Performance Analysis and Comparison of BLDC Motor Drive using PI and FOC

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Abstract— BLDC motors and their drives are gaining attention day by day from various industrial and household appliance manufactures because of its high efficiency, high power density, high torque, and low inertia, less noise, compact form, almost no maintenance, salient operation, and reliability. The BLDC motor can also be thought of an intermediate between a DC motor and a synchronous motor, which extracts the advantages of each of them and rejects their disadvantages. BLDC motor is inverter fed permanent magnet synchronous motor, having permanent magnet on rotor and trapezoidal or sinusoidal shaped back EMF. The BLDC motor employs a DC supply to stator phase winding of the motor by power devices, the commutation of phase is achieved by electronics commutation system instead of brushes and commutator. Hence the rotor position at six steps needed to achieve electronics commutation perfectly. The BLDC motor emerging as the dominant new technology in motion control.

The paper builds simple, accurate and fast running model of BLDC motor drive in MATLAB/Simulink. They are especially beneficial in the situation where actual system does not exist. Changing the values of parameters can often be done more quickly than by conducting a series of experimental studies on actual system. In this dissertation, Modelling, simulation and analysis of PI controller and field oriented controller (FOC) based sensor less scheme for a BLDC motor has been carried out.
Keywords—BLDC; SMO; PI; SVPWM; MATLAB; PWM

I. Introduction

In modern adjustable speed drive the demand is for continuous and precise control of speed and position with high efficiency long term stability and good transient response. The DC motor has satisfy some of the requirement, but its mechanical commutation is often undesirable because of frequent maintenance. AC motor are brushless and have robust rotor construction, which permits reliable maintenance free operation at high speed. However, these motors are inflexible in speed, when operated from a standard constant frequency AC supply. Brushless DC motor can be thought of an intermediate between conventional DC motor and synchronous motor, which extracts the advantages of each of them and rejects their disadvantages. The main objective of this paper is to identify performance of brushless DC motor using different speed control techniques and results are compared.

In this paper the basics of a BLDC motor, its speed control using two different strategies i.e.; using PI controller and field oriented controller (FOC) is given. The dynamic performance of brushless DC motor with the help of PI controller while no loading, under load, changing a step load torque with constant speed has been found. The result of simulation are presented in time domain.

In later case performance of brushless DC motor using sensor less field oriented controller is given by using Space Vector Pulse Width Modulation (SVPWM) technique to generate sinusoidal voltage and current due to its facility and high efficiency with low harmonic distortion. To solve the detection of rotor position and speed of brushless DC (BLDC) motors in sensor-less position control system, an improved estimation method of rotor position and speed based high order sliding mode observer is proposed. The whole drive system is simulated in MATLAB/Simulink based on the sliding mode observer. The aim of the drive system is to have speed control over wide speed range. Simulation result shows that the speed controller has a good dynamic response by using field oriented controller.

II. SYSTEM DEVELOPMENT

A. BRUSHLESS DC MOTOR USING PI CONTROLLER

Figure 1 shows the basic block diagram of Brushless DC motor (BLDC) drive based on PI controllers. The proposed drive consists of the motor, power electronic controller based on voltage source inverter speed controller, reference current generator, PWM current controller, position sensor. The speed of the motor is compared with its reference value and the speed error is processed in proportional- integral (PI) speed controller.

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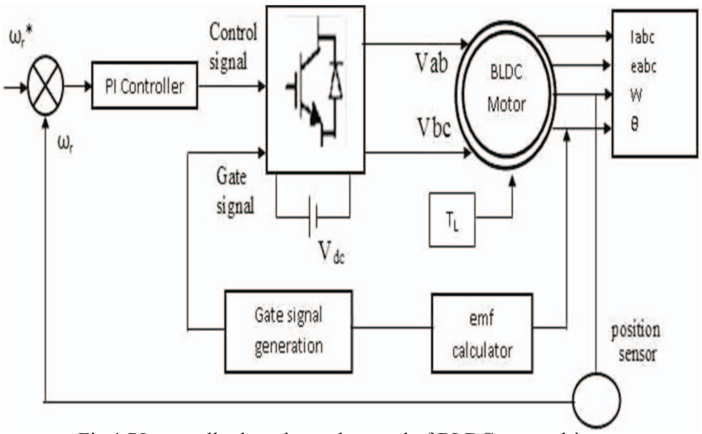

