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Modeling, Simulation of Speed Control of BLDC Motor Drive

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ABSTRACT: This paper mainly deals with the Brushless DC (BLDC) motor speed driving systems have sprouted in various small scale and large scale applications like automobile industries, domestic appliances etc. This leads to the development in Brushless DC motor (BLDCM). Brushless dc (BLDC) motor in many cases replaces conventional dc motors. Despite the name, BLDC motors are actually a type of permanent magnet synchronous motors. They are driven by dc voltage but current commutation is done by solid state switches. The commutation instants are determined by rotor position and the position of is detected either by position sensors or by sensor less techniques. The purpose of a motor speed controller in motor drive is to take a signal representing the demanded speed and to drive a motor at that speed. Closed Loop speed control systems have fast response, but become expensive due to the need of feedback components such as speed sensors. PID controller is a generic control loop feedback mechanism (controller) widely used in industrial control systems. The design and analysis of complex power electronics system such as motor drives is usually done using software, such as MATLAB/SIMULINK software.

I. INTRODUCTION

The brushless DC (BLDC) motor is becoming increasingly popular in sectors such as automotive (particularly electric vehicles (EV)), HVAC, white goods and industrial because it does away with the mechanical commutator used in traditional motors, replacing it with an electronic device that improves the reliability and durability of the unit. Another advantage of a BLDC motor is that it can be made smaller and lighter than a brush type with the same power output, making the former suitable for applications [1-5] where space is tight. The downside is that BLDC motors do need electronic management to run. For example, a microcontroller using input from sensors indicating the position of the rotor is needed to energize the stator coils at the correct moment. Precise timing allows for accurate speed and torque control, as well as ensuring the motor runs at peak efficiency.

BLDC motors have advantages over brushed DC motors and induction motors. They have better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation, higher speed ranges, rugged construction and so on. Also, torque delivered to the motor size is higher, making it useful in applications where space and weight are critical factors. With these advantages, BLDC motors find wide spread applications in automotive, appliance, aerospace, consumer, medical, instrumentation and automation industries.

Nowadays, brushless DC motors are widely used in various applications, right from motor vehicle, and industrial application to aircrafts for the control application. The primary reason of increasing usage of brushless DC motor can be attributed to good weight/size to power ratio, excellent acceleration performance, little or no maintenance and less acoustic and electrical noise than Brushed DC motors. This has led to significant researches for the speed control on the BLDC motors. In BLDC motor, the commutation of a BLDC motor is controlled electronically. To rotate the BLDC motor the stator windings should be energized in a sequence. It is important to know the rotor position in order to understand which winding will be energized following the energizing sequence. Rotor position is sensed using Hall-effect sensors embedded into the stator. Mostly BLDC motors have three Hall sensors inside the stator on the non-driving end of the motor. Whenever the rotor magnetic poles pass near the Hall sensors they give a high or low signal indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined.

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Brushless dc (BLDC) motor drives are becoming widely used in consumer and industrial systems, such as servo motor drives, home appliances, computer peripherals and automotive applications [1-5]. Consequently, many machine design and control schemes have been developed o enhance the performance of BLDC motor drives [6-7]. Brushless dc (BLDC) motor in many cases replaces conventional dc motors [8]. Despite the name, BLDC motors are actually a type of permanent magnet synchronous motors. They are driven by dc voltage but current commutation is done by solid state switches. The commutation instants are determined by rotor position and the position of is detected either by position sensors or by sensor less techniques [9]. A simple approach to current sensing pwm control of BLDC motors has been presented [10-11].

P controller, PI controller, PD controller and PID controller are the controller types which can be used in feedback or feed forward systems based on the system requirements. PID controller is widely implemented in closed-loop type of feedback control system for speed control of BLDC motors. P and PD controller is directly proportional to incoming error; hence a little change in error can cause system instability. PI controller is an accurate and provides good system stability i.e. less steady state error response. But the integral factor in controller takes more iteration to reduce error to zero. PID controller is the most reliable, accurate and provides better system stability i.e. less steady state error response as well as it helps to eliminate incoming error to zero with minimum iterations.

The purpose of a motor speed controller in motor drive is to take a signal representing the demanded speed and to drive a motor at that speed. Closed Loop speed control systems have fast response, but become expensive due to the need of feedback components such as speed sensors. PID controller is a generic control loop feedback mechanism (controller) widely used in industrial control systems; a PID is the most commonly used feedback controller. A PID controller calculates an "error" value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs. The PID controller calculation (algorithm) involves three separate constant parameters, and is accordingly sometimes called three-term control: the proportional, the integral and derivative values, denoted *P*, *I*, and *D*. Heuristically, these values can be interpreted in terms of time: *P* depends on the *present* error, *I* on the accumulation of *past* errors, and *D* is a prediction of *future* errors, based on current rate of change [12-13]. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve, or the power supplied to a heating element.

