Modeling and Simulation of a Controller of Brushless DC Motor for Electric Vehicle Application

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Abstract-Automotive industries are targeting sustainable transportation in future. Hence electric and hybrid vehicles are going to be popular due to their energy saving, sustainability and zero emission. People pay more attention to less polluting vehicles with the development of environmental protection awareness. Electric motor plays significant role in electric vehicle. AC motor, DC motor and reluctance motor are mostly used in Electric Vehicle. Brushless DC Motor has more demand in automotive application because of high power density, low maintenance cost and high efficiency. In this paper, A Controller of Brushless DC Motor for EV developed by using MATLAB/Simulink. Simulation results obtained from developed model are discussed which gives correct performance of model with various loading conditions.

Keyword-*Brushless DC Motor (BLDC); Proportional Integral Controller (PIC); Electric Vehicle (EV)*

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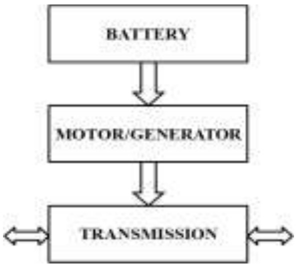
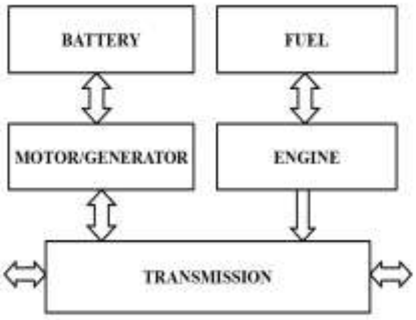
I. INTRODUCTION

Electric vehicle is more advantageous over internal combustion engine automobiles, including a significant reduction of air pollution, reduced gas emissions, and reducing energy dependence on diminishing oil reserves. Electricity stored in the battery will be used by EV to drive the motor, and the power can be rejuvenated with electricity generation using renewable energy. The most suitable motor for electric vehicle among various electric motors is BLDC motor, because this motor has high reliability, high power density, high efficiency, low cost, lower weight and low maintenance requirements [01].



(a) Electric Vehicle



(b) Hybrid Vehicle

Fig. 1. Block diagram of electric vehicle and hybrid vehicle structure

BLDC motor is normally powered by conventional three phase inverter which is controlled by the rotor position information obtained from Hall sensors or simply from hall position sensors [02-04]. In three phase windings use one Hall Sensor for each winding to provide three overlapping signals giving a 60° wide position range. A high or low signal will produce for indicating North or South Pole whenever the magnetic poles pass near the sensors. The controller has low cost and desirable stability. It can better perceive energy regenerative braking on an electric vehicle [05].

A separate motor mounted inside tire for each wheel for in-wheel technology instead of one central drive train propelling two or all wheels in conventional electric vehicles. It increases controllability of vehicle and decreases excess weight [06].

BLDC has more complex control algorithm compare to other motor types due to electronic commutation. Therefore accurate model of motor is required for complete and precise control scheme of BLDC. For the design of BLDC motor it is necessary to have motor model which gives precise value of torque must be related to current and back-EMF [07]. In this paper, model of 3 phase, 4 poles and trapezoidal back-EMF type of BLDC motor for application of transportation industries is modeled and simulated in MATLAB /Simulink. It is assumed that the developed design of BLDC motor drive and controller much suitable for automotive industry applications.

II. OVERALL SYSTEM MODEL

Trapezoidal and sinusoidal are two types of Brushless DC Motor with respect to back-EMF signals. According to sensors mounted for detecting rotor position there are also two types of BLDC motor [03]. For adjustment of PWM sequence of 3-phase Bridge inverter sensor signals are used. Speed independent position function techniques, flux linkage-based, back-EMF sensing, freewheeling diode conduction and back EMF integration are used in sensorless control for electronic commutation [08]. In designed model, Hall Effect signals are produced according to rotor position for commutation purpose. As voltage source a three-phase inverter made up of IGBTs is used. The model can be applicable for different control techniques. In loop control algorithm to control speed Proportional Integral (PI) controller is used. BLDC motor drive schematic system is shown in Fig. 2.

