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CONSTRUCTION OF A DYNAMIC MODEL FOR A TRANSVERSE FLUX MOTOR

ABSTRACT *The paper presents the simulation results of the modular reluctance motor (Transverse Flux Motor) with an outer rotor in different transient states. The main goal of the analysis was the developing process of a mathematical TFM model with a high level of accordance with real object. The mathematical model was implemented in Matlab/Simulink environment and compared with the filed-circuit model (FLUX3D). Several computer simulations were carried out for different TFM motor operating conditions.*

Keywords: *dynamic modelling, transverse flux motor, mathematical optimization*

1. INTRODUCTION

During the last several years it's been possible to observe dynamic advances in low and average power drives with high torque density. Electrical drives built on the base of switched reluctance motors deserve particular consideration.

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One of their modifications is a switched reluctance motor with an axial flux (Transverse Flux Motor). These kinds of motors are a part of brushless machines group, which have an electronic supply system as their integral part. Very close relation between electromagnetic torque and volume is the fundamental quality of these motors. The main disadvantage of this kind of motors is their construction, which is more complicated when compared to the classical SRM motors implying smaller durability and reliability [2].

The modular reluctance motor with an axial flux (TFM), characterized by a high efficiency and a high value of electromagnetic torque provides to use them as in-wheel drive of the electric vehicle. Exterior rotor enables direct energy transmission excluding gear and additional mechanical losses.

However, the TFM supply is realized on the basis of voltage converters. The motor phases are supplied sequentially depend on the radial rotor position. Decision for the voltage supply selection is made during the possibility of average electromagnetic torque maximizing depended on several construction parameters and predicted control method.

The main goal of this paper is the TFM mathematical model developing in transient states simulation and its comparison to field-circuit model (FLUX3D). The presented mathematical model will be used as a basic model in optimization process with application of an evolutionary or random algorithm of the best solution, which were searched for the task.

2. THE PHYSICAL MODEL OF TFM

The main object of the research is the switched reluctance motor with an axial flux (TFM). The prototype motor structure is shown schematically in Fig. 1. The considered motor consists of the three modules in which the rotors are shifted by 10 mechanical degrees in relation to each other. The stator modules are placed symmetrically on acid-resistant steel shaft. Each segment has twelve teeth and includes one phase belt that forms a solenoid. The rotor teeth were made of solid iron. The modules are isolated by nonmagnetic inserts. The outer layer and the rotor layer were made of nonmagnetic material (duralumin) [4].

A power converter (Fig. 2.) is required to activate and commutate the SRM phases, and the classic asymmetric half-bridge inverter is usually used, requiring two switching devices and two power diodes per phase [5]. Two control procedures are possible – *Hard-Chopping* and *Soft-Chopping*. The easiest motor electric control consists in sequentially switching *on* and *off* for the phase current (phases A, B, C, A etc.).

