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Fuzzy based Estimation of Low Cost Sensor- Less Control of Brushless DC Motor

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Abstract- This paper proposes a design for position control of sensor-less Brushless DC (BLDC) motor drive by means of the back electromotive force (EMF) method. A fuzzy controller based on regenerative observer is employed to control the BLDC motor drive. Most of the existing sensor-less methods have low performance at transients and low speed range. The controller is designed to overcome this problem. The whippings are avoided by the proposed controller using fuzzy switching gain adjustment. Additionally, the model for BLDC motor is also derived. Simulation results confirm the better performance and higher efficiency of the proposed model.

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I. Introduction

Recently, DC motors have been gradually replaced by BLDC motors due to their attractive features of high starting torque, high efficiency, low maintenance cost and compactness. The efficiency is likely to be higher than DC motor of equal size and more reliable due to the absence of commutator and brushes [1]. Hence the lateral stiffness of the motor is increased, allowing for high speed. When compared to the permanent magnet DC servo motor, BLDC motor has low inertia, large power to volume ratio, and low noise for the same output rating [2]. Therefore, due to high performance, BLDC motor drive has vast applications such as computers, robotics, automation, electric vehicles etc. The maximum speed of the BLDC motor is limited by the retention of the magnet against the centrifugal force alone. The power electronic converters required with BLDC motor are similar in topology to the PWM inverters used in induction motor drives. The device rating may be lower, if only a constant torque characteristic is required. The features of adjustable speed BLDC drive include energy saving, velocity or position control and amelioration of transients. However, BLDC motor still suffers from the extra mechanical position sensor for proper commutation. As a result, when a disturbance occurs on the position sensor, BLDC motor will run unsteady, and noise is produced. Additionally, the position sensor is easily damaged and poses difficulty in repair. Thus the cost of BLDC motor also increases due to the presence of the position sensor. Therefore, research on position sensor-less control for BLDC motor has become focus in the recent years [3]-[5]. In order to eliminate the position sensor, many position sensors-less control methods of BLDC motor with trapezoidal back EMF have been proposed in the literature over the last two decades [6]-[9]. The existing sensor-less drive methods of BLDC motor which are being widely used now have low performance in a transient state or low speed range and occasionally require additional circuits.

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To overcome this drawback, fuzzy logic technique is employed to estimate the back EMF in order to improve the performance of the system. A BLDC motor is highly coupled nonlinear multivariable system. Since it is difficult to obtain an accurate mathematical model, fuzzy controller is used rather than the classical Proportional-Integral-Differential (PID) controller. The classical PID controller need accurate mathematical model and perform well under linear conditions.

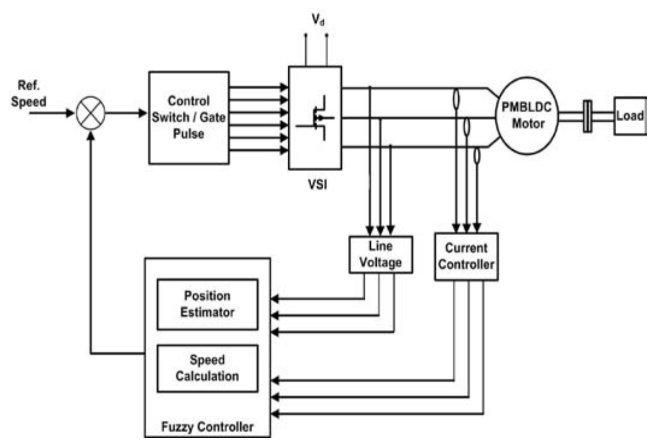

Figure 1 : Block diagram of proposed system

The fuzzy logic controller (FLC) is indeed capable of providing the high accuracy required by high performance drive system without the need of mathematical model. FLC accommodates nonlinearity without utilization of mathematical model. The FLC uses fuzzy logic as a design methodology which can be applied in developing nonlinear system for embedded control. Simplicity and less intensive mathematical design requirements are the most important features of the FLC. These features allow expeditious implementation of the controller, using inexpensive hardware technology. Fuzzy control is a real time controller using fuzzy rule base. Figure 1 shows the block diagram of proposed system. This system consists of BLDC motor, six-step inverter, gate drive of inverter, fuzzy controller and switching logic. In a fuzzy control of BLDC motor, the control accuracy is high and the response time is short. So, it is effective to control the speed of the motor.

