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The Simulation of Mathematical Model of Outer Rotor BLDC Motor

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Abstract – In this study, mathematical modeling of outer rotor brushless direct current motor (BLCD) is performed. Brushless direct current motor is highly preferred in industrial applications when compared the other motor types with considering advantages and disadvantages. Producing higher torque with smaller dimensions, being easily controllable and developing high efficiency electronic materials can be given such an example of these advantages. In this study, an outer rotor brushless DC motor which was used in the laboratory is modeled. This motor hasn't currently information parameters. For this reason, first of all, the metric measurements, phase winding orders are obtained for the motor parameters. With the motor parameters that we have, the motor was created and analyzed in Maxwell program environment. And then the parameters (torque constant, back EMF constant, phase resistance, etc.) were obtained required for the simulation. Mathematical model was completed with the obtained parameters in Matlab / Simulink environment. So, Torque characteristics, motor speed and trapezoidal back-EMF were determined. The motor currents matched with the Maxwell and Matlab / Simulink programs. So the accuracy of the simulation modeling has been confirmed.

Keywords *– Brushless Direct Current Motor, BLDC, Simulation Analysis, Matlab/Simulink, Maxwell.*

I. Introduction

Brushless Direct Current Motors (BLDC) are a special electrical machine that includes the features of the synchronous machine. BLDC motors are preferred in the industry because of their high efficiency, high torque and robust construction. They are especially used in aerospace, medical, computer technologies, industrial automation, military applications and robotics.

Tibor et al. simulated the mathematical model of the BLDC motor and showed the results via Matlab / Gui [3]. Jeon et al. proposed a new BLDC motor simulation model with an almost true Electromagnetic Force (EMF) waveform to reduce simulation error [1]. Patel and Pandey have created the PID model of a BLDC motor with the use of Matlab / Simulink [6]. Cai et al. proposed a control strategy for the BLDC used in the Electric Power Steering (EPS) system and analyzed the simulation model of this system [7]. Karapınar et al. modelled a BLDC motor in Matlab / Simulink program. In this study, they presented a cascade controller design including current, velocity and position cycles [8]. Vinatha et al. designed the simulation in the Matlab / Simulink program by controlling the speed and current of the BLDC motor. They made the evaluation of the model by performing various simulation studies [9]. Kürkçü et al. have modeled and applied a brushless DC Motor belonging to a military system under variable environmental dynamic conditions via Matlab/Simulink [10].

In this study, the mathematical model and simulation of a BLDC motor used in the laboratory is applied. The parameters required for the simulation (stator diameter, number of magnets, number of turns, air gaps, etc.) are taken from the motor. By using measured parameters, BLDC motor parameters (K_e (Back-EMF Constant), K_t (Torque Constant), R_s (Phase Resistance), L (Phase Inductance), J (Inertia Moment) etc.) required for mathematical model is determined by Maxwell program. The motor is simulated in Matlab/Simulink program by using the obtained motor parameters. As a result of the simulation, data related to motor phase currents, rotor speed, back EMF and motor torque are obtained.

II. Materials and Method

BLDC motors are divided into two as Inner and Outer according to their rotor structure. In this study, Outer rotor model is used. In Outer rotor models, the rotor of the motor is on the outside. The body of the motor rotates and the fixed part remains inside. Figure 1 shows the outer rotor BLDC motor structure.

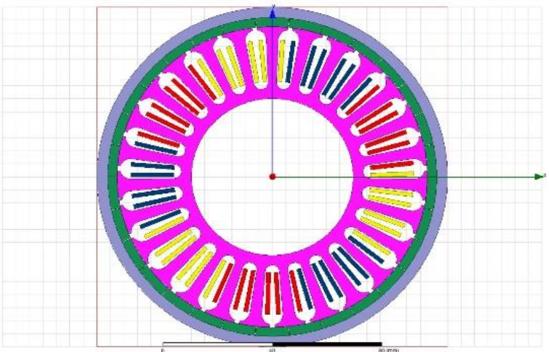

Fig. 1 The outer rotor BLDC motor structure

BLDC motors are not affected by changes in mains frequency since they operate with DC voltage. As the structure is electronic, the efficiency is high. Since electrical conduction is not transmitted by any brush, they do not form an arc due to friction [4]. Advantages and disadvantages of BLDC motors compared to other motor types are listed below.