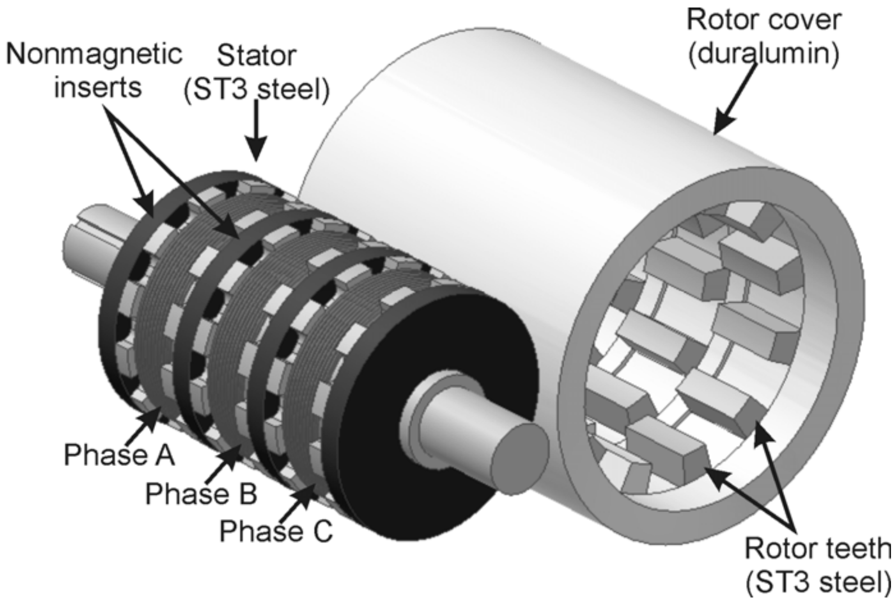

Fig. 1. Motor structure

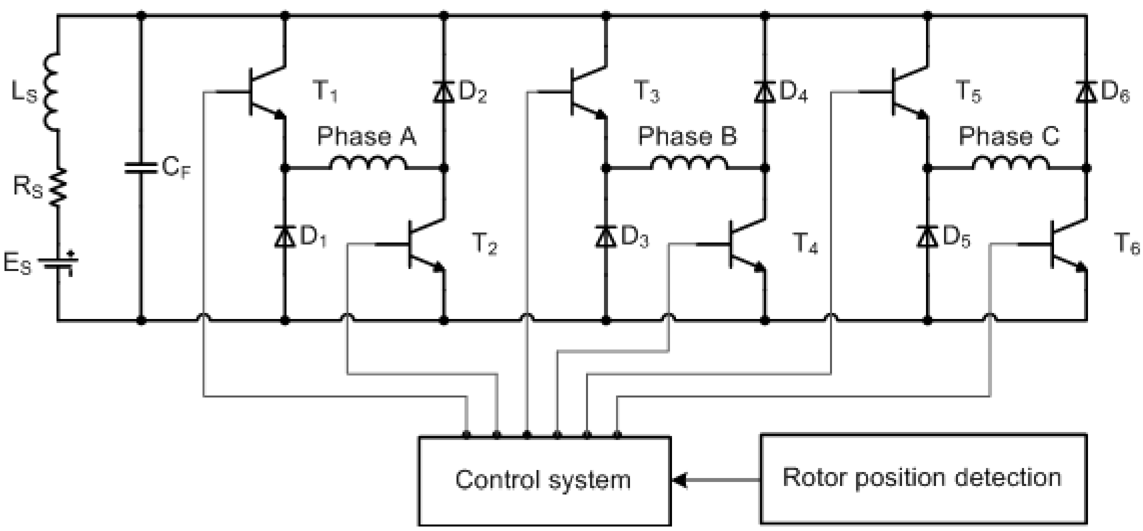

Fig. 2. The half-bridge ("H") TFM power converter

3. MODELING AND SIMULATIONS OF TRANSIENT STATES

The modeling process of SRMs with an axial flux is different from the techniques used in conventional motors cases. The main reason for that state is high nonlinearity of the reluctance motor. There are many interesting solutions for this type of problems in the bibliography [2, 3, 5].

As a base instrument describing motor in an electromagnetic and mechanical way during the mathematical model construction the following equations were used [2]:

$$u = Ri + \frac{d\psi}{dt} \tag{1}$$

where u is the supply voltage, R is the phase winding resistance, i is the phase current and ψ is the flux in phase winding,

$$T = T_l + k_\omega \omega + J\frac{d\omega}{dt} \tag{2}$$

where T is the electromagnetic torque, T_l is the load torque, k_ω is the friction damping coefficient, J is the moment of inertia of the rotor and ω is the rotor speed.

Solution for these equations is possible during the linear model adoption, which is unfortunately associated with considerable errors. The second way of solving these equations is to take into account the nonlinear flux and torque character. The magnetostatic calculation is one of the methods for including the nonlinearity. A FEM model (FLUX3D) for TFM shown on Fig. 3, was build especially for this case.