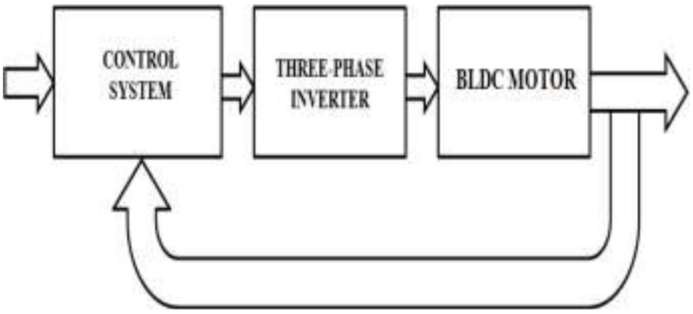


Fig. 2. System of BLDC motor drive

Simulation model consists of three parts such as Control system, Three-phase Inverter, BLDC motor as shown in Fig.2. Simulation of each part is done separately and combined in overall system simulation model.

III.BLDC MOTOR MODEL

In this paper a 3 phase, 4 poles trapezoidal back-EMF type BLDC motor is modeled. Mutual inductance between rotor and stator has trapezoidal shape referred as trapezoidal back-emf [09]. Therefore, instead of d-q axis, abc phase variable model is more applicable. Overall model is made with simplification of equations with following assumptions:

- Saturation of magnetic circuit is neglected.
- Semiconductor switches are ideal
- Mutual inductance, self inductance and resistance of stator for all phases are equal and constant
- Eddy current and hysteresis losses are eliminated.

The mechanical and electrical mathematical equations of BLDC motor are:

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

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

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

$$\begin{cases} E_a = K_e w_m F(\theta_e) \\ E_b = K_e w_m F\left(\theta_e - \frac{2\pi}{3}\right) \\ E_c = K_e w_m F\left(\theta_e + \frac{2\pi}{3}\right) \end{cases} \tag{4}$$

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

$$T_e = T_a + T_b + T_c \tag{6}$$

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

$$\theta_e = \frac{P}{2}\theta_m \tag{8}$$

$$w_m = \frac{d\theta_m}{dt} \tag{9}$$

Where

V_a, V_b, V_c Phase voltage for a, b, c applied from inverter to BLDC

i_a, i_b, i_c Phase current for phase a, b, c

R: Resistance of each phase of BLDC

L: Inductance of each phase of BLDC

M: Mutual inductance

T_a, T_b, T_c Electric torque produced by Phase a, b, c

E_a, E_b, E_c Phase Back – EMF

T_e : Electric torque produced by BLDC

K_e : Back – EMF constant

K_t : Torque constant

θ_m : Mechanical angle of Rotor

θ_e : Electrical angle of Rotor

w_m : Angular speed of Rotor

$F(\theta_e)$: Back – EMF Reference as function of Rotor position

β : Damping ratio

J : Inertia

State space form of equations (1), (2), (3) and (7) can be derived as:

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

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

Where,

$$i_a + i_b + i_c = 0$$

Neglecting mutual inductance after modifying equations (10) and (11),

We get,

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

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

For BLDC motor state space model can be written as:

$$\begin{bmatrix} i_a' \\ i_b' \\ w_m' \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 & 0 \\ 0 & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{\beta}{J} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ w_m \end{bmatrix} + \begin{bmatrix} \frac{2}{3L} & \frac{1}{3L} & 0 \\ -\frac{1}{3L} & \frac{1}{3L} & 0 \\ 0 & 0 & \frac{1}{J} \end{bmatrix} \begin{bmatrix} V_{ab} - E_{ab} \\ V_{bc} - E_{bc} \\ T_e - T_l \end{bmatrix} \qquad (14)$$

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

Model will get more complex after implementation of final state space equations (14) and (15). Even though neutral point of motor is not attainable but practically it is possible to approximate it with zero crossing point of back-EMF. State space to Laplace transform and vice versa can also be written for zero initial condition systems. Hence final state space equation is divided into two separate and easy mechanical as well as electrical Laplace equations applied by phase to neutral voltages with the help of this BLDC model will become more simple and convenient for implementation of various control techniques. According to electrical rotation of rotor in each phase separately ideal reference back-EMF signal of motor is also produced and applied as negative feedback to phase voltage.

Table I shows Hall Effect signal values for phase a, b and c according to electrical degree of rotor. Hall Effect signals of motor are produced according to electrical degrees [15].

