SENSORLESS CONTROL OF PMBLDC MOTOR WITH ROTOR FLUX ESTIMATION

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ABSTRACT

A Flux linkage observer (FLO) based sensorless estimation method for permanent magnet motors based on the integration of back EMF, with a simple start-up method, is proposed here. The rotor position is extracted from the rotor flux information using atan2 function. The estimated rotor position is improved using a phase locked loop structure which also uses a PI controller for speed estimation. Since the initial rotor position is not known, a simple start up strategy is also introduced. Using a ramp speed reference, an initial rotor position is used for motor control during starting. As the machine picks up speed, control is transferred to flux observer. The control method is validated using simulation results done in MATLAB/Simulink on a 24V, 4000rpm PMBLDC motor.

KEYWORDS: *PMBLDC motor, Sensorless control, Flux estimator, PLL structure*

I. INTRODUCTION

The brushless DC PM motor is used in both consumer and industrial applications due to its compact size, controllability and high efficiency. BLDC motors are usually operated with one or more position sensors, since the excitation must be synchronous to the rotor position. For reasons of cost reduction, reliability and mechanical packaging it is desirable to run the motor without position sensors – the so called sensorless operation.

Several sensorless control schemes have been introduced for PMBLDC motors in the last few decades. Of these, the most popular one is the back emf based control method. In this scheme, the rotor position is sensed indirectly by examining the zero crossing detection of the terminal voltages of unenergised phase [1]. Another control method is using Extended Kalman Filter (EKF) which is based on least square variance method [2]. This method provides excellent speed response but requires heavy online matrix computing. An offline FEM assisted position and speed observer has also been studied in the literature, [3]. Zero crossing of line to line PM flux linkage is used for estimation of speed and position.

Flux Linkage Observer (FLO) based sensorless method is investigated in this paper. The only two inputs to the observer are the machine voltages and currents. Using system equations, the rotor flux linkages are estimated in the α-β reference frame. Using 'arctan' function, the instantaneous rotor position is estimated. Speed is calculated using a PLL structure. Since at low speeds flux cannot be determined a starting method must be adopted.

This paper is organised as follows: Introduction (Section I), Mathematical Model of BLDC motor (Section II), Sensorless BLDC motor drive (Section III), Simulation Results (Section IV) and Conclusions (Section V).

II. MATHEMATICAL MODEL OF BLDC MOTOR

Referring to Fig. 1, the voltage equations of a three phase BLDC motor are [4]

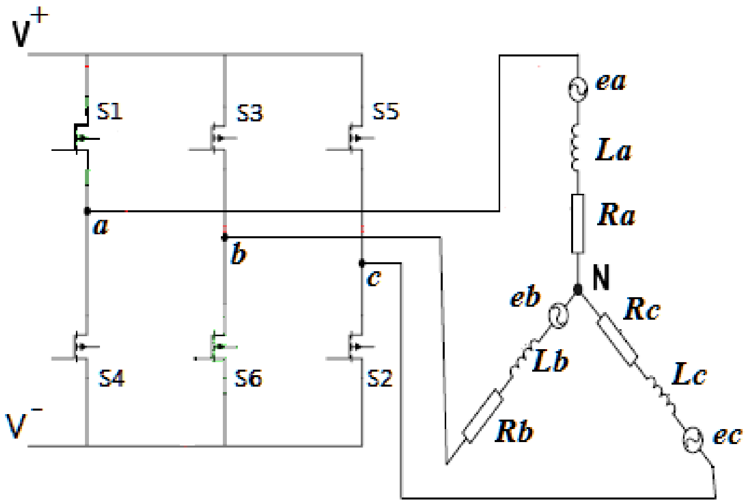

Figure 1. Circuit model of BLDC motor

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + e_a \tag{1}$$

$$v_b = R_b i_b + L_b \frac{di_b}{dt} + e_b \tag{2}$$

$$v_c = R_c i_c + L_c \frac{di_c}{dt} + e_c \tag{3}$$

Since the phase resistances are equal for a balanced system, $R_a=R_b=R_c=R$; and the self-inductances are independent of rotor position, $L_a=L_b=L_c=L$. The above equations are thus simplified as

