Sensorless Control of Three Phase BLDC Motor Drive with Improved Flux Observer

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Abstract— **A Flux linkage observer (FLO) based sensorless estimation method for permanent magnet BLDC motor 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 system equations. 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.**

Index Terms— **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 'atan2' 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), Starting method(Section IV)Simulation Results (Section V) and Conclusions (Section VI).

II. MATHEMATICAL MODELING OF BLDC MOTOR

The principle of operation of a BLDC motor is based on synchronizing the magnetic field produced by the stator with the magnetic field produced by the rotor. In relation to the rotor position the, the stator windings are switched on and off so that the magnetic field generated by the stator and rotor will be synchronized. The switching of the windings is done electronically by using power semiconductor devices to produce a rotating magnetic field that stays in a fixed position with respect to the field produced by the rotor. Normally, only two windings are energized at a time.

The voltage equations of a three phase BLDC motor are

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

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

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

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 in shape. 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 current for each phase as a function of θ is shown in Fig.1. The expression for f(θ) for each phase is obtained from the figure as

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

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

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

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

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

The equation for motion for a simple system is given by

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

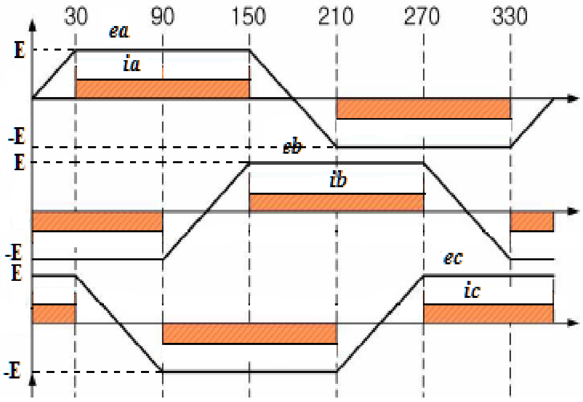


Figure 1. Back emf and phase currents of BLDC motor

III. Sensorless BLDC Motor Drive

The basic block diagram of flux observer based sensorless control of BLDC motor drive is shown in Fig 2. The main components are flux observer, speed controller and inverter fed BLDC motor. Each component will be explained in the following sections.

A. PM Flux Estimator

The flux estimator is designed based on the phasor diagram shown in Fig. 3, 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 [4]

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

$$V_{comp} = (k_p + k_i/s)\psi_s \tag{16}$$

The estimation of motor flux using a pure integrator results in ramp drift and dc offset in the output. Hence a PI