Fig.1 PI controller based speed control of BLDC motor drive

The outer loop is designed to improve the static and dynamic characteristics of the system. The disturbance caused by the inner loop can be limited by the outer loop. The emf is calculated by taking the angle θ and angular speed in to consideration which is used to generate gate signal that will be applied to the power electronic converter. On the other hand the rotor position sensor tracks the speed signal and then it will compared with the reference signal to determine the error signal which is then allowed to pass through PI controller for compensation and to generate the corresponding control signals for the inverter. The Hall Effect also called rotor position sensors provide the portion of information need to synchronize the motor excitation with rotor position in order to produce constant torque. The inverter is then used to control the speed.

B. BRUSHLESS DC MOTOR USING FIELD ORIENTED CONTROL

Vector or field oriented control technology has been widely used in control of permanent magnet synchronous motor (PMSM) where position of rotor is very much important. Shaft position sensor such as an optical position encoder or Hall Effect sensor are located on the rotor to provide a signal that is used to maintain an appropriate space angle between the rotor and stator fields in the motor.

Brushless DC motor actually is a permanent magnet synchronous motor with trapezoidal type of waveform. Field Oriented Control demonstrates that synchronous motor or BLDC motor could be controlled like a separately excited dc motor by current vector in relation to the rotor flux to achieve a desired objective and for that we usually refers to controllers which maintain a 90° electrical angle between rotor and stator field components. In DC motors, the flux and torque producing currents are orthogonal to each other and can be controlled independently and because of this reason DC machines are said to have decoupled or have independent control of torque and flux. On the other hand in AC machines, the stator and rotor fields are not orthogonal to each other and hence the only current that can be controlled is the stator current. Field Oriented Control is the technique used to achieve the independent control of torque and flux by transforming the stator current quantities (phase currents) from stationary reference frame to torque and flux producing currents components in rotating reference frame.

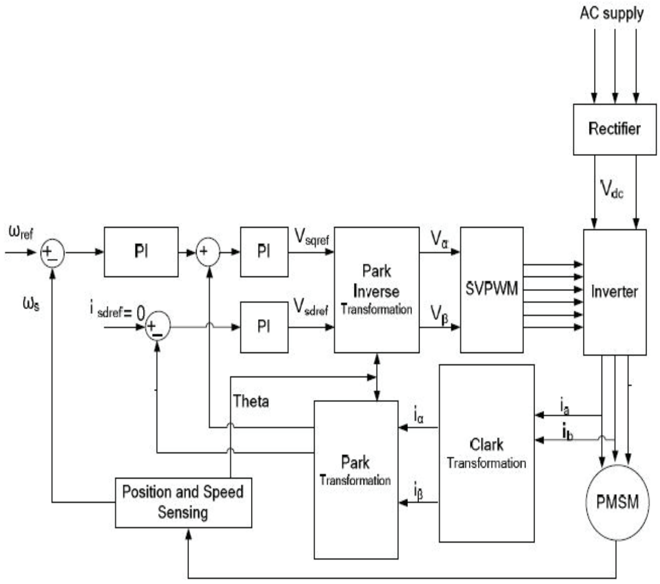

Fig.2 Field oriented control block diagram

To perform vector control, following steps are necessary:

i. The three phase stator currents are measured. These measurement gives values as i_a ,i_b and i_c. actually we want only two currents and third we can calculated by the following equation:

$$i_a + i_b + i_c = 0 \quad (1)$$

ii. The three phase currents are converted into a two-axis system. This conversion provides the variables i_α and i_β from the measured i_a and i_b and the calculated i_c values. i_α and i_β are quadrature axis current values as viewed from the stator.

iii. The two-axis coordinate system is then rotated to align with the rotor flux using a transformation angle. This conversion provides the i_d and i_q variables from i_α and i_β. i_d and i_q are the quadrature currents transformed to the rotating coordinate system. For steady state conditions, id and iq are constant.

