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SHORT OVERVIEW ABOUT MODELING THE INDUCTION MACHINE USING PSpICE

BY

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Abstract. The paper is a comparative analysis of the PSpice implementation of the two types of orthogonal model of the induction machine: in terms of currents or fluxes. In the first case, only the currents are used in voltage equations excluding the fluxes whereas in the second one, the currents are excluded and the total fluxes are retained. In each case an equivalent circuit is established and a full implementation is presented. The two cases are compared in terms of computing speed, precision and convergence.

Key words: induction machine; two-phase model; equivalent circuit; PSpice.

1. Introduction

The aim of this paper is to perform a comparative analysis of different types of PSpice implementation of the two-phase (orthogonal) model $dq-dq$ of the induction machine. Different forms of mathematical model were considered, using only currents or fluxes. In the first case only the currents are used in voltage eqs. excluding the fluxes and in the second one the currents are

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excluded and the total fluxes are retained. In each case an equivalent circuit is established and a full implementation is presented. The two cases are compared in terms of speed of computing analysis, precision and convergence. The study takes into account the simplicity of the PSpice implementation, the estimation of the model parameters, the computing speed, precision and convergence.

Induction machines are today extremely used in a great variety of industrial applications and household uses. Induction motors provide many advantages over other types of motors: price, construction, reliability, durability, ruggedness, type of power supply, ease of operation, can be used in hazardous locations. Induction machines operating as generators are used today in wind turbines and micro hydro installations due to their ability to work at varying rotor speeds. Unfortunately, in order to operate induction generators need reactive power from a source.

To describe the behavior of the induction machines, mathematical models with distributed or concentrated parameters are used. For single-phase and two-phase induction machines, the two-phase (orthogonal) model is a natural one. For three-phase induction machines, the natural model is the three-phase model, in phase coordinates.

However, very often the study of the induction machine operating as a motor or generator uses the two-phase model or spatial phasors model with concentrated parameters. The difference between these models is the eqs. mathematical form, but they are perfectly equivalent in terms of information provided.

The modeling of the (three-phase) induction machine relies on several hypotheses which allow the electrical and magnetic behaviors to be considered as totally linear and simplify the mathematical study (Justus, 1997; Ong, 1997).

Using these hypotheses, the analysis of the main phenomena of induction machine as a system is shown in Fig. 1.

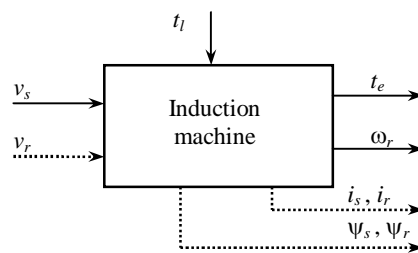


Fig. 1 - Induction machine as a block diagram.

The generic input and output quantities can be three-phase, two-phase or single-phase quantities.

Input quantities can be stator supply voltages, v_s ; rotor supply voltages, v_r ; load torque, t_l . Output quantities can be electromagnetic torque, t_e ; and rotor

angular speed, ω_r . Internal unknown quantities are: stator and rotor currents, i_s, i_r ; stator and rotor fluxes, ψ_s, ψ_r .

2. Two-Phase (Orthogonal) Model

In electrical machines study, the advantages of the two-phase (orthogonal) model over the three-phase model are well known. Using the Park transformation, the equivalent two-phase machine is supplied from a two-phase voltage system obtained from the three-phase supplying system (Cociu *et al.*, 2011) provide how can be used the Park transformation; thus, the three-phase system voltage is converted into a two-phase system which supplies the two phase equivalent machine.

