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BACK EMF DETECTION METHODS FOR SENSORLESS BRUSHLESS DC MOTOR DRIVES USING MATLAB/SIMULINK

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Abstract

Brushless dc (BLDC) motors and their drives are penetrating the market of home appliances, HVAC industry, and automotive applications in recent years because of their high efficiency, silent operation, compact form, reliability, and low maintenance. Traditionally, BLDC motors are commutated in six-step pattern with commutation controlled by position sensors. To reduce cost and complexity of the drive system, sensor less drive is preferred. The existing sensor less control scheme with the conventional back EMF sensing based on motor neutral voltage for BLDC has certain drawbacks, which limit its applications. To overcome these drawbacks this paper presents a state space modelling, simulation and control of permanent magnet brushless DC motor. By reading the instantaneous position of the rotor as an output, different variables of the motor can be controlled without the need of any external sensors or position detection techniques. In this paper BLDC motor with ideal back-EMF is modelled 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.

1. INTRODUCTION

Brushless dc (BLDC) motors have been desired for small horsepower control motors due to their high efficiency, silent operation, compact form, reliability, and low maintenance. However, the control complexity for variable speed control and the high cost of the electric drive hold back the widespread use of brushless dc motor. Over the last decade, continuing technology development in power semiconductors, microprocessors/logic ICs, adjustable speed drivers (ASDs) control schemes and permanent-magnet brushless electric motor production have combined to enable reliable, cost-effective solution for a broad range of adjustable speed applications. Household appliances include clothes washers, room air conditioners, refrigerators, vacuum cleaners, freezers, etc. Water heaters, hot-water radiator pumps, power tools, garage door openers etc.Brushless DC (BLDC) motor simulation can be simply implemented with the required control scheme using specialized simulink built-in tools and block sets such as simpower systems toolbox. But it requires powerful processor requirements, large random access memory and long simulation time. To overcome these drawbacks this paper presents a state space modelling, simulation and control of permanent magnet brushless DC motor. By reading the instantaneous position of the rotor as an output, different variables of the motor can be controlled without the need of any external sensors or position detection techniques.

In this paper, the motor is designed based on state space model to get information about the state of the system variables at some predetermined points along the flow of signals. By adopting this model, powerful processor requirement, large random access memory can be avoided with more design flexibility and faster results can be obtained.

2. MODELING THE BRUSHLESS DC MOTOR

The modeling of brushless dc motor involves solving many simultaneous differential equations, each depending upon the inputs to the motor and the simulation constants. Simulation constants are values like the phase inductance that do not change during simulation. Therefore these parameters can be treated as constants during a simulation. However, the model provides for dialogue boxes that can be used to vary the values of these constants. The equations for the brushless dc motor are listed as under. Star wound rotor is assumed. The core block for the brushless dc motor has been written as a state space model. During the course of the project, many approaches were tried and it was realized that state space modelling enabled accurate and easy description of the brushless dc motor.

2.1 STATE SPACE MODELING

The coupled circuit equations of the stator windings in terms of motor electrical constants are

$$\begin{bmatrix} V_{as} - v_n \\ V_{bs} - v_n \\ V_{cs} \quad v_n \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \mathbf{p} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix}$$

Where:

R_S: Stator resistance per phase

I_a,I_b, I_c: Stator phase currents

$p = \frac{d}{dt}$is the time derivative operator

E_a, E_b, E_c represent the back emfs in the respective phases in (1)

Vn: is the neutral point node voltage given by

$$V_n = \frac{1}{3}[V_{as} + V_{bs} + V_{cs}] - \sum \text{BEMFs}$$

Based on equation (1), the equivalent circuit of motors can be obtained as shown in Fig. 1.

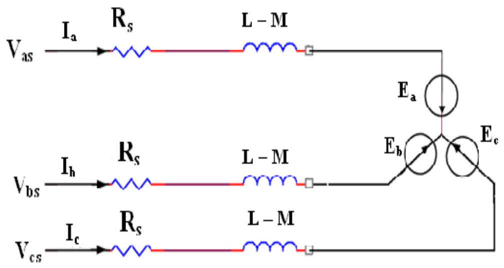

Fig. 1. Equivalent circuit for stator windings

The induced emfs are all assumed to be trapezoidal, whose peak value is given by

Ep = (BLv)N = N(Blrω) = NΦω = λω

where B is the flux density of the field in webers, L is the rotor length, N is the number of turns per phase, ω is the electrical angular speed in rad/sec, Φ represents flux linkage = BLr, λ represents the total flux linkage given as the product number of conductors and flux linkage/conductor. If there is no change in rotor reluctance with angle because of non-salient rotor and assuming three symmetric phases, inductances and mutual inductances are assumed to be symmetric for all phases as in [5]. Hence (1) becomes