iv. Error signals are formed using i_d, i_q and reference values for each.
   - The i_d reference is used to control rotor magnetizing flux
   - The i_q reference is used to control torque output of the motor
   - The error input signal is given to PI controllers
   - The output of the controllers provide V_d and V_q, are voltage vectors that will be sent to the motor

v. A new transformation angle is calculated where V_α, V_β, i_α and i_β are the inputs. The new angle guides the field oriented control system as to where to place the next voltage vector.

vi. The V_d and V_q are the output values from the PI controller are rotated back to the stationary reference frame using the new angle. This estimation provides the next quadrature voltage values V_α and V_β.

vii. The V_α and V_β values are transformed back to three phase values V_a, V_b and V_c. The three phase voltage values are used to calculate new values of new PWM duty cycle that generate the desired voltage vector. The entire process of transforming, PI iteration, transforming back and generating PWM is illustrated in Figure.2.

To build simulation model of brushless DC motor drive using PI controller and sensorless field oriented controller mathematical and Simulink model of PI controller, three phase inverter, a-b-c to d-q transformation, d-q to α-β Transformation, Sliding mode observer, Space Vector Pulse Width Modulation and brushless DC motor is given

C. PI CONTROLLER

A PI controller is a feedback control control system for recovering the actual motor speed to the reference speed. The reference and measured speed are the input to PI controller. The controller output is given by

$$K_p\Delta + K_i \int \Delta * dt \qquad (2)$$

Where, Δ is deviation of measured speed to the reference speed

$$\Delta = \omega_m - \omega_{ref} \qquad (3)$$

K_p *and* K_i are the values of the controller and are determined by trial and error method. The controller output is limited to give the reference torque, its integral term has the effect of memorization, accumulation and delay, which enable PI controller to remove the static error. The simulation block limits the amplitude of the three phase reference current to the demanding range.

D. COORDINATE TRANSFORMATION

There are two kinds of coordinate system in field oriented control technology. One is fixed on the stator and hence it is a static coordinate system and other is fixed on the rotor and that's why it is a revolving coordinate system. Both the three-phase stator A-B-C coordinate system based on three-phase winding and the two-phase stator α-β coordinate system are the static coordinate system. The two-phase stator α-β coordinate system is made up of α axis fixed on A axis and β axis which is vertical to α axis. While d-q coordinate system with d axis fixed on the rotor spool thread is revolving. Figure 3.3 shows the relationship of α-β coordinate system and d-q coordinate system. θ is the angle between d and α axis.

To perform the sensor less control of a BLDC, the motor is generally modeled in stationary reference frame because angular speed and position information are ready to be drawn out in this reference frame.

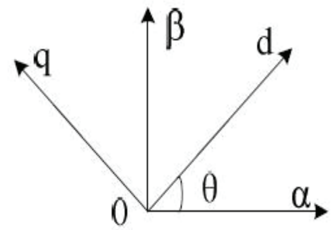

Fig.3 Relationship between α-β and d-q coordinate system

E. SLIDING MODE OBSERVER

Though control of brushless DC motor using sensors like hall effect sensors, optical encoders is very easy and valuable but the cost of mechanical sensors is high and is difficult to incorporate them that's why it is very much necessary to avoid their uses and to study sensor-less control. The sensor less approach has several advantages:

i. Compact drive.
ii. Absence of connecting leads prevents electromagnetic interference.
iii. Cost of position-encoding device such as hall effect sensors is avoided.
iv. mechanically robust.
v. Suitable for hostile environments.
vi. Low maintenance.

There are many categories of sensor-less control strategies. However, the most popular category is based on back electromotive forces. Sensing back electromotive force of unused phase is the most cost efficient method to obtain the commutation sequence in star wound motors. Since back-EMF is zero at standstill and proportional to speed, the measured terminal voltage cannot detect zero crossing at low speeds. That is the reason why performance of all back-EMF-based sensor-less methods are limited. Sliding mode observer is also used for estimating the position and speed of a permanent magnet synchronous motor (PMSM) to achieve sensor-less drive system.

F. SPACE VECTOR PULSE WIDTH MODULATION

The main aim of any modulation technique is to obtain variable output having a maximum component with minimum harmonics. Space Vector PWM (SVPWM) method is an advanced technology than PWM method and possibly the best techniques for variable frequency drive application. Because of the constraint that the input lines must never be shorted and the output current must always be continuous, a voltage source inverter can assume only eight distinct topologies. out of these eight only six are the non-zero output voltage and are known as non-zero switching states and the remaining two are the zero output voltage and are known as zero switching states.