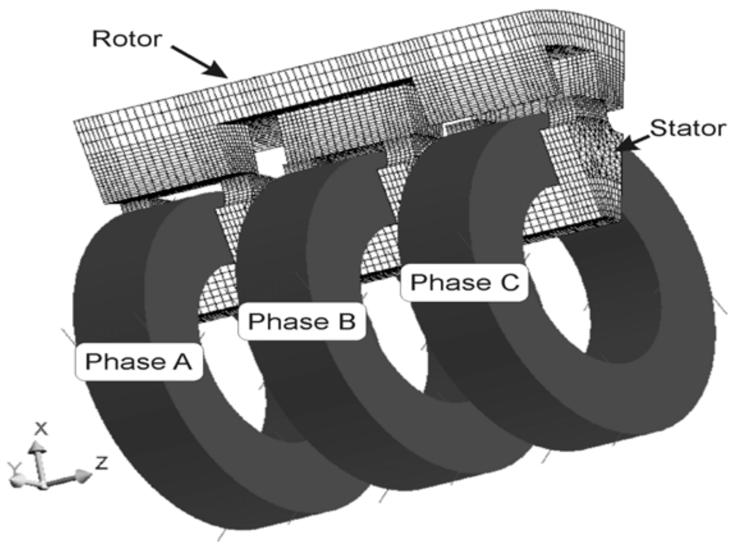

Fig. 3. Finite element model (FLUX3D)

The nonlinear flux character depended on current and rotor position is taken into account by applying the mathematical function $\psi = f(i,\Theta)$ (Fig. 4a). Such like approach was adopted for electromagnetic torque characteristic by pointing out function $T = f(i,\Theta)$ (Fig. 4b). Both functions were calculated for the motor FEM model and verified by the measurements from the experimental tests on physical motor model.

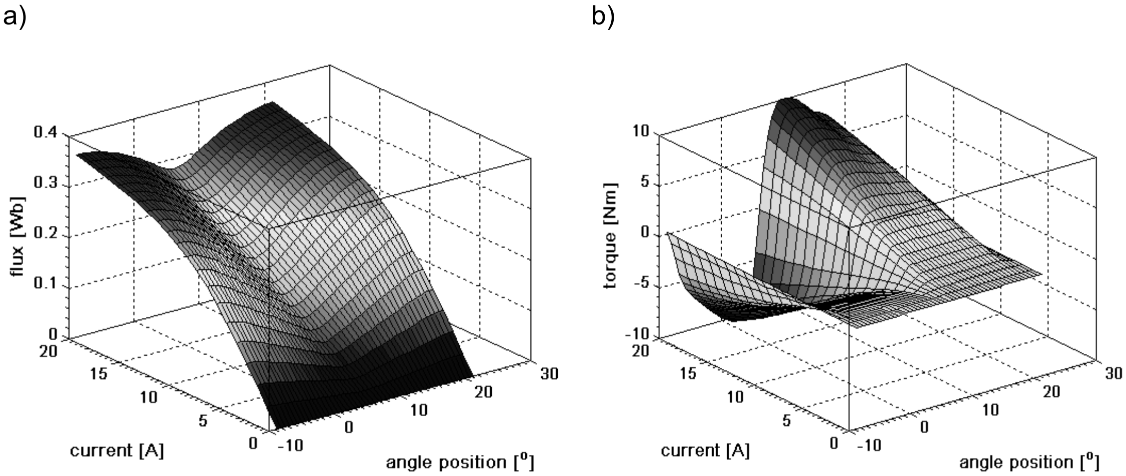

Fig. 4. Flux (a) and electromagnetic torque (b) vs. phase current and rotor position

The calculations of transient states using the FEM field-circuit model are very complicated and consume a lot of time. Mentioned software (FLUX3D) makes it possible to solve the FEM model in transient states, coupling an external power circuit with the control system. The task is to find other solutions for multiply optimization computation in shorter time. The field-circuit computations should be taken into account as a checking tool. The nonlinear mathematical model based on magnetostatic FEM results may be used as an alternative solution.