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R_s{}^{*} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + P \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad (1)$$

Simplifying (4) further we get the following

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R_s{}^{*} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + P \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad (2)$$

And torque generated is given by:

$$T_e = \frac{[E_a I_a + E_b I_b + E_c I_c]}{\omega} \qquad \text{(in Nm)} \qquad (3)$$

The induced emfs can be written as

$$E_a = f_a(\theta)\lambda\omega$$

$$E_b = f_b(\theta)\lambda\omega$$

$$E_c = f_c(\theta)\lambda\omega \quad \text{......................}(4)$$

wherefa(θ), fb(θ), fc(θ) are functions having same shapes as back emfs. The values from (6) can be substituted in (5)

to obtain the value of torque. Also,

$$J\frac{d\omega}{dt} + B\omega = T_e - T_l \quad \text{......................}(5)$$

whereTl is the load torque, J is the moment of inertia, B is the friction coefficient. Electrical rotor speed and position are related by

$$\frac{d\theta}{dt} = \left(\frac{P}{2}\right) * \omega \quad \text{..}(6)$$

where P is the number of poles in the motor. From the above equations, the system state equations are written in the following

$$\dot{x}(t) = Ax(t) + Bu(t)$$

where the states are chosen as x(t) = [IaIbIc ω θ]T

Thus the system matrices as given below,

$$A = \begin{bmatrix} -R_s/L_1 & 0 & 0 & \left(\lambda_p * f_a(\theta)\right)/J & 0 \\ 0 & -R_s/L_1 & 0 & \left(\lambda_p * f_b(\theta)\right)/J & 0 \\ 0 & 0 & -R_s/L_1 & \left(\lambda_p * f_c(\theta)\right)/J & 0 \\ \left(\lambda_p * f_a(\theta)\right)/J & \left(\lambda_p * f_b(\theta)\right)/J & \left(\lambda_p * f_c(\theta)\right)/J & -B/J & 0 \\ 0 & 0 & 0 & P/2 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 1/L_1 & 0 & 0 & 0 \\ 0 & 1/L_1 & 0 & 0 \\ 0 & 0 & 1/L_1 & 0 \\ 0 & 0 & 0 & -1/J \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

............................(7)

The input vector is defined as u(t) = [VaVbVcTl]T

whereLl = L – M, L is the self inductance of the winding per phase, M is the mutual inductance per phase and Va,Vb, Vc are the per phase impressed voltage on the motor windings.

3. IDEAL BACK EMF MODEL OF BLDC MOTOR:

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. 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. 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.

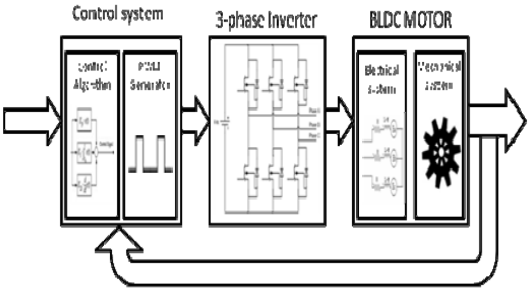

Fig. 2 Schematic system of BLDC motor drive

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. 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.

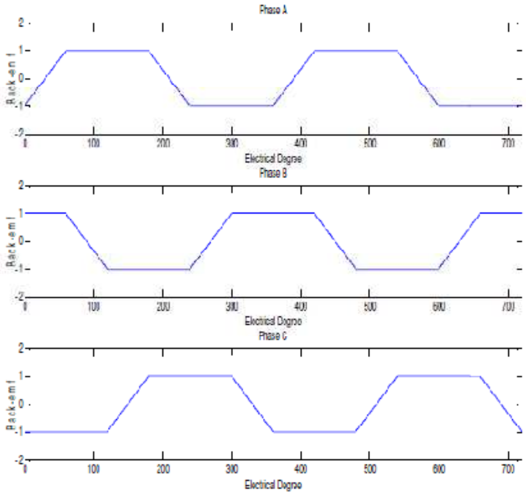

Fig. 3. Ideal Back-EMF waveforms

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 are used state space equations. 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.

