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Modelling AC Induction Drive in PSpice

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Introduction

Advanced electric drive is a mechatronic system, which contains both mechanical and electronic units. Induction drives operate at transients when the amplitude and frequency of electric variables or speed vary in time. The typical examples of induction motor transients are: direct staring after turn off, sudden mechanical loading sudden short circuit, reconnection after a short supply fault, behaviour during short intervals of supply voltage reduction, performance with PWM converter fed.

The investigation of transients may be carried out directly by circuit models or by coupled finite element method (FEM) circuit models of different degrees of complexity. Usually the powerful tool *Matlab* is used for the simulation of AC induction drives [1 – 4]. However when drive includes such a complex electronic unit as frequency converter, the electronic circuit simulation programs offer an advantage against the *Matlab* software. Unfortunately, as a rule the electronic circuit simulation programs do not include the suitable model of the AC induction motor. Because of this, the development of AC induction motor models adopted for the simulation using electronic circuit simulation software becomes important. The article deals with the model of the induction motor developed for electronic circuit simulation program *PSpice*. The results of simulation of performance characteristics of the mechatronic system with AC induction motor using program *PSpice* are presented as well.

Mathematical model of AC induction motor

The induction motor can be observed as a system of electric and magnetic circuits, which are coupled magnetically and electrically. Therefore the three phase induction motor is represented by six circuits (one per phase). Each of them includes self inductance and 5 mutual inductances. The stator and rotor inductances as well as mutual inductances between stator or rotor phases do not depend on rotor position. The mutual inductance between stator and rotor phases depends on rotor position. So the 8th order nonlinear model with time variable coefficients describes the transients in the induction motor. To reduce number of equations, determining performance of induction motor, the complex variable model is used, where the complex variables of stator and rotor currents are introduced as space phasors [5, 6].

Applied voltage should be balanced by voltage drop across the resistance and rate of flux linkages space phasors as:

$$\overrightarrow{u_S^S} = R_S \overrightarrow{i_S} + \frac{d\overrightarrow{\psi_S}}{dt}, \quad (1)$$

$$\overrightarrow{u_R^R} = R_R \overrightarrow{i_R} + \frac{d\overrightarrow{\psi_R}}{dt}, \quad (2)$$

where $\overrightarrow{u_S^S}$ and $\overrightarrow{u_R^R}$ are voltage space phasors; $\overrightarrow{\psi}_S$ and $\overrightarrow{\psi}_R$ are phasor flux linkages of stator and rotor, expressed as:

$$\overrightarrow{\psi_S} = L_S \overrightarrow{i_S} + M_{SR} \overrightarrow{i_R} e^{j\theta_{ER}}, \quad (3)$$

$$\overrightarrow{\psi_R} = L_R \overrightarrow{i_R} + M_{SR} \overrightarrow{i_S} e^{-j\theta_{ER}}, \quad (4)$$

and

$$L_S = L_{S\sigma} + M_{SR}, \quad (5)$$

$$L_R = L_{R\sigma} + M_{SR}, \quad (6)$$

where rotor position $\theta_{er} = p_1\theta_r$; p_1 is number of pole pairs, θ_r is actual rotor position; L_S is inductance of stator, composed from self inductance $L_{S\sigma}$ and mutual inductance of stator and rotor windings M_{SR}, L_R is inductance of rotor, $L_{R\sigma}$ is rotor self inductance.

The stator variables in Eq. (3) are presented in stator coordinates, in Eq. (4) – in rotor coordinates.

Using rotation of stator and rotor coordinates at speed α_k, the equations of flux linkages obtain the form:

$$\vec{u}_S = R_S\vec{i}_S + \frac{d\vec{\psi}_S}{dt} + \vec{\psi}_S j\alpha_k, \quad (7)$$

$$\vec{u}_R = R_R\vec{i}_R + \frac{d\vec{\psi}_R}{dt} + \vec{\psi}_R j\left(\alpha_k - \omega\right). \quad (8)$$

R_S, R_R are phase resistances of stator and rotor and ω is speed of rotor.