The SVPWM uses two neighboring effective vectors and a null vectors of the eight basis space voltage vector and their different act time to obtain the equivalent space voltage vector that the motor needs, as shown in figure 4.

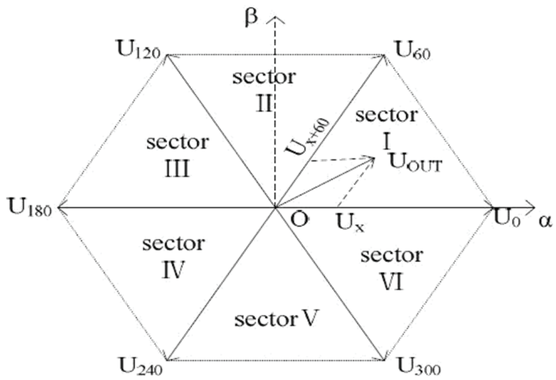

Fig. 4 Basic voltage vectors and reference vector

III. PERFORMANCE ANALYSIS

This section deals with test results of actual system of PI controller based brushless dc motor drive and its dynamic modeling and its speed control using two different strategies *i.e.;* using PI controller and field oriented controller (FOC)

A. EXPERIMENTAL RESULTS OF BRUSHLESS DC MOTOR USING PI CONTROLLER

Figure 5 shows Actual System of PI Controller Based Brushless DC Motor drive based on micro 4011. Micro 4011 is a 16 bit digital signal controller card based on dsPIC30F 4011. This controller card enables to help in performing digital motor control by PWM generation. The controller possess the feature of both the DSP engine and the micro-controller.

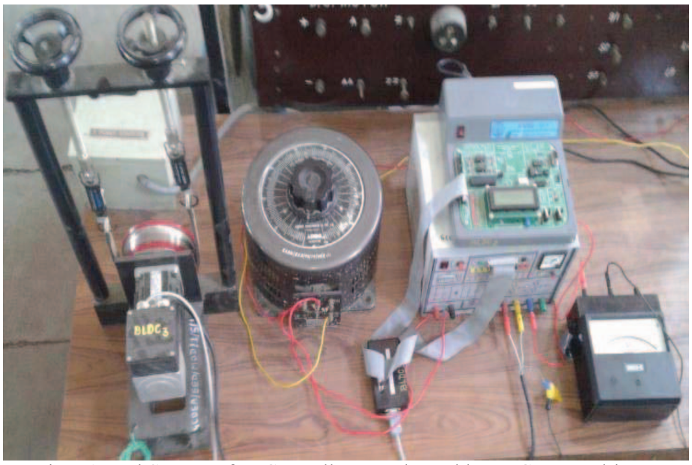

Fig.5 Actual System of PI Controller Based Brushless DC Motor drive

1. Equipment's required

i. VPET- 106 A power module
ii. BLDC motor with spring balance loading arrangement
iii. Dspic 30f 4011 controller
iv. Patch cords
v. 26 pin FRC cable
vi. 34 pin FRC cable
vii. 6 pin RJ- 45 cable (Ethernet cable)
viii. Dspic kit 2programmer
ix. USB cable

2. Connection procedure

i. Connect the single phase AC supply terminals ―R, Y, B‖ AC input terminals of the VPET- 106 A power module through the autotransformer.
ii. Connect the VPET- 106 A power module output terminals ―U, V, W‖ to the input terminals of BLDC motor.
iii. Connect Dspic 30f 4011 controller to power supply.
iv. Connect 34 pin PWM output connector to Dspic 30f 4011trainer to the input connector of the VPET- 106 A power module.
x. Connect the 6 pin RJ 45 (Ethernet cable) from Dspic 30f 4011 to Dspic kit 2 programmer

TABLE I. SPECIFICATION OF BLDC MOTOR

SR.	*Parameter*	*Specifications*
1	No. of poles	4
2	Rated Speed	4600 rpm
3	Rated Voltage	310 V DC
4	Rated Current	4.52 A
5	Rated Power	1/1.1 HP
6	Phase	3
7	Rated Torque	2.2 Nm
8	Back EMF constant	0.4223 V/rad/sec

To examine the performance of brushless DC motor at no load and at change in mechanical load, following results are obtained.