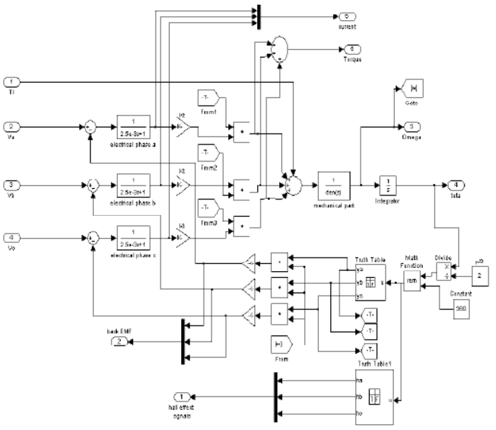

Fig. 4 BLDC motor model

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 modelled.

Overall model of BLDC motor drive is shown in Fig. 5.

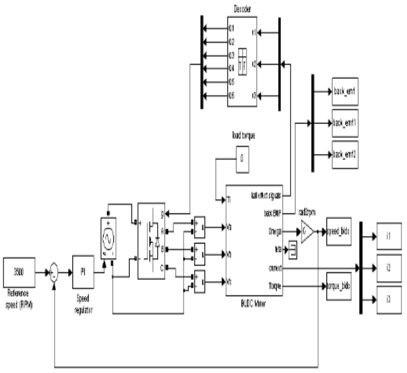

Fig. 5 Overall model of BLDC motor drive

4. SENSORLESS CONTROL OF BLDC MOTOR USING BACK EMF TECHNIQUE:

The simulation has five main blocks. They are BLDC motor, controller block, inverter block, estimate block and changer block shown in Fig. 6. Each main block has several sub-blocks. Some blocks are logical and some are made using S-Function. The BLDC motor block contains state space sub-block where matrices A, B, C, D are located with the provision that the initial condition can be varied. In the S-Function, coding file is linked and is shown in Fig. 7 The simulation starts with a starter block that generates 3Φ input voltage to the system's core block for one cycle. A changer block is used to close the control loop after the random ramping of the motor. Once the loop is closed, the starter block will be disconnected from the system and the motor will start receiving the phase voltages from the connected controller through inverter.

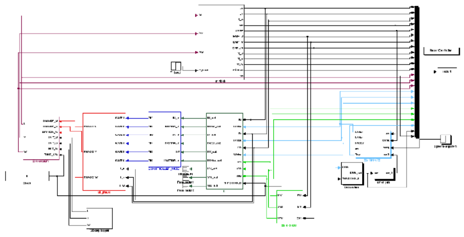

Fig. 6. Simulink model of BLDC motor

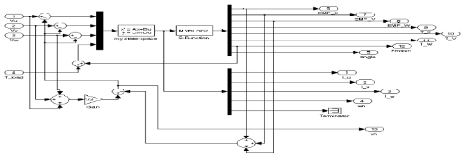

Fig. 7. Inside the core block in BLDC motor block

The PID controller is tuned by Ziegler Nichols method. By this method, the values of Kp=16.61, Ki=0.0134 and Kd=0 are chosen. An S-Function block is connected to the state space block to choose the motor specifications such as, the number of conductor turns per phase, resistance per phase, rotor dimensions etc as defined by the user. The S-Function will read the instantaneous position among twelve positions which are separated by 30º. Depending on the position, the back e.m.f and torque in each phase will be defined. The estimate block contains the PID controller. The block again is an M-file S-Function. This block calculates the reference phase current from the speed and required torque. Required torque is calculated by actual speed and the speed error value. The above value will be read and used in a PID controller. The required torque is calculated as follows,

$$T_{req} = \left[E \times \left(K_p + (K_i \times 0.5 \times t_s) + \frac{K_d}{t_s}\right)\right] + \left[E_{-1} \times \left(0.5 \times t_s \times K_i - \frac{K_d}{t_s}\right)\right]$$

where E is the angular speed error, E-1 is the previous time step error in angular speed, ts is the sampling time, Kp, Ki, Kd are proportional, integral and derivative constants.

The required current is calculated from the instantaneous required torque. Then it is converted by means of an approximated Park's Transformation to three phase currents. The approximated park's transformation gives thecorresponding phase current to every stator phase according to the rotor's position. A hold block is used to hold on both the required and instantaneous current values in the open loop. Once the changer block closes the control loop, the hold block will give an access to the current values to pass to the present controller scheme. In this simulation, hysteresis controller function is chosen. Usually, the controller is used to fire the gates of six step inverter switches, as in.