In this paper, a fuzzy control is employed to improve the dynamic response and reduce the steady state error of the system. Due to the presence of parameter variation and load disturbance in a BLDC motor, closed loop control is necessary to obtain a desirable behavior. BLDC motor has three phase windings on stator and permanent magnet on rotor. In order to control the speed of the motor, rotor position is estimated by the proposed fuzzy control technique. Thus the exact back EMF estimation senses the position and speed of the BLDC motor. The estimated back EMF can measure the error at low speed which is the main drawback of existing system. Additionally, the proposed control technique can estimate the speed of the rotor continuously at transients as well as steady state even with changes in the external conditions.

Based on establishing the mathematical model for the BLDC motor and control system, the fuzzy controller for the position sensors-less motor drive was developed and simulated for different conditions. The simulation results confirm the better performance and higher efficiency of the proposed model.

II. System Design for Position Sensors-Less BLDC Motor

The control system of position sensors-less BLDC motor is shown in figure 1. The PWM based inverter topology is designed with six-switch voltage source configuration with constant dc-link voltage V_d.

For analysis and simplification, the following assumptions are made:

- The motor magnetic saturation is neglected.
- Stator resistances of all the windings are equal and self and mutual inductances are constant.
- Iron losses are negligible.
- The power switches are ideal.

The BLDC motor employed in this study is designed to generate trapezoidal back EMF in the stator terminal. The equivalent circuit topology of BLDC motor is shown in figure 2.

The model of BLDC motor involves solving many simultaneous differential equations; each one depends on the inputs to the motor and the constant parameters. In addition the model provides for dialogue boxes that can be used to vary the values of these constants. The state space equation for the BLDC motor model is derived as follows.

$$\begin{bmatrix}Va\\Vb\\Vc\end{bmatrix} = \begin{bmatrix}Ra&0&0\\0&Rb&0\\0&0&Rc\end{bmatrix}\begin{bmatrix}ia\\ib\\ic\end{bmatrix} + p\begin{bmatrix}La&0&0\\0&Lb&0\\0&0&Lc\end{bmatrix}\begin{bmatrix}ia\\ib\\ic\end{bmatrix} + \begin{bmatrix}ea\\eb\\ec\end{bmatrix} \qquad (1)$$

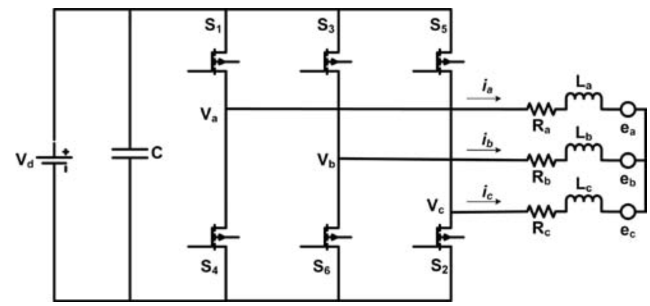

Figure 2 : BLDC motor configuration

The stator resistance per phase is assumed to be equal for all the three phases, therefore $R_a = R_b = R_c = R_s$

The induced back EMF's are all assumed to be trapezoidal, whose peak value is given by

$$E_P = (BLv)N = N(BLr\omega) = N\phi\omega = \lambda\omega \qquad (2)$$

Where λ is the flux linkage and ω is the angular velocity.

$$\begin{bmatrix}Va\\Vb\\Vc\end{bmatrix} = \begin{bmatrix}Rs&0&0\\0&Rs&0\\0&0&Rs\end{bmatrix}\begin{bmatrix}ia\\ib\\ic\end{bmatrix} + p\begin{bmatrix}La&0&0\\0&Lb&0\\0&0&Lc\end{bmatrix}\begin{bmatrix}ia\\ib\\ic\end{bmatrix} + \begin{bmatrix}ea\\eb\\ec\end{bmatrix} \qquad (3)$$

