

Mathematical Modeling and Simulation for Performance Analysis Using MATLAB/SIMULINK

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Abstract: -- Automotive Industry is targeting sustainable transportation in near future. Therefore hybrid and electric vehicles are going to be popular due to their sustainability, energy saving, and zero emission. Electric motors play a significant role in EV's. In-wheel motor technology is being used in modern electric vehicles to improve efficiency, safety, and controllability of vehicle nowadays. BLDC motor has been demanding as an in-wheel motor in electric vehicles because of high efficiency, desired torque versus speed characteristics, high power density and low maintenance cost. In this paper, BLDC motor with ideal back-EMF is modeled and simulated in MATLAB / SIMULINK. The simulation model of the controller and BLDC drive are also presented. In order to validate the model, various simulation models are studied. Simulations results depict from developed model are satisfactory and show correct performance of model.

Keywords— Simulation of BLDC Motor, In-wheel Motor, Electric Vehicle.

I. INTRODUCTION

BLDC have been used in different applications such as industrial automation, automotive, aerospace instrumentation and appliances since 1970's. BLDC motor is a novel type of DC motor which commutation is done electronically instead of using brushes. Therefore it needs less maintenance. Also its noise susceptibility is less, looking forward to have integral motor. Electronic commutation technique and permanent magnet rotor cause BLDC to have immediate advantages over brushed DC motor and induction motor in electric vehicle application [1]. In-wheel technology is using a separate motor mounted inside tire for each wheel instead of one central drive train propelling two or all four wheels in conventional electric vehicles. It increases controllability of vehicle and decreases chassis weight. With using in-wheel and by-wire technologies instead of mechanical, hydraulic and pneumatic control systems; idea of an Intelligent Fully Electronically Controlled Vehicle (IFECV) approaches to reality. Two wheel drive train system of a commercial IFECV. BLDC has more complex control algorithm compare to other motor types due to electronically commutation. Therefore accurate model of motor is required to have complete and precise control scheme of BLDC. To design of BLDC motor drive system, it is necessary to have motor model gives precise value of torque which is related to current and back-EMF [2]. Different simulation models have been presented to analyze performance of BLDC motor [3-6]. Lots of various modeling techniques according to different applications of BLDC motor have been used. Although all the previous works made a great contribution to modeling BLDC motor, but there is no simple model

appropriate for in-wheel motor application. Hence in this paper model of 3 phases, 4 poles, Y connected, trapezoidal back-EMF type of BLDC motor for automotive industry application is modeled and simulated in MATLAB / SIMULINK.

OVERALL SYSTEM MODEL

There are two types of BLDC with respect to back-EMF signal of motor; sinusoidal and trapezoidal. There are also two types of BLDC according to have sensors for detecting rotor position or not. Normally Hall Effect sensors were being used for low cost, low resolution requirements and optical encoder for high resolution requirements [7]. Sensor signals are using to adjust PWM sequence of 3-phase bridge inverter. In sensorless control back-EMF sensing, back-EMF integration, flux linkage-based, freewheeling diode conduction and speed independent position function techniques are using for electronic commutation [8]. In this model, Hall Effect signals are produced according to rotor position for commutation. Also a 3-phase inverter using MOSFETs is used as voltage source. Different control techniques can be applied to the model. Hence control techniques of BLDC are not objective of used in loop control algorithm to control speed. Schematic system of BLDC motor drive. simulation model is consisting of three parts. Each part is simulated separately and integrated in overall simulation model. For decoding Hall Effect signals in PWM generator, MATLAB code is written.

