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NUMERICAL SIMULATION OF BRUSHLESS DC ELECTRICAL DRIVES. OPEN–LOOP CONTROL

BY

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Abstract. The authors present in this paper an accurate and fast running Matlab®/ Simulink® open-loop model of the BLDC electrical drive system. For analysis, we chose an experimental system with a Hurst type BLDC motor. The numerical simulation results confirm that the mathematical model is accurately enough and reproduces with sufficient precision physical behavior of the electric drive system.

Key words: BLDC motor; numerical simulation; open–loop control; Matlab/Simulink.

1. Introduction

The conventional brushed motors are attractive because of their properties such as high efficiency and linear mechanical characteristics. The control of conventional Direct Current (DC) motor supposes a mechanical switch and not requires complex hardware tools. This mechanical switch requires periodic maintenance because the brushes need to be replaced. The Brushless DC (BLDC) motors replace often the brushed DC motors. The

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current commutation is not done by a mechanical switch, rather by a solid state switches inverter. The commutation instants are determined by the rotor position. The position is directly or indirectly detected by sensored/sensorless techniques (Zhou Zhao-Yong *et al*., 2003).

The electrical drive analySe is a delicate process since electrical drive systems are complex (characterized by fast processes) (Lyshevski, 2003). Before the practical implementation of every system, an important role is occupied by numerical simulation stage. To meet this goal was developed many programming tools for real systems and especially for electrical drive systems numerical simulation.

The purpose of this paper is to build an accurate and fast running Matlab®/ Simulink® open-loop model of the BLDC motor electrical drive system (Chiasson, 2005). The goal is to test most important working regimes which are hard to be implemented in reality and to provide the important information to motion law implementation.

2. Numerical Simulation of BLDC Electrical Drive System

The position is sensed by sensored techniques and was applied some assumption such: the magnetic saturation and eddy current losses are neglected, symmetrically phase windings distribution, the mutual inductances of the phases are neglected, trapezoidal distribution of the air gap magnetic field, etc. The mathematical model was deduced by state eq. form (Saxena *et al*., 2010; Tibor *et al*., 2011) and is presented like in following state-eqs.:

$$\begin{cases} \dfrac{\mathrm{d}i_A}{\mathrm{d}t} = \dfrac{e_A}{L} - \dfrac{R}{L} i_A + \dfrac{1}{L} u_A, \\ \dfrac{\mathrm{d}i_B}{\mathrm{d}t} = \dfrac{e_B}{L} - \dfrac{R}{L} i_B + \dfrac{1}{L} u_B, \\ \dfrac{\mathrm{d}i_C}{\mathrm{d}t} = \dfrac{e_C}{L} - \dfrac{R}{L} i_C + \dfrac{1}{L} u_C, \\ \dfrac{\mathrm{d}\omega_\mathrm{r}}{\mathrm{d}t} = \dfrac{m_e}{J} - \dfrac{m_r}{J}, \\ \dfrac{\mathrm{d}\theta_r}{\mathrm{d}t} = \omega_r, \end{cases} \tag{1}$$

where u_A, u_B, u_C are the phase supply voltages, e_A, e_B, e_C – the induced phase Back-Electromotive Forces (BEMF), i_A, i_B, i_C – the phase currents, L_A=L_B=L_C=L and R_A=R_B=R_C=R – the phase inductances and, respectively, resistances, ω_r – the angular speed, θ_r – the rotor angle, m_e – the electromagnetic torque, m_r – the load torque and J – the total inertia of the electrical drive system.

The BEMF and electromagnetic torque can be expressed as (Cai *et al.*, 2010)

$$\begin{cases} e_A = K_e f\left(\theta_r\right)\omega_r, \\ e_B = K_e f\left(\theta_r - \dfrac{2\pi}{3}\right)\omega_r, \\ e_A = K_e f\left(\theta_r - \dfrac{4\pi}{3}\right)\omega_r, \end{cases} , \tag{2}$$

$$m_e = Kf\left(\theta_r\right)i_A + Kf\left(\theta_r - \frac{2\pi}{3}\right)i_B + Kf\left(\theta_r - \frac{4\pi}{3}\right)i_C, \tag{3}$$

where K_e is the BEMF constant, K – the torque constant and $f(\theta_r)$ – a periodic function which characterizes the trapezoidal nature of the BEMF waveform.