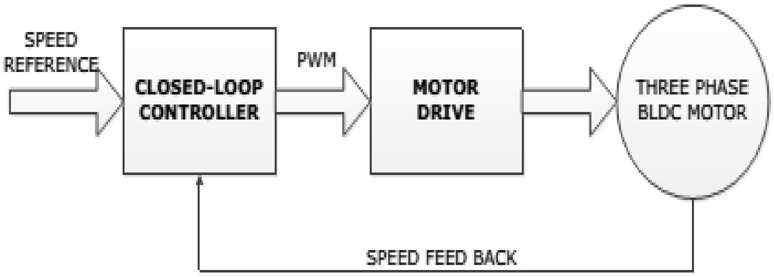

Fig 1 Closed Loop Control Method

PID controller is the most widely used in closed-loop control system. The algorithm works on the error generated from the difference between the reference speed and the actual speed. PID parameters Proportional gain Kp, Integral Gain Ki, and Derivative Gain Kd affects system’s overall performance. Hence choosing right parameters for a system is a difficult process and can be done by using several tuning methods which includes manual tuning, Ziegler-Nicholas tuning and Cohen-coon tuning. Normally a mathematical model of the system is designed along with PID controller and the system performance is observed with applied set of values of PID parameters to finalize the best suited values.

Following are the effects of PID parameters (Kp, Ki, and Kd)

- System Rise time will be reduced by Kp, it provides faster response in variable load condition
- Steady state error will be reduced by Ki , hence the motor speed is pushed near to reference speed

- Settling time and overshoot will be reduced by Kd, hence provides faster response.

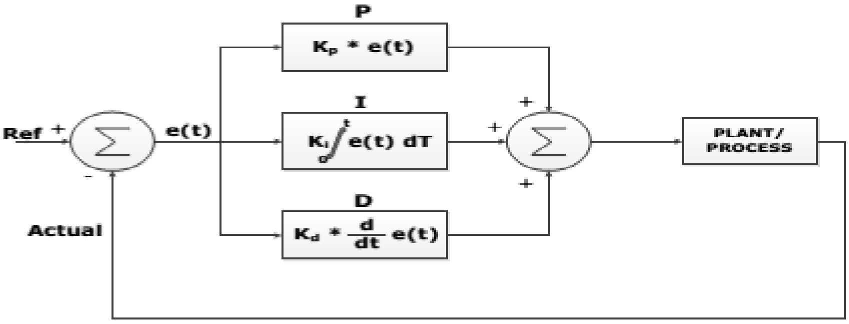

Fig 2 Block Diagram of a System with PID Controller and Feedback loop

There are several methods for tuning a PID loop. The most effective methods generally involve the development of some form of process model and then choosing P, I, and D based on the dynamic model parameters. Manual tuning methods can be relatively inefficient, particularly if the loops have response times on the order of minutes or longer. If the system must remain online, one tuning method is to first set and Ki values to zero. Increase the Kp until the output of the loop oscillates, and then the Kp should be set to approximately half of that value for a "quarter amplitude decay" type response. Then increase Ki until any offset is corrected in sufficient time for the process. However, too much Ki will cause instability. Finally, increase Kd, if required, until the loop is acceptably quick to reach its reference after a load disturbance. However, too much Kd will cause excessive response and overshoot. A fast PID loop tuning usually overshoots slightly to reach the set point more quickly; however, some systems cannot accept overshoot, in which case an *over-damped* closed-loop system is required, which will require a Kp setting significantly less than half that of the Kp setting causing oscillation [14-15].

II. MODELLING

Modelling of a BLDC motor can be developed in the similar manner as a three phase synchronous machine. Since its rotor is mounted with a permanent magnet, some dynamic characteristics are different. Flux linkage from the rotor is dependent upon the magnet. Therefore, saturation of magnetic flux linkage is typical for this kind of motors. As any typical three phase motors, one structure of the BLDC motor is fed by a three phase voltage source as shown in Fig 3. The source is not necessary to be sinusoidal. Square wave or other wave- shape can be applied as long as the peak voltage is not exceeded the maximum voltage limit of the motor.

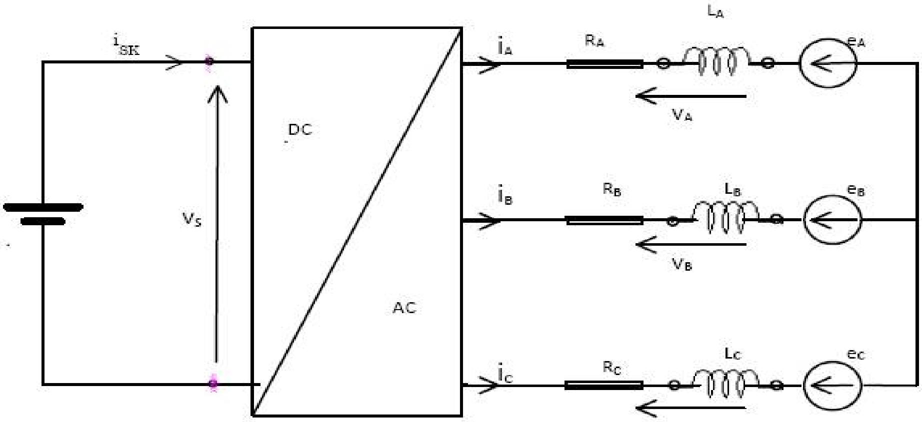

Fig 3 BLDC Model

Applying Kirchhoff's voltage law for the three phase stator loop winding circuit's yields:

$$v_a = R_a + L_a \frac{di_a}{dt} + M_{ab}\frac{di_b}{dt} + M_{ac}\frac{di_c}{dt} + e_a \tag{1}$$

$$v_b = R_b + L_b \frac{di_b}{dt} + M_{bc}\frac{di_a}{dt} + M_{ba}\frac{di_c}{dt} + e_b \tag{2}$$

$$v_c = R_c + L_c \frac{di_c}{dt} + M_{ca}\frac{di_a}{dt} + M_{cb}\frac{di_b}{dt} + e_c \tag{3}$$

Where the back-EMF waveforms e_a, e_b, e_c are functions of angular velocity of the rotor shaft, so

$$e = K_e \omega_m \tag{4}$$

Where K_e is the back-emf constant

So the BLDC motor mathematical model can be represented by the following equation in matrix form:

$$\begin{bmatrix} L_a & M_{ab} & M_{ac} \\ M_{ba} & L_b & M_{bc} \\ M_{ca} & M_{cb} & L_c \end{bmatrix} \frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{5}$$

If we assume that the rotor has a surface-mounted design, which is generally the case for today's BLDC motors, there is no saliency such that the stator self inductances are independent of the rotor position, hence:

$L_a = L_b = L_c = L$

And the mutual inductances will have the form:

$M_{ab} = M_{ac} = M_{ba} = M_{ca} = M_{cb} = M$

Assuming three phase balanced system, all the phase resistances are equal:

$R_a = R_b = R_c = R$

Rearranging the equation (5) yields;

$$\begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{6}$$

The electromechanical torque is expressed as

$$T_{em} = J\frac{d\omega_r}{dt} + B\omega_r + T_L \tag{7}$$

But the electromagnetic torque for this 3-phase BLDC motor is dependent on the current, speed and back-EMF waveforms, so the instantaneous electromagnetic torque can be represented as:

$$T_{em} = \frac{1}{\omega_m}\left(e_a i_a + e_b i_b + e_c i_c\right) \tag{8}$$

The symbols v, i and e denote the phase voltages, phase currents and phase back-emf's respectively, in the three phases a, b and c. The resistance R and the inductance L are per phase values and T_e and T_L are the electrical torque and the load torque. J is the rotor inertia; K_f is a friction constant and ω_m is the rotor speed. The back-emf and the electrical torque can be expressed as

$$e_a = \frac{k_e}{2}\omega_m F(\theta_e) \tag{9}$$

$$e_b = \frac{k_e}{2}\omega_m F\left(\theta_e - \frac{2\pi}{3}\right) \tag{10}$$

$$e_c = \frac{k_e}{2}\omega_m F\left(\theta_e - \frac{4\pi}{3}\right) \tag{11}$$

$$T_e = \frac{k_t}{2}\left[F(\theta_e) + F\left(\theta_e - \frac{2\pi}{3}\right) + F\left(\theta_e - \frac{4\pi}{3}\right)\right] \tag{12}$$

respectively, where K_e and K_t are the back-emf constant and the torque constant.

Machine models are often transformed to a rotating reference frame for simplification and to improve computational efficiency. This approach is not used here as it has been shown that when the supply voltage is not sinusoidal, such transformation will not improve computational efficiency.

