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Controlling of Permanent Magnet Brushless DC Motor using Instrumentation Technique

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Abstract - *The paper characterizes the controlling the permanent magnet brushless DC motor with sensor via instrumentation technique. A Permanent magnet brushless DC motor is gaining popularity since its uses sensors instead of brushes and commutators. A Brushless DC motor has been used in this paper since it has high efficiency, reliable and requires lower maintenance cost. PWM technique is used for the controlling of FPGA (Field Programmable Gate Array) device that calculates the duty cycle as required. The paper deals with the analyses of speed control of the Brushless DC motor which can be done using PID controller.*

Keywords - *Permanent Magnet Brushless DC motor (PMBLDC), Pulse Width Modulation (PWM), Hall position sensors, Proportional-Integral-Derivative (PID) Controller, Decoder.*

I. INTRODUCTION

A Brushless DC motor is more advantageous as compared to the other motors because a Brushless DC motor have better characteristics and performance. A DC motor has a linear relationship between current-torque and voltage-rpm characteristics. A Brushless DC motor uses electronic commutators and sensors rather than the mechanical commutation process, which is used in a brushed DC motor. The use of Brushless DC motor reduces mechanical losses and hence efficiency is improved. A Brushless DC motor has high dynamic response, better speed-torque characteristics, high efficiency and more reliable as compared to a brushed DC motor. A Brushless DC motor has more lifetime (as there are no brushes) and has noiseless operation. A Brushless DC motor is a high performance motor and is mainly used for applications which need good accuracy. The speed of the motor can be controlled using open loop control method or close loop control method, which can be obtained by varying the duty cycle.

II. CONTROL TECHNIQUES AND MODELLING FOR A PMBLDC MOTOR

In general there are several methods for controlling a Permanent Magnet Brushless DC Motor. The two important techniques that are commonly used are sensor method and sensor less method. A sensor control technique involves the requirement of exact rotor position for better and improved performance of a BLDC motor and for the calculation of the next commutation level. For the detection of the rotor position a BLDC motor uses an inverter and a position sensor. In consideration to the system response for speed and stability factor, a conventional PID controller is used. A conventional PID controller also amplifies the speed of the motor since the characteristics of the PID controller includes simplicity, easy adjustment and high reliability. A PWM technique is used to control high energy with maximum efficiency and power saving which can be generated using an FPGA (Field Programmable Gate Array) control. A PWM control also adjusts the duty cycle. The frequency of the PWM technique should be 10 times to that of the maximum frequency of the circuit. The design uses 6 switches which can be either MOSFET's or IGBT's, which can be controlled using Hall sensors. The rotor position of the motor is also sensed using Hall Effect sensors. In this method two coils will work at a same time for a 3-phase supply and a phase shifting of 60° and 120° is given to the coils. The speed control of a Brushless DC motor can be done using an open loop control and close loop control. A close loop having Proportional-Integral-Derivative (PID) control uses feedback mechanism which is used in industrial control system. The values of K_p, K_d and K_i are calculated using Ziegler-Nicholas method.

Mathematical model of a Brushless DC motor is not much different from a conventional DC motor. The dynamics of a Brushless DC motor are described by the set of mathematical differential equations.To obtain the electrical equations of a BLDC motor, a basic circuit is considered for the calculation of the per phase voltage equations.

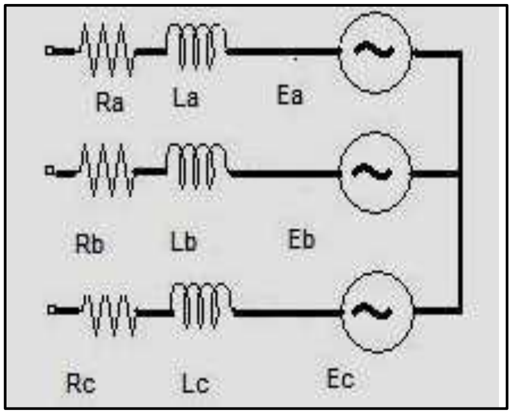


Fig. 1: Mathematical Modelling circuit of motor

The voltage equations of a BLDC are given as:

$$V_a = R_a i_a + \frac{d}{dt}(L_{aa} i_a + L_{ab} i_b + L_{ac} i_c) + e_a$$
$$V_b = R_b i_b + \frac{d}{dt}(L_{ba} i_a + L_{bb} i_b + L_{bc} i_c) + e_b$$
$$V_c = R_c i_c + \frac{d}{dt}(L_{ca} i_a + L_{cb} i_b + L_{cc} i_c) + e_c$$

Considering a balanced system, the voltage equations of a BLDC system becomes:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

The mathematical model of a BLDC motor is described by the above equation where rotor induced currents are neglected. Since the stator winding resistances are equal, therefore rotor reluctances does not change and hence the equations become:

$$L_{aa} = L_{bb} = L_{cc} = L$$
$$L_{ab} = L_{ba} = L_{ac} = L_{ca} = L_{bc} = L_{cb} = M$$

The inductances are now assumed to be constant for self and mutual induction so the voltage equation becomes:

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

Since the stator phase currents are considered to be balanced, therefore:

$$i_a + i_b + i_c = 0$$

Considering the mutual inductances to be same for the matrices, the space state equation becomes:

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

It is now considered that the back EMF of a BLDC motor will have a Trapezoidal waveform with magnitude of ±1.