The simulation model was built in Matlab/Simulink environment. Its structure has a hierarchic character with a fundamental part – single phase (Fig. 5). Each

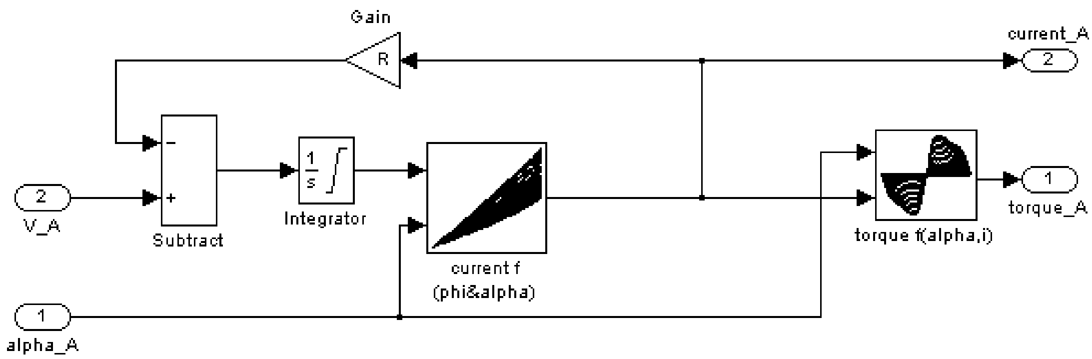

Fig. 5. Phase_A sub-system

single-phase sub-system includes two look-up tables with calculated flux and torque functions. During the simulation these data tables are interpolated and extrapolated with the object to receive the best projection of the nonlinear model characteristic.

On account of the switched reluctance motor with an axial flux nature it is necessary to simulate the power converter with control system. The classic asymmetric half-bridge inverter was implemented in the second sub-system using the Matlab Plecs toolbox. All electronic nonlinear switching parts (transistor, diode) were taken into account by the Plecs circuit. The control procedures for the turn on and off angle were used by Matlab function forms for each phase. Figure 6 presents the complete power converter sub-system.