The evolution of this nonlinear function per electrical cycle is given by following relations:

$$f\left(\theta_r\right) = \begin{cases} 1, & 0 \le \theta_r < \pi/3, \\ -(6/\pi)\theta_r + 3, & \pi/3 \le \theta_r < 2\pi/3, \\ -1, & 2\pi/3 \le \theta_r < 4\pi/3, \\ (6/\pi)\theta_r - 9, & 4\pi/3 \le \theta_r < 5\pi/3, \\ 1, & 5\pi/3 \le \theta_r < 2\pi. \end{cases} \tag{4}$$

The Simulink® model of open loop BLDC system is presented in Fig. 1. This model includes the *Logical Block* that is responsible for electronically commutation of the motor, the *Inverter Block*, which is responsible for the BLDC motor phases supplying with rectangular voltage waveforms and the *BLDC Motor Block* that includes also the *Hall-Effect position sensor block*.

The *Inverter Block* model is presented in Fig. 2. The inverter is implemented using the following equations:

$$\begin{cases} u_{AN} = 0.5U_a(\varepsilon_{\mathrm{PWM1}} - \varepsilon_{\mathrm{PWM2}}), \\ u_{BN} = 0.5U_a(\varepsilon_{\mathrm{PWM3}} - \varepsilon_{\mathrm{PWM4}}), \\ u_{CN} = 0.5U_a(\varepsilon_{\mathrm{PWM5}} - \varepsilon_{\mathrm{PWM6}}), \end{cases} \tag{5}$$

where U_a is DC link voltage, $\varepsilon_{\mathrm{PWM}x}$, [%], is duty cycle of command signal applied to x transistor (x = 1,…,6, see Fig. 3).