TABLE I. HALL EFFECT SIGNALS

Hall Effect Signals			**Back Emf of Phase**		
ha	***hb***	***hc***	***emf_a***	***emf_b***	***emf_c***
0	0	0	0	0	0
0	0	1	0	-1	1
0	1	0	-1	1	0
0	1	1	-1	0	1
1	0	0	1	0	-1
1	0	1	1	-1	0
1	1	0	0	1	-1
1	1	1	0	0	0

TABLE II. SWITCHING OF IGBT

Back Emf of Phase			**Switches(IGBT)**					
emf_a	***emf_b***	***emf_c***	***Q1***	***Q2***	***Q3***	***Q4***	***Q5***	***Q6***
0	0	0	0	0	0	0	0	0
0	-1	+1	0	0	0	1	1	0
-1	+1	0	0	1	1	0	0	0
-1	0	+1	0	1	0	0	1	0
+1	0	-1	1	0	0	0	0	1
+1	-1	0	1	0	0	1	0	0
0	+1	-1	0	0	1	0	0	1
0	0	0	0	0	0	0	0	0

Overall model of motor is designed with the implementation of 3-phase full bridge inverter and Proportional Integral speed regulator.

IV. SIMULATION RESULTS

Simulation results of Brushless DC motor under various loading conditions are shown:

(I)No-load condition, (II) For 15Nm load

As shown in Fig. (3) during no-load condition current is 0.16 Amp for phase A and Fig. (4) Shows trapezoidal back-emf is 236 produced in phase A of motor. Fig.(5) show Speed also it can be said dynamic response of BLDC is 3219 rpm is high due to its permanent magnet rotor or low inertia. 0.59 Nm is pulsating torque of BLDC motor shown in Fig. (6). Hall Effect signals and Switching of IGBTs for all three phases are given according to Table I and Table II respectively. A specification of BLDC motor to investigate performance of developed model is shown in Table III.

TABLE III. BLDC MOTOR SPECIFICATION

Description	Value	Unit
Voltage	220	Volt AC
Phase Resistance(Rs)	2.8750	Ω
Phase Inductance(Ls)	8.5	m-H
Inertia(J)	1.25e-3	Kg-m²
Damping ratio(B)	1e-3	N-s/m
Poles	4	-