Where V_a, V_b and V_c are phase voltages. If there is no change in rotor reluctance with angle because of non-salient rotor and assuming three symmetric phases, inductances and mutual inductances M are assumed to be symmetric for all phases, i.e. (3) becomes:

$$\begin{bmatrix}V_a\\V_b\\V_c\end{bmatrix} = R_s * \begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}\begin{bmatrix}I_a\\I_b\\I_c\end{bmatrix} + \mathbf{p}\begin{bmatrix}L&M&M\\M&L&M\\M&M&L\end{bmatrix}\begin{bmatrix}I_a\\I_b\\I_c\end{bmatrix} + \begin{bmatrix}E_a\\E_b\\E_c\end{bmatrix}$$

$$\begin{bmatrix}Va\\Vb\\Vc\end{bmatrix} = R_s\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}\begin{bmatrix}ia\\ib\\ic\end{bmatrix} + p\begin{bmatrix}L&M&M\\M&L&M\\M&M&L\end{bmatrix}\begin{bmatrix}ia\\ib\\ic\end{bmatrix} + \begin{bmatrix}ea\\eb\\ec\end{bmatrix} \qquad (4)$$

The generated electromagnetic torque is given by

$$T_e = \left[e_a i_a + e_b i_b + e_c i_c\right]\frac{1}{\omega} \qquad (5)$$

The torque runs into computational difficulty at zero speed as the induced EMF is zero and hence a reformulation independent of the speed is desirable. As the induced EMF is proportional to the product of rotor speed and airgap flux linkage which is a function of rotor position θ, the induced EMF can be written as :

$$e_a = f_a(\theta)\ \lambda\ \omega$$
$$e_b = f_b(\theta)\ \lambda\ \omega$$
$$e_c = f_c(\theta)\ \lambda\ \omega$$

Electrical rotor speed and position are related by

$$\frac{d\theta}{dt} = \left(\frac{p}{2}\right) * \omega$$

The equation of motion for a simple system with inertia constant J, friction coefficient B, load torque T_l, electromagnetic torque T_e and mechanical speed ω is given by

$$J\frac{d\omega}{dt} + B\omega = T_e - T_l \qquad (6)$$

The state space model of BLDC motor is given by

$$X' = AX + BU \qquad (7)$$

Where $X = [i_a \quad i_b \quad i_c \quad \omega \quad \theta]^T$

$$A = \begin{bmatrix} \frac{-R_s}{L} & 0 & 0 & 0 & 0 \\ 0 & \frac{-R_s}{L} & 0 & 0 & 0 \\ 0 & 0 & \frac{-R_s}{L} & 0 & 0 \\ \frac{\lambda p * f_a(\theta)}{J} & \frac{\lambda p * f_b(\theta)}{J} & \frac{\lambda p * f_c(\theta)}{J} & \frac{-B}{J} & 0 \\ 0 & 0 & 0 & \frac{p}{2} & 0 \end{bmatrix};$$

$$B = \begin{bmatrix} \frac{1}{L} & 0 & 0 & 0 \\ 0 & \frac{1}{L} & 0 & 0 \\ 0 & 0 & \frac{1}{L} & 0 \\ 0 & 0 & 0 & \frac{-1}{J} \\ 0 & 0 & 0 & 0 \end{bmatrix}; \quad U = [V_a \quad V_b \quad V_c \quad T_L]^T$$

III. Estimation of Speed and Position Based on Fuzzy Logic Controller

The proposed fuzzy back EMF is divided into two parts. One is the stator current observed in terms of state equation and the other is the fuzzy function. The fuzzy membership functions for error, change in error and control output are shown in figure 3.

Fuzzy logic controller contains four main parts, out of which two perform transformations. They are fuzzifier (transformation 1), knowledge base, inference engine and defuzzifier (transformation 2).

a) Fuzzification

Fuzzification measures the values of input variables and converts them into suitable linguistic values. Knowledge base consists of a database and provides necessary definitions, which are used to define linguistic control rules. This rule base characterizes the control goals and control policy of the domain experts by means of a set of linguistic control rules. The input and output has five sets associated with seven linguistic labels: (NB) Negative Big, (NS) Negative Small, (Z) Zero, (PS) Positive Small and (PB) Positive Big as shown in figure 3.

