

Modeling of BLDC Motor with Ideal Back-EMF for Automotive Applications

A. Tashakori, *Member IAENG*, M. Ektesabi, *Member IAENG* and N. Hosseinzadeh

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 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 have been demanding as 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. 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.

Index terms — 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 is shown in Fig. 1 [1].

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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.

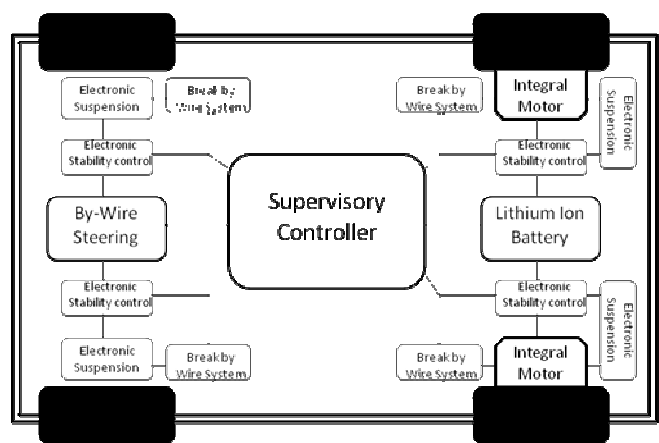


Fig. 1 Two wheel drive train system of a commercial IFECV

It is supposed that the advanced presented model makes design of BLDC motor drive and controller much easier in automotive industry applications.

II. 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 paper; therefore proportional plus integral (PI) controller is used in loop control algorithm to control speed. Schematic system of BLDC motor drive is shown in Fig. 2.

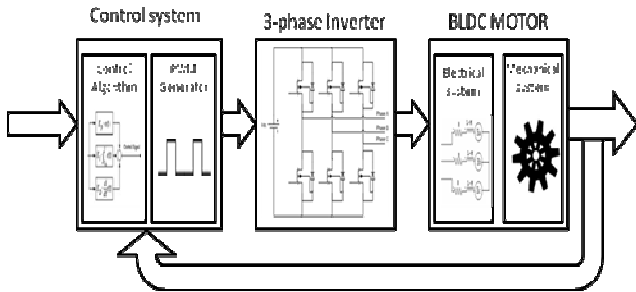


Fig. 2 Schematic system of BLDC motor drive

As shown in Fig. 2 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.

III. 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 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.

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 k= a, b, c

V_k : k_{th} Phase voltage applied from inverter to BLDC

i_k : k_{th} Phase current

R : Resistance of each phase of BLDC

L : Inductance of each phase of BLDC

M : Mutual inductance

E_k : k_{th} Phase back - EMF

T_k : Electric torque produced by k_{th} phase

T_e : Electric torque produced 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

$F(\theta_e)$: 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.

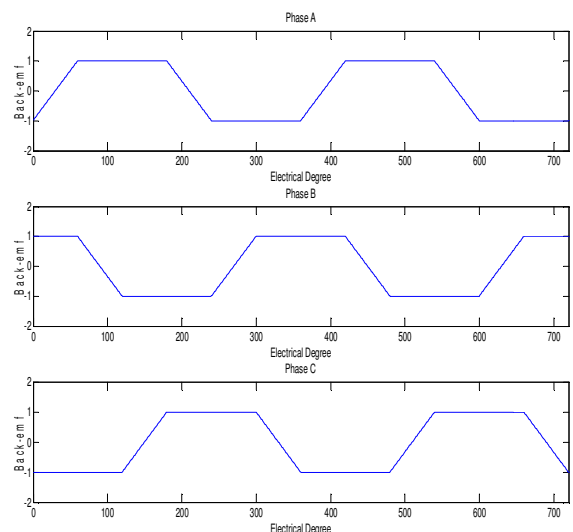


Fig. 3 Ideal back-EMF reference waveforms of all three phases

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,

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

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

Then state space model of BLDC motor is:

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

$$\begin{bmatrix} \dot{i}_a \\ \dot{i}_b \\ \dot{i}_c \\ \dot{\omega}_m \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -1 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ \omega_m \end{bmatrix} \quad (15)$$

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. 4.