As known, in the stationary reference frame, the classical orthogonal model dq - dq eqs. are

a) stator and rotor voltage eqs.

$$\begin{cases} v_{sd} = R_s i_{sd} + \frac{d\psi_{sd}}{dt}, \\ v_{sq} = R_s i_{sq} + \frac{d\psi_{sq}}{dt}, \\ v_{rd} = R_r i_{rd} + \frac{d\psi_{rd}}{dt} + \omega_r \psi_{rq}, \\ v_{rq} = R_r i_{rq} + \frac{d\psi_{rq}}{dt} - \omega_r \psi_{rd}; \end{cases} \quad (1)$$

b) flux eqs.

$$\begin{cases} \psi_{sd} = L_s i_{sd} + L_m i_{rd}, \\ \psi_{sq} = L_s i_{sq} + L_m i_{rq}, \\ \psi_{rd} = L_r i_{rd} + L_m i_{sd}, \\ \psi_{rq} = L_r i_{rq} + L_m i_{sq}; \end{cases} \quad \begin{matrix} L_s = L_{\sigma s} + L_m, \\ L_r = L_{\sigma r} + L_m; \end{matrix} \quad (2)$$

c) electromagnetic torque expression

$$t_e = p(i_{rd} \psi_{rq} - i_{rq} \psi_{rd}); \quad (3)$$

d) motion eq.

$$t_e - t_l = \frac{J}{p} \cdot \frac{d\omega_r}{dt} + \frac{F_\alpha}{p\omega_r}. \quad (4)$$

The analysis of the system eqs. renders evident the non-linear character of the orthogonal model. Ten unknown quantities correspond to the eqs. above as follows: two mechanical output quantities (electromagnetic torque t_e ; and rotor angular speed, ω_r), four currents (two for the stator and two for the rotor) and four fluxes (two for the stator and two for the rotor).

The mathematical model aims to establish functional relationships between quantities that describe the induction machine behavior. Therefore, Fig. 2 presents the block diagram corresponding to the two-phase model of the induction machine.

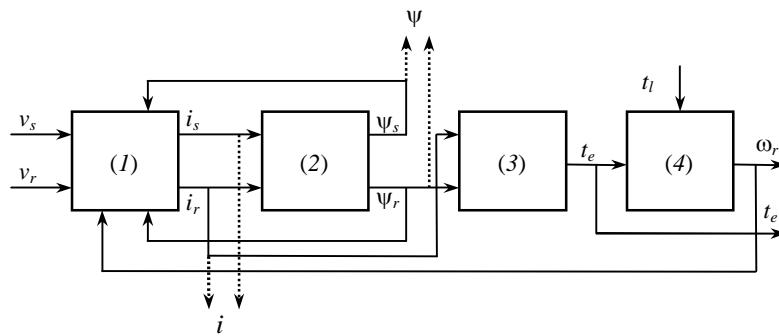


Fig. 2 – Block diagram corresponding to the two-phase model of the induction machine.

The block diagram provides the relationships between the electromagnetic quantities (voltages, currents, fluxes) and mechanical ones (electromagnetic torque and rotor angular speed).

Since the aim of the analysis or simulation is to determine the two mechanical output quantities, it is natural to eliminate the currents and the fluxes from (1),..., (3) in order to simplify the mathematical calculation. But when the purpose is to process the mathematical model to implement in a soft program, a serious analysis is necessary.

PSpice is able to compute very complicated mathematical expressions. Linear and non-linear eqs. and systems can be solved. The natural and direct method is based on PSpice implementation of the typical equivalent circuit (Cociu & Cociu, 1997). But the model eqs. system can be also solved by generic integrators based on *Analog Behavioral Modeling* facilities.

For the a.c. machines, which have more windings, implementing the equivalent circuit is proved to be more efficient (Cociu & Cociu, 1997; Justus, 1997) in terms of computing speed analysis, precision and convergence.

3. Modeling the Induction Machine Using only Currents

At first, the behavior of the induction machine described by the mathematical model using only the currents, excluding the fluxes, was considered. This approach is widely used in many situations. The primary

advantage consists of a new eqs. system based on which the equivalent circuit of the induction machine can be obtained. Using a natural method, this can be very easily implemented in PSpice.