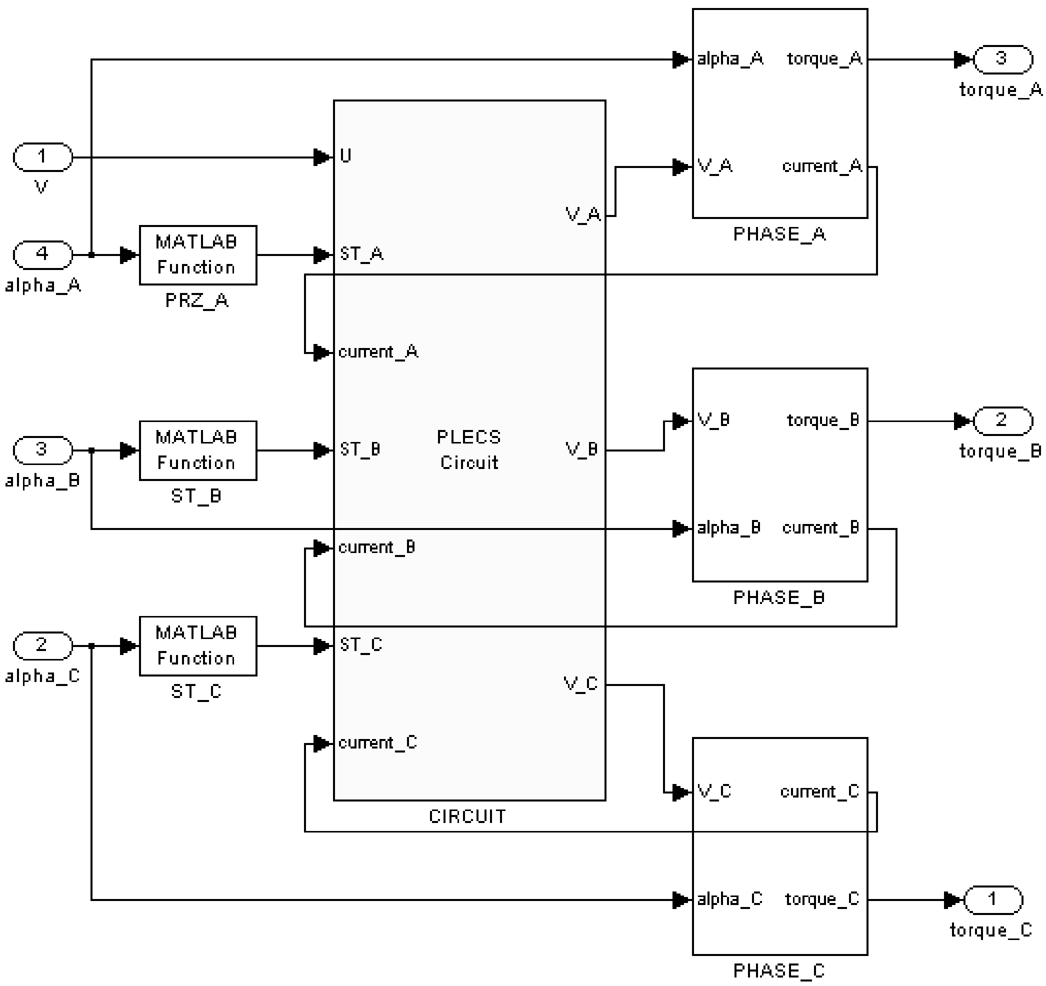

Fig. 6. Phases control sub-system

The final and the most exterior system, presented in the Fig. 7, allows to implement the significant mechanical parameters – load torque, moment of inertia and friction damping coefficient.

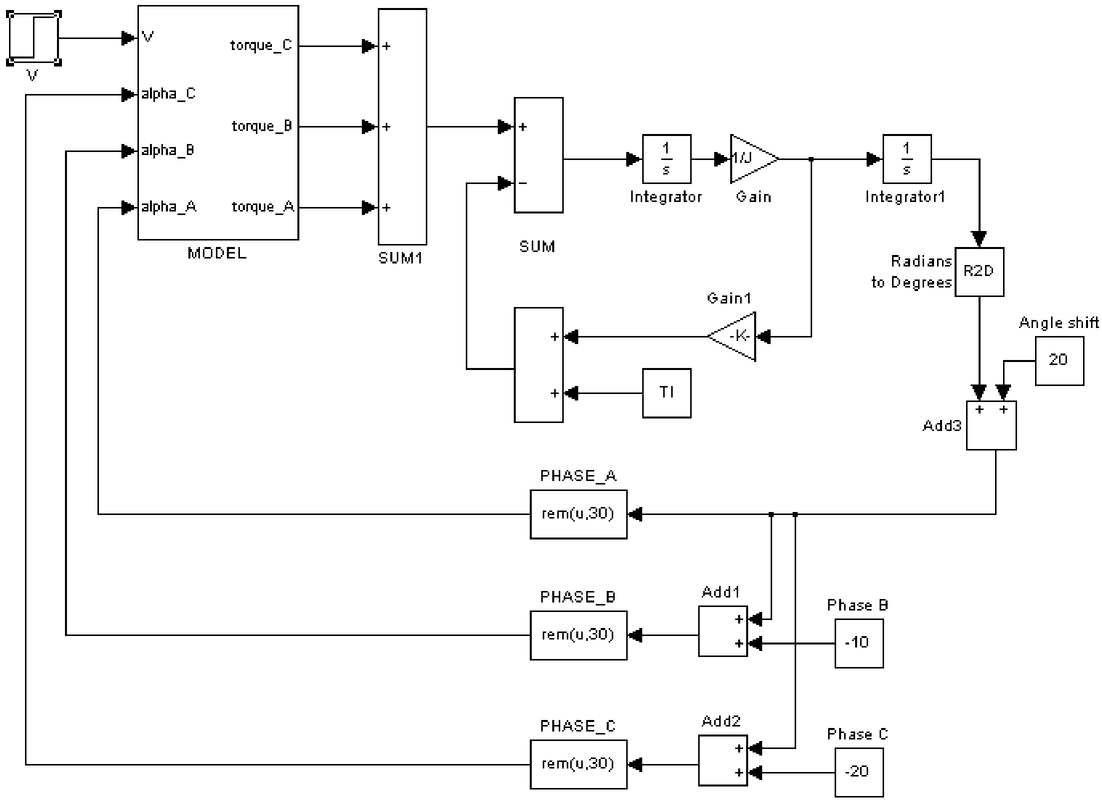

Fig. 7. Final mathematical SRM motor system

The simulation model (Fig. 7) output data were the motor total torque and the speed. By adding new components to the mathematical model it is possible to simulate other dynamic operating states like the change of load and breaking.