$$v_a = Ri_a + L\frac{di_a}{dt} + e_a \tag{4}$$

$$v_b = Ri_b + L\frac{di_b}{dt} + e_b \tag{5}$$

$$v_c = Ri_c + L\frac{di_c}{dt} + e_c \tag{6}$$

When a PMBLDC motor rotates, a back emf is generated in each winding which is trapezoidal. For constant torque production, the three phase currents fed to the machine must be of quasi-square wave shape. The back emf generated is a function of rotor position, θ, with amplitude $E = K_e.\omega$ where ω is the rotor speed in mechanical rad/sec. The instantaneous back emf is thus given by the formula

$$e_a = f_a(\theta).E \tag{7}$$

$$e_b = f_b(\theta).E \tag{8}$$

$$e_c = f_c(\theta).E \tag{9}$$

The back emfs and phase currents for each phase, as a function of θ, are shown in Fig.2. The expression for $f(\theta)$ for each phase is obtained from the figure as

$$f_a(\theta)=\begin{cases}\left(6/\pi\right)\theta & \left(0\le\theta\le\pi/6\right)\\ 1 & \left(\pi/6\le\theta\le 5\pi/6\right)\\ -\left(6/\pi\right)\theta+6 & \left(5\pi/6\le\theta\le 7\pi/6\right)\\ -1 & \left(7\pi/6\le\theta\le 11\pi/6\right)\\ \left(6/\pi\right)\theta-12 & \left(11\pi/6\le\theta\le 2\pi\right)\end{cases} \qquad (10)$$

$$f_b(\theta)=\begin{cases}-1 & \left(0\le\theta\le\pi/2\right)\\ \left(6/\pi\right)\theta-4 & \left(\pi/2\le\theta\le 5\pi/6\right)\\ 1 & \left(5\pi/6\le\theta\le 9\pi/6\right)\\ -\left(6/\pi\right)\theta+10 & \left(9\pi/6\le\theta\le 11\pi/6\right)\\ 1 & \left(11\pi/6\le\theta\le 2\pi\right)\end{cases} \qquad (11)$$

$$f_c(\theta)=\begin{cases}1 & \left(0\le\theta\le\pi/6\right)\\ -\left(6/\pi\right)\theta+2 & \left(\pi/6\le\theta\le\pi/2\right)\\ -1 & \left(\pi/2\le\theta\le 7\pi/6\right)\\ \left(6/\pi\right)\theta-8 & \left(7\pi/6\le\theta\le 9\pi/6\right)\\ 1 & \left(9\pi/6\le\theta\le 2\pi\right)\end{cases} \qquad (12)$$

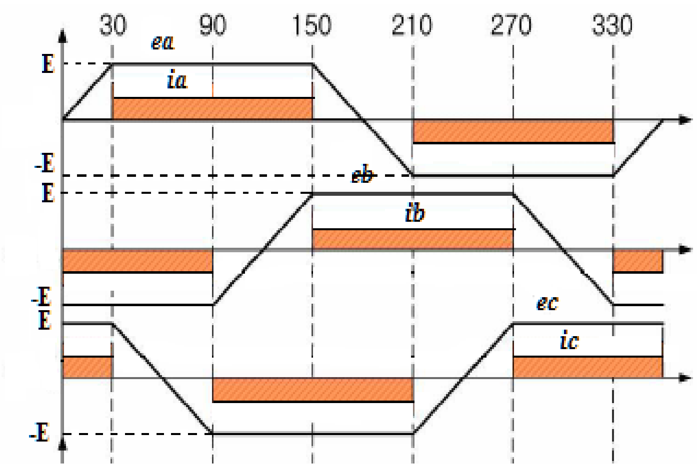

Figure.2 Back emf and phase currents of BLDC motor

The torque produced by each phase depends on rotor position and is proportional to the respective phase current. The total electromagnetic torque generated by the motor is given by the equation

$$T_e = K_t\{f_a(\theta)i_a + f_b(\theta)i_b + f_c(\theta)i_c\} \qquad (13)$$

The equation for motion for a simple system is given by

$$T_e - T_l = J\left(\frac{d\omega}{dt}\right) + B\omega \qquad (14)$$

III. SENSORLESS BLDC MOTOR DRIVE

The basic block diagram of flux observer based sensorless control of BLDC motor drive is shown in Figure 3. The main components are flux observer, speed controller and inverter fed BLDC motor. Each component will be explained in the following sections.