BLDC MOTOR MODEL

In this paper a 3 phases, 4 poles, Y connected trapezoidal back-EMF type BLDC is modeled. Trapezoidal back-EMF is referring that mutual inductance between stator and rotor has trapezoidal shape [3]. Therefore abc phase variable model is more applicable than d-q axis. With the intention of

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simplifying equations and overall model the following assumptions are made:

- Magnetic circuit saturation is ignored.
- Stator resistance, self and mutual inductance of all phases are equal and constant.
- Hysteresis and eddy current losses are eliminated.
- All semiconductor switches are ideal.
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The electrical and mechanical mathematical equations of BLDC are:

$$V_a = Ri_a + (L - M) \frac{di_a}{dt} + E_a \quad (1)$$

$$V_b = Ri_b + (L - M) \frac{di_b}{dt} + E_b \quad (2)$$

$$V_c = Ri_c + (L - M) \frac{di_c}{dt} + E_c \quad (3)$$

$$\begin{cases} E_a = K_e \omega_m F(\theta_e) \\ E_b = K_e \omega_m F(\theta_e - \frac{2\pi}{3}) \\ E_c = K_e \omega_m F(\theta_e + \frac{2\pi}{3}) \end{cases} \quad (4)$$

$$\begin{cases} T_a = K_t i_a F(\theta_e) \\ T_b = K_t i_b F(\theta_e - \frac{2\pi}{3}) \\ T_c = K_t i_c F(\theta_e + \frac{2\pi}{3}) \end{cases} \quad (5)$$

$$T_e = T_a + T_b + T_c \quad (6)$$

$$T_e - T_l = J \frac{d^2\theta_m}{dt^2} + \beta \frac{d\theta_m}{dt} \quad (7)$$

$$\theta_e = \frac{P}{2} \theta_m \quad (8)$$

$$\omega_m = \frac{d\theta_m}{dt} \quad (9)$$

Where = a, b, c,

V_k : kth Phase voltage applied from inverter to BLDC

i_k : ith Phase current

R : Resistance of BLDC per phase

L : Inductance of BLDC per phase

M : Mutual inductance

E_k : kth Phase back-EMF

T_k : Electric torque produce by kth phase

T_e : Electric torque produce by BLDC

K_e : Back-EMF constant

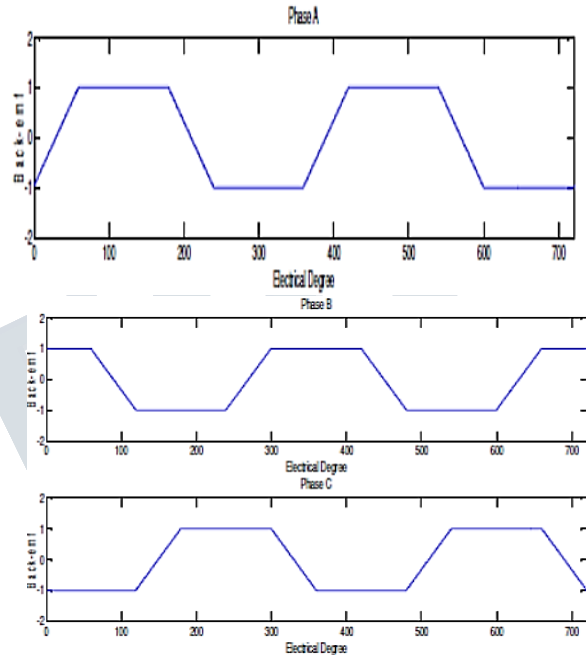
K_t : Torque constant

ω_m: Angular speed of rotor

Θ_m: Mechanical angle of rotor

Θ_e: Electrical angle of rotor

F(Θ_e): Back-EMF reference as function of rotor position
MATLAB code is written to produce Ideal Back-EMF of BLDC as function of rotor position. Simulation result of Ideal back-EMF reference waveforms of all phases versus electrical angle are shown in Fig. 3.



Hence it is assumed that phase zones are distributed symmetrically to different phase windings; back-EMF signals have 120 degree phase shift with respect to each other. For convenient implementation of equation in MATLAB / SIMULINK, most of references [3-5] are used state space equations. Hence most of motor manufacturers do not wire motor neutral point, phase to phase voltage equations are used like in [9]. State space form of equations (1), (2), (3) and (7) can be derived as

$$V_{ab} = R(i_a - i_b) + (L - M) \frac{d}{dt}(i_a - i_b) + E_{ab} \quad (10)$$

$$V_{bc} = R(i_b - i_c) + (L - M) \frac{d}{dt}(i_b - i_c) + E_{bc} \quad (11)$$

Where $i_a + i_b + i_c = 0$ therefore after modifying equations (10) and (11) and neglecting mutual inductance,