Replacing the flux eqs. (2) in the voltage eqs. (1) gives

$$\begin{cases} v_{sd} = R_s i_{sd} + L_s \frac{di_{sd}}{dt} + L_m \frac{di_{rd}}{dt}, \\ v_{sq} = R_s i_{sq} + L_s \frac{di_{sq}}{dt} + L_m \frac{di_{rq}}{dt}, \\ v_{rd} = R_r i_{rd} + L_r \frac{di_{rd}}{dt} + L_m \frac{di_{sd}}{dt} + e_{rd}, \\ v_{rq} = R_r i_{rq} + L_r \frac{di_{rq}}{dt} + L_m \frac{di_{sq}}{dt} - e_{rq}, \end{cases} \quad (5)$$

where

$$\begin{cases} e_{rd} = \omega_r (L_r i_{rq} + L_m i_{sq}), \\ e_{rq} = \omega_r (L_r i_{rd} + L_m i_{sd}). \end{cases} \quad (6)$$

The electromagnetic torque eq. (3) can also be written in terms of currents

$$t_e = pL_m (i_{rd} i_{sq} - i_{rq} i_{sd}). \quad (7)$$

The internal phenomena of the induction machine are the same, but the block diagram is modified like in Fig. 3.

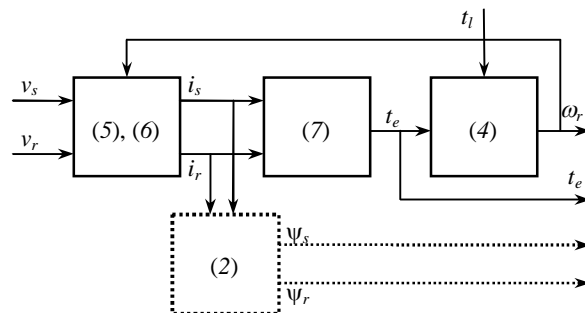


Fig. 3 – Block diagram of the two-phase model of the induction machine using only currents.

This very important simplification of the eqs. describing the operation of the induction machine leads to an easy way to implement the mathematical model in PSpice (Cociu & Cociu, 1997, 2005; Justus, 1997). As known, starting

from the mathematical model described by the operation eqs., using relations (5) and (6), an equivalent electrical circuit can be obtained, as in Fig. 4.

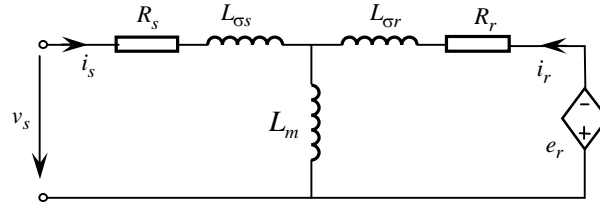


Fig. 4 – Generic equivalent circuit of the two-phase model of the induction machine.

To implement eqs. (7) and (4), generic integrators can be used (Cociu & Cociu, 2005; Justus, 1997). If the flux analysis is required, eqs. (2) can be used, implemented in generic calculators as in Fig. 3.

4. Modeling the Induction Machine Using only Fluxes

Starting from the classic model eqs., a new approach is presented by Araujo (2012) and Simion (2008). The proposed model excludes the presence of the currents and angular speed using only total fluxes and angular positions. Our proposal is not the critical analysis of this theory but only a comparative analysis of the PSpice implementation of this new model and the classical one. The currents will be excluded and the total fluxes will be used to model the behavior of the induction machine. But we will retain the angular speed in the final model eqs.

To eliminate the currents, from eqs. (2), using the notation

$$\Delta_L = L_s L_r - L_m^2, \quad (8)$$

we can determine the current expressions related to the fluxes

$$\begin{cases} i_{sd} = \frac{L_r}{\Delta_L} \Psi_{sd} - \frac{L_m}{\Delta_L} \Psi_{rd}, \\ i_{sq} = \frac{L_r}{\Delta_L} \Psi_{sq} - \frac{L_m}{\Delta_L} \Psi_{rq}, \\ i_{rd} = \frac{L_s}{\Delta_L} \Psi_{rd} - \frac{L_m}{\Delta_L} \Psi_{sd}, \\ i_{rq} = \frac{L_s}{\Delta_L} \Psi_{rq} - \frac{L_m}{\Delta_L} \Psi_{sq}. \end{cases} \quad (9)$$

