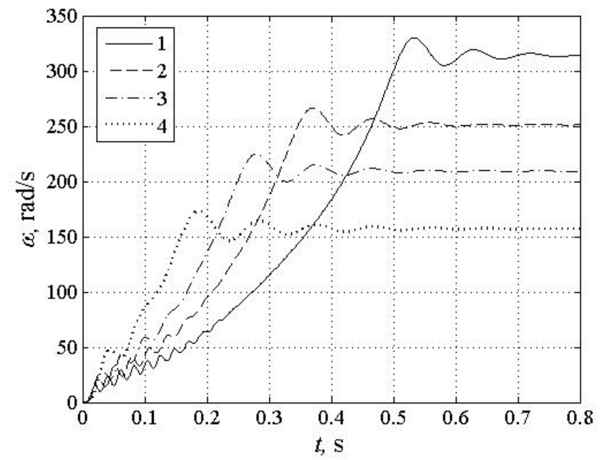

Fig. 2 Starting speed transients of six-phase induction motor at different reference speed

Response of torque, developed by six-phase induction motor is presented in Fig. 3. The greatest value of torque is equal to 177.5 N·m. After 0.8 s induction motor rotor speed reaches synchronous speed and torque reduces to zero.

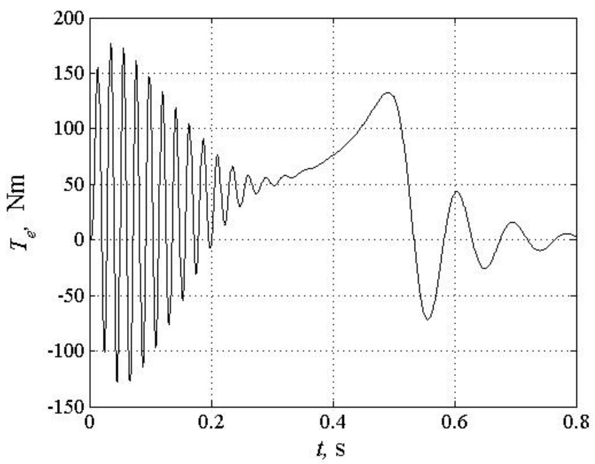

Fig. 3 Torque response of six-phase induction motor at reference speed 314 rad/s

Fig. 4 shows torque response of six-phase induction motor when reference speed is 1.25 times reduced. The greatest value of torque is equal to 183.3 N·m, after 0.62 s induction motor rotor speed reaches steady state.

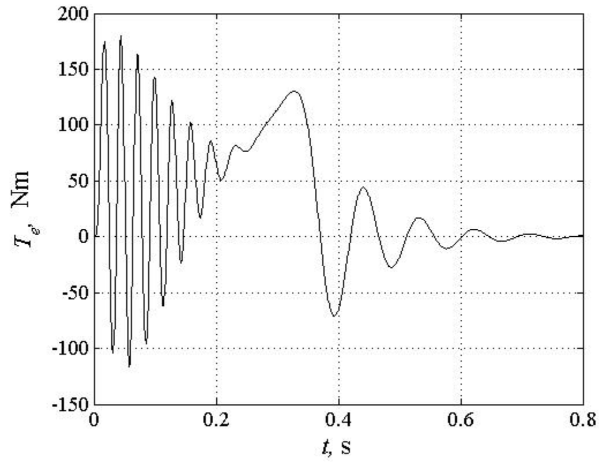

Fig. 4 Torque response of six-phase induction motor at 1.25 times reduced reference speed

Frequently induction motor should be started smoothly. For this frequency and voltage have to be changed by law shown in Fig. 5. This law can be expressed by equations:

$$u_{qs1} = 20 + (100\pi - 20)\cdot t, \tag{6}$$

$$u_{qs2} = 20 + (100\pi - 20)\cdot t, \tag{7}$$

$$\omega = 100\pi \cdot t. \tag{8}$$

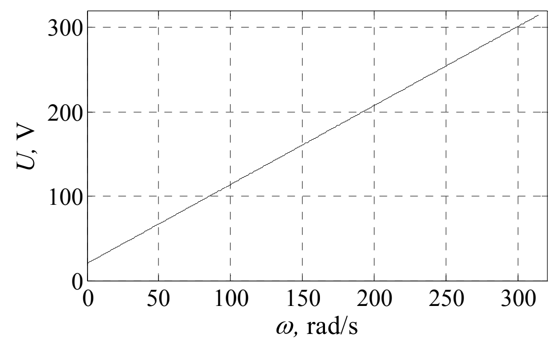

Fig. 5 Dependence voltage against frequency

For comparison the control algorithm and program was elaborated. Program solves differential equations up to time, equal to 1 s. Then the final values of variables are assumed as the initial states in the program, where the rotor speed is replaced by its steady state value.