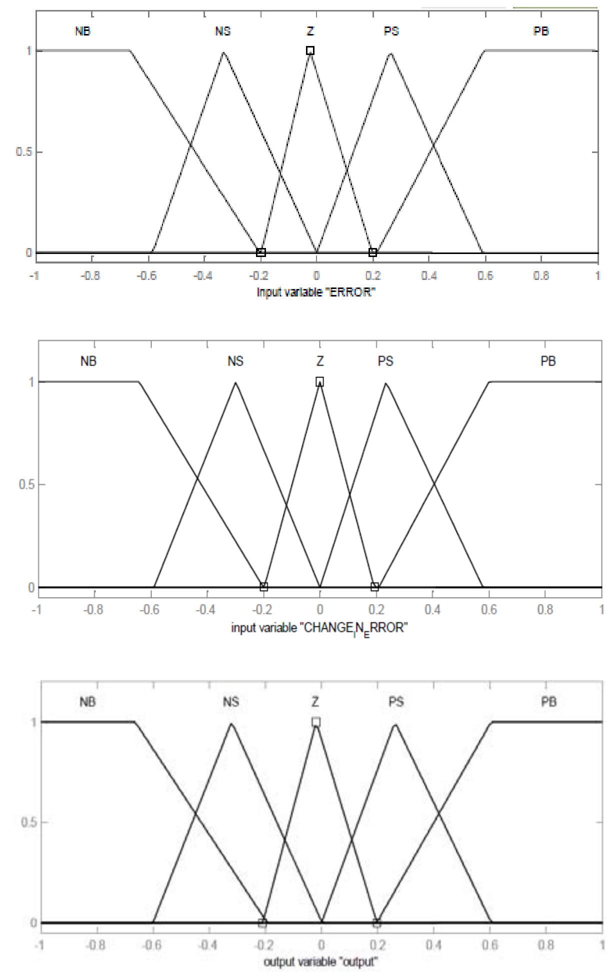

Figure 3 : Membership function

b) Inference Engine

Decision making logic or inference mechanism is a main part of fuzzy controller. It has the capability of simulating human decision making based on fuzzy concepts and of inferring fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic. A typical rule is described as *IF (condition 1) AND (condition 2) THEN (conclusion).* Fuzzy inference consists of two processing methods namely, Mamdani's method and Sugeno or Takagi-Sugeno-Kang method to calculate fuzzy output [9]. Out of it Mamdani's method is more suitable for DC machine and induction machine control. The Table 1 shows the fuzzy rule-base.

c) Defuzzification

Defuzzification is a scale mapping, which converts the range of values of output variables into corresponding universe of discourse and also yields a non-fuzzy control action from an inferred fuzzy control action. The fuzzy function converts its internal fuzzy output variables into crisp values so that the actual system can use these variables. One of the most common ways is the center of area method, and will be used here.

Table 1 : Fuzzy Rules

Change in error	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

IV. Simulation Results

The mathematical model is simulated by MATLAB / SIMULINK block. The closed loop model is shown in figure 4.

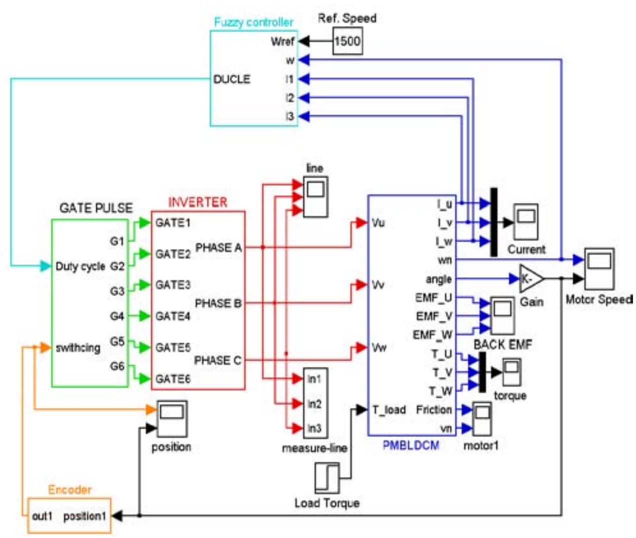

Figure 4 : Simulink model of proposed system

The block diagram of the proposed drive system is given in figure 1. The line voltage is measured from the DC-link. The line current of the BLDC motor is also calculated. Using these calculated values, back EMF is estimated with the help of Fuzzy Block. The speed and the rotor position are calculated by the estimated back EMF. The estimated speed is fed to the error detector which finds the difference between the actual and desired values. The error output is finally fed to the control switch where the pluses for the inverter are decided. Thus the inverter produces the exact voltage required for the BLDC motor.

The speed measured by fuzzy technique is almost same as the sensor value. The fuzzy based speed estimation is reliable and cost of the sensor is also eliminated. Thus the Fuzzy logic is found to be somewhat superior. That is, it doesn't need any physical component for the measurement of speed. Therefore the overall system cost is reduced and the maintenance problem of the sensor is also eliminated.