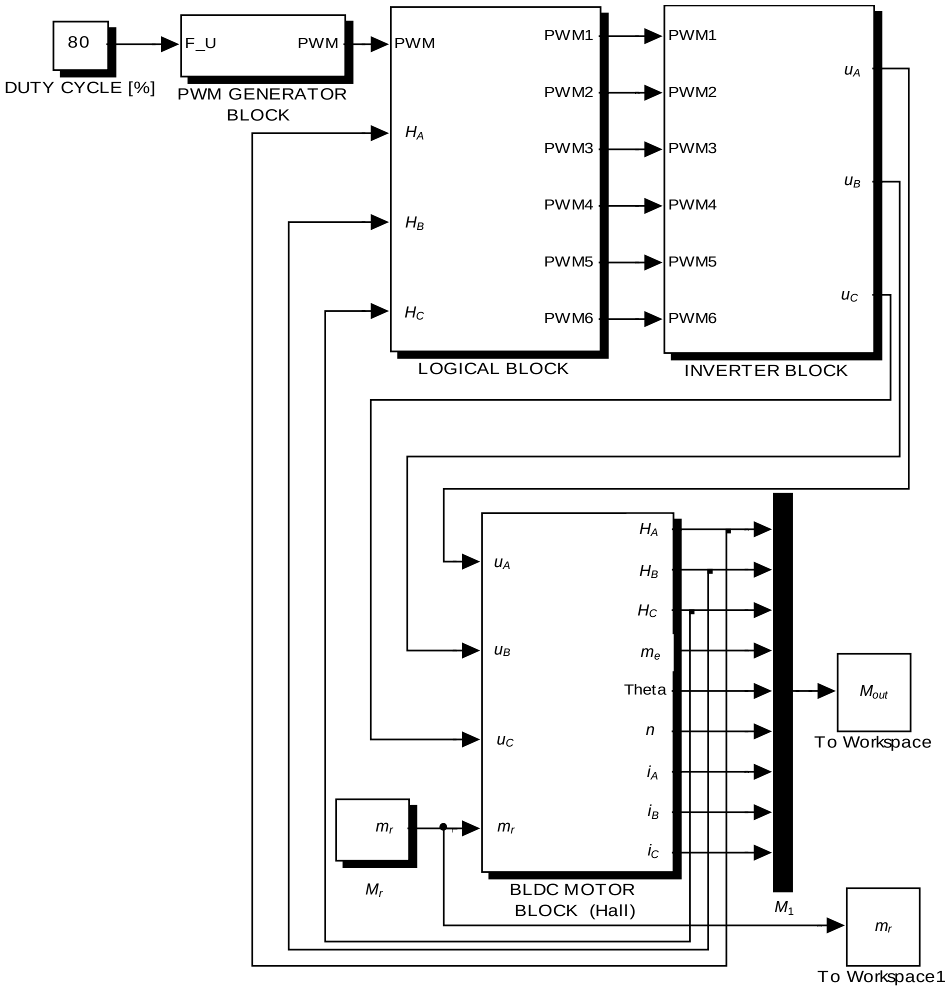


Fig. 1 – Simulink model of the open-loop control structure.

The inverter supplies the input voltage for the three phases of the BLDC motor (based on two-phase-on rule, see Fig. 3). Appropriate pairs of transistors are driven based on the Hall-effect sensors input. As sensors are the direct feed back of the rotor position, synchronization between stator and rotor flux is permanently achieved.

The *BLDC Motor Block* includes the *BEMF Block*, the in fact BLDC motor block and the Hall-effect position block. The first two block models can be seen in Fig. 4.

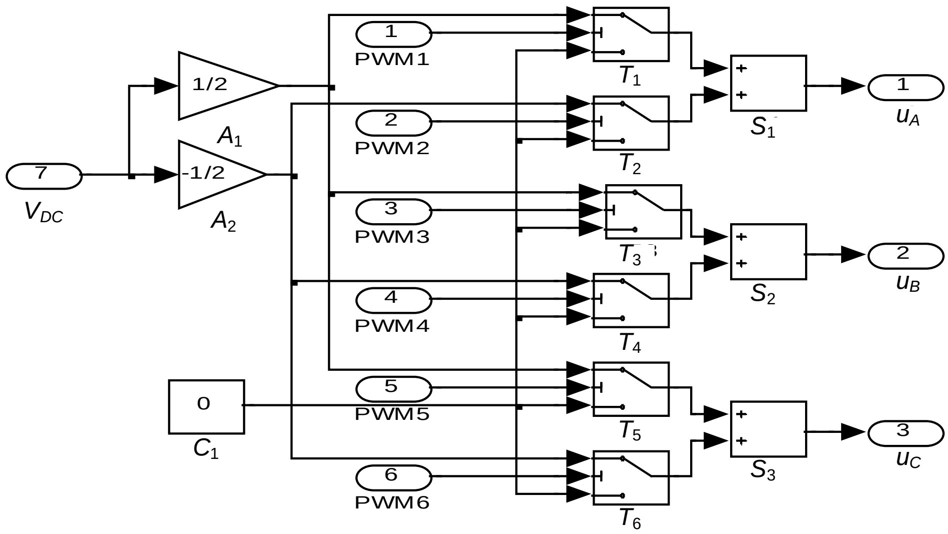


Fig. 2 – Simulink model of the *Inverter Block*.

