Modeling and Simulation of the BLDC Motor in MATLAB GUI

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Abstract-**The paper proposes a model of brushless DC motor considering behavior of the motor during commutation. The torque characteristic of BLDC motor presents a very important factor in design of the BLDC motor drive system, so it is necessary to predict the precise value of torque, which is determined by the waveforms of back-EMF. After development of simple mathematical model of the BLDC motor with sinusoidal and trapezoidal waveforms of back-EMF the motor is simulated in the MATLAB/Simulink environment. Based on analysis of the time responses a comparison study of results of both BLDC motor types is presented in Graphical User Interface of MATLAB environment.**

I. INTRODUCTION

The Brushless Direct Current (BLDC) motor is rapidly gaining popularity by its utilization in various industries, such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment and Instrumentation. As the name implies, the BLDC motors do not use brushes for commutation; instead, they are electronically commutated. The BLDC motors have many advantages over brushed DC motors and induction motors [1]. A few of these are:

- Better speed versus torque characteristics
- High dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges

In addition, the ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors [2].

The torque of the BLDC motor is mainly influenced by the waveform of back-EMF (the voltage induced into the stator winding due to rotor movement). Ideally, the BLDC motors have trapezoidal back-EMF waveforms and are fed with rectangular stator currents, which give a theoretically constant torque. However, in practice, torque ripple exists, mainly due to emf waveform imperfections, current ripple and phase current commutation. The current ripple result is from PWM or hysteresis control. The emf waveform imperfections result from variations in the shapes of slot, skew and magnet of BLDC motor, and are subject to design purposes. Hence, an error can occur between actual value and the simulation results. Several simulation models have been proposed for the analysis of BLDC motor [1], [4], [5]. One of the models has a real back-EMF waveform whose appearance is close to a sinusoidal shape. This paper attempts to compare various types of BLDC motor models - with the trapezoidal and sinusoidal back-EMF waveforms. The simple motor model of a BLDC motor consisting of a 3-phase power stage and a brushless DC motor is shown in Fig. 1.

II. CONSTRUCTION AND OPERATING PRINCIPLE

The BLDC motor is also referred to as an electronically commuted motor. There are no brushes on the rotor and the commutation is performed electronically at certain rotor positions. The stator magnetic circuit is usually made from magnetic steel sheets. The stator phase windings are inserted in the slots (a distributed winding), or can be wound as one coil on the magnetic pole. The magnetization of the permanent magnets and their displacement on the rotor are chosen in such a way that the back-EMF shape is trapezoidal. This allows the three-phase voltage system, with a rectangular shape, to be used to create a rotational field with low torque ripples. In this respect, the BLDC motor is equivalent to an inverted DC commutator motor, in that the magnet rotates while the conductors remain stationary.
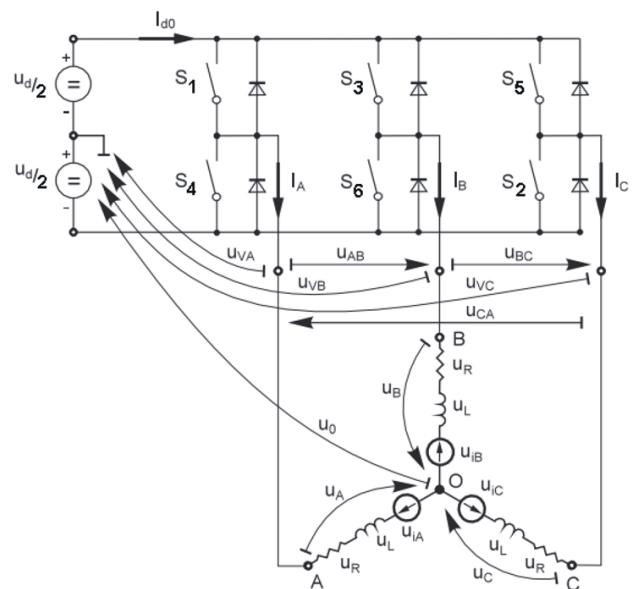

Fig. 1. BLDC motor model of electrical circuits [3]

In the DC commutator motor, the current polarity is reversed by the commutator and the brushes, but in the brushless DC motor, the polarity reversal is performed by semiconductor switches which are to be switched in synchronization with the rotor position. Besides the higher reliability, the missing commutator brings another advantage. The commutator is also a limiting factor in the maximal speed of the DC motor. Therefore the BLDC motor can be employed in applications requiring high speed [1], [3].