$$\frac{di_a}{dt} = -\frac{R}{L} i_a + \frac{2}{3L} (V_{ab} - E_{ab}) + \frac{1}{3L} (V_{bc} - E_{bc}) \quad (12)$$

$$\frac{di_b}{dt} = -\frac{R}{L} i_b - \frac{1}{3L} (V_{ab} - E_{ab}) + \frac{1}{3L} (V_{bc} - E_{bc}) \quad (13)$$

$$\begin{bmatrix} \dot{i}_a \\ \dot{i}_b \\ \dot{\omega}_m \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 & 0 \\ 0 & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{\beta}{J} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ \omega_m \end{bmatrix} + \begin{bmatrix} \frac{2}{3L} & \frac{1}{3L} & 0 \\ \frac{1}{3L} & \frac{1}{3L} & 0 \\ 0 & 0 & \frac{1}{J} \end{bmatrix} \begin{bmatrix} V_{ab} - E_{ab} \\ V_{bc} - E_{bc} \\ T_e - T_l \end{bmatrix} \quad (14)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \\ \omega_m \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -1 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ \omega_m \end{bmatrix} \quad (15)$$

Then state space model of BLDC motor is: Implementing of final state space equations (14) and (15) will make model more complex. Although neutral point of motor is not accessible but virtually is possible to estimate it with zero crossing point of back-EMF. Also for linear and zero initial condition systems, State space to Laplace transform and vice versa can be written. Therefore final state space equation is divided to two simple and separate electrical and mechanical Laplace equations applied by phase to neutral voltages. It makes the BLDC model more simple and convenient for various control techniques implementation. Ideal reference back-EMF signal of motor also is produced according electrical rotation of rotor in each phase separately and applied as negative feedback to phase voltage. BLDC motor model is shown in Fig. 1.

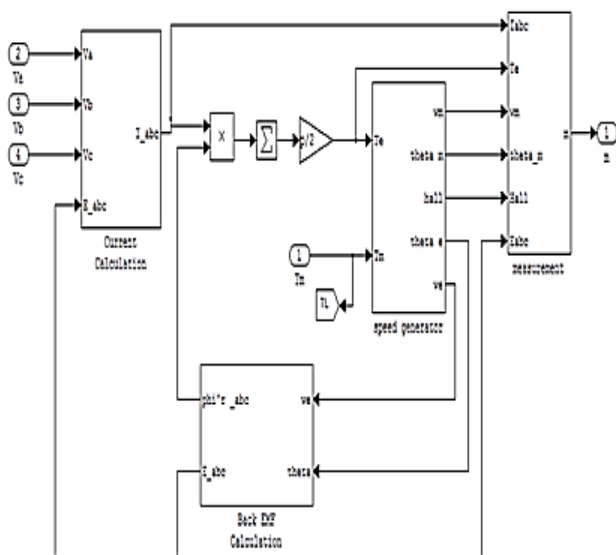


Fig.1. BLDC Motor Model

Hall Effect signals of motor are produced according to electrical degree. Table I shows Hall Effect signal values according to electrical degree of rotor.

TABLE.I
HALL EFFECT SIGNAL

ELECTRIC DEGREE	HALL1	HALL2	HALL3
0-60	1	0	1
60-120	0	0	1
120-180	0	1	1
180-240	0	1	0
240-300	1	1	0
300-360	1	0	0

With implementing of a 3-phase full bridge inverter and a PI speed regulator overall model of motor is modeled. Overall model of BLDC motor drive is shown in Fig. 2.