TABLE II. TEST RESULTS OF BLDC MOTOR

REF. SPEED	WEIGHT (gram)		RAD. (cm)	TORQUE T=m*g*r	I (Amp)	ACT. SPEED
	T1	T2				
1000	0	0	7	0	0.1	1000
1000	200	600	7	0.2746	0.5	1009
1000	300	800	7	0.3433	1.0	1005
1000	400	1400	7	0.6867	1.5	1009

B. SIMULATION OF BRUSHLESS DC MOTOR USING PI CONTROLLER IN MATLAB/SIMULINK

The performance of the developed brushless DC system mode is examined under following condition

i. Start
ii. Change of mechanical load
iii. Change of reference speed

The simulation is carried out using MATLAB/Simulink

The BLDC motor is fed by three phase MOSFET based inverter. The inverter gates signals are produced by decoding the Hall Effect signals of the motor, which are require to maintain the current constant within 60° interval of one electrical revolution of the rotor. The three-phase output of the inverter are applied to the stator windings. The load torque applied to the machine's shaft is first set to 0 and them steps to its nominal value.

The PI controller process on the speed error signal and the outputs to the limiter to produce reference torque. The actual speed is feedback to the speed controller to minimize the error in tracking the reference speed, thus it is closed loop drive system. Values of proportional and integral constant are set as .4 and 14 respectively by trial and error method.

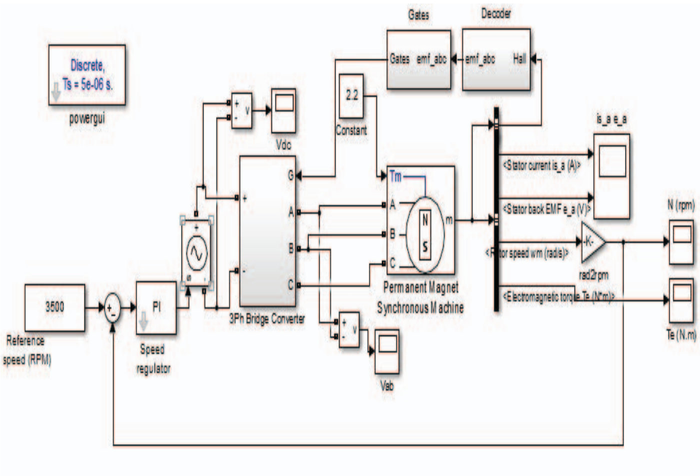

Fig.6 MATLAB/Simulink Model of BLDC Motor drive with PI controller

Simulation of brushless DC motor during no-load condition and change in mechanical load has been observed. The simulation results are given in the form of following figures:

i. Mechanical speed of the rotor
ii. Electromagnetic torque
iii. Line to line voltage
iv. Rotor angle error

Simulation of brushless DC motor during no-load and under change in load torque is carried out. The current increases in steps of 0.5 A to meet the extra load with increase in electromagnetic torque. The motor reaches to steady state speed at 0.08 sec. which is more than at no load condition. Back EMF settles at 44 V. once the load is removed all the parameters returns to no load condition. The following conclusion can be drawn

i. The taken to reach the set speed increases with the applied load.
ii. Increase in current magnitude.

Simulation of motor at rated speed and torque

The performance of motor by changing reference speed, following results are obtained. The reference speed is set at 4600 rpm with load torque of 2.2 Nm.