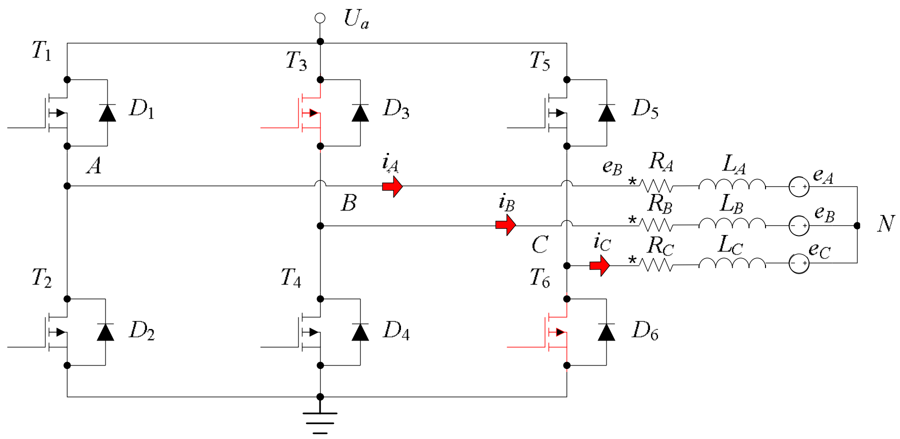


Fig. 3 – Electrical diagram of *BLDC Motor* - *Inverter* assembly.

In Fig. 5 are illustrated the inside *BEMF's Block* for counterclockwise sense. The BEMFs amplitude, who directly influences the phase current amplitude, is given by eqs. (2) and waveforms trapezoidal nature is forced by f_{ABC} *Block*. This bloc have three *S Function* blocks which defines $f(\theta_r)$ functions.

The *Hall Block* has the goal to emulate those three digital signals provided by the rudimentary Hall-effect transducer, usually build on BLDC motors. From these three digital signals combination can be obtained the sector information (see *CGZ Block* in Fig. 6), information set as input in *Logical Block* (Fig. 7).