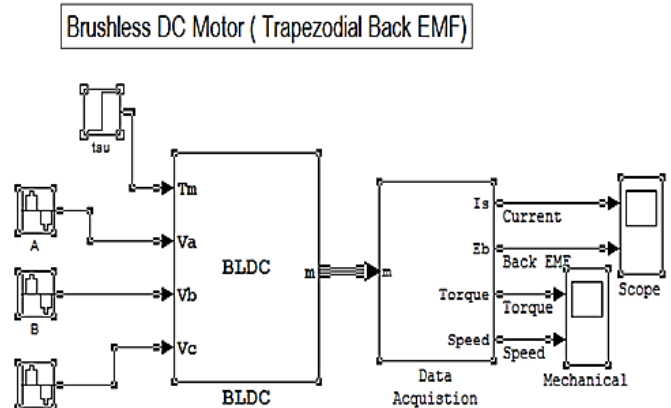


Fig.2. Overall made of BLDC motor

SIMULATION RESULTS

Simulation results of BLDC motor under no load and load conditions are shown. As it can be seen in Fig. 3, dynamic response of BLDC due to its permanent magnet (low inertia) rotor is high. Pulsating torque of BLDC is shown in Fig. 4. Fig. 5. shows back-EMF produced in phase A of motor. Hall Effect signals of all three phase are shown in Fig. 6. according to table I. Table II shows BLDC motor specification to investigate performance of advanced model.

TABLE.II.

BLDC MOTOR SPECIFICATION

DESCRIPTION	VALUE	UNIT
POWER	10	KW
DC VOLTAGE	220	V
PHASE RESISTANCE(R)	1	
PHASE INDUCTION(L)	0.25	m-H
INERTIA(J)	15.17e-6	Kg-m ²
DAMPING RATIO(β)	0.001	N-s/m
POLES	4	