The complex variables (state phasors) can be decomposed in plane along two orthogonal axes, rotating with speed α_k. Substituting equations (3, 4) to (7, 8) gives equations of motor variables decomposed along x axis:

$$\begin{cases} u_{Sx} = R_S i_{Sx} + L_{S\sigma}\dfrac{di_{Sx}}{dt} + M_{SR}\left(\dfrac{di_{Sx}}{dt} + \dfrac{di_{Rx}}{dt}\right) - \psi_{Sy}\alpha_k, \\ \psi_{Sx} = L_S i_{Sx} + M_{SR} i_{Rx}, \\ u_{Rx} = R_R i_{Rx} + L_{R\sigma}\dfrac{di_{Rx}}{dt} + M_{SR}\left(\dfrac{di_{Rx}}{dt} + \dfrac{di_{Sx}}{dt}\right) - \psi_{Ry}\left(\alpha_k - \omega\right), \\ \psi_{Rx} = L_R i_{Rx} + M_{SR} i_{Sx}. \end{cases} \tag{9}$$

In the same way is derived system of equations for variables, aligned along y axis:

$$\begin{cases} u_{Sy} = R_S i_{Sy} + L_{S\sigma}\dfrac{di_{Sy}}{dt} + M_{SR}\left(\dfrac{di_{Sy}}{dt} + \dfrac{di_{Sy}}{dt}\right) + \psi_{Sx}\alpha_k, \\ \psi_{Sy} = L_S i_{Sy} + M_{SR} i_{Ry}, \\ u_{Ry} = R_R i_{Ry} + L_{R\sigma}\dfrac{di_{Ry}}{dt} + M_{SR}\left(\dfrac{di_{Ry}}{dt} + \dfrac{di_{Sy}}{dt}\right) + \\ +\psi_{Rx}\left(\alpha_k - \omega\right), \\ \psi_{Ry} = L_R i_{Ry} + M_{SR} i_{Sy.} \end{cases} \tag{10}$$

Using program *PSpice,* the expressions of equation sets (9) and (10) can be presented as closed loops with appropriate electric elements. Each equation corresponds to one loop.

The loops aligned along *x* axes are modelled according to Eq. (9), and aligned along *y* axis – according to Eq. (10). The first loop describes the stator, the second – the rotor circuits. The last terms in the equations, which include the magnetic flux, can be modelled by voltage sources connected to the corresponding loops. The sources take into account the influence of loops presented on the different axis to each other, e.g. influence of loops on *x* axis to the loops on *y* axis.

Magnetic fluxes Ψ_{Sx}, Ψ_{Rx}, ψ_{Sy} and ψ_{Ry} are modelled by two connected in series current controlled voltage sources, whose gain is equal to corresponding inductance.

Mechanical part is described by equation:

$$\omega = \frac{1}{J_R}\int T_{em}dt = \\ = \frac{1}{J_R}\cdot\frac{pM_{SR}}{L_R L_S + M_{SR}}\int\left(\Psi_{Sy}\Psi_{Rx} - \Psi_{Sx}\Psi_{Ry}\right)dt,$$

where J_R – inertia of the motor and drive [kg·m^2];
T_{em} – developed electromagnetic torque [N·m].

The PSpice is program specialized for the simulation of electronic circuits, therefore, all mechanical variables, such as speed and torque must be replaced by electrical those [7]. The current in the developed model replaces the torque, the capacity - inertia and the voltage – speed.

The equivalent circuit of the induction motor model is shown in Fig.1. Each node has its number, which is presented in oval label.

The labels of nodes serve for creating of motor model. The further explanation uses node labels.

A lot of software for analyzing of electrical circuits is developed on the base of PSpice. They are different by their possibilities, price, convenience of interface and other parameters. Nevertheless they have common properties – description of electrical circuits is more so less matched with original PSpice. Here only standard PSpice possibilities were used for developing of induction motor model, therefore carried out model should operate in the any software developed on PSpice base. Gnucap program, running in Linux operational system was used for elaborating of motor model. This program is not based on PSpice, but many commands used to describe electrical circuit fully match PSpice syntaxes.