4. RESULTS OF ANALYSIS

The main goal of the analysis was to develop the TFM motor mathematical model for the transient states simulations and their comparison to the field-circuit model (FLUX3D). The following figure 8 shows the simulated transient results compared with the field-circuit FEM model of the phase currents, the motor speed and the total torque. It's an idle motor start-up from zero with 6 V reduced voltage supply level.

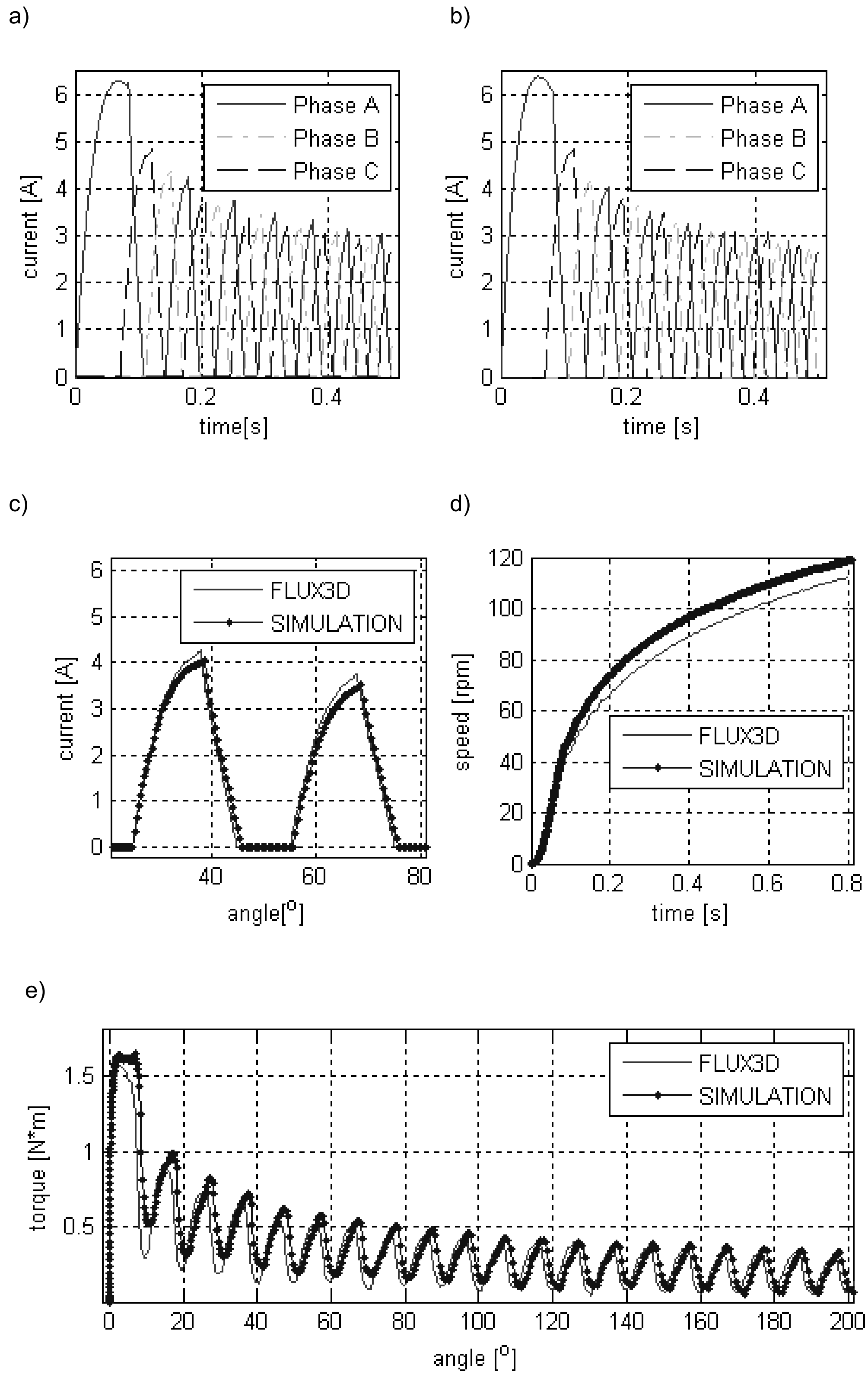

Fig. 8. Phases currents for 6 V reduced voltage supply
a) FLUX3D, b) Matlab/Simulink, c) phase_A current, d) rotor speed, e) total electromagnetic torque

Figure 9 shows the simulated transient results of SRMs start-up from zero to full speed with an external load (T_l = 0,5 N·m) and for rated voltage supply (U_{zas} = 12 V). The mathematical model simulation results were compared with field-circuit FEM model. Small range of divergence is the result of inaccuracy by phase switching in FEM model.