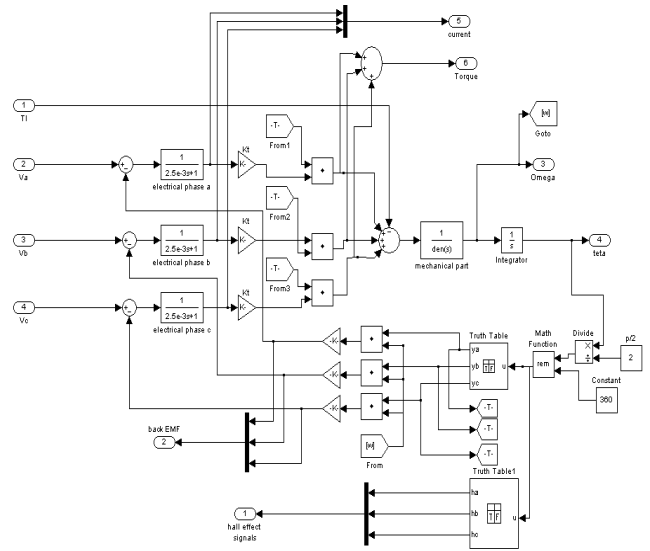


Fig. 4 BLDC motor model

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 SIGNALS

ELECTRICAL DEGREE	HALL 1	HALL 2	HALL 3
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. 5.

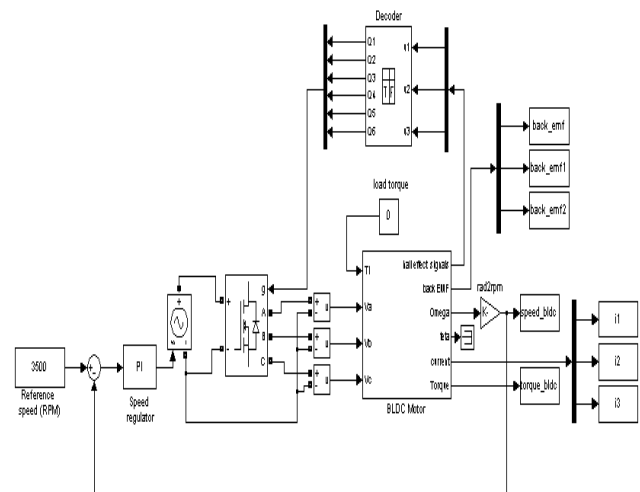


Fig. 5 Overall model of BLDC motor drive

IV. SIMULATION RESULTS

Simulation results of BLDC motor under no load and load conditions are shown. As it can be seen in Fig. 6, dynamic response of BLDC due to its permanent magnet (low inertia) rotor is high. Pulsating torque of BLDC is shown in Fig. 7. Figure 8 shows back-EMF produced in phase A of motor. Hall Effect signals of all three phase are shown in Fig. 9 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	240	v
PAHSE RESISTANCE (R)	1	Ω
PHASE INDUCTANCE (L)	0.25	m-H
INERTIA (J)	15.17e-6	Kg-m ²
DAMPING RATIO (β)	0.001	N-s/m
POLES	4	-