The parameters of modelled induction motor 4A100L2 are presented in Table 1.

Table 1. Parameters of modelled motor

Para-meter	U	P	n	R_S	L_S	M_{SR}	R_R	L_R
Units	V	kW	rpm	Ω	mH	mH	Ω	mH
Value	220	5.5	3000	1.05	3.6	253	0.754	7.3

Inertia of the motor is $J_R = 0.0075\ \text{kg}\cdot\text{m}^2$.

Description of electrical circuit, presented in Fig. 1, for Gnucap program is carried out for stationary reference frame at $\alpha_k = 0$ as:

```
* Circuit along x axis
V_sx 1 0 sin Amplitude=310 Frequency=50 IOffset=0.005
R_s_x 1 2 1.05
L_s_ro_x 2 3 3.6m IC=0
E_sx 3 4 16 0 0
L_sr_x 4 0 253m IC=0
E_rx 5 4 19 0 1
L_r_ro_x 5 6 7.3m IC=0
R_r_x 6 7 0.754
V_rx 7 0 0

* Circuit along y axis
V_sy 8 0 sin Amplitude=310 Frequency=50
R_s_y 9 8 1.05
L_s_ro_y 10 9 3.6m IC=0
E_sy 11 10 18 0 0
L_sr_y 11 0 253m IC=0
E_ry 11 12 24 0 1
L_r_ro_y 12 13 7.3m IC=0
R_r_y 13 14 0.754
V_ry 14 0 0

* Flux Psi_sy            (10)
H1_Psi_sy 15 0 V_ry 253m
H2_Psi_sy 16 15 V_sy 257m
R_Psi_sy 16 0 100

*Flux Psi_sx
H1_Psi_sx 17 0 V_rx 253m
H2_Psi_sx 18 17 V_sx 257m
R_Psi_sx 18 0 100

* Flux Psi_ry
H1_Psi_ry 20 0 V_sy 253m
H2_Psi_ry 21 20 V_ry 260m
R_Psi_ry 21 0 100
```