III. SIMULINK MODEL FOR BLDC MOTOR

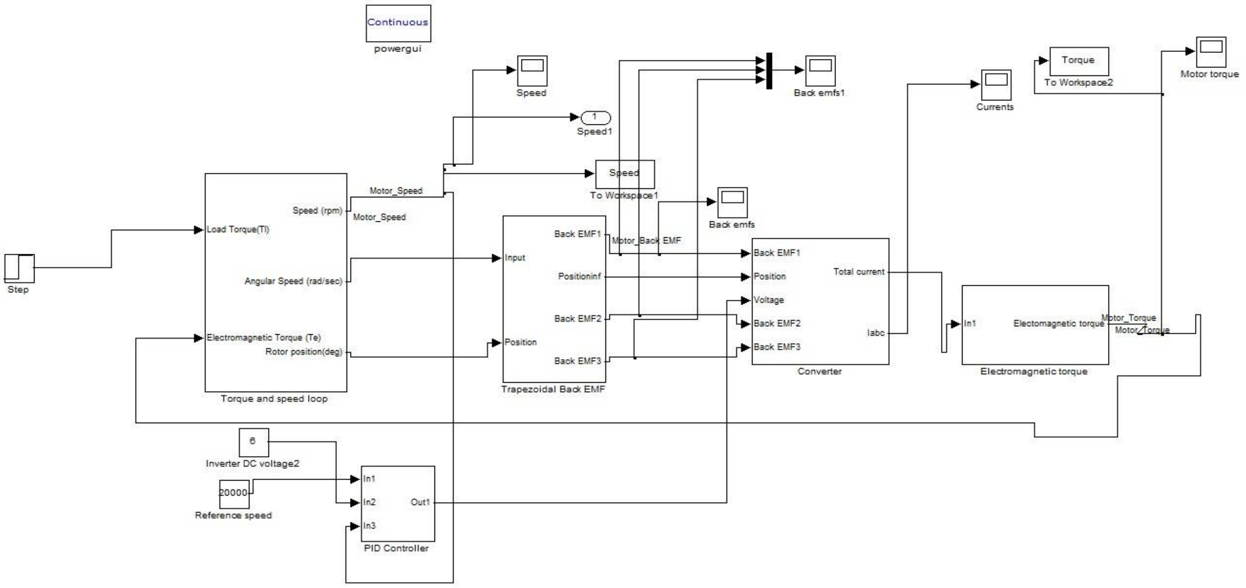

Fig 4 Simulink model for BLDC Motor

As shown in fig 4, the overall block diagram of the developed model for BLDC Motor consists of four main blocks. They are torque speed block, Back emf block, converter block and Electromagnetic torque block. Each main block has several sub-blocks.

A) Speed Control Block

Speed and torque characteristics of the BLDC motor can be explained with equation (7), neglecting the damping factor as

$$\omega_r = \frac{1}{J}\int\left(T_e - T_L\right)dt = \frac{1}{J}\int\left[\left(T_a + T_b + T_c\right) - T_L\right] \tag{13}$$

And the Rotor position is calculated as

$$\theta_e = \int\left(\omega_r\right)dt \tag{14}$$

The torque speed block takes in the difference between the electrical torque and mechanical torque and generates the speed and rotor position signals, as shown in fig 5.

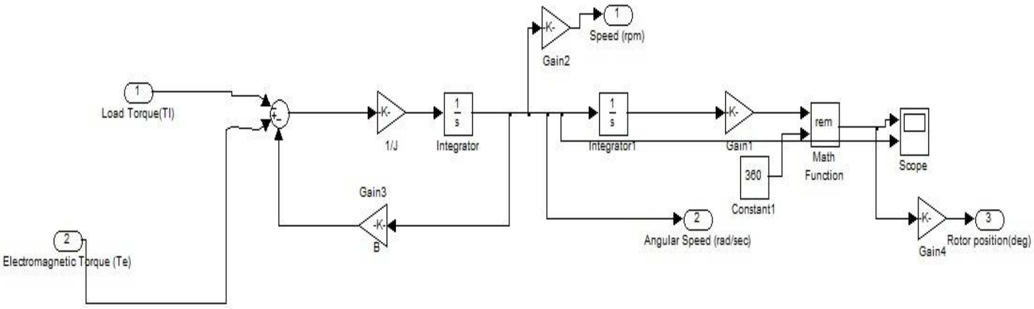

Fig 5 Calculation of Speed Position signals

B) Back EMF Block

As shown in fig 5, the back EMF is function of rotor position (θ) and the amplitude $E = K_e \cdot \omega_r$ (K_e is the back EMF constant). In this work the modeling of the back EMF is performed under the assumption that all three phases have identical back EMF waveforms. Based on the rotor position, the numerical expression of the back EMF is obtained as equations (9), (10) and (11), and it is implemented as shown in the fig 6. The trapezoidal functions and the position signals are stored in lookup tables that change their output according to the value of the rotor position.

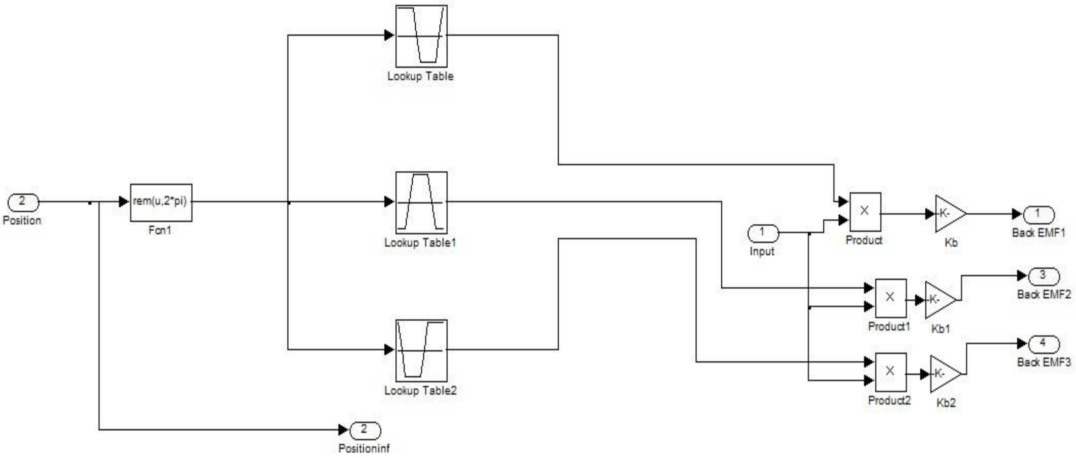

Fig 6 Back-EMF generating block from rotor positions

C) Converter Block

The torque is the function of back emf and rotor position (θ) and phase currents. Based on the rotor position, the numerical expression of the back EMF is obtained as equations (8), and (12), and it is implemented as shown in the fig 7. The trapezoidal functions and the position signals are stored in lookup tables.