Replacing the current eqs. (9) in the voltage eqs. (1) it results

$$\begin{cases} v_{sd} = \frac{R_s L_r}{\Delta_L} \psi_{sd} + \frac{d\psi_{sd}}{dt} - \frac{R_s L_m}{\Delta_L} \psi_{rd}, \\ v_{sq} = \frac{R_s L_r}{\Delta_L} \psi_{sq} + \frac{d\psi_{sq}}{dt} - \frac{R_s L_m}{\Delta_L} \psi_{rq}, \\ v_{rd} = \frac{R_r L_s}{\Delta_L} \psi_{rd} + \frac{d\psi_{rd}}{dt} - \frac{R_r L_m}{\Delta_L} \psi_{sd} + \omega_r \psi_{rq}, \\ v_{rq} = \frac{R_r L_s}{\Delta_L} \psi_{rq} + \frac{d\psi_{rq}}{dt} - \frac{R_r L_m}{\Delta_L} \psi_{sq} - \omega_r \psi_{rd}, \end{cases} \quad (10)$$

and using the notations

$$\begin{aligned} v_{sr} &= \frac{R_s L_r}{\Delta_L}, & v_{sm} &= \frac{R_s L_m}{\Delta_L}, \\ v_{rs} &= \frac{R_r L_s}{\Delta_L}, & v_{rm} &= \frac{R_r L_m}{\Delta_L}, \end{aligned} \quad (11)$$

we get the final form of the voltage eqs. in terms of fluxes

$$\begin{cases} v_{sd} = v_{sr} \psi_{sd} + \frac{d\psi_{sd}}{dt} - v_{sm} \psi_{rd}, \\ v_{sq} = v_{sr} \psi_{sq} + \frac{d\psi_{sq}}{dt} - v_{sm} \psi_{rq}, \\ v_{rd} = v_{rs} \psi_{rd} + \frac{d\psi_{rd}}{dt} - v_{rm} \psi_{sd} + \omega_r \psi_{rq}, \\ v_{rq} = v_{rs} \psi_{rq} + \frac{d\psi_{rq}}{dt} - v_{rm} \psi_{sq} - \omega_r \psi_{rd}. \end{cases} \quad (12)$$

The electromagnetic torque eq. can also be expressed using total fluxes

$$t_e = \frac{p}{\Delta_L} (\psi_{sd} \psi_{rq} - \psi_{sq} \psi_{rd}). \quad (13)$$

The new model of induction machine in terms of fluxes is composed by the voltage eqs. (12), torque eq. (13) and motion eq. (4). The block diagram provides the relationships between the quantities of interest. If the current analysis is required, eqs. (9) can be used as in Fig. 5, implemented in generic calculators.

Based on the voltage eqs. system, the equivalent circuit can be established like in Fig. 6.

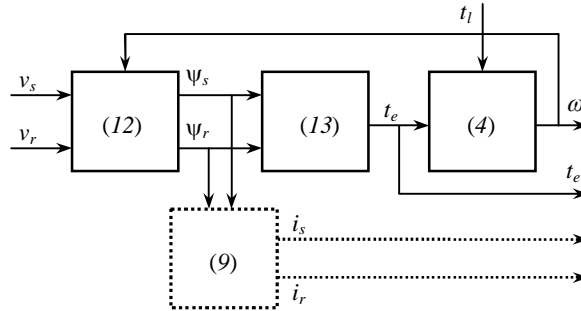


Fig. 5 – Block diagram of the two-phase model of the induction machine using only fluxes.

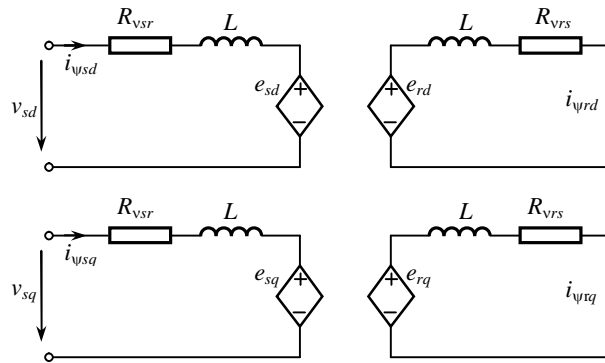


Fig. 6 – Equivalent circuits of the two-phase model of the induction machine using only fluxes.