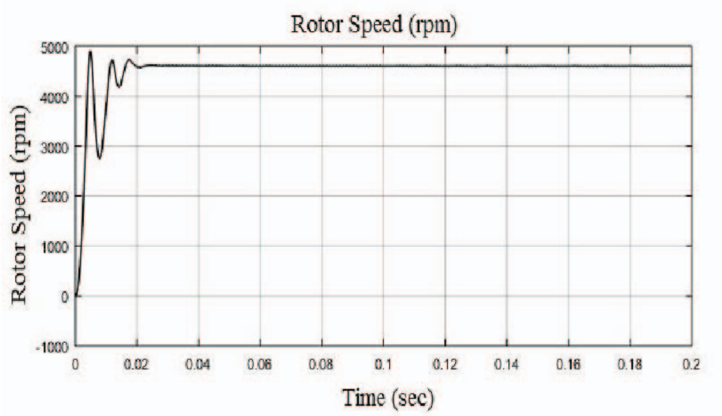

Fig.7 Rotor speed at load torque T= 2.2 Nm

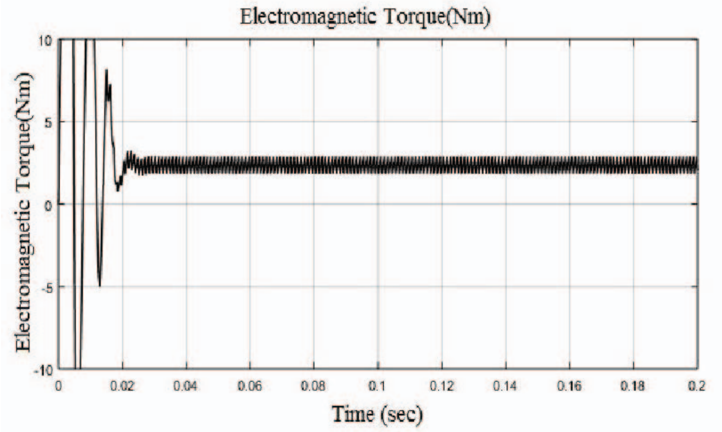

Fig.8 Electromagnetic torque at load torque T=2.2Nm

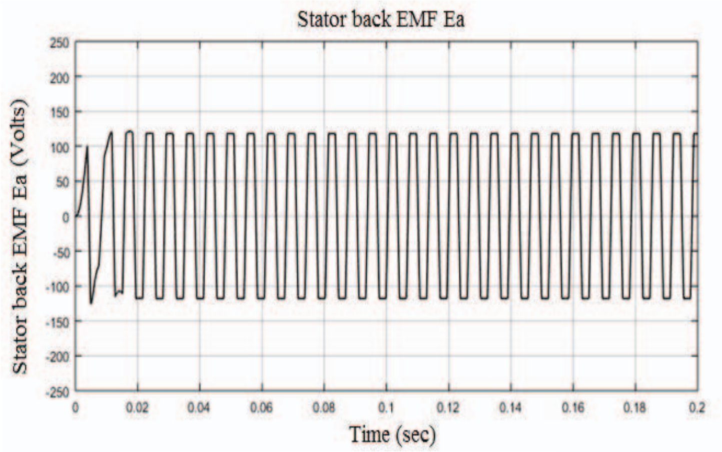

Fig.9 Electromotive force at load torque T= 2.2Nm

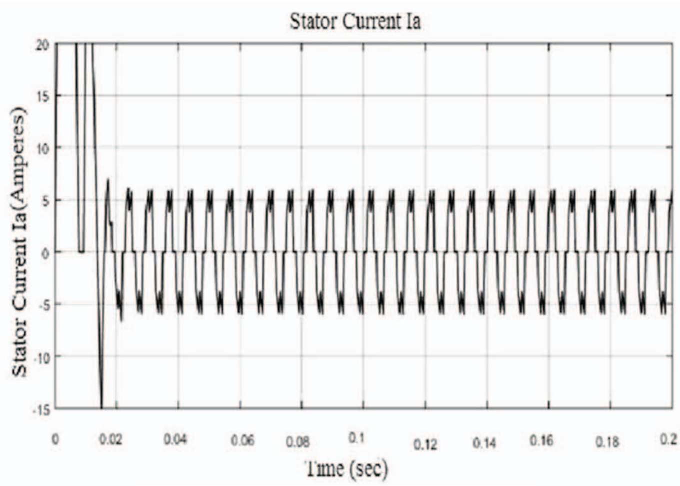

Fig.10 Stator Current at load torque T= 2.2Nm

C. SIMULATION OF BRUSHLESS DC MOTOR USING FIELD ORIENTED CONTROLLER IN MATLAB/SIMULINK

The performance of the developed brushless DC system mode is examined under rated load condition and change in load torque. The parameters of motor are as given in Table I. The simulation results under change in load torque shows following characteristics.