Replacement of a DC motor by a BLDC motor place higher demands on control algorithm and control circuit. Firstly, the BLDC motor is usually considered as a three-phase system. Thus, it has to be powered by a three-phase power supply. Next, the rotor position must be known at certain angles, in order to align the applied voltage with the back-EMF. The alignment between the back-EMF and commutation events is very important. In this condition the motor behaves as a DC motor and runs at the best working point. But the drawbacks of the BLDC motor caused by necessity of power converter and rotor position measurement are balanced by excellent performance and reliability, and also by the ever-falling prices of power components and control circuits.

III. MATHEMATICAL MODEL OF THE BLDC MOTOR

Modeling of a BLDC motor can be developed in the similar manner as a three-phase synchronous machine. Since there is a permanent magnet mounted on the rotor, some dynamic characteristics are different. Flux linkage from the rotor depends upon the magnet material. Therefore, saturation of magnetic flux linkage is typical for this kind of motors. As any typical three-phase motors, one structure of the BLDC motor is fed by a three-phase voltage source. The source is not necessarily to be sinusoidal. Square wave or other wave-shape can be applied as long as the peak voltage does not exceed the maximum voltage limit of the motor. Similarly, the model of the armature winding for the BLDC motor is expressed as follows:

$$V_a = Ri_a + L\frac{di_a}{dt} + e_a \tag{1}$$

$$V_b = Ri_b + L\frac{di_b}{dt} + e_b \tag{2}$$

$$V_c = Ri_c + L\frac{di_c}{dt} + e_c \tag{3}$$

where
L is armature self-inductance [H],
R - armature resistance [Ω],
V_a, V_b, V_c - terminal phase voltage [V],
i_a, i_b, i_c - motor input current [A],
and e_a, e_b, e_c - motor back-EMF [V].

In the 3-phase BLDC motor, the back-EMF is related to a function of rotor position and the back-EMF of each phase has 120º phase angle difference so equation of each phase should be as follows:

$$e_a = K_w f(\theta_e)\omega \tag{4}$$

$$e_b = K_w f(\theta_e - 2\pi/3)\omega \tag{5}$$

$$e_c = K_w f(\theta_e + 2\pi/3)\omega \tag{6}$$

where
K_w is back EMF constant of one phase [V/rad.s^{-1}],
θ_e - electrical rotor angle [° el.],
ω - rotor speed [rad.s^{-1}].

The electrical rotor angle is equal to the mechanical rotor angle multiplied by the number of pole pairs p:

$$\theta_e = \frac{p}{2}\theta_m \tag{7}$$

Where
θ_m is mechanical rotor angle [rad].

Total torque output can be represented as summation of that of each phase. Next equation represents the total torque output:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega} \tag{8}$$

where
T_e is total torque output [Nm],

The equation of mechanical part is represents as follows:

$$T_e - T_l = J\frac{d\omega}{dt} + B\omega \tag{9}$$

where
T_l is load torque [Nm],
J - inertia of rotor and coupled shaft [kgm^2],
B - friction constant [Nms.rad^{-1}].

IV. SIMULINK MODEL OF THE BLDC MOTOR

Fig. 2 shows the BLDC motor SIMULINK model. The model was developed in the rotor reference frame of the BLDC motor using equations shown above [5].

Fig. 3 shows the detail of the BLDC motor block. Fig.4 shows SIMULINK diagram of back-EMF. Fig. 4(a) is of trapezoidal back-EMF and Fig. 4(b) is of sinusoidal back-EMF. The trapezoidal functions and the position signals are stored in lookup tables that change their output according to the value of the electrical angle [5].

Unlike a brushed DC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor, the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing
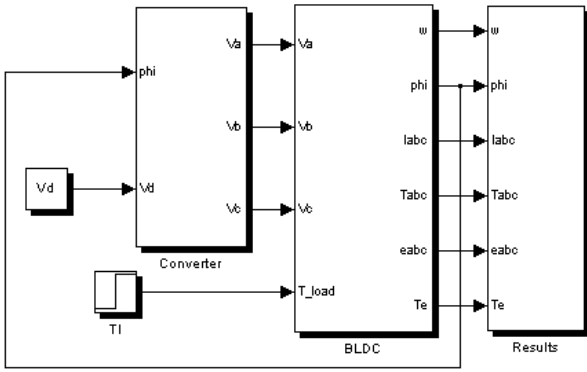
Fig.2. SIMULINK model of the BLDC motor

Fig. 4(a). Trapezoidal model of the back-EMF

Fig. 4(b). Sinusoidal model of the back-EMF

sequence. Rotor position is sensed using Hall Effect sensors embedded into the stator. Most BLDC motors have three Hall sensors embedded into the stator on the non-driving end of the motor.