Fig. 7 shows the generic calculators of the currents. The controlled-current generators, G_{ixx} , use *Analog Behavioral Modeling* facilities to perform the current values.

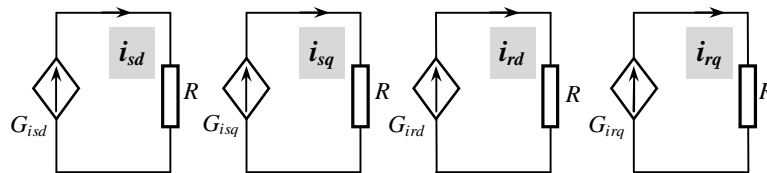


Fig. 7 – Generic current calculators.

The integration of differential eqs. in PSpice can be performed by using generic integrators, implementing electrical circuits with controlled-voltage

sources (E -type) or controlled-current sources (G -type). These integrators can be used to solve the torque and motion eqs. Fig. 8 a presents a circuit using a controlled-current source to calculate the torque value and a capacitor to integrate the motion eq. Fig. 8 b represents a circuit using controlled-voltage source to calculate the torque value and an inductor to integrate the motion eq. The obtained result is a voltage or, respectively, a current.

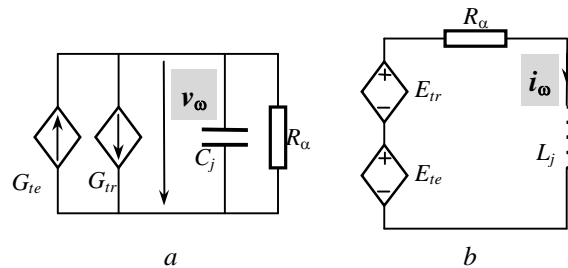


Fig. 8 – Mechanical quantities circuits calculators.

5. Simulation Results

To compare the two orthogonal model implementations in PSpice, the simulation of the behavior of an induction machine has been performed, rated as follows:

$$\begin{aligned}
 P_n &= 5 \text{ kW}; & R_1 &= 1.4 \Omega; & L_{\sigma 1} &= 7.5 \text{ mH}; & J &= 30 \text{ g.m}^2; \\
 U_{1n} &= 380 \text{ V}; & R'_2 &= 1.5 \Omega; & L'_{\sigma 2} &= 8.0 \text{ mH}; & F_\alpha &= 30 \text{ N.m.s/rad}; \\
 f_1 &= 50 \text{ Hz}; & & & Y\text{-connection}; & L_m &= 117.5 \text{ mH}; & p &= 1.
 \end{aligned}$$

Fig. 9 shows a comparison between the PSpice implementation of the two types of orthogonal model of the induction machine: in terms of currents and in terms of fluxes. A representative and complex operation case was considered – the start-up of the induction machine. On the left we can see the simulation results using only the currents, excluding the fluxes, and on the right – the simulation results using only the fluxes, excluding the currents.

The analysis has been made using the following computer configuration: Gigabyte 945GCMX-S2 MB, Intel Pentium D 925 2.4 GHz CPU, 2048 MB DDR2 RAM, Samsung SP0812N HDD. The analysis time interval has been of 1...2 s and the integration step time was of 0.1 ms.

Firstly, the output mechanical quantities, torque (a , b) and angular speed (c , d) have been considered. Then, the directly calculated internal quantities, currents in the first case (e) and fluxes in the second case (f) have been presented. Finally, in order to compare the results, the supplementary quantities, fluxes in the first case (g) and currents in the second case (h) were considered.