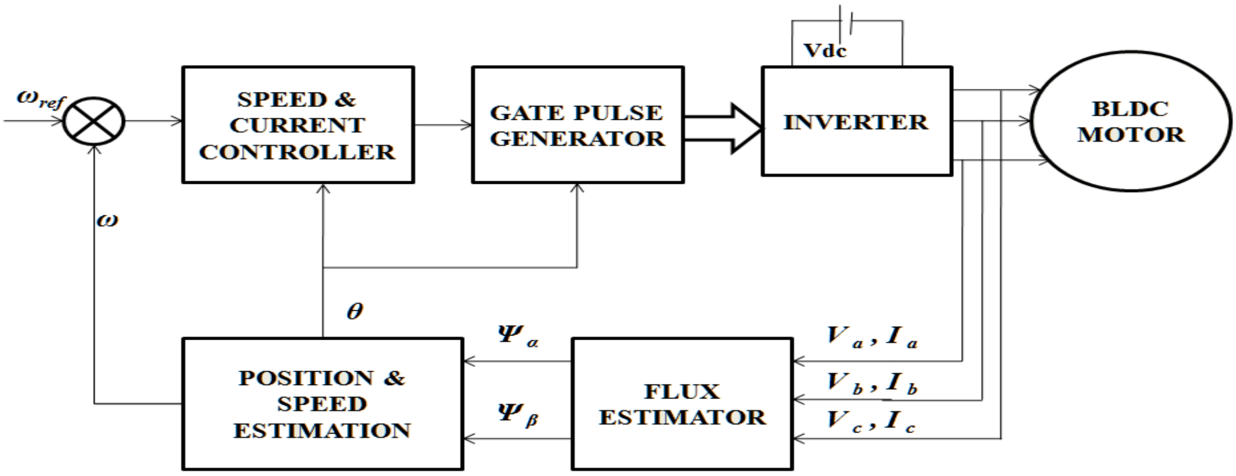


Figure2.Sensorless BLDC Motor Drive using flux observer

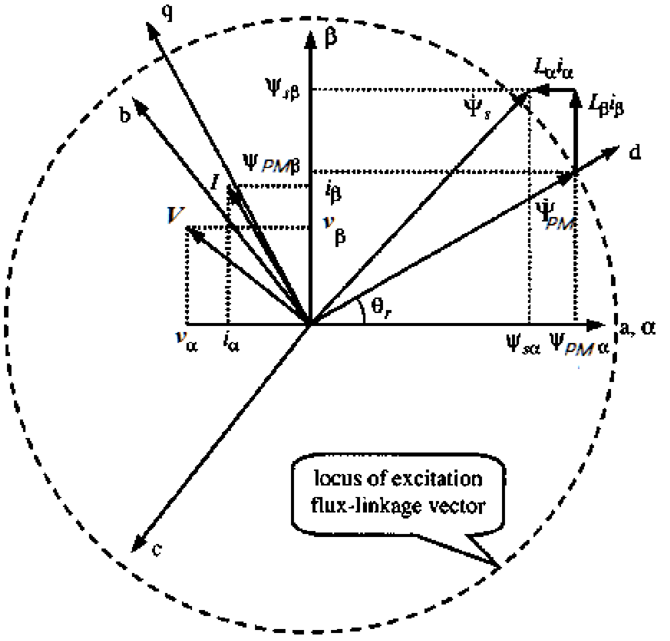


Figure 3.Phasor diagram of PM BLDC motor

correction feedback (*Vcomp*) can be used along with the integrator. The PM flux linkage is calculated as

$$\psi_{PM} = \psi_S - LI \qquad (17)$$

Therefore, in the α-β coordinate, (17) can be used to calculate $\Psi_{PM\alpha}$ and $\Psi_{PM\beta}$ components of Ψ_{PM} as shown in Fig3.

In the conventional method, the rotor position θ is computed as:

$$\theta = \arctan\left(\frac{\psi_{PM\beta}}{\psi_{PM\alpha}}\right) \qquad (18)$$

Speed can be calculated from the estimated rotor position by differentiation. But this will result in significant noise. This can be avoided by using a PLL structure to obtain the motor speed as shown in Fig 4.[1]

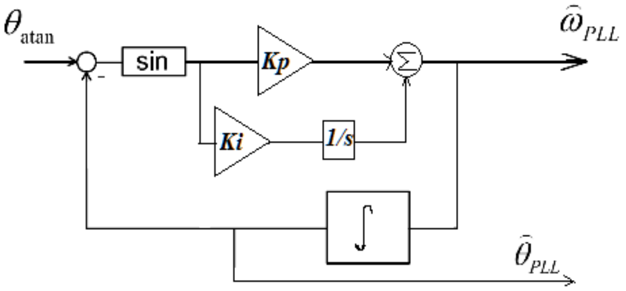


Figure4. Conventional PLL based position and speed observer

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 $\hat{\omega}_{PLL}$. The k_p and k_i values are selected by trial and error method.

$$\hat{\omega}_{PLL} = \left(k_p + {k_i}/{s}\right) \qquad (19)$$

$$\hat{\theta}_{PLL} = \frac{\hat{\omega}_{PLL}}{s} \qquad (20)$$

B. Alternate PLL Structure

A derived PLL structure for position and speed observer is shown in Fig 5. It eliminates the atan2 function and has as inputs the per unit values of the estimated fluxes .The proposed PLL structure estimates the rotor position and speed from the non sinusoidal flux functions given by the flux observer. The PI controller from this structure has the same coefficients as previous.

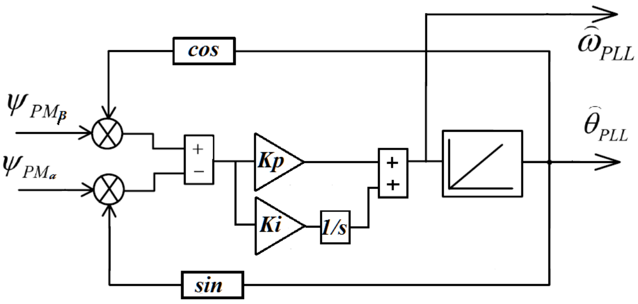


Figure 5. Proposed PLL based observer

The PLL error $\Delta\theta = \theta_{est} - \theta_{PLL}$ is obtained from the imaginary part of the vector product $\mathrm{Im}(\Psi_{PM}, \Psi)$, where

$$\hat{\psi}_{PM} = \psi e^{j\theta_{est}} = \psi_{PM\alpha} + j\psi_{PM\beta} \tag{21}$$

$$\hat{\psi} = e^{-j\theta_{PLL}} = \cos\theta_{PLL} - j\sin\theta_{PLL} \tag{22}$$

$$\begin{aligned} \mathrm{Im}(\hat{\psi}_{PM}, \hat{\psi}) &= \sin\Delta\theta \cong \Delta\theta \\ &= \psi_{PM\beta}\cos\theta_{PLL} - \psi_{PM\beta}\sin\theta_{PLL} \end{aligned} \tag{23}$$

Since the atan2 function is eliminated the estimated values will be more accurate.