The results shown below reveal that the proposed fuzzy based control of BLDC motor is efficient. The back EMF of the BLDC motor has been shown in figure 5. Similarly the rotor position angle of the motor is also determined by the speed of the motor which is shown in figure 6. The speed of the motor determined by the estimated back EMF is shown in figure 7.

The speed is also varied from one point to another; from zero to full rated speed and from half rated to full. In all above aspects the simulations are done, performance is good for fuzzy based estimation of sensor-less control of BLDC motor. The maximum overshoot and ripples are reduced effectively after adding the Fuzzy controller. The simulation results confirm the better performance and higher efficiency of the proposed model. To realize the result, some of the waveforms taken after simulation for different speed range are given here for the purpose of reference.

The change in speed of the BLDC motor from 1000 rpm to 1200 rpm is shown in figure 8. Its corresponding back EMF and rotor position angle are shown in figure 9 and figure 10 respectively.

The results due to change in speed of the BLDC motor from 1000 rpm to 800 rpm are shown in figure 11. Its corresponding rotor angle is shown in figure 12.

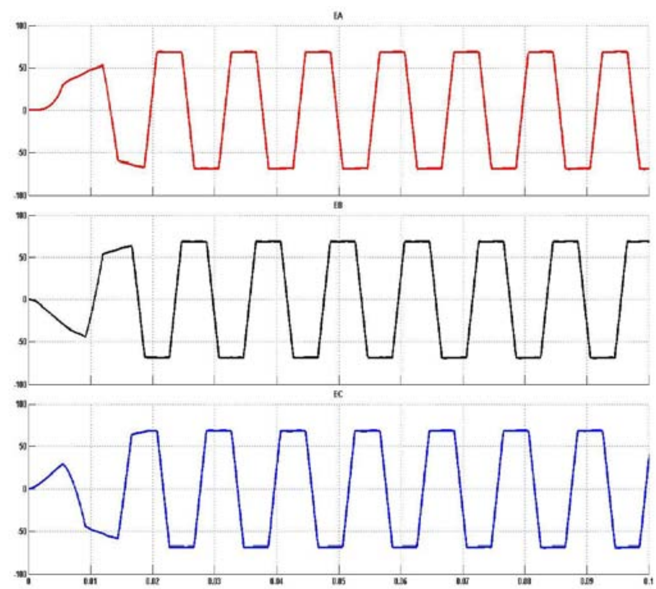

Figure 5 : Trapezoidal Back EMF

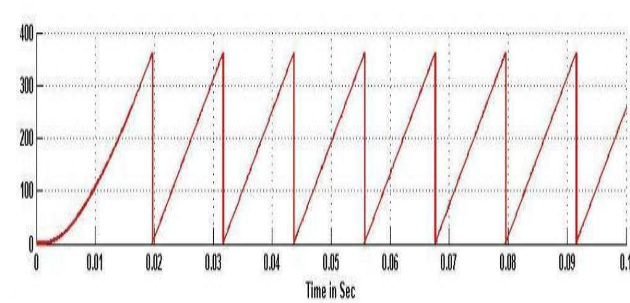