Advantages of BLDC motor compared to other motor types [5];

- ✓ Torque/Volume is very high for BLDC motors.
- ✓ They have high efficiency.
- ✓ Reliable. They work quietly.
- ✓ They do not form arc.
- ✓ They do not need excitation current.
- ✓ High speeds can be achieved.
- ✓ There is no coal dust because they are brushless.

Disadvantages of BLDC motor compared to other motor types;

- ✓ Their prices are higher than other motor types because of the magnet shelter inside.
- ✓ The rotor position must be known in order to trigger the phase which can generate torque.
- ✓ The control circuits are more complex than the control circuits of other motors.

A. BLDC Motor Structure

In order to drive BLDC motors, an inverter structure that can trigger the phases correctly and Hall Effect sensors or an encoder to determine the rotor position are required. Position information is taken from the hall effect sensors in the motor. Table 1 shows the physical parameters of the 27/30 BLDC motor used in the study.

Table 1. the physical parameters of the 27/30 BLDC motor

Parameters	Value
Pole Number/ Magnet Number	27/30
Stator Outer Diameter	114.8 mm
Stator Inner Diameter	60 mm
Rotor Outer Diameter	129.9 mm
Rotor Inner Diameter	115 mm
Package Length	30 mm
Connection Type	Y3

B. Mathematical Model of BLDC Motor

The phase variable approach is generally preferred in terms of simplicity in BLDC motors. The source can be applied as a sinusoidal, square wave, trapezoidal or other wave as long as the peak voltage does not exceed the maximum voltage limit of the motor. Electrical and mechanical equations of BLDC motor are given below. Equations of phase voltage values are given in Equations 1, 2 and 3.

$$V_{as} = R.i_{as} + (L-M)\frac{di_a}{d_t} + e_a \quad (1)$$

$$V_{bs} = R.i_{bs} + (L-M)\frac{di_{bs}}{d_t} + e_b \quad (2)$$

$$V_{cs} = R.i_{cs} + (L-M)\frac{di_{cs}}{d_t} + e_c \quad (3)$$

Where, L: Phase Inductance ($L = L_a = L_b = L_c$), M: Mutual Inductance, R: Phase Resistance ($R = R_a = R_b = R_c$), I_{as}, I_{bs}, I_{cs}: Phase Currents, V_{as}, V_{bs}, V_{cs}: Phase Voltages and e_a, e_b, e_c: Back-EMF.

The torque of the BLDC motor is mainly influenced by the waveform of the back EMF ([1] - [3]). The opposite voltage that occurs in the stator windings when the motor is working is called the Back-EMF. The Back-EMF depends on the magnetic flux, speed and position parameters. Equations 4, 5 and 6 formulate the back-EMF voltages that occur in each phase.

$$e_a = K_e.f(\theta_e).w_m \quad (4)$$

$$e_b = K_e.f(\theta_e - (2\pi/3)).w_m \quad (5)$$

$$e_c = K_e.f(\theta_e + (2\pi/3)).w_m \quad (6)$$

Where, K_e: Back-EMF Constant, w_m: Mechanical Angular Speed and θ_e: Electric Motor Angle. The trapezoidal EMF generator function $f(\theta_e)$ is given in Equation 7.

$$f(\theta_e) = \begin{cases} 0 \le \theta_e \le 30, & 0 \\ 30 < \theta_e \le 90, & 1 \\ 90 < \theta_e \le 150, & 1 \\ 150 < \theta_e \le 210, & 0 \\ 210 < \theta_e \le 270, & -1 \\ 270 < \theta_e \le 330, & -1 \\ 330 < \theta_e \le 360, & 0 \end{cases} \quad (7)$$

The electromagnetic torque values of each phase are expressed in Equations 9, 10 and 11. Total electromagnetic torque is given in Equations 8 and 12.

$$T_e = (e_a.I_a + e_b.I_b + e_c.I_c)/w_m \quad (8)$$

$$T_a = K_t.f(\theta).I_a \quad (9)$$

$$T_b = K_t.f(\theta - 2\pi/3).I_b \quad (10)$$

$$T_c = K_t.f(\theta + 2\pi/3).I_c \quad (11)$$

$$T_e = T_a + T_b + T_c \quad (12)$$

Where, K_t: Torque Constant. The formula for mechanical torque is given in Equation 13.