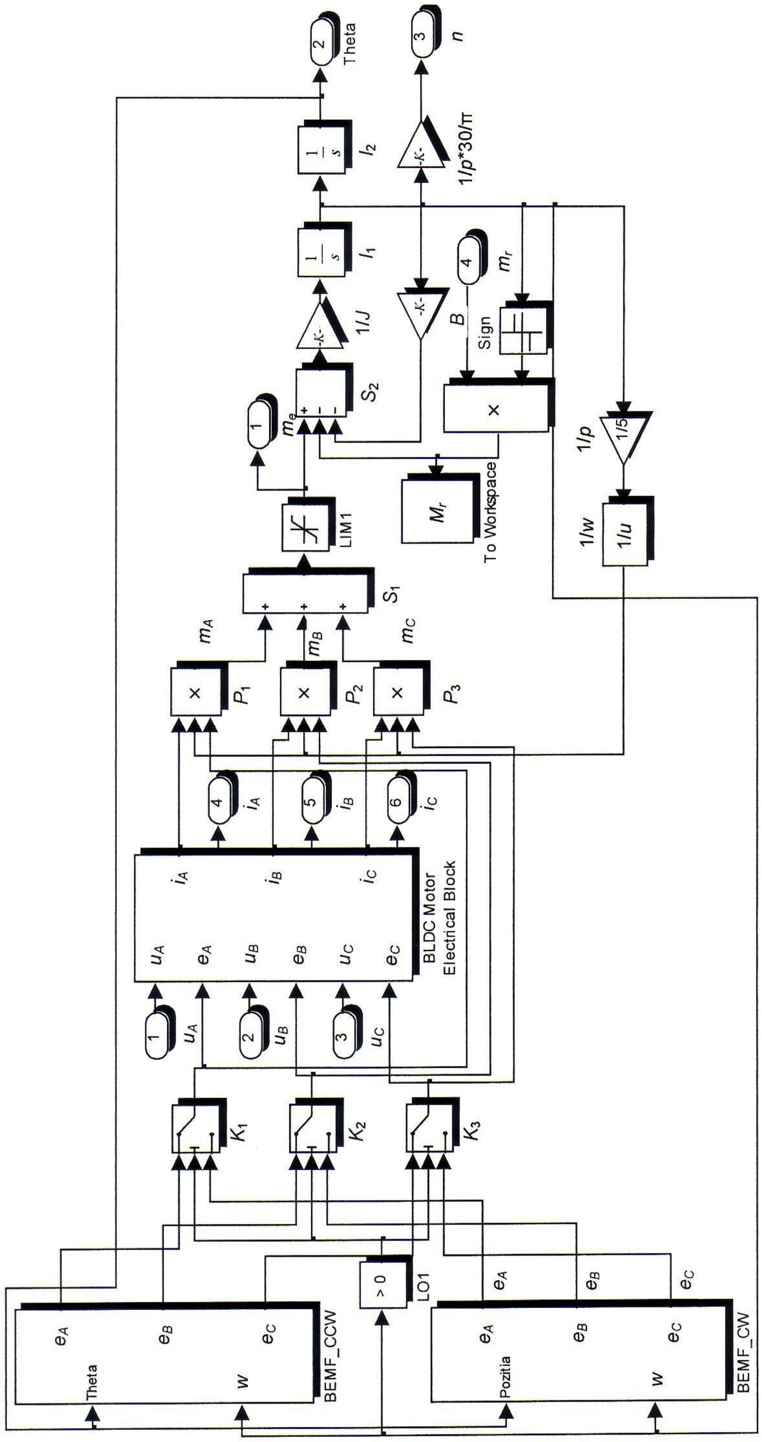


Fig. 4 – Simulink model of the *BLDC Motor*.

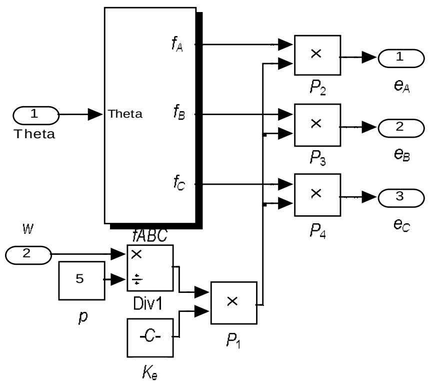


Fig. 5 – Simulink model
of the *BEMF Subsystem.*

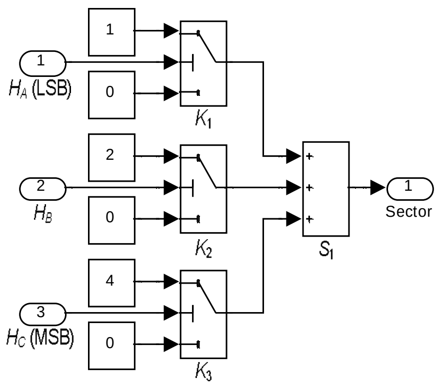


Fig. 6 – Simulink model
of the *CGZ Block*.

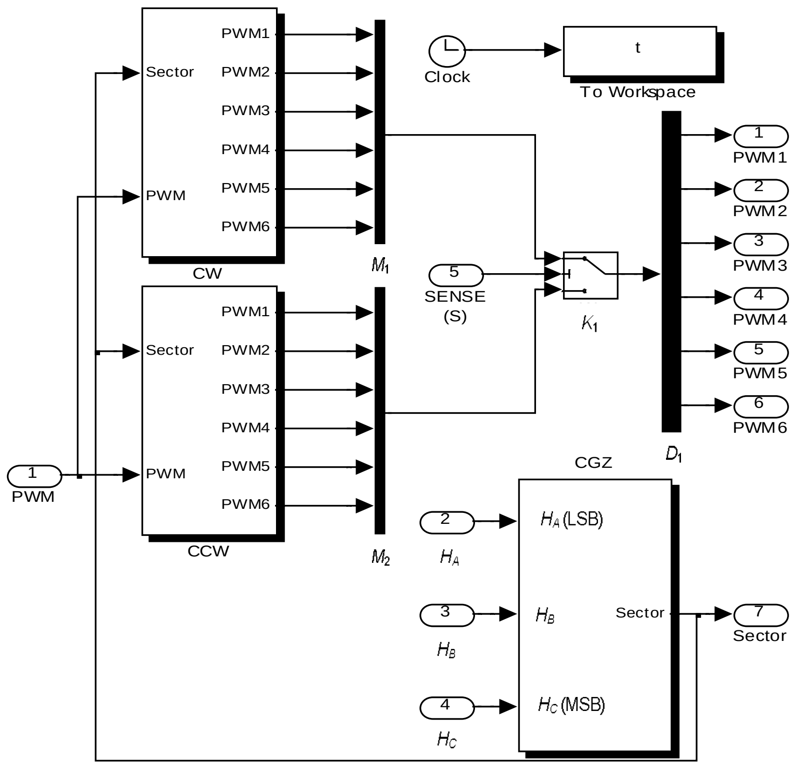


Fig. 7 – Simulink model of the *Logical Block.*

In order to integrate differential eqs. system, the Simulink® platform was automatically configured in *ode45 mode*, with variable integration step (Chung-Wen H. *et al.*, 2007).