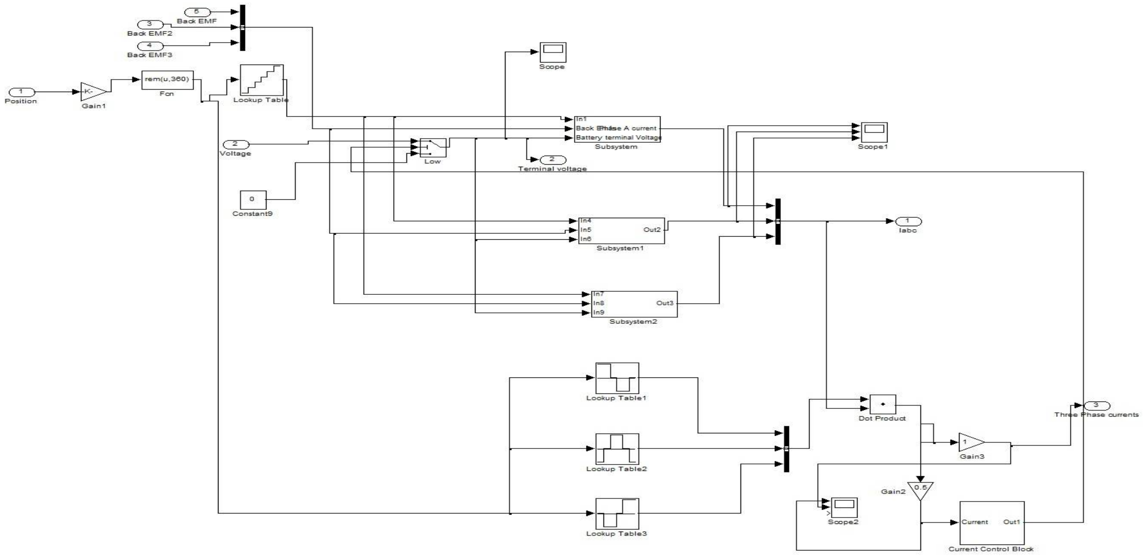

Fig 7 Phase current and torque generating block from rotor positions and Back-EMFs

As per the equations (1), (2) and (3), the phase currents are the functions of Back EMFs, phase voltages, winding inductance (L) and resistance (R) and these equations are implemented as shown in fig.6. In BLDC motor, only two phases conduct current at any time, leaving the third phase floating. The commutation phase sequence is like AB-AC-BC-BA-CA-CB as shown in phase energizing sequence table 1.The rotor positions representing the integer numbers are stored in the lookup tables.

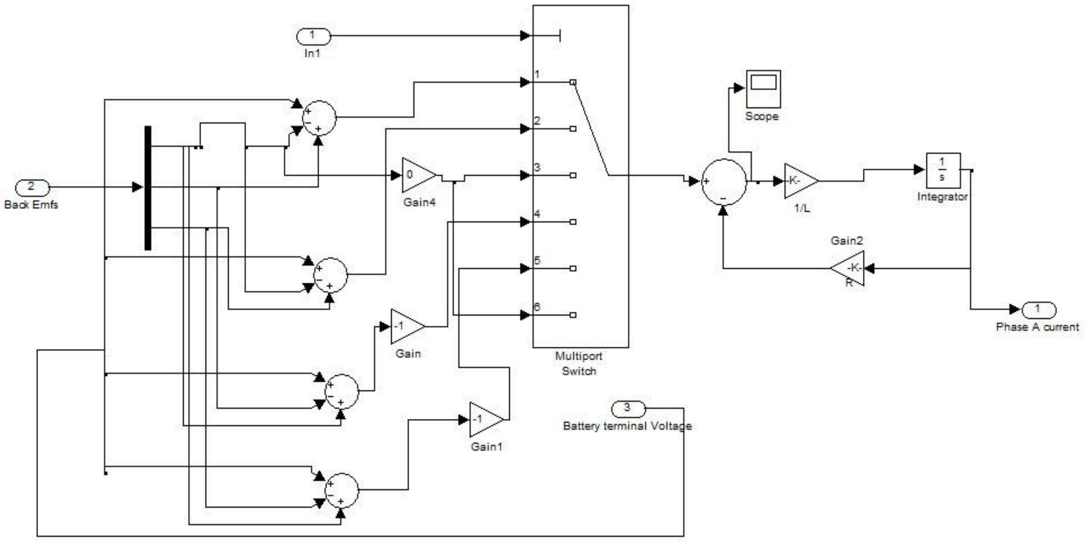

Fig 8 Phase current generating block from rotor positions and Back-EMFs

D) Current Controller Block

In this work only one current controller is used. This strategy, suggested and presented in [11], is simple and avoids difficult sensing of the DC-link current. A signal equivalent to DC-link current is synthesized from the measurement of two phase currents. A necessary condition for the validity of this method is that the sum of the phase currents is zero. This method is suits the BLDC motor used here as it is a three phase star-connected motor with an ungrounded neutral point. The proposed current control is implemented in Simulink as shown in the fig.7.