$$T_m = T_{load} + J.\frac{dw_m}{d_t} + \beta.w_m \quad (13)$$

Where, β the friction coefficient and J is the inertia moment. Phase voltages can be calculated as Equations 14 and 15 by using $V_{ab} = V_a - V_b$ and $E_{ab} = E_a - E_b$ since it can be modeled more easily from phase voltage equations.

$$V_{ab} = V_a - V_b = R_s(I_a - I_b) + (L-M)\frac{d}{d_t}(I_a - I_b) + E_{ab} \quad (14)$$

$$V_{bc} = V_b - V_c = R_s(I_b - I_c) + (L-M)\frac{d}{d_t}(I_b - I_c) + E_{bc} \quad (15)$$

If the mutual inductance is ignored and $I_a + I_b + I_c = 0$, the flow equations are given in Equation 16, 17 and 18.

$$\frac{di_a}{d_t} = -\frac{R}{L}i_a + \frac{2}{3L}(V_{ab} - E_{ab}) + \frac{1}{3L}(V_{bc} - E_{bc}) \quad (16)$$

$$\frac{di_b}{d_t} = -\frac{R}{L}i_b - \frac{1}{3L}(V_{ab} - E_{ab}) + \frac{1}{3L}(V_{bc} - E_{bc}) \quad (17)$$

$$I_c = -(I_a + I_b) \quad (18)$$

C. Maxwell Program

The Maxwell program is a software package that solves problems in the electromagnetic field using Maxwell's equations. In this study, parameters required for simulation of BLDC motor are obtained by using Maxwell software package. The design of the motor is made in this program from the beginning. It's parameters needed in this process are obtained from the motor.

This Parameters;

- ✓ Pole Number:30
- ✓ Slot Number:27
- ✓ Turn Number:34
- ✓ Stator Inner/Outer Diameter:60 mm / 114,8 mm
- ✓ Rotor Inner/Outer Diameter:115 mm / 129,9 mm
- ✓ Magnet Thickness:3,45 mm
- ✓ Package Length:30 mm
- ✓ Connection Type: Star connection.

After the parameter measurements, the motor is designed in Maxwell program. Figure 2 shows the phase sequence used in this design.

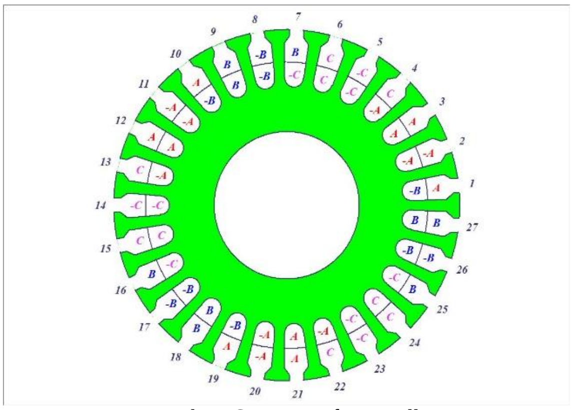

Fig. 2 Phase Sequence of Maxwell Motor

As a result of the design, the parameters required for simulation were obtained. These parameters are given in Table 2.

Table 2. Parameters Obtained from Maxwell Program

Parameters	Value
K_e (Vs/rad)	1.46
K_t (Nm/A)	1.39
J (kg.m^2)	$6.651e^{-3}$
L (H)	$3.456e^{-3}$
Rs (ohm)	0.454

D. *Simulation of BLDC Motor*

Matlab/Simulink program is used to simulate the mathematical model of the BLDC motor. Figure 3 shows the BLDC block and the window for the parameters to be entered. The mathematical model of the system is extracted and expressed as a block diagram in Simulink program. As a result of the simulation, mechanical angular velocity (w_m), electrical angular velocity (w_e), phase currents (I_a, I_b, I_c) and phase electromagnetic voltages (E_a, E_b, E_c) can be calculated.