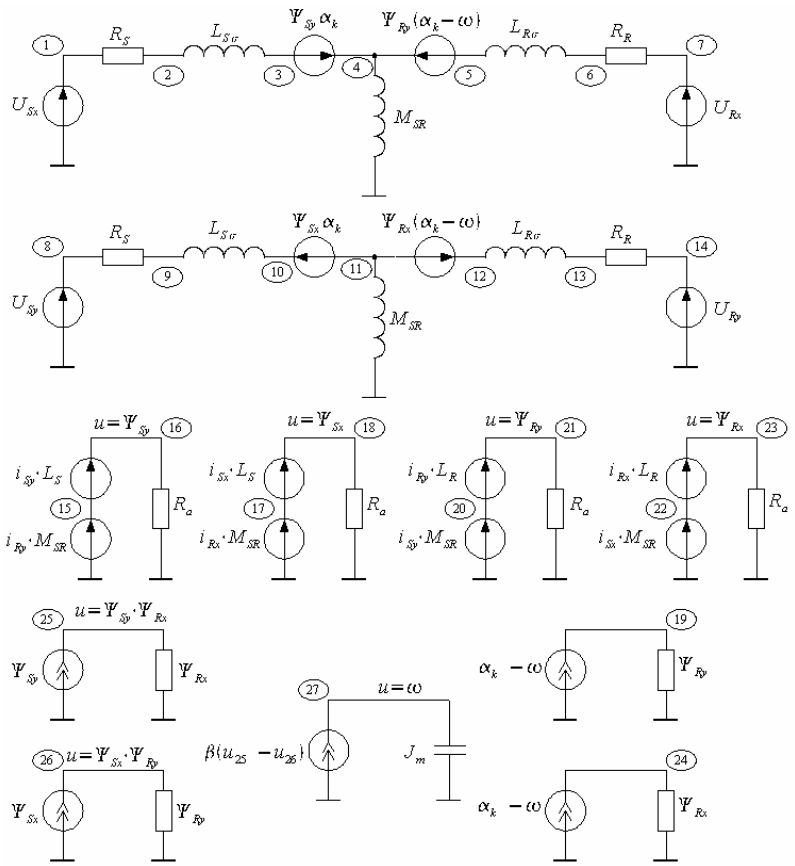

Fig. 1. Equivalent circuit of the induction motor model

```
* Flux Psi_rx
H1_Psi_rx 22 0 V_sx 253m
H2_Psi_rx 23 22 V_rx 260m
R_Psi_rx 23 0 100

* Calculation of electromagnetic torque
G1_mom 25 0 16 0 1
.VCR R_Psi_rx 25 0 23 0 1
G2_mom 26 0 18 0 1
.VCR R_Psi_ry 26 0 21 0 1
G_momentas 27 0 25 26 76
C_J 27 0 0.05 IC=0

* Calculation of speed and feedback
G1_ggr 19 0 27 0 poly 0 1
.VCR R1_ggr 19 0 21 0 1
G2_ggr 24 0 27 0 poly 0 1
.VCR R2_ggr 24 0 23 0 1
```

Simulation of transients at sine voltage supply

Simulation results showing transients of motor starting at no-load are presented in Fig. 2 and Fig. 3. According to Fig. 2 the starting stator current 8 times exceeds the rated that, which is equal about 10 A. After transients period finished, the no-load current flows in the stator winding.

Transients of rotor speed are presented in Fig. 4. To avoid oscillations of rotor speed, the double value of motor inertia was assumed. This assumption matches better the transients in the motor, operating at real engineering equipment which is also characterized by its own inertia. The transient period of speed lasts about 1 sec. Steady state of speed is equal to synchronous speed, which is 100π rad/sec.

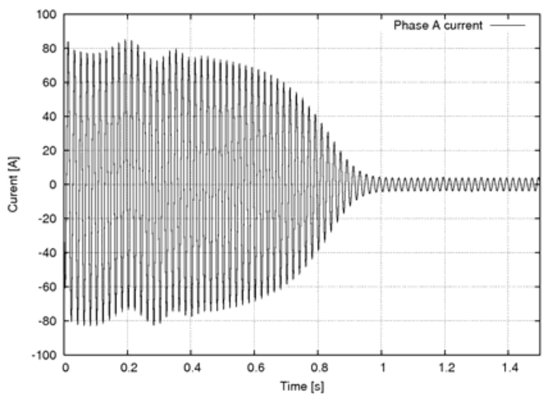

Fig. 2. Transients of stator phase A current

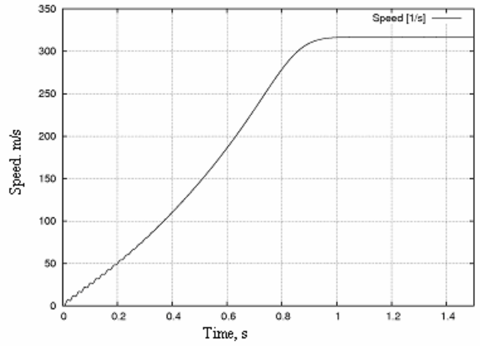

Fig. 3. Transients of rotor speed at starting of no-load motor

Transients of electromagnetic torque at starting are presented in Fig. 4. Torque transient period can be divided into two stages: the first one – oscillating and the second one – without oscillations. The amplitude of torque at oscillations exceeds more than twice the steady state value of rated torque. At this period the negative value of torque is also observed. After oscillating period the torque rises and reaches the value by 40 % exceeding the rated that. Motor starting at no-load gives steady state torque equal to zero.

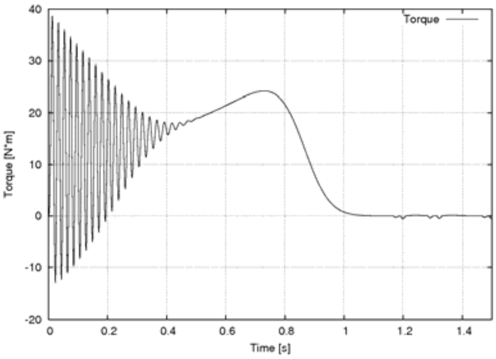

Fig. 4. Transients of electromagnetic torque at starting

Conclusions

1. The implementation of developed model of motor allows representing the mechatronic system comprising power electronic devices and AC induction motor with its electrical and mechanical parts, as unified model that can be realized using program PSpice.
2. Developed electromagnetic torque in the initial period of motor starting 2.2 times exceeds the rated that.
3. Starting current exceeds 6.5 times the rated that at starting.
4. Carried out model allows to investigate transients at drive operation motoring, breaking and generating modes.