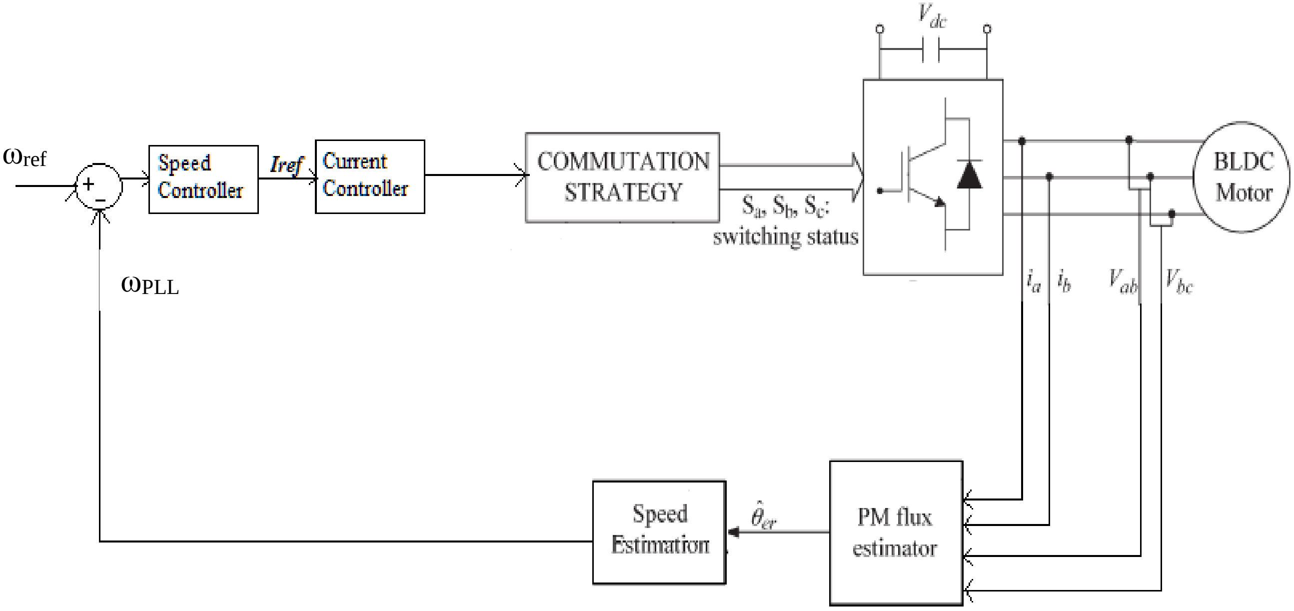

Figure 3. Sensorless BLDC Motor Drive using flux observer

3.1 PM Flux Estimator

The flux estimator is designed based on the phasor diagram shown in Figure 4, where V and I are the stator voltage and current vectors, ψ_s is the stator flux linkage and ψ_{PM} is the PM flux linkage along the *d*-axis. *V* and *I* are the applied voltage and current.

The instantaneous rotor position is the angle between d-axis and α-axis. It is estimated as follows. The stator flux linkage is given as[2]

$$\psi_s = \int \left(V - IR - V_{comp}\right) dt \qquad (15)$$

where $V_{comp} = (k_p + {k_i}/{s})\psi_s$

The estimation of motor flux using a pure integrator results in ramp drift and dc offset in the output. Hence a PI correction feedback (*Vcomp*) can be used along with the integrator. Now the PM flux linkage is calculated as

$$\psi_{PM} = \psi_s - LI \qquad (16)$$

Therefore, in the α-β coordinate, (16) can be used to calculate $\Psi_{PM\alpha}$ and $\Psi_{PM\beta}$ components of ψ_{PM}, as shown in Fig4.