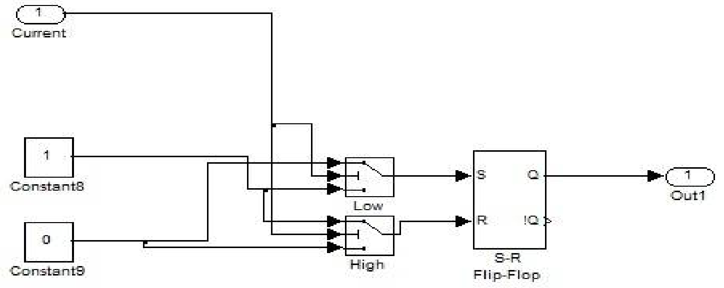

Fig 9 Current control subsystem

E) Speed Controller Block

A PID speed controller proposed in this work, for closed loop operation of the BLDC motor is implemented as shown in the fig 10 PID controller is a promotional, integral plus derivative controller whose transfer function is:

$$G_{PID}(s) = K_P(1+\frac{1}{T_i s}+T_d s) \tag{15}$$

The selection of the Proportional, Integral and derivative (PID) controller parameters have been obtained using manual tuning methods. In this method to first Integral gain Ki and Derivative gain Kp values set to zero. Proportional Kp is increased until the output of the loop oscillates; they Kd should be set to approximately half of that value for a "quarter amplitude decay" type response. Then Ki, has been increased until any offset is corrected in sufficient time for the process. Finally, Kd has been increased until the loop is acceptably quick to reach its reference after a load disturbance.

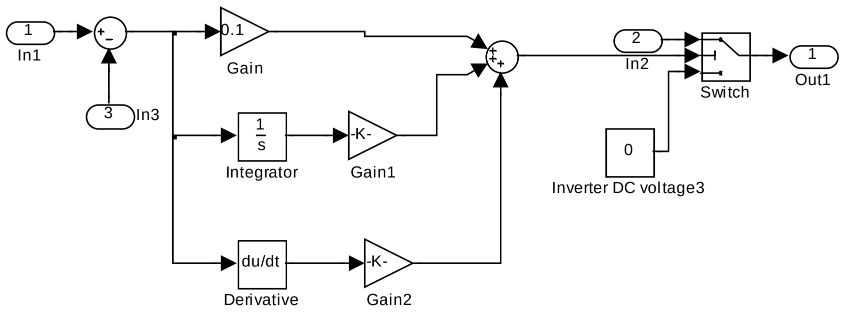

Fig 10 PID Speed controller subsystem

IV. Simulation

The simulations are done in MATLAB and Simulink using the default solver ode45. The simulation time is 0.15 Seconds. Fig 11 shows the open loop motor speed plot. A peak over shoot is observed in the open loop response. A correct value of the no load speed is achieved by selecting a suitable value of friction constant. Otherwise, the no-load speed becomes a little too high. Fig.10 shows the electrical torque. The stall torque is about 0.50m Nm which agrees well with the value in the table 1.