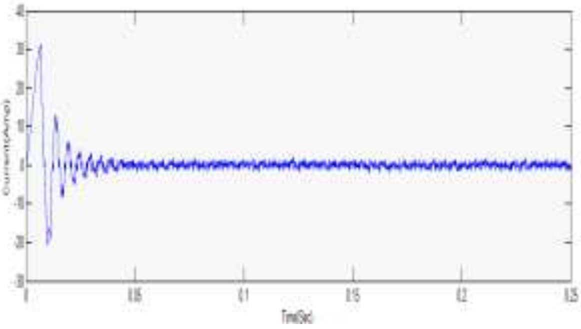


Fig. 3. No load condition current characteristics

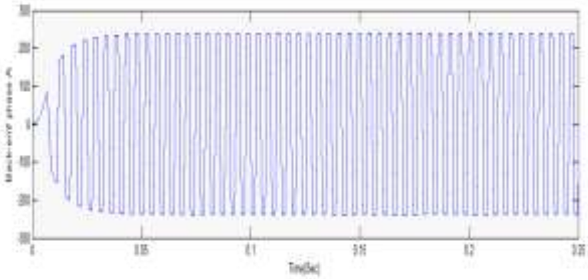


Fig. 4. No load condition Back-emf of Phase A

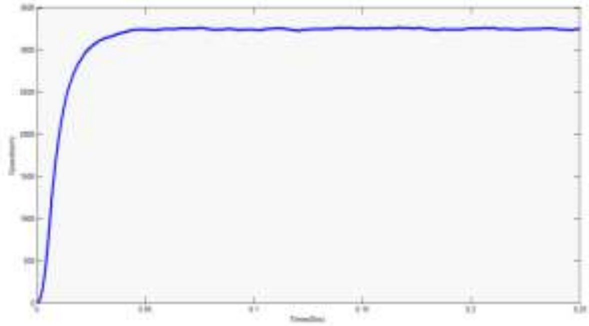


Fig. 5. No load condition speed characteristics

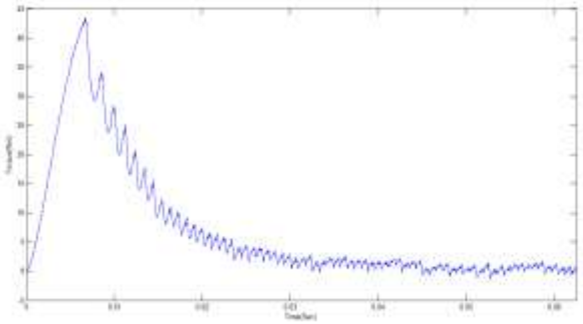


Fig. 6. No load condition torque characteristics

Model has been simulated under 15 Nm load torque condition gives Speed characteristic for BLDC is shown in Fig.(9) that is 2252 rpm. It is observed that under load condition time required by speed to reach its final value is increased. Fig. (7) Shows current characteristics of motor for phase-A during load condition. Maximum value of current is 30 amps for phase-A.

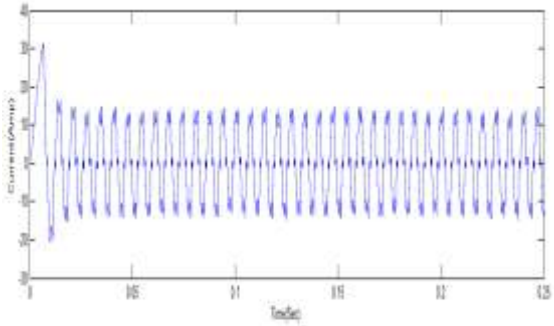


Fig. 7. Current characteristics under load of 15Nm

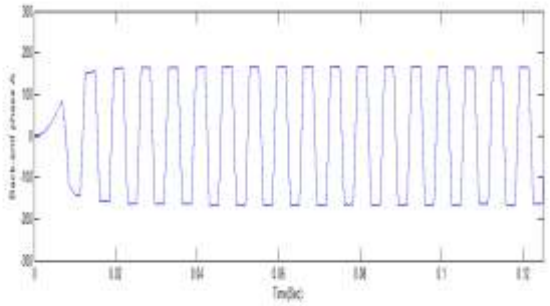


Fig. 8. Back-emf of phase A under load torque of 15Nm

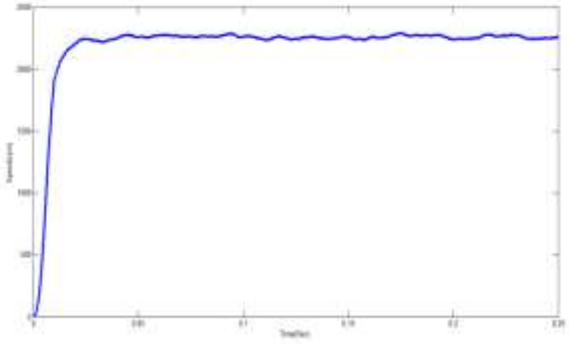


Fig. 9. Speed characteristics under load torque of 15Nm

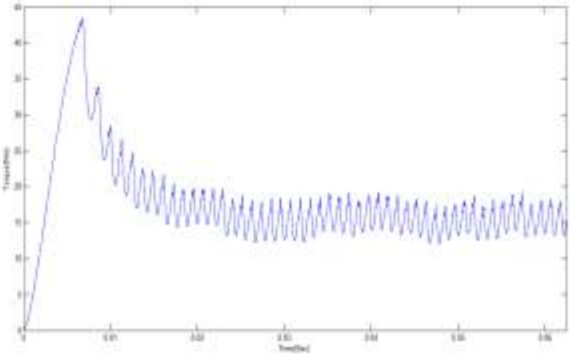


Fig. 10. Torque characteristics under load torque of 15Nm

V. CONCLUSION

In future, sustainable transportation is a need due to green house gases emission and reduces energy consumption all over the world. Electrical and Hybrid vehicles are the good solution for solving global warming issues. In automotive industry to increase controllability of a vehicle, efficiency and safety has been always one of the most important challenges. This paper shows that BLDC motor is a good choice for automotive industries due to higher power density, higher efficiency and higher speed range. In this paper, BLDC motor model with trapezoidal back-EMF is presented. The proposed model of BLDC motor is simulated in MATLAB / Simulink software. Results obtained under no load and during load condition are showing proper performance of model. Simplicity and output characteristics of model make it effectively useful for the design of BLDC motor drives for various applications with different control algorithms.

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