Whenever the rotor magnetic poles pass near the Hall sensors, the give a high or low signal, indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined.

The converter block was developed using equations below:

$$V_a = (S_1)V_d/2 - (S_4)V_d/2 \qquad (10)$$

$$V_b = (S_3)V_d/2 - (S_6)V_d/2 \qquad (11)$$

$$V_c = (S_5)V_d/2 - (S_2)V_d/2 \qquad (12)$$

Every 60 electrical degrees of rotation, one of the Hall sensors changes the state. Given this, it takes six steps to complete an electrical cycle. Corresponding to this, with every 60 electrical degrees, the phase current switching should be updated.

However, one electrical cycle may not correspond to a complete mechanical revolution of the rotor. The number of electrical cycles to be repeated to complete a mechanical rotation is determined by the rotor pole pairs. For each rotor pole pairs, one electrical degree is completed. The number of electrical cycles/rotations equals the rotor pole pairs [6].
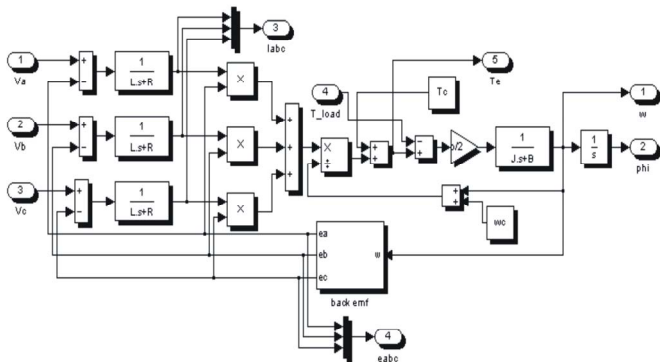
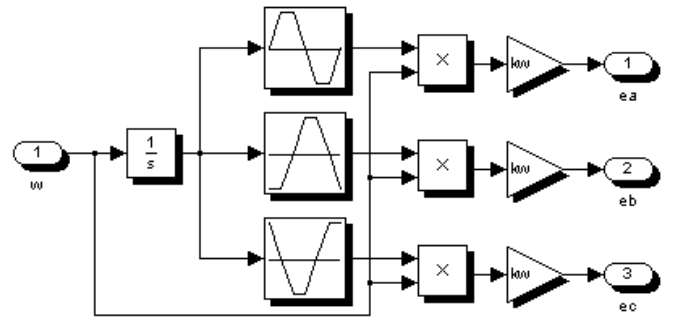

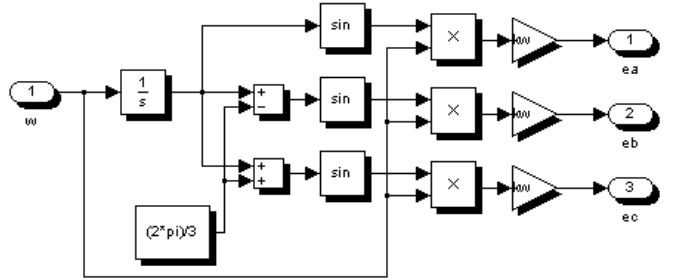Fig. 3. Detailed SIMULINK model of the BLDC motor

V. SIMULATION RESULTS

Fig. 5 - 9 shows results of simulation of a BLDC motor with the following parameters: V_d = 30 V, R = 4,98 Ω, L = 5,05 mH, p = 4, J = 15,17.10^{-6} kgm^2, k_w = 56,23.10^{-3} V/rad.s^{-1}, T_l = 0.1 Nm. The load time is 0,15 s.