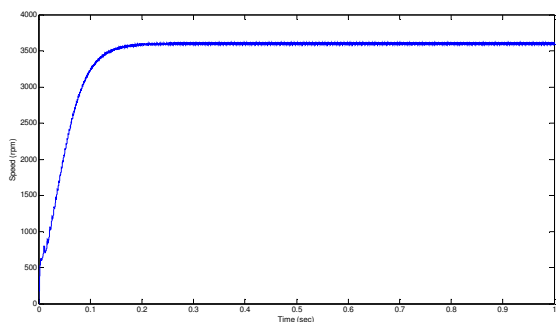


Fig. 6 Speed characteristics under no load condition

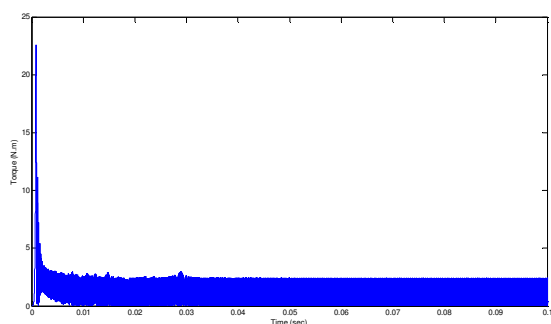


Fig. 7 Torque characteristics under no load condition

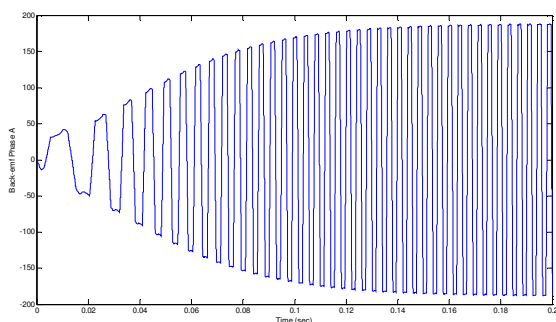


Fig. 8 Back-EMF of phase A

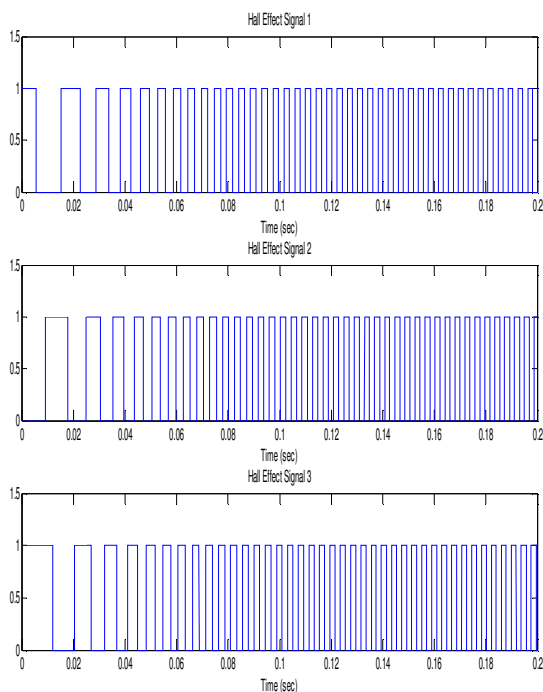


Fig. 9 Hall Effect signals

Output and Input power characteristics of motor under no load condition is shown in Fig. 10 and Fig. 11. With respect to steady state values of power, efficiency of system is 94.6%. System shows high efficiency operation of BLDC.

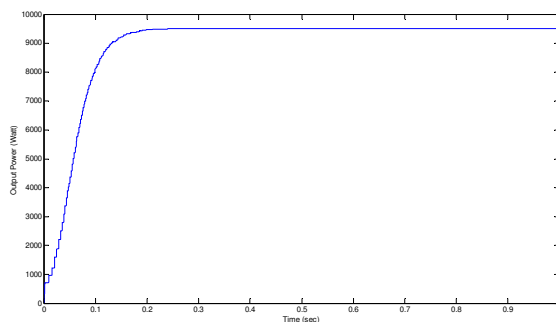


Fig. 10 Output power characteristics under no load condition

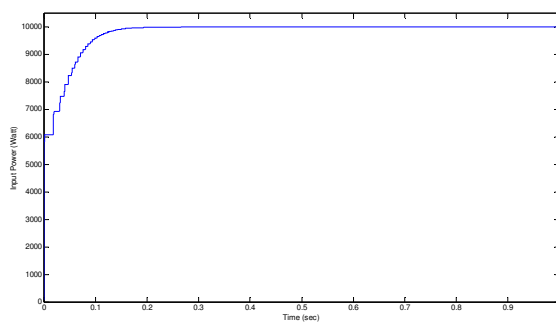


Fig. 11 Input power characteristics under no load condition

Simulation also has been done under 10 N.m load torque. BLDC speed characteristic is shown in Fig. 12 under load

condition. It can be seen that under load condition time for speed to reach its final value is increased. Current characteristics of phase A of motor under load condition is shown in Fig. 13. Maximum value of current is 40 amps.

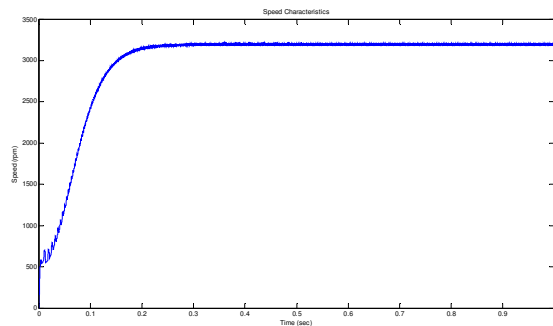


Fig. 12 Speed characteristics under load condition

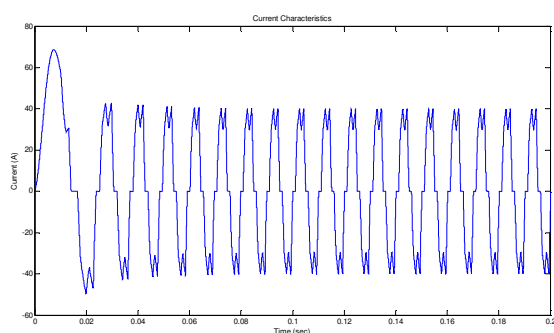


Fig. 13 Current characteristics under load condition

V. CONCLUSION

Sustainable transportation is a need in near future due to reduce energy consumption and greenhouse gases emission in the world for solving global warming issue. Hybrid and electrical vehicles are the good solution in this case. Increase of safety, efficiency and controllability of a vehicle has been always one of the most important challenges in automotive industry. Design of intelligent fully electronically controlled vehicle (IFCEV) can be the solution for many of challenges in this field.

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.

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