In the conventional method, the rotor position θ can be computed by equation (17) as:

$$\theta_{a\tan} = \arctan\left(\frac{\psi_{PM\beta}}{\psi_{PM\alpha}}\right) \qquad (17)$$

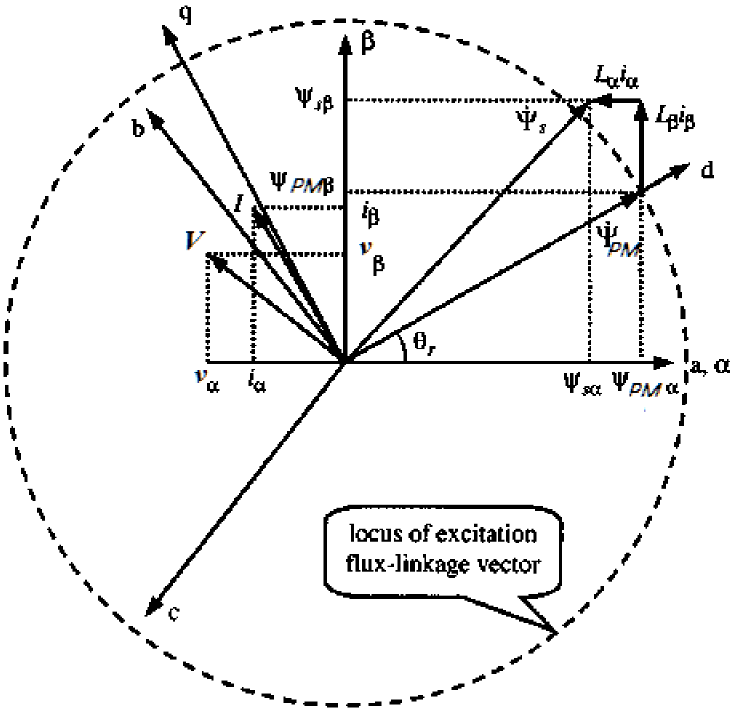

Figure 4 Phasor diagram of PM BLDC Motor

Speed can be calculated from the estimated rotor position by differentiation. But this will result in significant noise. Estimated position is improved using 4th order sinusoidal harmonic term in [5]. Here a PLL structure is used to improve position and motor speed as shown in Fig 5 [6],[7].

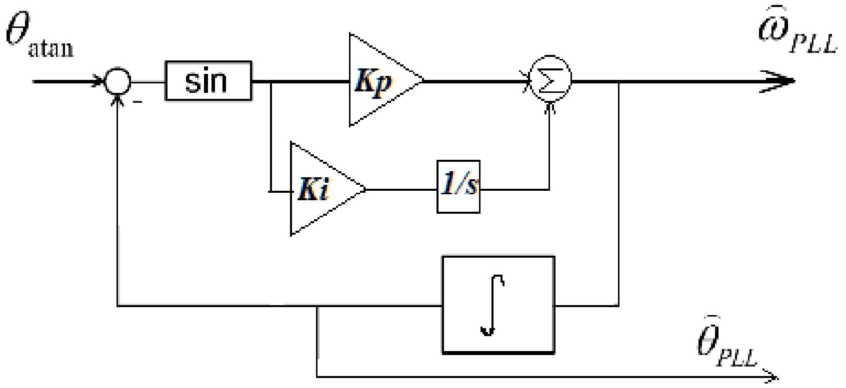

Figure 5..PLL based position and speed observer

The error between the estimated rotor position and its previous value is fed to the PLL. Since the error is very small, $(\theta_{atan} - \theta_{PLL}) \approx \sin(\theta_{atan} - \theta_{PLL}) = \varepsilon$. A PI controller is used to process this error and estimate the speed $\hat{\omega}_{PLL}$.

$$\hat{\omega}_{PLL} = (k_p + {k_i}/{s}).\varepsilon \qquad (18) \qquad\qquad \hat{\theta}_{PLL} = \frac{\hat{\omega}_{PLL}}{s} \qquad (19)$$

The speed and current controllers employed are conventional PI controllers with inner current control loop and outer speed control loop.