3. Simulation Results

The electric motor used is a Brushless DC machine with trapezoidal BEMF adapted to digital control (star connection), Hurst DMA0002024C1010, with parameters described in Table 1.

Table 1
Rated Values of the Motor Prototype

Parameter	Value
Rated Power, [W]	26.46
Rated Torque, [N.m]	0.076
Rated Voltage, [V]	24
Rated Current, [A]	1.16
Phase Resistance, [Ω]	2.015
Phase Inductance, [H]	0.0023
Rated Speed, [rot/min]	2,054
Total Inertia, [kg.m^2]	4.43e-6
Number of poles	p = 10

For a constant load torque, $m_r = M_r$ = ct., in the following figures can be seen the input and the output waveforms in/from the blocks forward described namely

a) *Hall Block* (Fig. 8);
b) *Logical Block* (Fig. 9);
c) *Inverter Block* (Fig. 10);
d) *BEMF Blocks* (Fig. 11).

As simulation results are visualized the mechanical most important waveforms for load step variation (Fig. 12).

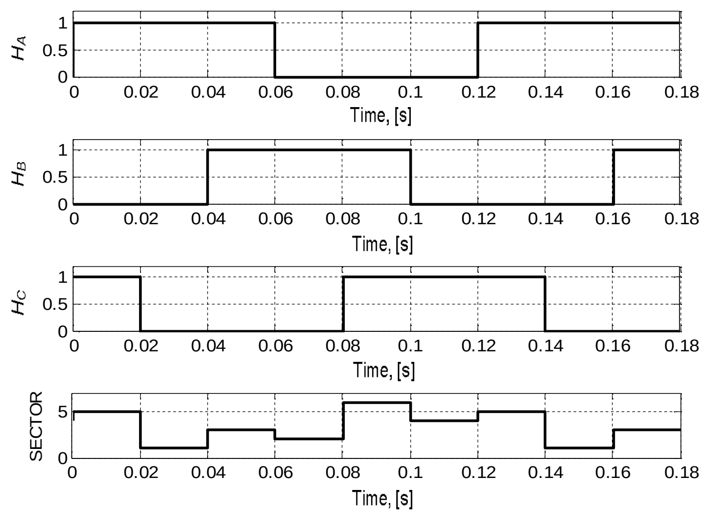


Fig. 8 – *Hall Block* time diagrams.

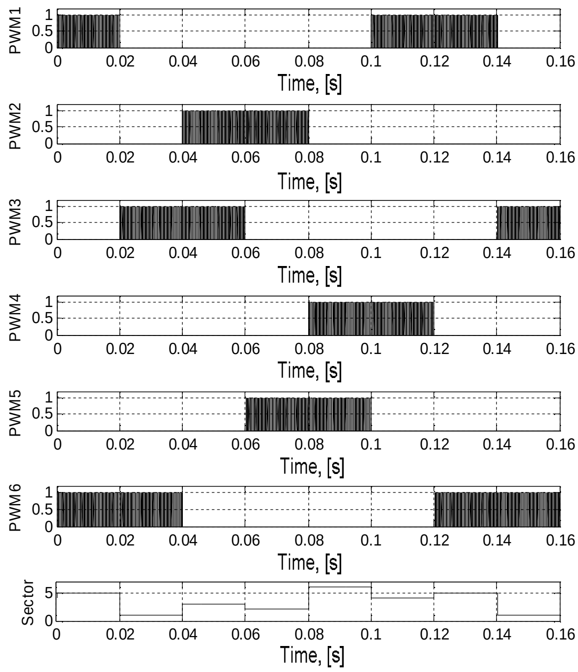


Fig. 9 – The *Logical Block* time diagrams.