In Fig. 6 solid line (1) shows starting transients of six-phase induction motor at no load, when frequency and voltage was changed by law shown in Fig. 2. Dashed (2), dashed-dotted (3) and dotted (4) lines indicate soft starting transients of six-phase induction motor when V/Hz ratio is reduced respectively 1.25, 1.5 and 2 times.

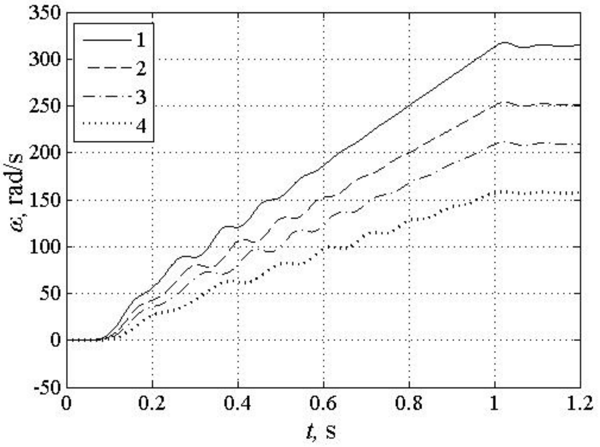

Fig. 6 Starting speed transients of six-phase induction motor at soft starting

Fig. 7 shows starting torque response of six-phase induction motor when frequency and voltage was changed by law shown in Fig. 2. The greatest value of torque is equal to 67 N·m. After 1.33 s induction motor torque reaches steady state and reduces to zero.

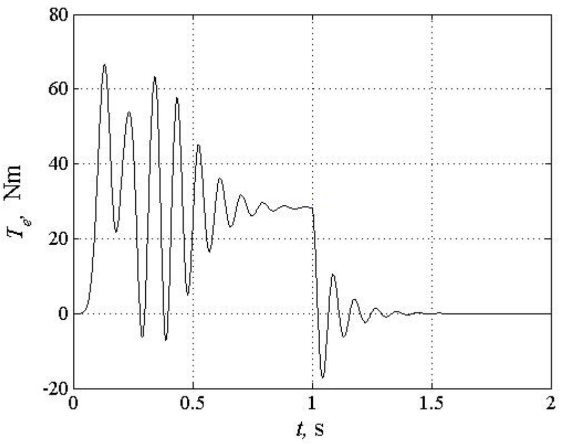

Fig. 7 Starting torque response of six-phase induction motor when V/Hz ratio is constant

Starting torque response of six-phase induction motor at soft starting at reduced 1.25 voltage and frequency ratio times is shown in Fig. 8. The greatest value of torque is equal to 66 N·m. After 1.3 s induction motor torque reaches steady state and reduces to zero, if the motor operates at no load.

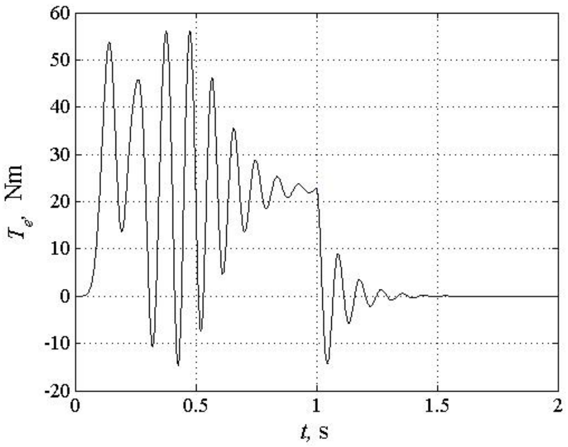

Fig. 8 Torque response of six-phase induction motor at constant V/Hz ratio reduced 1.25 times

It is evident that the speed settling time of uncontrolled six-phase induction motor is smaller than elaborated model with control opportunity. The control algorithm gives possibility to avoid over speed ripples. At soft starting smaller torque is required to start the controlled six-phase induction motor comparing with uncontrolled six-phase induction motor.

IV. Conclusion

The mathematical and simulation models of six phase induction motor are elaborated, allowing simulating soft start of the motor.

Torque developed by uncontrolled motor, is 2.6 times greater than soft starting.

Proposed control algorithm and developed program allows controlling the speed settling time and speed value steady state of the motor.

The average value of torque during starting remains almost constant and at low reference speed slightly depends on boost voltage.

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