The time courses in Fig. 5(a) belong to the BLDC motor with trapezoidal back-EMF and the responses in Fig. 5(b) are valid for the sinusoidal back-EMF BLDC motor. There is a very good correlation with the responses of the BLDC motor models known in the references [5], [6].
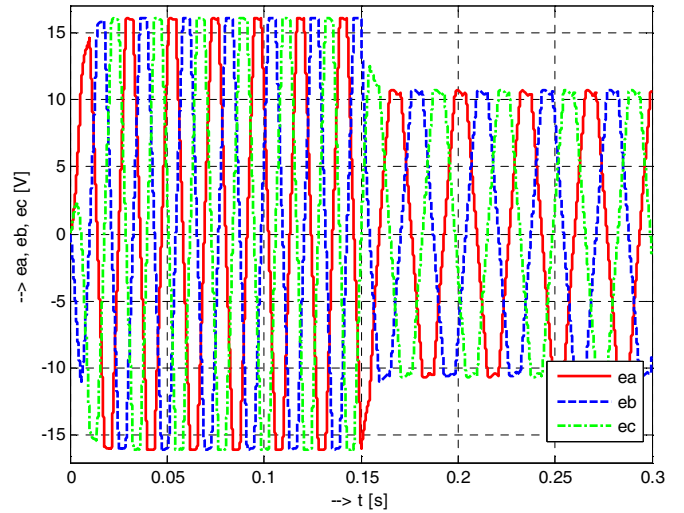

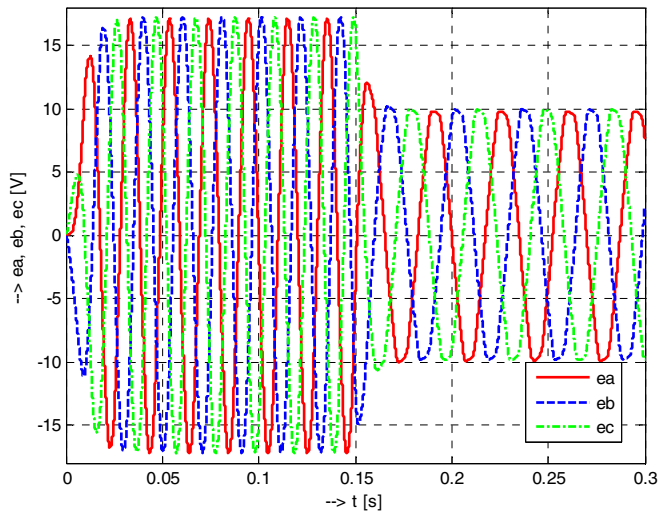Fig. 5(a). Time courses of the trapezoidal back-EMF

Fig. 5(b). Time courses of the sinusoidal back-EMF

VI. GRAPHICAL USER INTERFACE IN MATLAB

A graphical user interface (GUI) is a pictorial interface to a program. A good GUI can make programs easier to use by providing them with a consistent appearance and with intuitive controls like pushbuttons, list boxes, sliders, menus, and so forth. The GUI should behave in an understandable and predictable manner, so that a user knows what to expect when he or she performs an action. For example, when a mouse click occurs on a pushbutton, the GUI should initiate the action described on the label of the button.

If GUIs were not used, people would have to work from the command line interface, which can be extremely difficult and frustrating [7].

A graphical user interface provides the user with a familiar environment in which to work. This environment contains pushbuttons, toggle buttons, lists, menus, text boxes, and so forth, all of which are already familiar to the user, so that he or she can concentrate on using the application rather than on the mechanics involved in doing things. However, GUIs are harder for the programmer because a GUI-based program must be prepared for mouse clicks (or possibly keyboard input) for any GUI element at any time [7].

The three principal elements required to create a MATLAB Graphical User Interface are:

- Components
- Figures
- Callbacks

In GUI program, we can simulate the equations that describe not only mechanical but also electrical transients. Fig. 6 is shown GUI for modeling and simulation of the BLDC motor. By blue pushbutton e_a, e_b, e_c we can see time courses of trapezoidal back-EMF in three-phase stator windings of the BLDC motor. Fig. 7 is shown mentioned back-EMF voltages before and after the load mount in time 0.15 s.
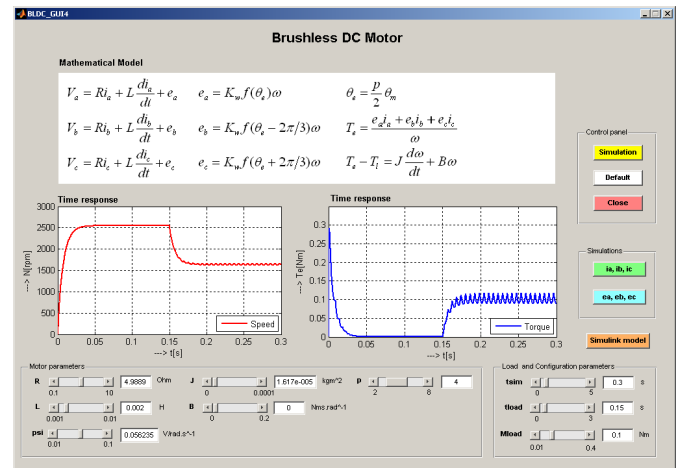