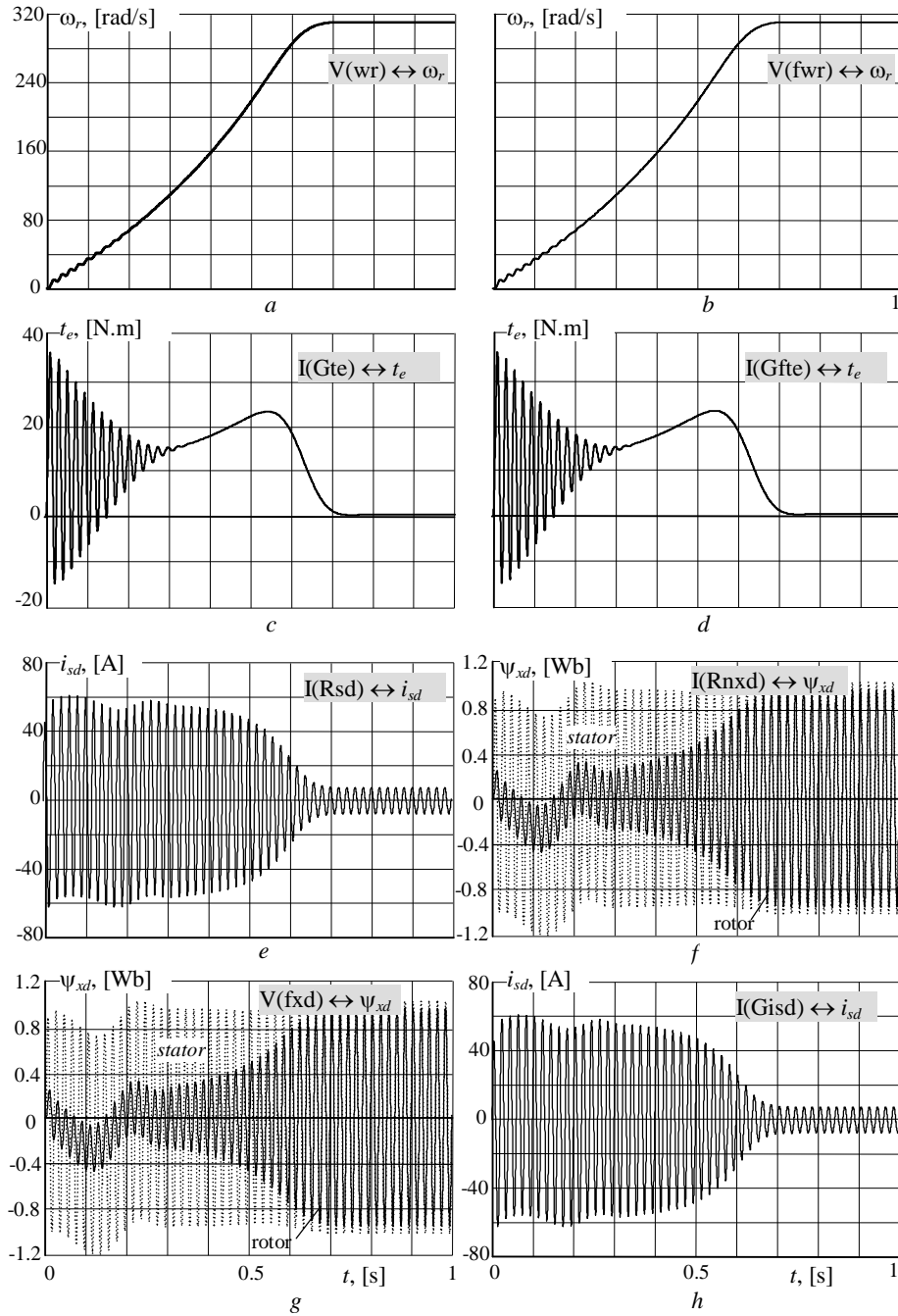


Fig. 9 – Comparison between simulation results.
 Left: using current-only model; right: using total flux-only model.

All the simulation results are practically identical when using the first or the second type model. This is an expected outcome, because it is about the same eqs. model processed in two different ways.

Firstly, the simulation of a start-up operation in a range of 0...1 s is considered. When using the current-only model without fluxes calculation, the time simulation was of 1.71 s and the output data file had 2,336 kB. When the program also performed the fluxes calculation, the time increased to 2.30 s and the output data file increased to 3,746 kB. In the case of the fluxes-only model, the simulations gave 1.86 s, 2.73 s and 2,650 kB, respectively, 4,059 kB.