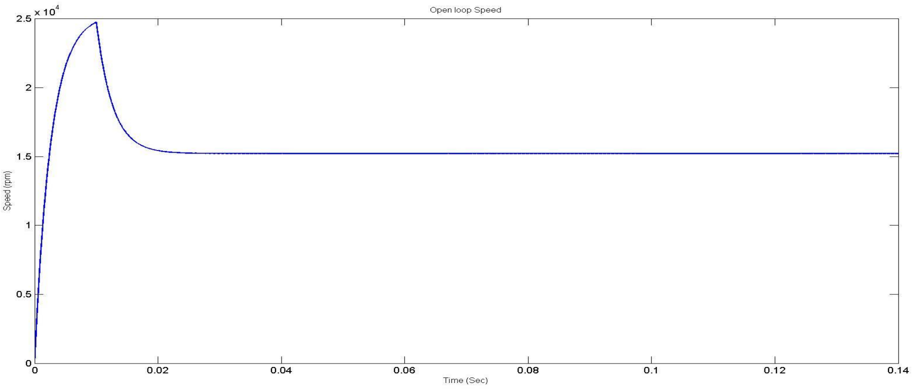

Fig 11 Open loop Rotor Speed

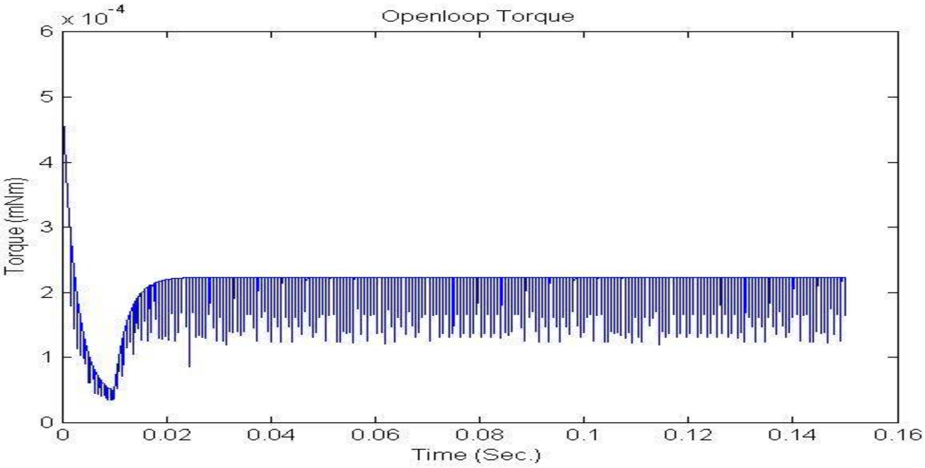

Fig 12 Open loop Electrical Torque

A plot of torque Vs speed is shown in the fig13. The torque speed characteristics follow a straight line with the exception of the points where notches occur in the torque. The stall torque is about 0.50 mNm which is in accordance with the motor data.

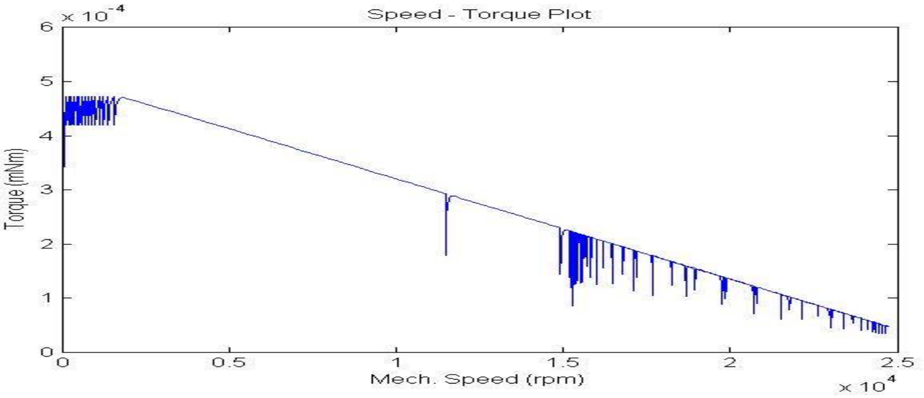

Fig 13 Torque- Speed plot

Fig.14 shows the phase currents. The current starts with a high value and decays as the motor speeds up until no- load current which is about 60 mA which agrees with the value in table 1. The current is raises again when the load torque is applied and reaches a steady state value of 250 mA. The current has perfect quasi-square wave shape. The only deviation from the quasi-square wave shape occurs at commutation points. The notches at the commutation points occur because the raise of the current in the phase that is being turned on is slower than the decay of the current in the phase that is being turned off. The notches are the cause of the well known torque ripples of BLDC motors.