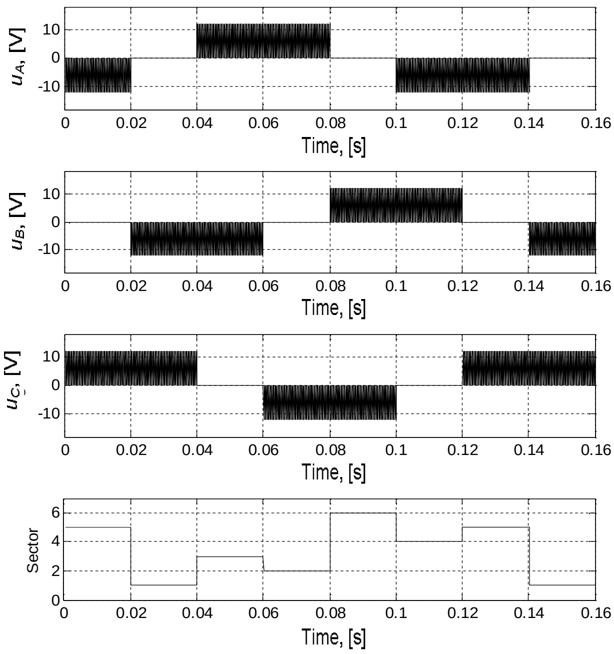
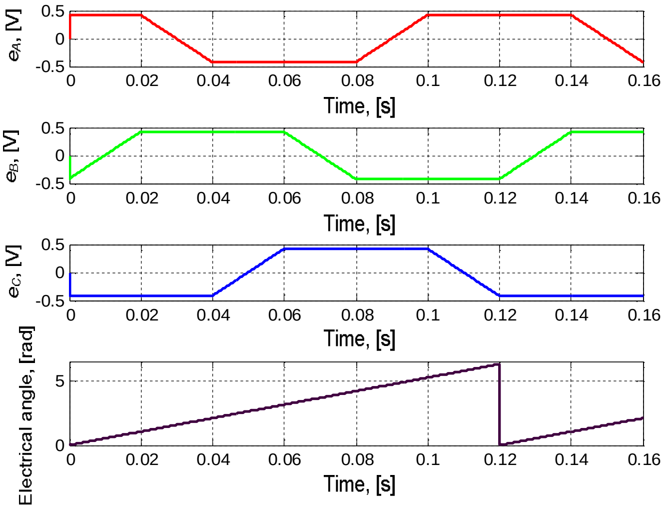
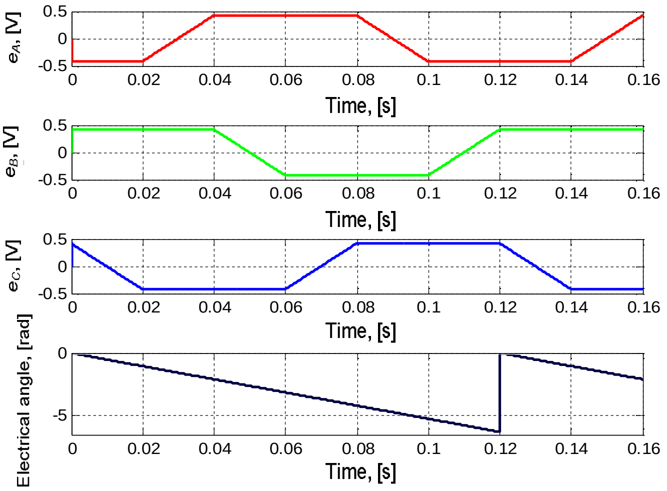


Fig. 10 – The *Inverter Block* time diagrams.



a – Counterclockwise sense.