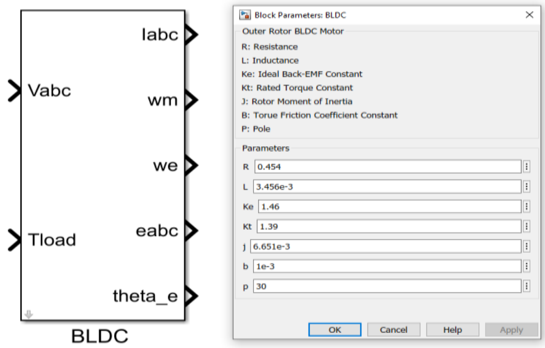

Fig. 3 BLDC Motor General Block Diagram and Parameter Input Window

As shown in the BLDC block, the load torque and voltage values of each phase are given as input and the phase currents, mechanical angular velocity, electrical angular velocity, electromagnetic voltage and electrical angle are given as output. The BLDC motor block (Figure 4) contains blocks with current equations, torque equations, and opposite EMF equations. For the system to operate at full speed at nominal speed, the load is selected to be approximately 7.80 Nm. Thus, the maximum torque of the motor is determined.

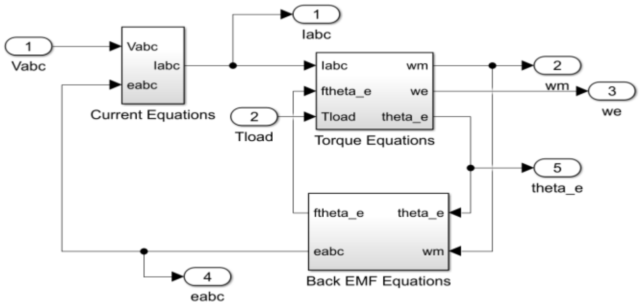

Fig. 4 Current, Torque and Opposite EMF Equation Blocks

III. Results

As a result of this study, a mathematical model of an outer rotor BLDC motor with 350W and 320RPM speed is applied and simulated. In the Maxwell and Matlab/Simulink programs, the currents at full load are observed. In the Matlab / Simulink program, the maximum current of each phase is observed as 13.65A and the effective value is calculated as 9.65A from the formula I_{max} / √2. In Maxwell program, the maximum current of each phase is 13.86A and the effective value is 9.79A. It has been proved that the simulation works correctly with an error of 1.51% from the obtained current values. The current graph for each phase calculated in Matlab / Simulink is shown in Figure 5. There are 120 degree phase differences between the phases.

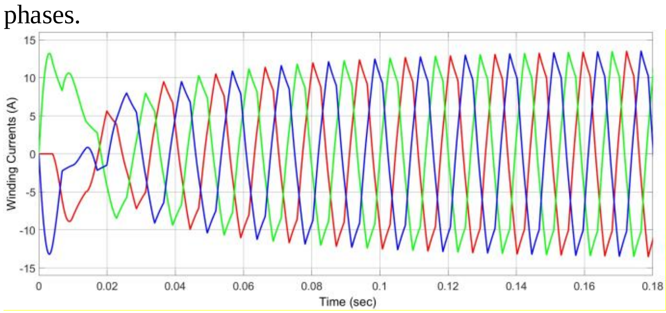

Fig. 5 Current Graph at Full Load of BLDC Motor Obtained from Matlab/Simulink

In Figure 6, the current graph obtained from Maxwell program which corresponds to the same load value is given.

As seen in both figures, the data obtained from Maxwell and Matlab/Simulink support each other.

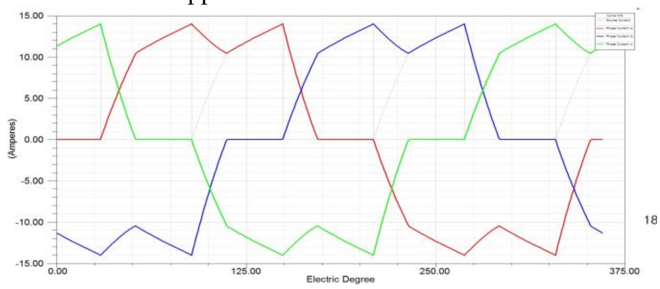

Fig. 6 Current Graph at Full Load of BLDC Motor Obtained from Maxwell Program

IV. CONCLUSION

In this study, a brushless direct current motor used in the laboratory is simulated. 350W and 320 RPM speed design of the motor is made in Maxwell program. Thanks to this design, the necessary parameter information is obtained in the simulation. In the Matlab/Simulink program, the mathematical model of the BLDC motor is simulated. Maxwell and Matlab/Simulink programs are compared at full load currents. The approximate equality of the currents indicate the accuracy of the simulation.

The mechanical and electrical properties of the motor are determined by using the physical properties of the BLDC motor. Like these models can be used to control many applications such as robot, electric vehicle, and industrial environment. These model parameters and simulation study are the infrastructure for future applications.

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