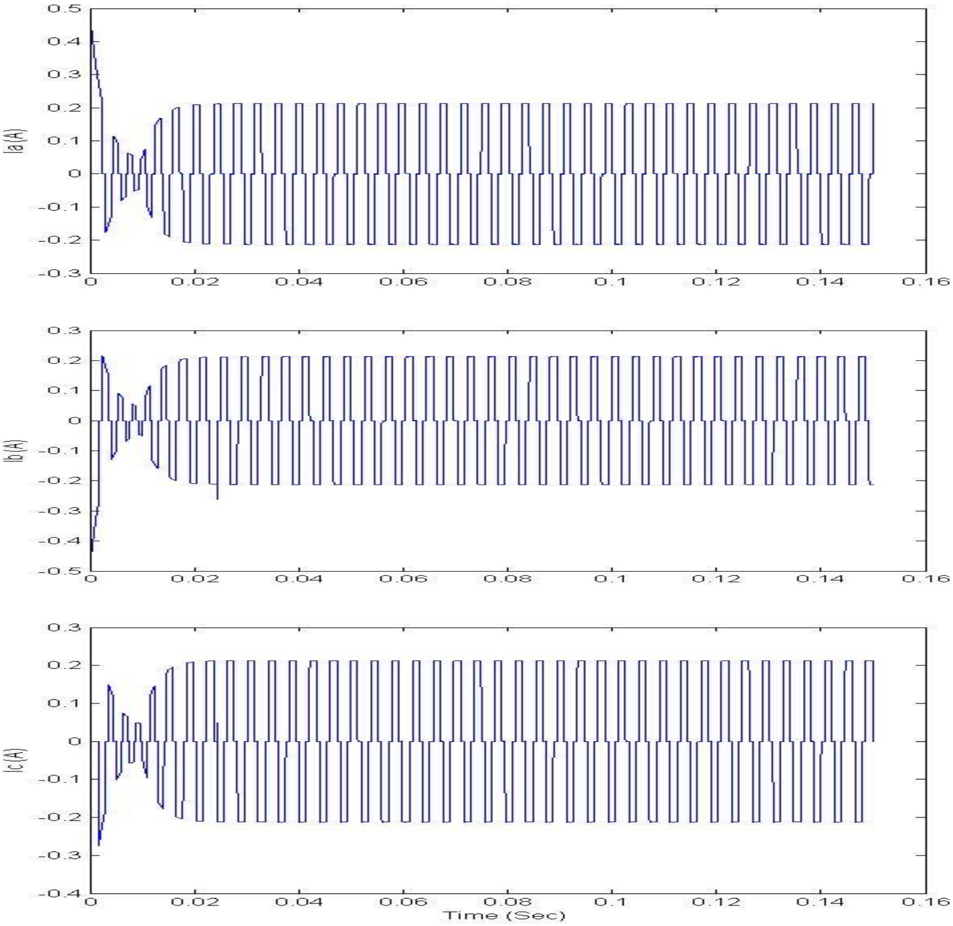

Fig 14 Phase Currents

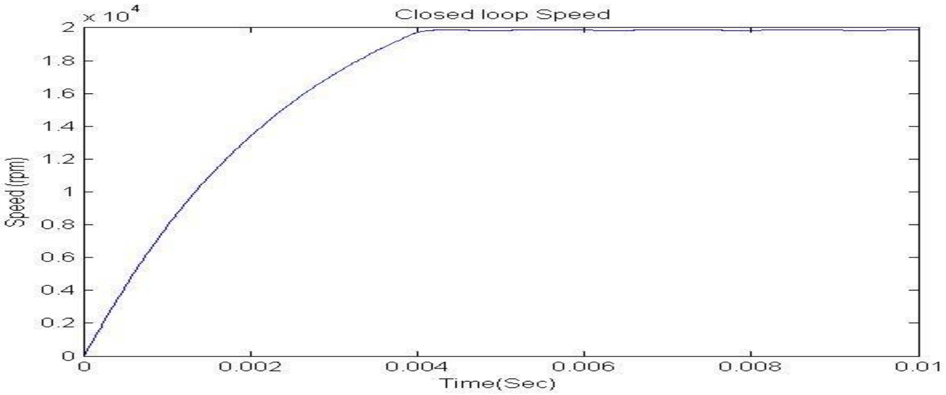

Fig 15 Closed loop Speed

Fig 15 and fig.16 shows the closed loop speed and torque plots. From the fig.15 it can be observed that, the overshoot in the motor speed response is zero and the steady state error is almost zero. But the speed response is taking more time to reach reference speed the steady state.

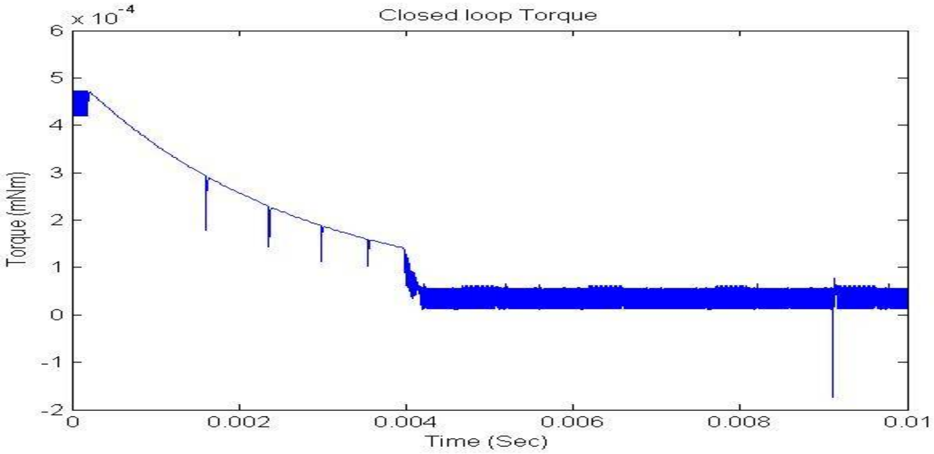

Fig.16 Closed loop Torque

The model appears to be correct. The torque- speed relationship is linear and the stall torque, no-load speed and no load current all agrees with the values given in the motor's data sheet.

V. CONCLUSIONS

A new and simple method is proposed to reduce the cost and to improve the performance of the drive. The proposed method obtains the actual phase current values by using a single DC link current sensor, thus reducing the cost and the size of the drive. The PID controller design has been simulated and observed the good performance, the results show that the over shoot before adding the PID controller was 25%, but after adding PID controller the maximum overshoot was approximately zero which is a good result.

Also, if the current sensor is placed on the ground line, insulated systems are not necessary and a low cost resistor can be used. Here the undesirable imbalances in the phase currents as well as pulsating torque due to mismatched in the current sensor sensitivities is also avoided. The simulation results show that, by using the proposed method, drive gives the same closed loop performance as that of the conventional method.

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