Secondly, a new simulation in a range of 0...2 s composed by a start-up operation followed by a load of 15 N.m at 1 s is considered. Using the first model, the time simulation was of 3.62 s and the output data file had 4,825 kB and when the fluxes calculation was performed the time was of 4.90 s and the output data of 7,642 kB. Using the second model the simulations gave 3.70 s, respectively, 5.15 s and 5,451 kB, respectively, 8,268 kB.

All the rotor quantities are transformed in quantities with the same frequency as the stator quantities, using well known relations.

5. Conclusions

When the aim of a simulation is to determine the mechanical output quantities, it is natural to eliminate the currents or/and the fluxes from the voltage eqs. in order to simplify the mathematical calculation. The natural and direct method, when using PSpice, is based on implementing the typical equivalent circuit and solving the mechanical eqs. by using generic integrators.

Replacing the internal quantity *current* with the internal quantity *total flux* maintains the same aim of the orthogonal model eqs., yielding the same simulation results. There are no differences from the point of view of the simplicity of the PSpice implementation, precision and convergence.

The study highlights the differences between the two types of modelling, concerning the model parameters and computing speed. The new unusual parameters $\Delta_L, v_{sr}, v_{sm}, v_{rs}, v_{rm}$, must additionally be calculated by the program in order to solve the eqs. system.

The classical type of orthogonal model, using currents, has proved to be a little faster than the fluxes model. In all situations, the computing time was smaller in the first case. Comparing the voltage eqs. in classical form (5) and in the new approach using only total fluxes form (10) it results similar format except the two derivatives in the classical form instead of only one derivative when total fluxes are used. However, the analysis of the circuits gives similar but not identical topologies. The model using only fluxes has a supplemental controlled-voltage source and a supplemental node. That is why, in this case, the simulation is a little slower and the output data file a little greater. This situation is specific for PSpice implementation.

REFERENCES

- Araujo R.E. (Ed.), *Induction Motors – Modelling and Control*. Intech, Rijeka, Croatia, 2012.
- Cociu L., Cociu V.R., *Aspects Regarding Pspice Electrical Machines Simulation*. The 5th Internat. Conf. on Electromech. a. Power Syst. SIELMEN'05, Chişinău, Rep. Moldova, Oct. 6-8, 2005, Vol. II, 842-845.
- Cociu L., Haba C.G., Cociu V.R., *Particularities of Park Transformation in Special Cases*. Proc. of the 7th Internat. Symp. Adv. Topics in Electr. Engng., May 12-14, 2011, Bucharest, 455-460.
- Cociu V.R., Cociu L., *Modeling of Converter–Induction Machine Assemblies Including Nonlinear and Parametric Components Using PSpice*. ISEM, Braunschweig, May 1997.
- Justus O., *Dynamisches Verhalten elektrischer Maschinen. Eine Einführung in die numerische Modellierung mit PSPICE*. Vieweg & Sohn Verlagsges. Braunschweig/Wiesbaden, 1993.
- Ong C.M., *Dynamic Simulation of Electric Machinery*. Prentice Hall PTR Upper Saddle River, New Jersey, 1997.
- Simion Al., *Study of the Steady-State Regime of the Two-Phase Induction Machine Using the Mathematical Model with Total Fluxes*. Bul. şt. Univ. Politehnica, Timişoara, **53 (67)**, Sp. Issue, 243-248 (2008).

SCURTĂ PRIVIRE ASUPRA MODELĂRII MAŞINII DE INDUCŢIE UTILIZÂND PSPICE

(Rezumat)

Se prezintă rezultatele unui studiu comparativ privind implementarea în PSpice a variantelor modelului bifazat (ortogonal) al maşinii de inducţie. S-au avut în vedere modelul scris numai în curenţi, excluzând fluxurile, şi cel scris numai în fluxuri totale, excluzând curenţii. În fiecare caz în parte s-a stabilit un circuit echivalent care ulterior a fost implementat în PSpice. La acestea au fost adăugate module de calcul specifice mărimilor mecanice şi a celor excluse în prima etapă. Cele două tipuri de modele matematice au fost comparate din punct de vedere al uşurinţei implementării, vitezei de simulare, preciziei şi convergenţei.