5. Simulation Results And Discussion

5.1 IDEAL BACK EMF METHOD:

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 rotor is high. Pulsating torque of BLDC is shown in Fig. 7. Figure 8 shows back-EMF produced in phase A of motor. Table II shows BLDC motor specification to investigate performance of advanced model. 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.

TABLE II: BLDC MOTOR SPECIFICATION

DESCRIPTION	VALUE	UNIT
POWER	10	KW
DC VOLTAGE	240	V
PHASE 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	--

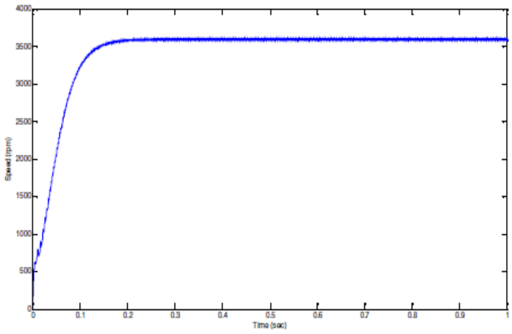

Fig. 8 Speed characteristics under no load condition

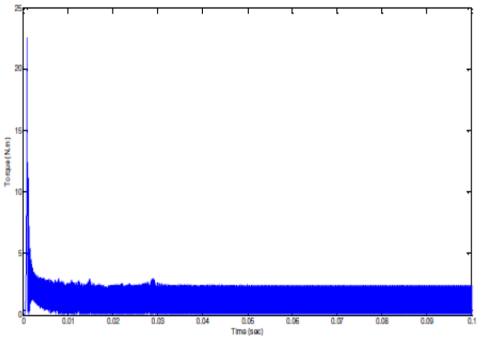

Fig. 9 Torque characteristics under no load condition

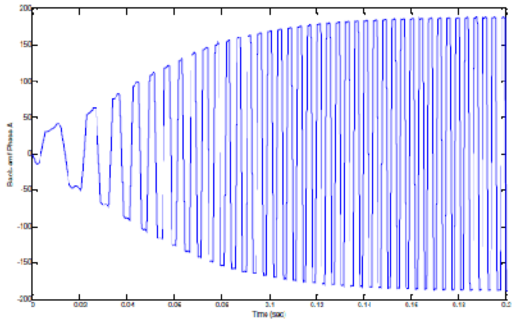

Fig.10 Back-EMF of phase A

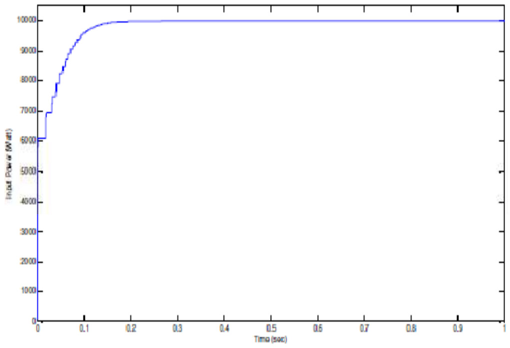

Fig11 Output power characteristics under no load condition

Fig.12 input power characteristics under no load condition

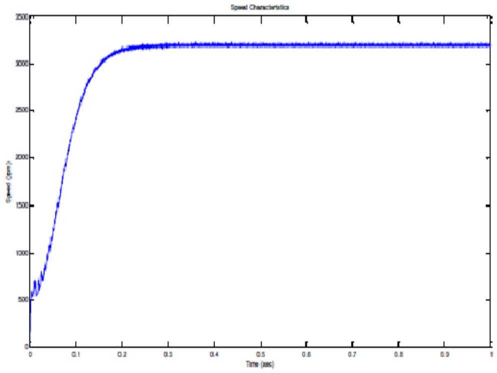

Fig. 13 Speed characteristics under load condition

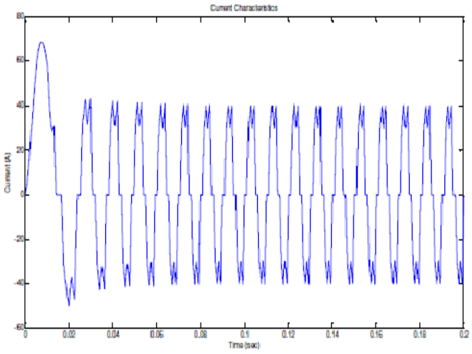

Fig. 14 Current characteristics under load condition

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.