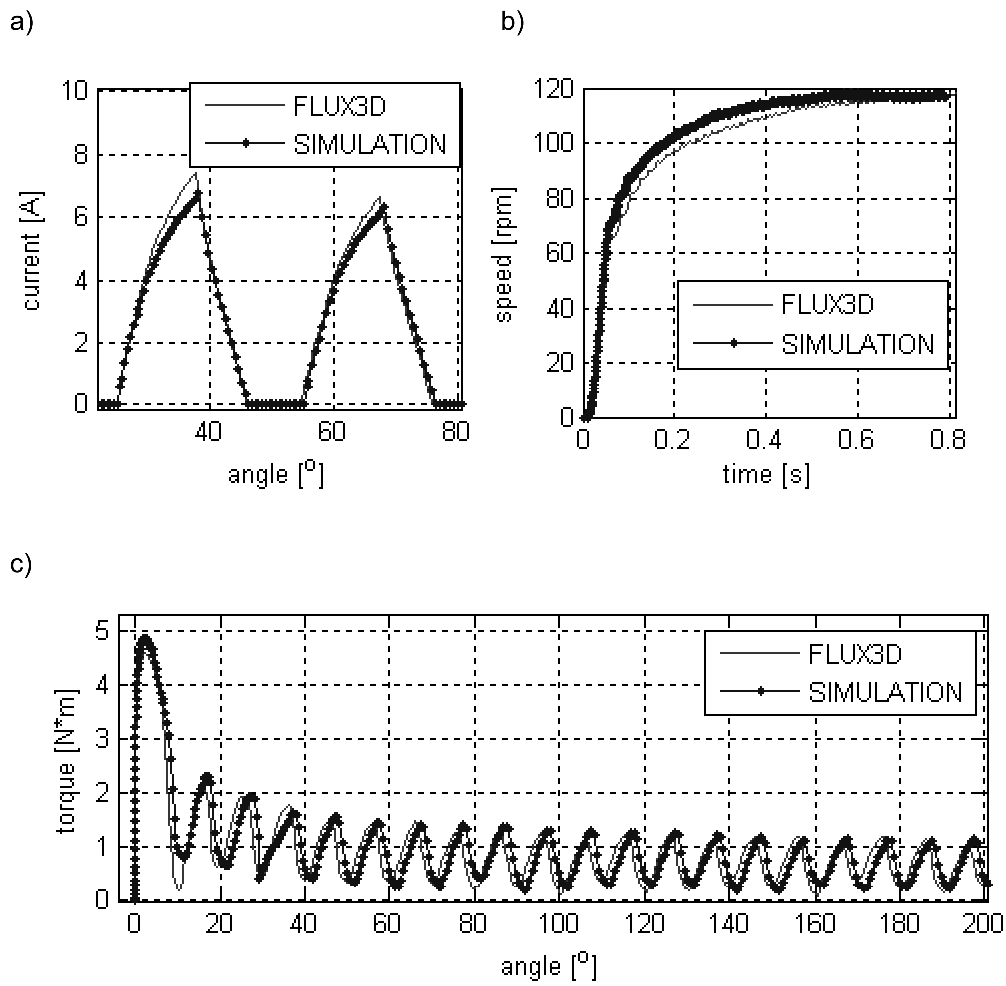

Fig. 9.
a) Phase_A current, b) rotor speed, c) total electromagnetic torque

6. CONCLUSIONS

The paper describes mathematical model, which enables the process of simulating SRMs with an axial flux in different transient states. The simulation research results were compared with field-circuit computation data. Nonlinear multivariable function, used in the mathematical model, provided the increasing of the projection agreement with the real object. Good convergence between these approaches allows replacing complicated FEM computations (FLUX3D) with simpler mathematical model (Matlab/Simulink). The obtained measurement data enable to apply introduced model as the basis for further optimization process using genetic algorithms.

LITERATURE

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MODELOWANIE I SYMULACJA
STANÓW DYNAMICZNYCH SILNIKA TFM

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STRESZCZENIE *Praca zawiera wyniki badań symulacyjnych stanów dynamicznych silnika reluktancyjnego o budowie modułowej z wirnikiem zewnętrznym ze strumieniem poprzecznym (TFM). Silnik zbudowany jest z trzech modułów oddzielonych od siebie przekładkami dystansowymi, każdy z modułów zawiera 12 zębów oraz jedno uzwojenie (rys. 1). Poszczególne moduły wirnika przesunięte są względem siebie o dziesięć stopni mechanicznych, natomiast moduły stojana są ułożone symetrycznie względem siebie. Do zasilania w/w silnika zastosowano układ półmostkowy typu „H", składający się z sześciu tranzystorów i diod zwrotnych.*

Zasadniczym celem badań było opracowanie modelu matematycznego silnika TFM zapewniającego dobre odzwierciedlenie zjawisk występujących w tego rodzaju napędach elektrycznych. Model matematyczny zaimplementowano w środowisku Matlab/Simulink, oraz Tolboox PLECS do zamodelowania układu zasilania. Nieliniowość strumienia magnetycznego zależnego od prądu i położenia kątowego uwzględniono stosując w modelu matematycznym funkcję $\psi = f(i,\Theta)$ *(rys. 4a). Podobne podejście zastosowano w przypadku momentu elektromagnetycznego wyznaczając funkcję* $T = f(i,\Theta)$. *Funkcje te wyznaczono w na drodze obliczeń polowych zweryfikowanych pomiarowo.*

Struktura modelu symulacyjnego ma charakter hierarchiczny. Składa się z podsystemów każdego z pasm (rys. 5), układu zasilania i sterowania (rys. 6) oraz z bloku implementacji wielkości mechanicznych (rys. 7).

W punkcie 4 zamieszczono wykresy będące porównaniem badań symulacyjnych przy użyciu modelu matematycznego (Matlab/Simulink) oraz obarczonego dużymi nakładami obliczeniowymi modelu polowo-obwodowego (FLUX3D). Na rysunku 8 (a-e) przedstawiono jałowy rozruch silnika TFM przy obniżonym napięciu zasilania. Rysunek 9 (a-c) obrazuje rozruch pod obciążeniem dla znamionowej wartości napięcia zasilania. Porównanie modelu matematycznego z modelem polowo-obwodowym pozwala na wyciągnięcie wniosku o zadowalającej dokładności modelu matematycznego. Otrzymano szereg charakterystyk dla różnych warunków pracy silnika TFM w znacznie krótszym czasie niż dla obliczeń polowo-obwodowych. Opracowane narzędzie umożliwi dalsze, bardziej zaawansowane badania optymalizacyjne z wykorzystaniem metod stochastycznych poszukiwania rozwiązań danego problemu.