C. Inverter and Control Circuit

The estimated speed is compared with the reference value and error is fed to a PI controller. The PI controller is tuned so as to minimize the error and provide necessary correction. The control signal generated by the PI controller is logically combined with switching sequence shown in Table 1 to generate the triggering pulses.

TABLE 1
SWITCHING SEQUENCE

Rotor position, θ	Phase A	Phase B	Phase C
0^0-30^0	-	$-I_B$	I_C
30^0 - 90^0	I_A	$-I_B$	-
90^0 – 150^0	IA	-	$-I_C$
$150\ ^0$– 210^0	-	I_B	$-I_C$
$210\ ^0$– 270^0	$-I_A$	I_B	-
$270\ ^0$– 330^0	$-I_A$	-	I_C
$330\ ^0$- 360^0	-	$-I_B$	I_C

IV. STARTING METHOD

The initial rotor position is unknown for Sensorless control of BLDC motor. Hence a starting method is required. An arbitrary ramp speed reference f^* is used to generate an initial value of rotor position θ_{ref} which is fed as input to the switching logic to generate gating pulses. When machine picks up speed, control transferred to sensorless scheme.

$$f^* = kt^2 \tag{24}$$

$$\theta_{ref} = \int 2\pi f^* dt \tag{25}$$

V. SIMULATION RESULTS

A. Motor Model

The BLDC motor was modeled using eqns. (4)-(14) in MATLAB/Simulink. The simulation block diagram is shown in Fig. 6. The phase voltages V_{an},V_{bn} and V_{cn} are generated using an inverter. The switching functions for the inverter switches are generated based on rotor position, θ.

The voltage, current, speed and back emf waveforms are shown in Fig. 7, 8, 9 and 10. The motor parameters used for simulation is given in Table 2.

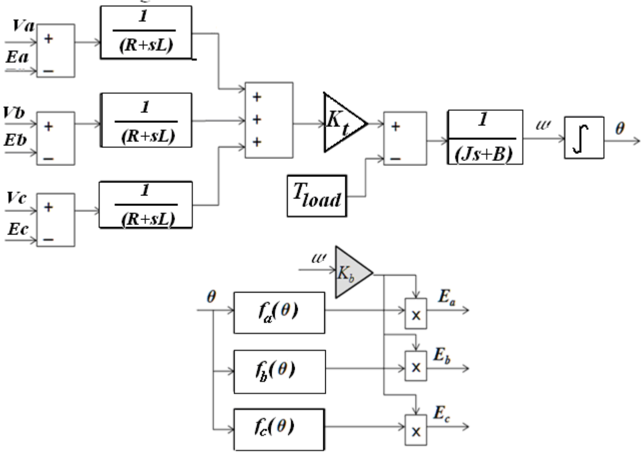


Figure.6 Simulation block diagram of bldc motor

TABLE 2
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 N-m/A
Rotor inertia	4.8 kgm2
Maximum speed	4000 rpm