3.2 Starting Procedure

A simple starting method is employed here. Since initial rotor position is unknown, a ramp speed reference is used to estimate an initial value[8]. Using this assumed value of rotor position, a switching logic is generated so that the rotor rotates in the desired direction (here clockwise). When the machine picks up speed (around 500 rpm) the control is transferred to the flux observer.

IV. SIMULATION RESULTS

The BLDC motor was modelled using eqns. (4)-(14) in MATLAB/Simulink. The simulation block diagram is shown in Figure 6. The phase voltages *Van*, *Vbn* and *Vcn* are generated using an inverter. The switching functions for the inverter switches are generated based on rotor position theta. The motor parameters used for simulation is given in Table 1.

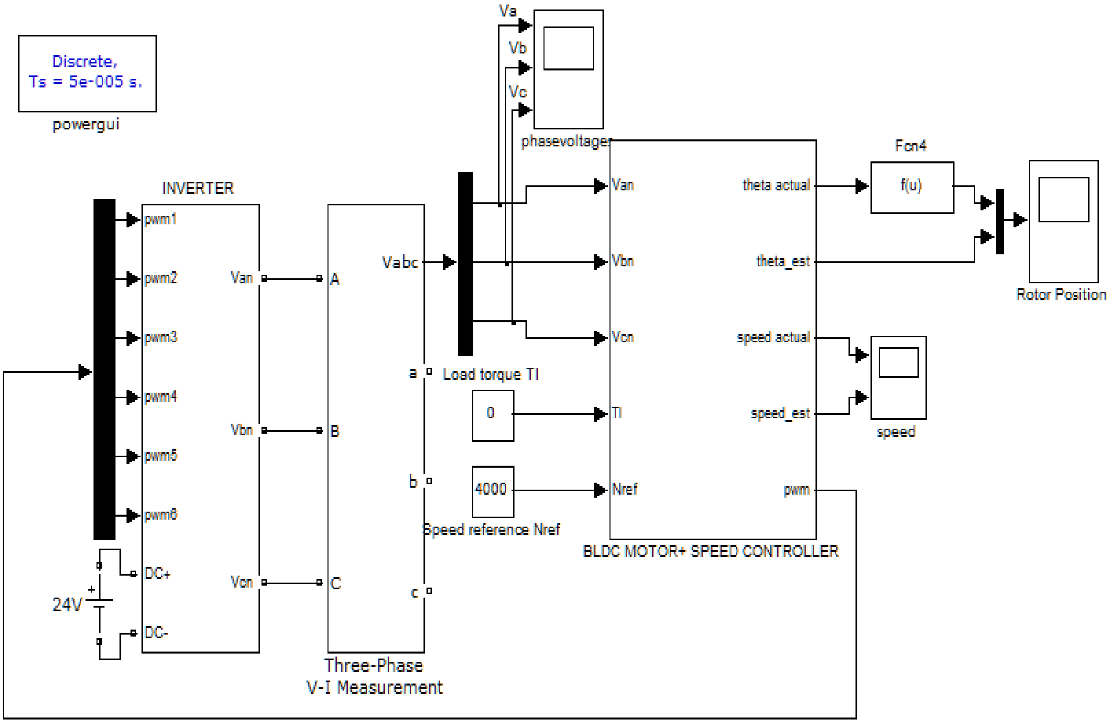

Figure 6. MATLAB Model of Sensorless BLDC motor drive using flux observer

Table 1 Motor Parameters

Rated voltage	24 V
No. Of poles	8
Stator resistance per phase	0.36 Ω
Stator inductance per phase	0.6 mH
Torque constant	0.036 Nm/A
Rotor inertia	4.8kgm^2
Maximum Speed	4000 rpm

The inverter supply voltage is 24V. The model was run under no load conditions. The back emf and stator voltage waveforms for reference speed of 4000rpm are shown in Figs. 7 and 8.