Figure 6 : Rotor angle

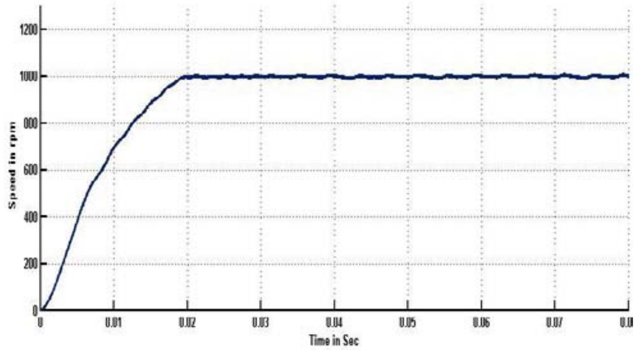

Figure 7 : Speed response of BLDC motor

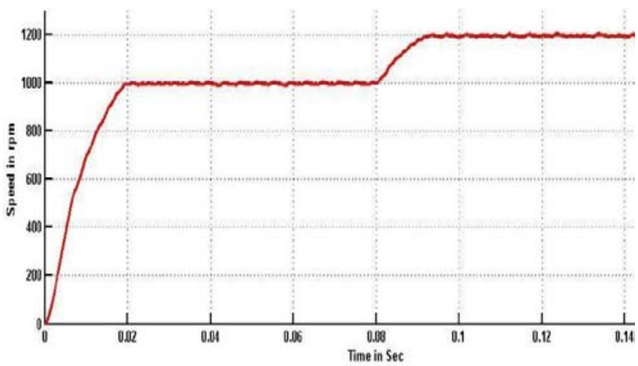

Figure 8 : Speed response of BLDC motor

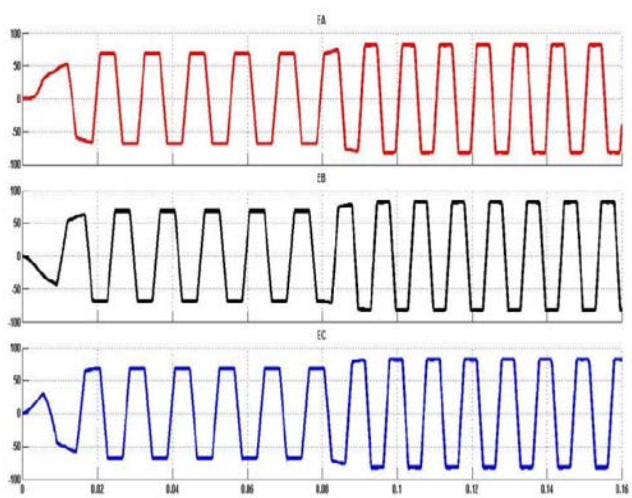

Figure 9 : Trapezoidal back EMF

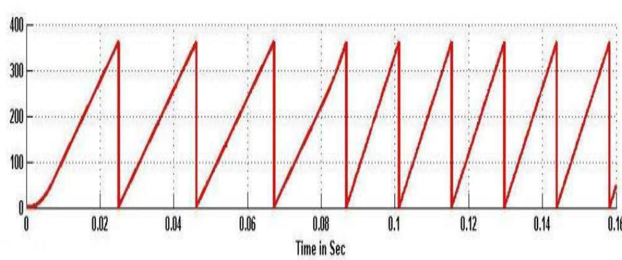

Figure 10 : Rotor angle

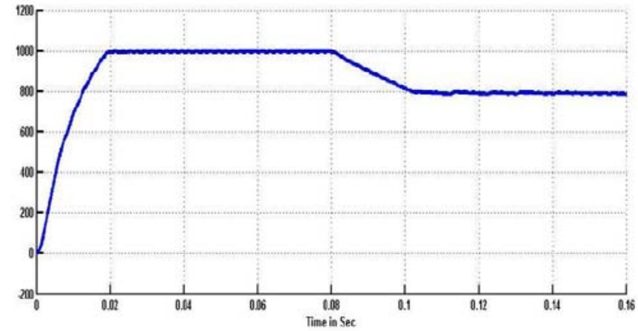

Figure 11 : Speed response of BLDC motor

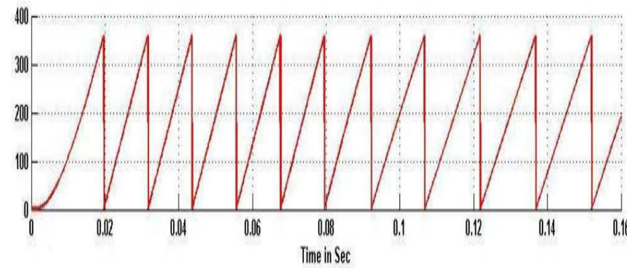

Figure 12 : Rotor angle

Motor Parameter Used

Phase Voltage	300 V
No. of Poles	4
Number of turns per phase	800
Rated Speed	1000 RPM
Resistance per phase (Rs)	10 Ohms
Self Inductance (La)	10 mH
Mutal Inductance (M)	1.5 mH
Maximum flux density	0.8167 web/m2
Moment of Inertia (J)	0.0021 Kg-m2
Friction Co-efficient (B)	0.089 Nm/(rad/sec)

V. Conclusion

A control system to estimate the speed and rotor position based on fuzzy back EMF observer is developed with the help of fuzzy logic technique for BLDC motor without position sensors. The proposed model is used to estimate the speed of BLDC motor under variable and fixed condition of back EMF. The proposed method has higher performance than the conventional sensors-less method without any additional circuitries. Simulation results confirm the better performance and higher efficiency of the proposed model.

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