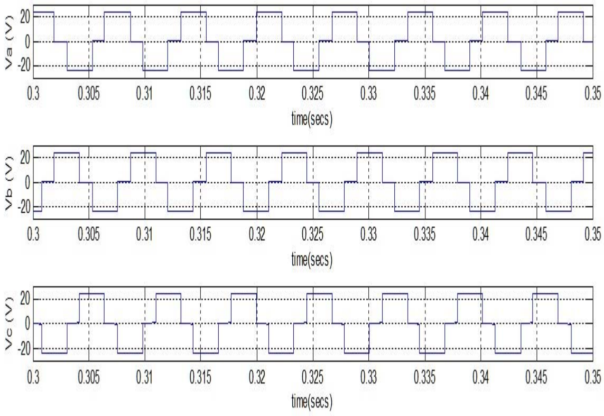


Figure 7. Stator voltages

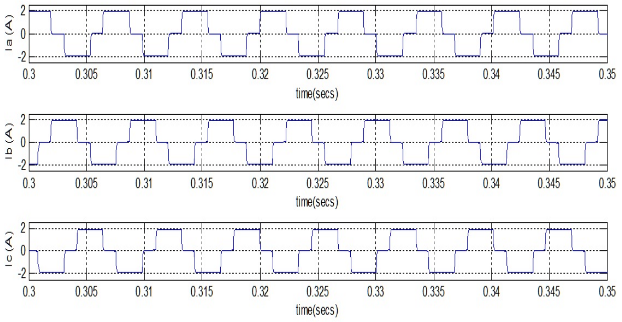


Figure 8. Stator currents

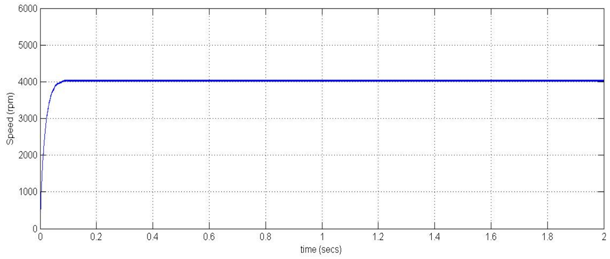


Figure.9 Rotor speed in rpm

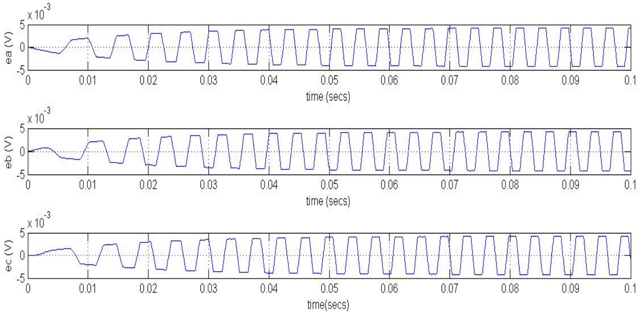


Figure10. Back emf waveforms

B. Steady State Tests

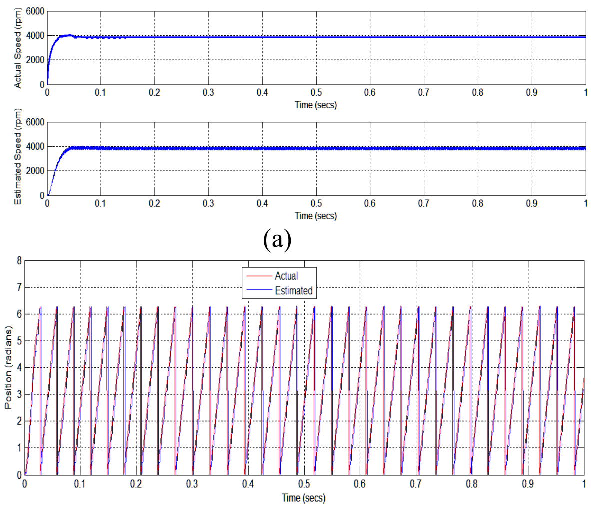
Figure 11 shows the simulation results for a constant speed reference of 4000rpm. A good agreement between estimated and measured values of speed and position can be observed.

For the given motor parameters smooth speed control was possible in the range of 1500rpm to 4000rpm.

C. Dynamics

The system response to step change in speed reference from 2000rpm to 4000rpm at 0.25 secs is shown in Fig 12. It can be observed that the drive follows the reference speed at settles down to its final value at 0.3secs.

The transient behavior of the drive to change in load torque is illustrated in Fig13. .The load torque was changed from no load to 0.125 Nm (rated torque) at 0.25secs.It can be observed that the system speed settles back to the reference value after a small glitch.



(a)

(b)

Figure 11 (a) Actual speed and estimated speed at 4000rpm reference (b) Estimated and actual rotor position

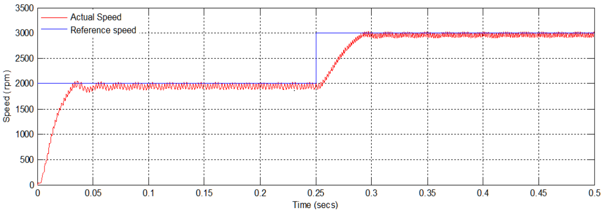


Figure 12 Dynamic response to change in reference speed

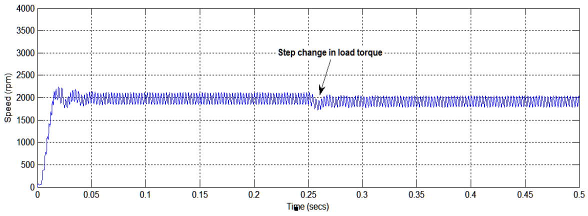


Figure 13. Transient behavior during change in load torque

VI. CONCLUSIONS

A sensorless control method for PM BLDC motor based on flux linkage estimation is presented in this paper. The main advantage of flux observer is the ease of calculation of rotor position and speed. This method is parameter dependent and uses terminal voltages and currents for position estimation. A PLL structure is also utilized to improve the estimated position. Speed control is achieved using PI controller. It was observed that speed control is possible in the range of 1500 to 4000 rpm. The load torque variation is possible up to rated value at 2000rpm. However, the control range reduces to 0-0.05Nm at 4000rpm.

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