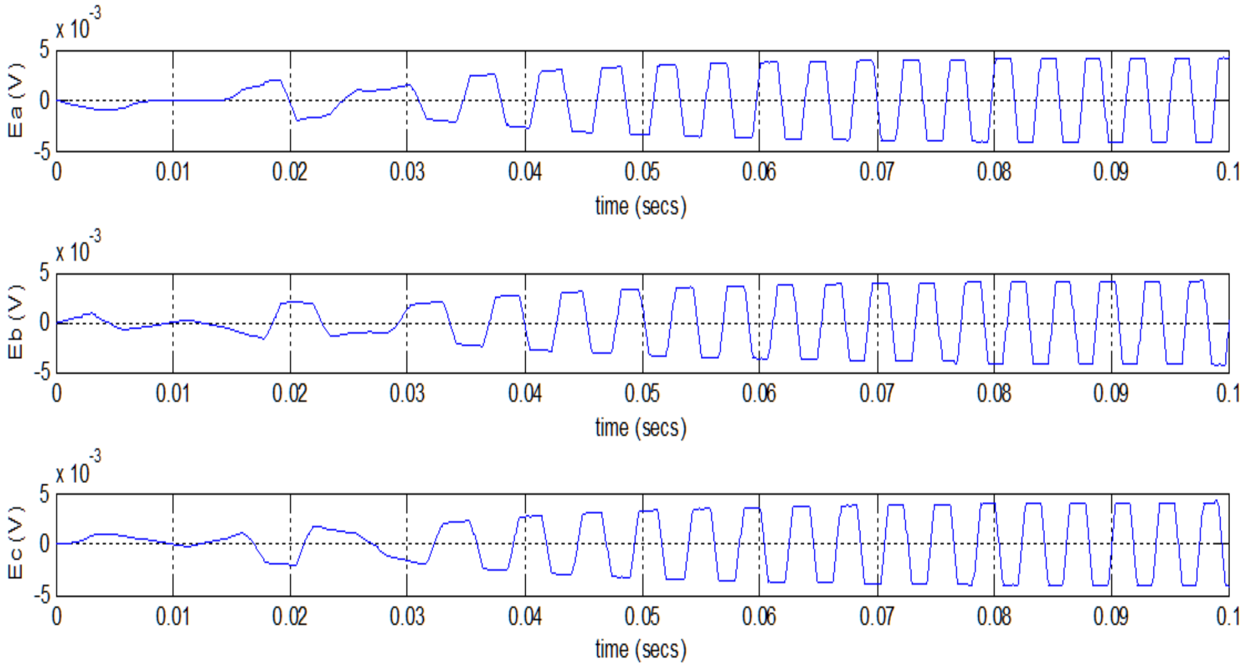

Figure 7. Back emf waveforms

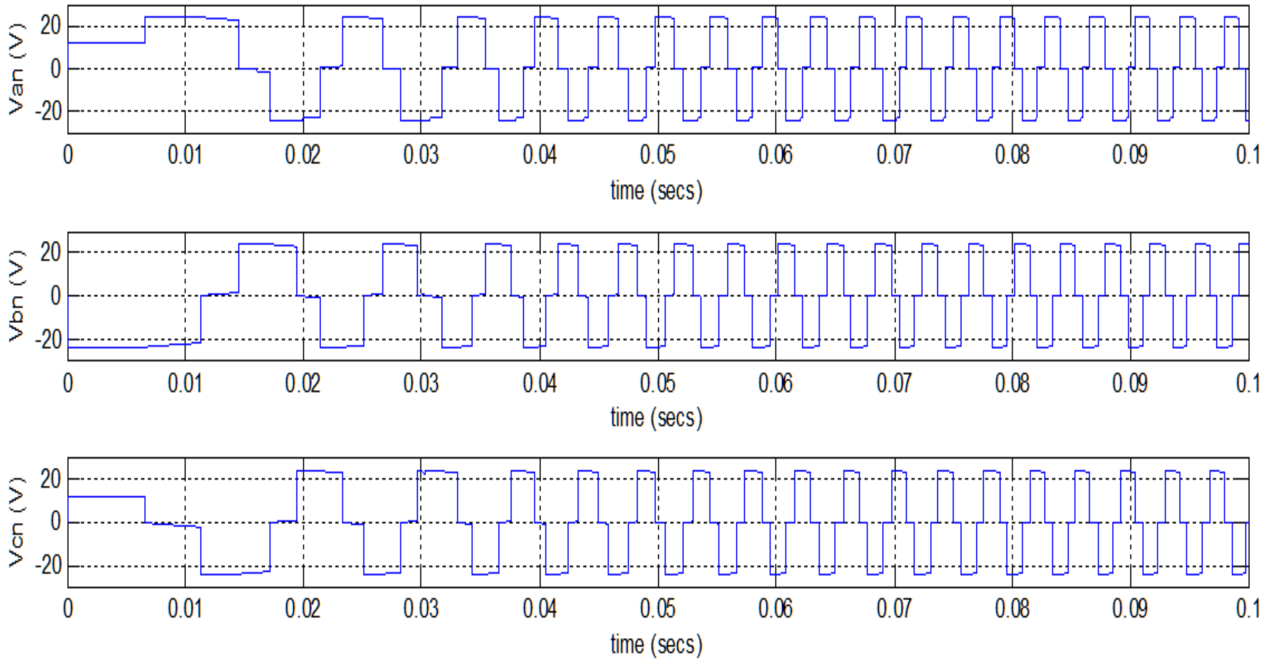

Figure 8. Stator voltages

The reference speed was set to 4000 rpm. The simulated waveforms of rotor speed and rotor position is given in Figs. 9 and 10.