Rotor angle theta quickly settles to its original value to meet the extra load with increase in electromagnetic torque. The motor reaches to steady state speed at 0.01 sec which is same as that of no load condition. Line to line voltage remains same as applied voltage that is at 310 V.

The performance of motor by changing reference speed, following results are obtained. The reference speed is set at 4600 rpm with load torque of 2.2 Nm.

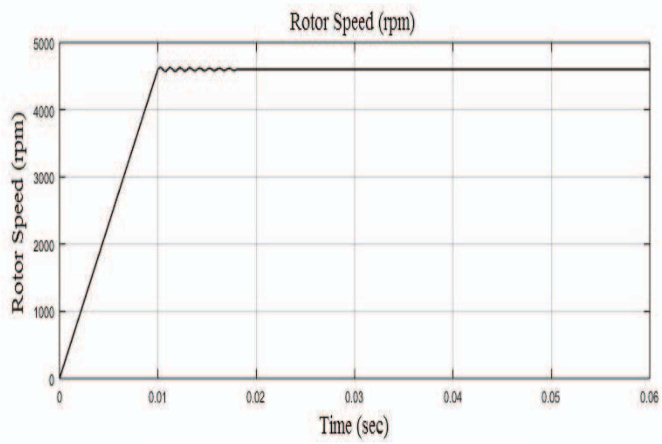

Fig.11 Rated speed at load torque T= 2.2 Nm

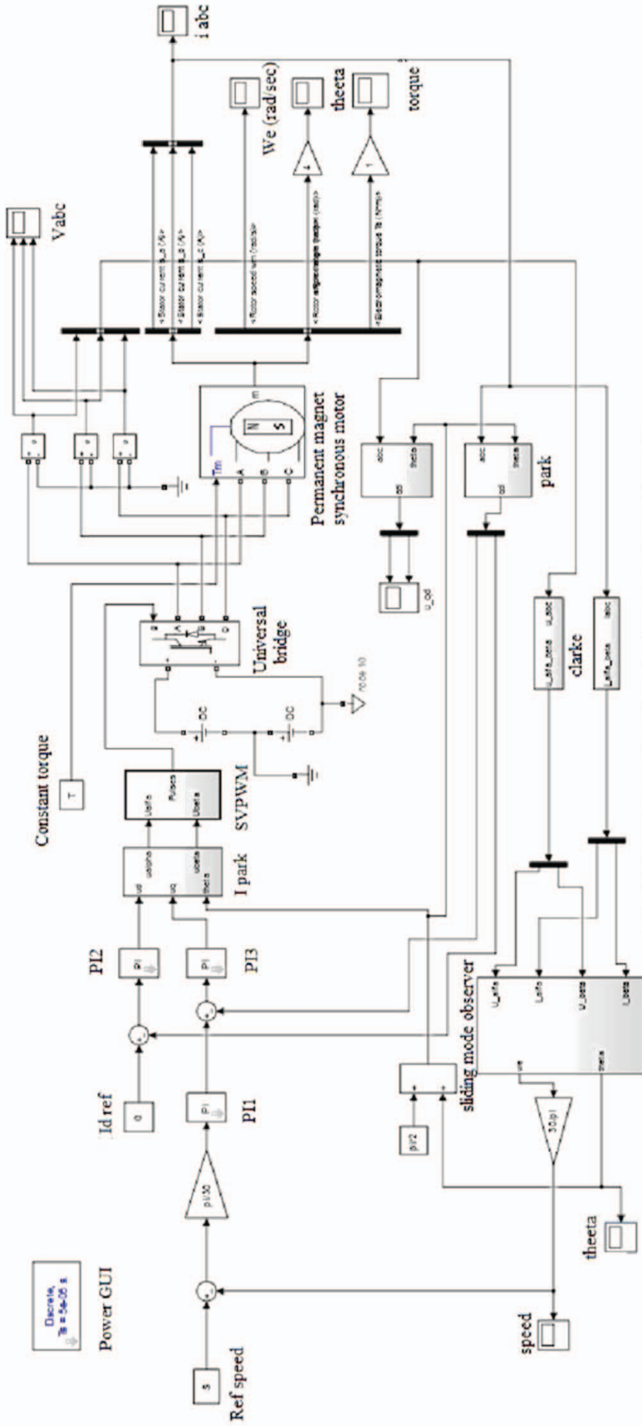

Fig.12 Simulink model of sensorless brushless DC motor

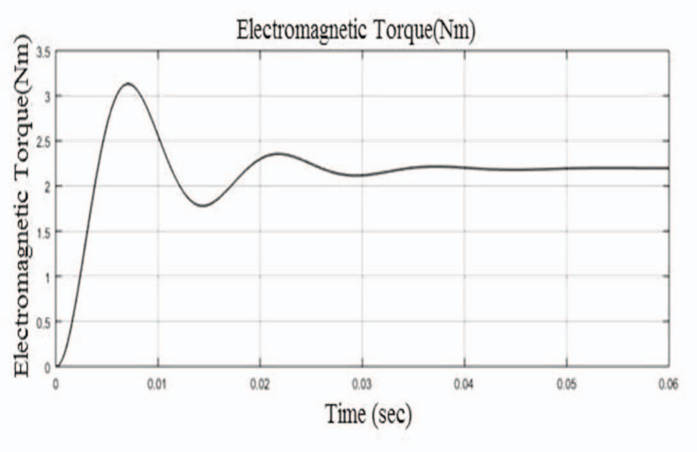

Fig.13 Electromagnetic torque at load torque T= 2.2Nm

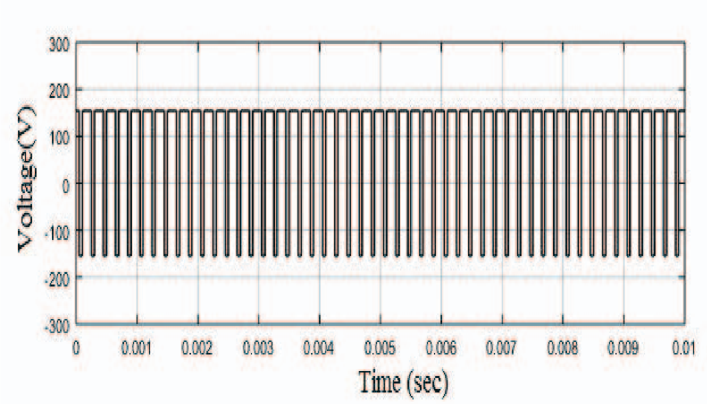

Fig.14 Electromagnetic force at load torque T= 2.2 Nm