The Electromagnetic torque of the motor is given by the equation:

$$Te = (e_a i_a + e_b i_b + e_c i_c)/w_r \text{ (N-m)}$$

And the equation of motion is given as:

$$\frac{dw_r}{dt} = (T_e - T_L - Bw_r)/J$$

Therefore:

$$\frac{Jd^2\theta}{dt^2} - T_e + T_L + Bw_r = 0$$

The above equation is the universal torque equation, where:
B is damping coefficient
T_e is electrical torque
T_L is load torque
w_r is damping torque
J is the moment of inertia
$w_r = d\theta/dt$

III. PWM CONTROL FOR A BLDC MOTOR

The pulse width modulation (PWM) switching technique is the most widely used technique for controlling the speed of the motor.

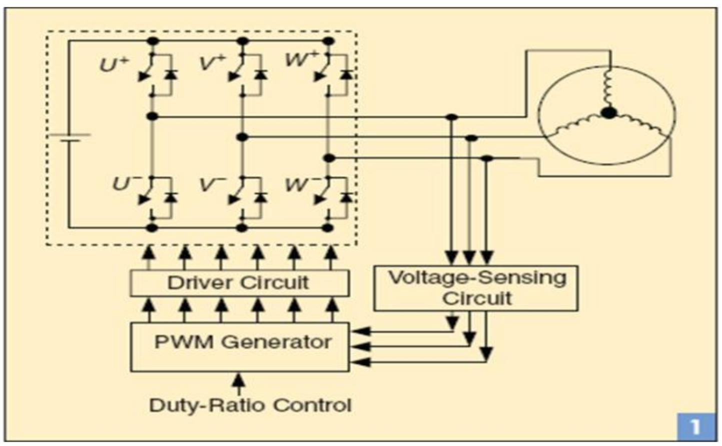


Fig. 2: Motor Drive System using PWM Control

In the PWM technique the methods employs a fixed DC input voltage to the inverter and a controlled AC output voltage is obtained by adjusting the ON and OFF periods of an inverter components, which is done by adjusting the firing angle of the IGBT's used in the circuit which works as a switch in the circuit. The advantages of the PWM techniques are those that the output voltage is controlled without any of the additional components and also that the lower order harmonics can be eliminated or minimized along with the output voltage control. A PWM control technique does not have an inherent current controlling capacity, unlike hysteresis current controller. Hence there is a necessity of introducing a current limiter in the circuit.

To vary the speed using hall output sensors the circuit should be pulse width modulated. When the signals of the inverter based drive sources i.e. VSI are marked by the PWM control strategies for switching on or off the signal according to the sequence then the motor will run at the rated speed. According to the Thumb rule the PWM signal frequency should be 10 times to that of the maximum frequency given to the circuit. By varying the duty cycle of the VSI system which is designed using IGBT's the stator voltage of the overall system can be increased which hence increases the speed of the motor. PWM signal also serves to control the average output voltage which was given a fixed input voltage. This is achieved by using power switches to vary time for which the DC input is applied to the load. The voltage controlled signal ($V_{control}$) is compared with the saw-tooth signal ($V_{sawtooth}$) to produce a PWM signal. If the voltage control signal is greater than the saw-tooth signal, then the switch is turned on for current conduction else the switch is turned off for current conduction.

IV. OPERATION OF HALL SENSORS AND SPEED CONTROL STRATEGIES

The hall sensors are embedded into stator slots on non driving ends of the motor. These are used to sense the accurate position of the rotor with respect to the stator. The stator windings of a BLDC motor are energized in a sequence.

The direction of force is determined by changing the direction of current and applying Fleming's left hand rule. The design is implemented to use six coils that are IGBT's and two coils are used at a time with a phase shift of 60° and 120°,so the permanent magnet of the rotor and the rotor of a BLDC motor starts moving in a clockwise direction.