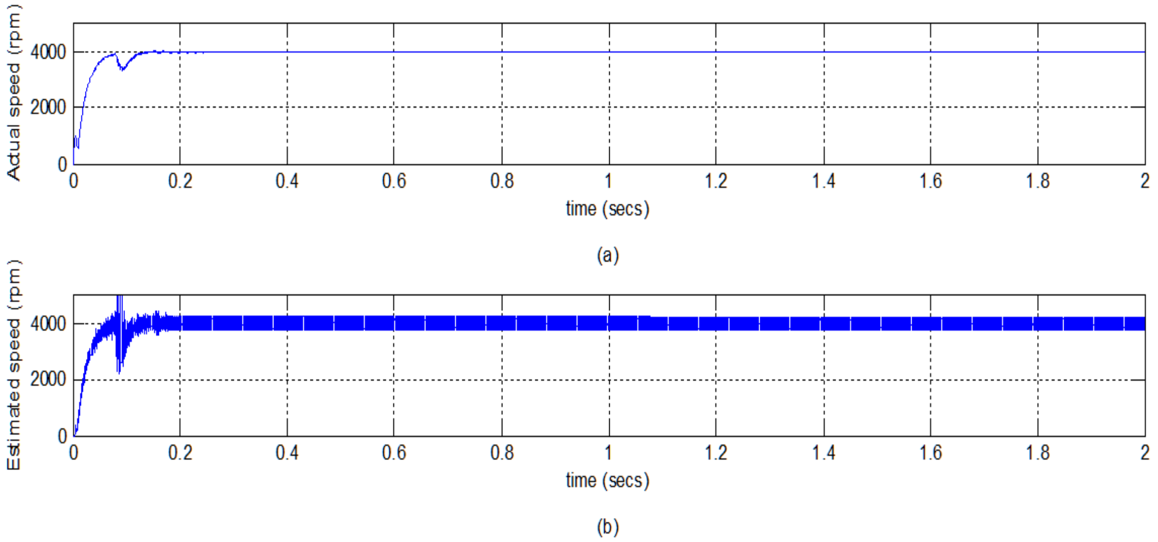

Figure 9. (a)Actual Rotor speed (b) Estimated speed

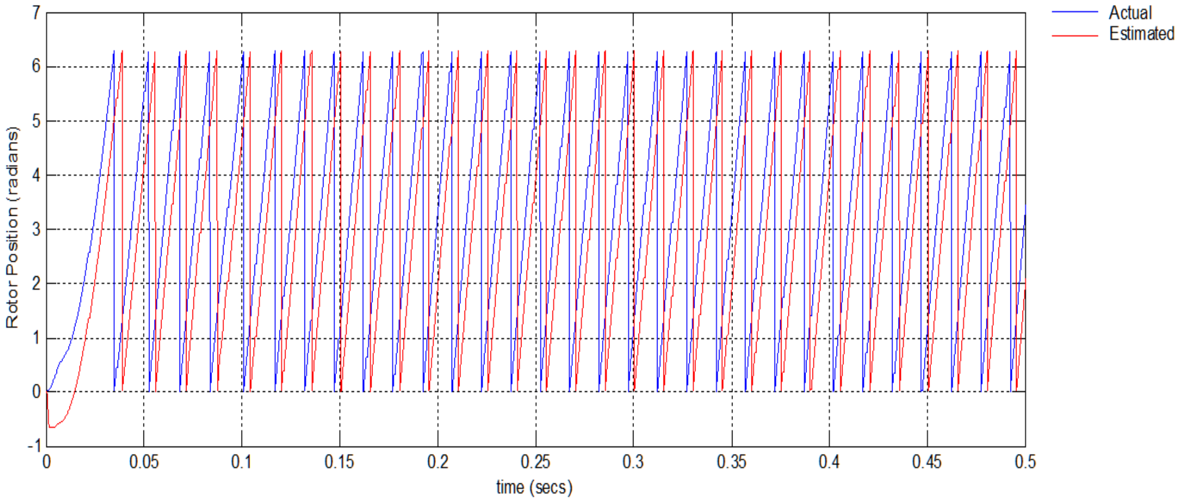

Figure 10. Estimated and actual rotor positions

The reference speed was changed from 4000 rpm to 2000 rpm at 0.955secs. It can be seen from Fig.11 that the machine settles down to the reference speed at 0.18secs.

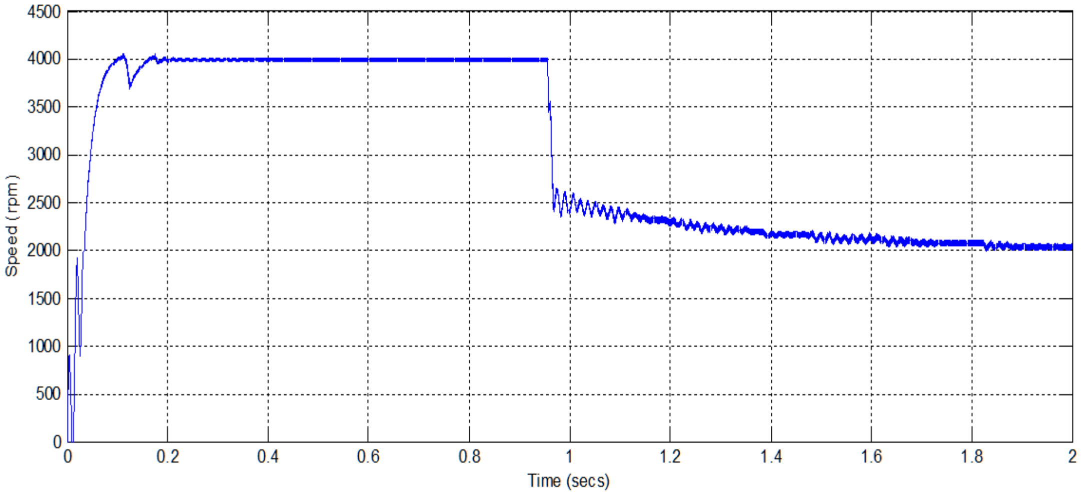

Figure 11. Response to change in reference speed

V. FUTURE WORK

The $\tan^{-1}$ function used to estimate the rotor position may reduce the accuracy of the system. Simulations with a new design eliminating $\tan^{-1}$ function are underway with results due soon.

VI. CONCLUSIONS

A sensorless control method for PM BLDC motor based on flux linkage estimation is presented in this paper. This method is parameter dependent and uses terminal voltages and currents for position estimation. A PLL structure is also utilized to improve the position estimation. Speed control is achieved using PI controller. It was observed that speed control is possible in the range of 950-4000 rpm. The oscillations in the speed waveform during starting can be controlled by the ramp reference constant.

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