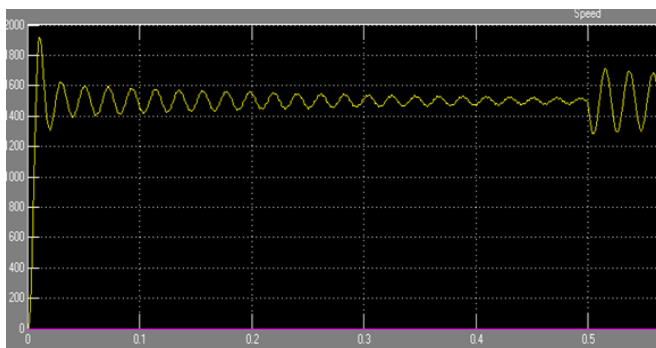


Fig.3.Speed characteristics under load condition

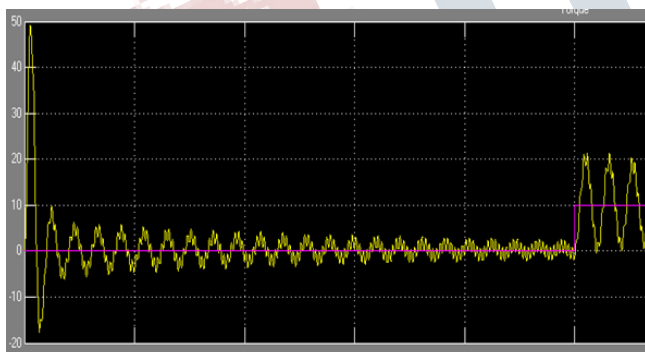


Fig.4.Torque characteristics under load condition

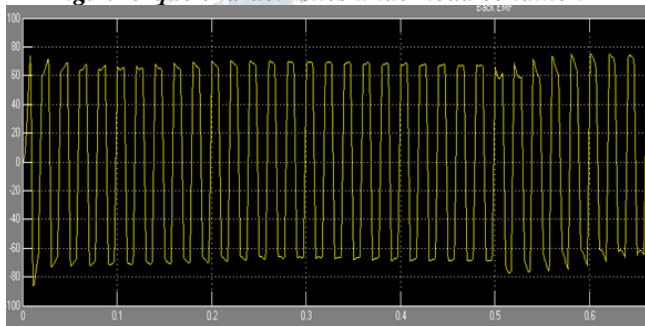


Fig.5.BACK-EMF of phase A

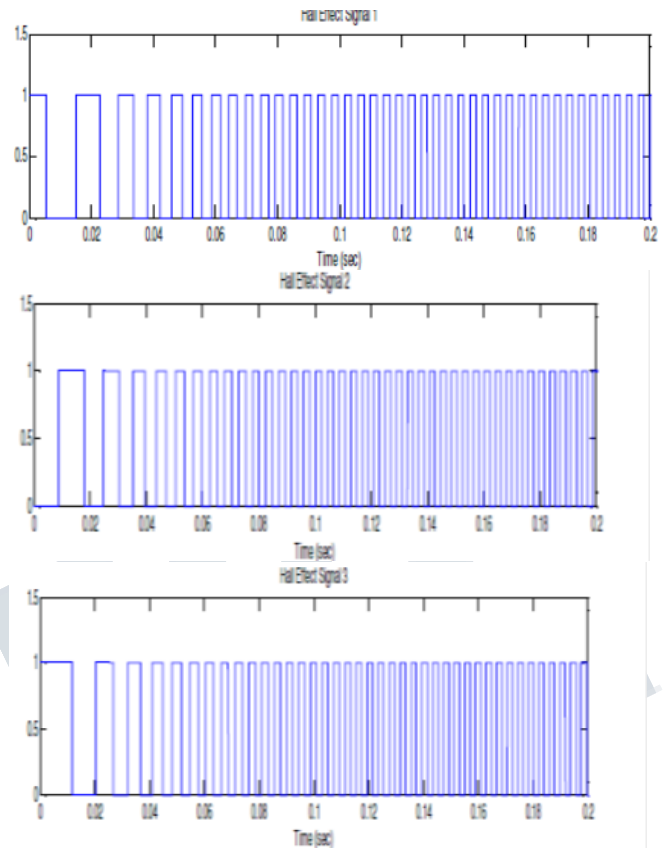


Fig.6.Hall Effect signal

II. CONCLUSION

In this paper it is shown that BLDC motor is a good choice in automotive industry due to higher efficiency, higher power density and higher speed ranges compare to other motor types. BLDC motor model with ideal back-EMF is presented in this paper. The proposed model is simulated in MATLAB / SIMULINK. Simulation results under no load and load conditions are showing proper performance of model. Output characteristics and simplicity of model make it effectively useful in design of BLDC motor drives with different control algorithms in different applications.

REFERENCES

[1] A. Tashakori, M. Ektesabi and N. Hosseinzadeh, "Characteristic of suitable drive train for electric vehicle", 2010 3rd International Conference on Power Electronic and Intelligent Transportation System (PEITS), 20-21 Nov 2010, Shenzhen, China.

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[2] Y. S. Jeon, H. S. Mok, G. H. Choe, D. K. Kim and J. S. Ryu, "A new simulation model of BLDC motor with real back EMF waveform", IEEE CNF. On Computer and Power Electronics, 2000. COMPEL 2000. Pp.217- 220, July 2000.

[3] S. Vinatha, S. Pola, K.P. Vittal, "Simulation of four quadrant operation & speed control of BLDC motor on matlab / simulink", TENCON 2008- 2008 IEEE Region 10 Conference, 19- 21 Nov 2008, Hyderabad, India.

[4] Congzhao Cai, Hui Zhang, Jinhong Liu, Yongjun Gao, "Modelling and simulation of BLDC motor in electric power steering", Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific, 28-31 March 2010, Chengdu, China.

[5] Wonbok Hong, Wootaik Lee, Byoung-Kuk Lee, "Dynamic simulation of brushless DC motor drives considering phase commutation for automotive applications", Electric Machines & Drives Conference, 2007. IEMDC '07. IEEE International, 3-5 May 2007, Antalya, Turkey.

[6] R. Saxena, Y. Pahariya, A. Tiwary, "Modeling and simulation of BLDC motor using soft computing techniques", Second International Conference on Communication Software and Networks, 2010, ICCSN '10, 26- 28 Feb, Singapore.

[7] Padmaraja Yedamale, "Brushless DC (BLDC) Motor Fundamentals", AN885, 2003 Microchip Technology Inc.

[8] Tae-Hyung Kim, M. Ehsani, "Sensorless control of the BLDC motors from near-zero to high speeds", IEEE Transaction on Power Electronics, ISSN 0885-8993, P. 1635, Nov 2004. [9] Stefan Baldursson, "BLDC motor modelling and control- a MATLAB / SIMULINK implementation", Master Thesis in Electrical Power Engineering, Chalmers University of Technology, May 2005, Gothenburg, Sweden.