Fig. 6. Time courses of the BLDC motor in MATLAB GUI

In the bottom of GUI simulation model are sliders to change the BLDC motor parameters. After changing the motor parameters we can monitor the behavior of the motor and show time courses of parameters that we want to monitor and analyze.

Students by GUI simulation can better understand the theoretical knowledge acquired from lectures into real devices. Via the GUI simulation we can monitor and analyze response time of physical quantities that are available.

Fig. 8 is shown a response time of the load variations of 0.1 Nm to 0.2 Nm. After changing we can analyze by the increase in the size of the load that speed of the motor and also back-EMF voltages in each three-phase in the stator winding were decreased.

VII. EDUCATIONAL USE OF MODELS

A whole set of electrical machines virtual models developed in GUI MATLAB environment have been successfully integrated in electric machinery courses. They serve for easier understanding operation principles and after performing virtual experiments the students enter the laboratory to work on real devices.
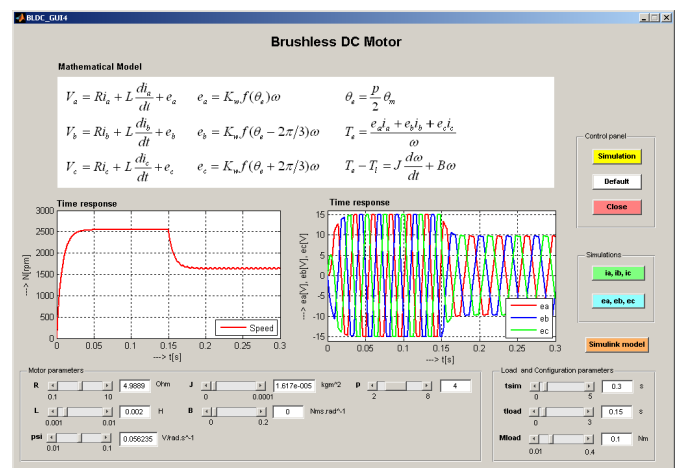

Fig. 7. Experimentation on BLDC motor virtual model
- time courses of the speed and back-EMF voltages

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The behavior of developed BLDC motor virtual model is shwon in Figs. 7. and 8. The GUI window is completed by basic BLDC motor equations and schemes to be evocated by pushing a button. The motor parameters are set by shifters what enables to observe influence of parameters to the motor operation and modes of the virtual model are set by buttons.

Most of the models are integrated to into the web page [9].
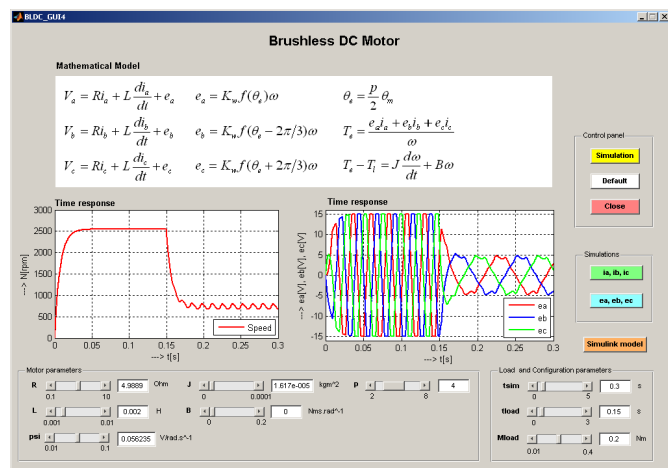

Fig. 8. Experimentation on BLDC motor virtual model
- time courses of the speed and back-EMF voltages after increasing the load

VIII.   CONCLUSION

The modeling procedure presented in this paper helps in simulation of various types of BLDC motors. The performance evaluation results show that, such a modeling is very useful in studying the drive system before taking up the dedicated controller design, accounting the relevant dynamic parameters of the motor.

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