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R. Rinkevičienė, A. Petrovas. Modelling AC Induction Drive in PSpice // Electronics and Electrical Engineering. – Kaunas: Technologija, 2007. – No. 1(73). – P. 29–32.

Problems of modelling of AC induction drive in PSpice are analyzed. Mathematical model of the motor is referred as to system of electric and magnetic circuits, which are coupled magnetically and electrically. Two systems of equations with decomposed motor variables along x and y axis are used to develop model of induction motor in PSpice. The program in Gnucap, running in Linux operational system was carried out for developing control of induction motor model. The equivalent circuit of the induction motor model in PSpice is presented. Simulation results of stator and rotor current, speed and torque at starting motor at no-load are presented and considered. Developed electromagnetic torque at the initial period of motor starting exceeds 2.2 the rated value. Stator starting current exceeds 6.5 times the rated that. Carried out model in PSpice allows to investigate transients at drive operation in motoring, breaking and generating modes. Ill. 4, bibl. 7 (in Lithuanian, summaries in English, Russian and Lithuanian).

Р. Ринкявичене, А. Петровас. Моделирование асинхронного привода с помощью программы PSpice // Электроника и электротехника. – Каунас: Технология, 2007. – № 1(73). – С. 29–32.

Обсуждаются вопросы, связанные с моделированием асинхронной машины с помощью программы PSpice. В модели используются только электрические цепи и цепи с взаимной индукцией, а сама модель построена по трансформированным уравнениям асинхронного двигателя. Моделирование проводилось в операционной системе Linux при помощи PSpice – подобной программы GnuCAP. Также для программы PSpice разработана схема замещения асинхронного двигателя. В статье приводятся результаты моделирования: переходные процессы тока статора, скорости и электромагнитного момента при холостом пуске двигателя. Максимальное значение пускового момента 2,2, а тока 6,5 раз превышает номинальные значения. Предлагаемая модель применима при анализе двигательного, тормозного и генераторного режимов работы двигателя. Ил. 4, библ. 7 (на английском языке; рефераты на английском, русском и литовском яз.).

R. Rinkevičienė, A. Petrovas. Kintamosios srovės asinchroninės pavaros modeliavimas naudojantis programa PSpice // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2007. – Nr. 1(73) . – P. 29–32.

Nagrinėjamos kintamosios srovės asinchroninės pavaros modelio sudarymo, naudojantis PSpice programine įranga, problemos. Pateiktas asinchroninės pavaros matematinis modelis, sudarytas iš elektrinių ir magnetinių grandinių, turinčių abipusį magnetinį ryšį. Asinchroninio variklio modeliui sudaryti panaudotos dvi lygčių sistemos, kuriose variklio kintamieji yra projektuojami į x ir y ašis. Modeliui valdyti panaudota Linux operacinėje sistemoje veikianti Gnucap terpėje parašyta programa. Pateikta ekvivalentinė asinchroninės pavaros modelio schema PSpice. Pateikti ir išanalizuoti imitacijos rezultatai: statoriaus srovės, greičio, elektromagnetinio momento pereinamieji procesai paleidžiant neapkrautą variklį. Variklio sukuriamo momento maksimali vertė 2,2 karto viršija variklio nominalųjį momentą, statoriaus srovė paleidimo metu 6,5 karto didesnė už nominaliąją. Sudarytas PSpice kintamosios srovės asinchroninės pavaros modelis leidžia tirti variklinio, stabdymo ir generatorinio režimo pereinamuosius procesus. Il. 4, bibl. 7 (lietuvių kalba; santraukos anglų, rusų ir lietuvių k.).