5.2 SIMULATION RESULTS OF SENSORLESS CONTROL OF BLDC MOTOR USING BACK EMF TECHNIQUE

The motor specifications used in this simulation are shown in Table. III. The simulation was run for 0.13seconds (simulation time). When the reference speed equals 4000 rpm, the simulation curves of 3Φ back emfs, 3Φ currents,3Φ torques and rotor position are shown in Fig. 5, 6, 7, 8, and Fig. 9. Load torque is applied at 0.01 seconds. The motor speed stabilizes in 0.058 seconds with 0% overshoot. From Fig. 5 and Fig. 6, the back emf is almost trapezoidal with 120º phase difference. Since the three phase torques are calculated from 3Φ currents, it gives 120ºphase difference between each phases as shown in Fig. 7. From Fig. 8, the rotor position can be analyzed under various aligned and unaligned conditions.

TABLE III: Specifications of BLDC Motor Drive:

Current	34A	Rotor length	30cm
Torque	0.9 N-m	Rotor radius	20cm
Self inductance per winding	2.72mH	No of turns per phase	100
Mutual inductance between windings	-1.5mH	Flux density	0.8167wb
Motor inertia	0.0002	Coulomb friction	0.0178N
Rated speed	4500 RPM	Static friction	0.089N
Number of poles	4	Viscous friction	0.002N
Number of phases	3	Input dc voltage	160V
Winding resistance per phase	0.7Ω	No. of slots per pole per phase	100

RESULTS:

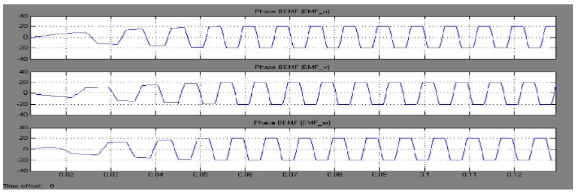

Fig15.: Three Phase Back EMF

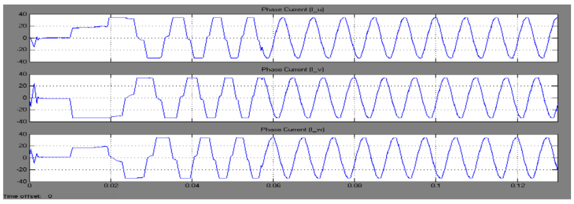

Fig16. Three Phase Currents

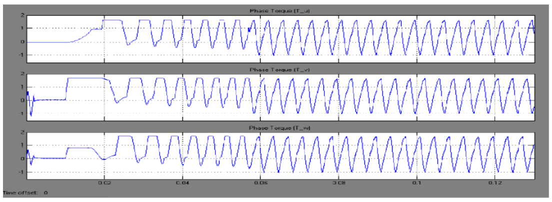

Fig17.three phase torque

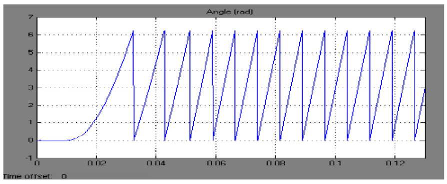

Fig18.Rotor Position

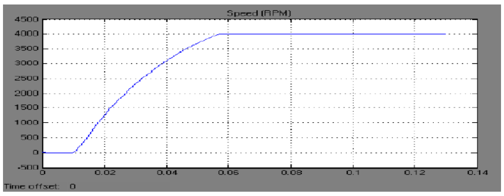

Fig19.speed

6. Conclusions:

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 method and sensorless control of BLDC motor using Back EMf Technique is presented in this paper. The proposed model is simulated in MATLAB / SIMULINK. Simulation results in first case 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. Second Method is implemented using State space Technique. BLDC motor analysis based on state space model can be easily carried out using MATLAB 7.3 version. This model has many advantages over transfer function model. The simulation study using state space model has been validated with the results obtained using transfer function model. Further using state space model, the performance characteristics of the BLDC motor can be evaluated for different machine parameters, which can be easily varied in the simulation study and useful information can be obtained.

The simulation results demonstrate that the simulated

Waveforms fit theoretical analysis well. However, the simulation involves solving many simultaneous differential

equations and the results obtained are highly dependent upon the choice of the system solver, where some solver gives highly accurate results, but need longer time to terminate. Through the modularization design, a lot of time spent on design can be saved and the design efficiency can be promoted rapidly. The second method proposed in this paper provides a novel and effective tool for analyzing and designing the control system of brushless DC motor.

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