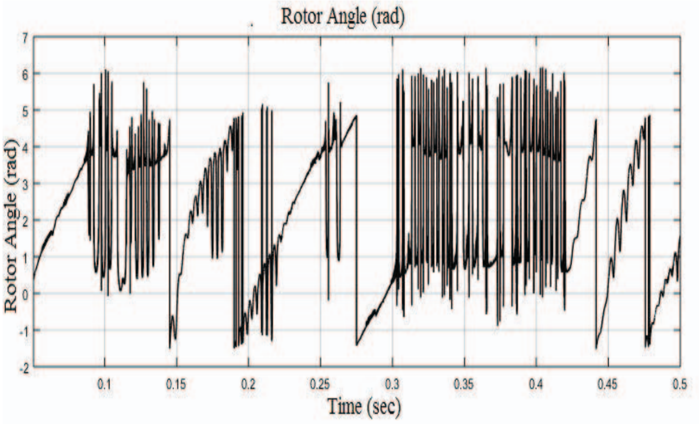

Fig.15 Rotor Angle at load torque T= 2.2 Nm

IV. Conclusion

1. Speed remains virtually constant and matches exactly with actual speed. In the FOC the speed curve comes to steady state value in less time than PI controller.
2. The lower relative torque ripple is seen in FOC compared to traditional BLDC with PI
3. FOC is utilized for the fundamental and there is harmonic reduction
4. The SMO scheme has been implemented and applied to the FOC of BLCD drive which has effectively minimized speed error. Speed performance improved than conventional PI controller.
5. In FOC sliding Mode Observer has been used which acts as a damper to sustain oscillation which can be observed in PI

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