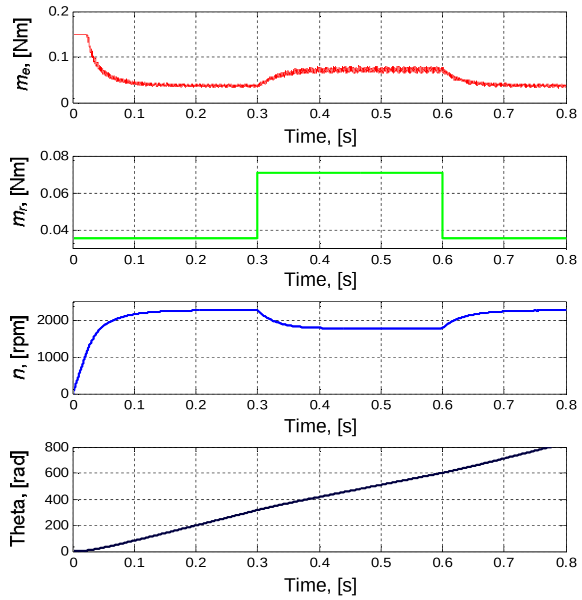
b – Clockwise sense.

Fig. 11 – The *BEMF Block* time diagrams.

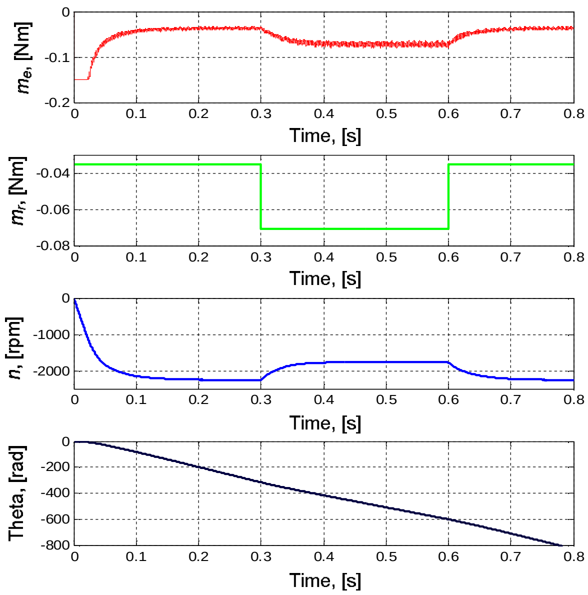
As can be seen, because of open-loop BLDC system structure, the speed of the motor is reduced when load is changing. To eliminate this speed error, more complex control structure is needed, such closed-loop control structure with PI controller.

4. Conclusions

The numerical simulation is an important stage in computer assisted design of electrical drive systems. The simulation advantages with respect to other experimental methods are: energy economy of experiments, the possibility to test hard regimes, difficult to be implemented on proper installation, the important information providing for control law implementation.



a – Counterclockwise sense.



b – Clockwise sense.

Fig. 12 – Mechanical variables time diagrams for load step variation.

This paper presents the mathematical modeling and numerical simulation of BLDC motor system. From construction and operation of BLDC motor is derived the mathematical model of electrical drive system in state eqs. form. Based on this, the Simulink® model designed here corresponds to an open-loop structure (with Hall-effect position transducer). For analysis, we chose a Hurst type BLDC motor experimental system.

Numerical simulation results confirm that the mathematical model that is accurately enough and reproduces with sufficient precision physical behavior of the electric drive system.

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MODELAREA MATEMATICĂ ŞI SIMULAREA NUMERICĂ A ACŢIONĂRILOR ELECTRICE CU MOTOARE DE CURENT CONTINUU FĂRĂ PERII

(Rezumat)

Se prezintă rezultatele modelării matematice şi simulării numerice a unui sistem de acționare electrică cu motor de c. c. fără perii (BLDC). Este prezentat modelul matematic al sistemului sub forma ecuațiilor de stare. Pe baza modelului obținut a fost conceput modelul Simulink® al sistemului corespunzător funcționării în circuit deschis (traductor de poziție cu senzori Hall). Pentru analiză s-a ales un motor BLDC de tip Hurst. Rezultatele simulării numerice confirmă faptul că modelul matematic reproduce cu suficientă precizie comportarea fizică a sistemului de acționare electrică.