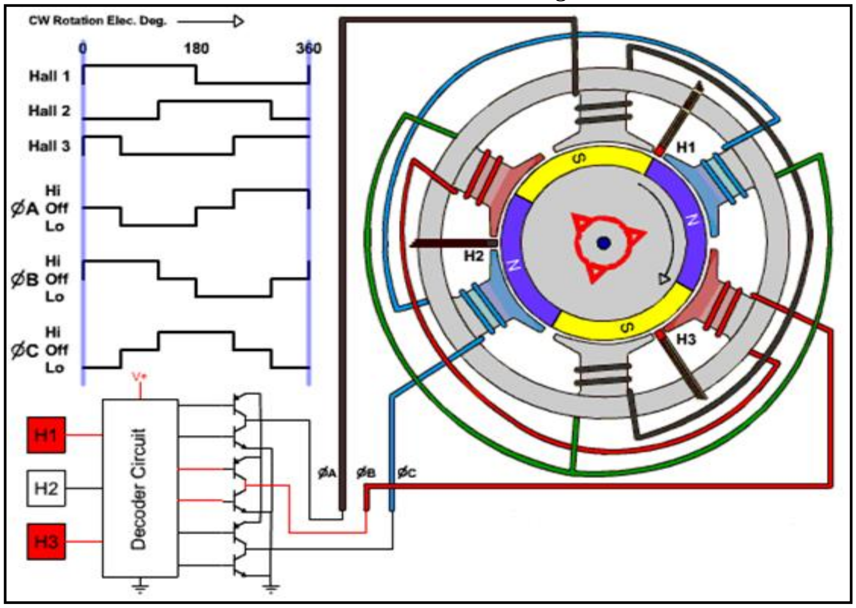


Fig 3: Hall Sensor circuit operation with 4 pole DC motor

The figure shows the operation and output waveforms of a 4 pole BLDC motor for hall sensor operation where the output is a square waveform which is taken from 0° to 360° for one complete cycle. The effect of the hall sensors on rotor magnetic poles is such that the hall sensor gives high or low signals indicating north or south poles whenever rotor magnetic poles pass through the hall sensors. The exact sequence of the commutation is determined using three hall sensor signals.

The speed control strategies for a Brushless DC motor can be open loop control or close loop control, which can be done using PID controller for the given circuit.

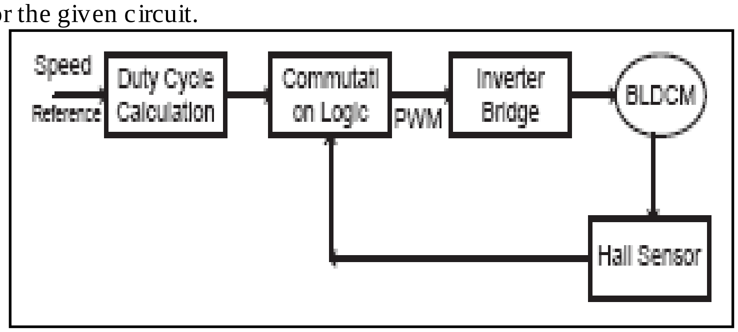


Fig. 4: Open Loop Speed Control of a BLDC Motor

In an open loop control technique there is no feedback provided for the controlling of the speed. In this technique a reference speed is already set at the starting of the motor and hence the stability of the system is maintained in this technique as compared to the closed loop control method for speed control.

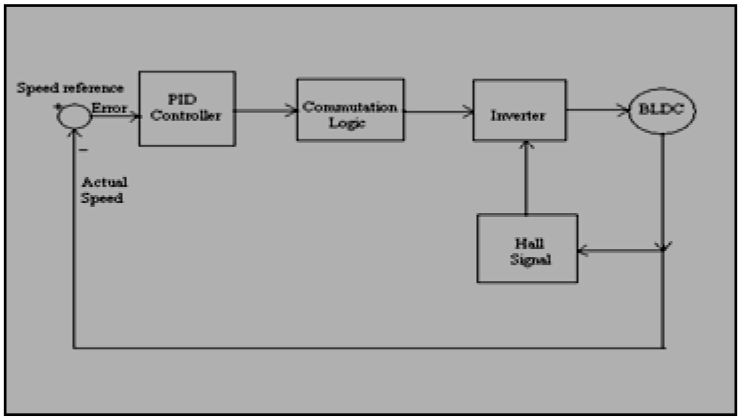


Fig. 5: Close Loop Speed Control of a BLDC Motor

In a close loop control technique a feedback loop is provided for controlling the speed of the motor. A closed loop PID controller is desirable for a stable system which involves a cascade control loop this includes an inner current control loop and an outer speed control loop. Figure 6 shows the diagram where actual speed of the motor is calculated using a rotor position sensor. The error is generated when there is a difference between the reference speed and the actual speed of the motor. A PID controller can be used to amplify the speed errors and dynamically adjusts the PWM duty cycle.

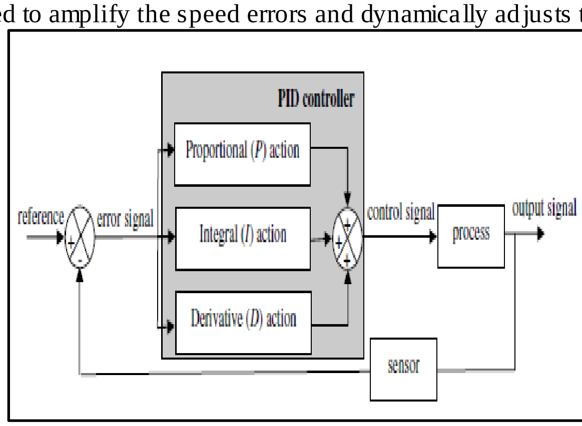


Fig. 6: PID Controller for a Closed Loop Control

RESPONSE	RISE TIME	OVERSHOOT	SETTLING TIME	STEADY STATE ERROR
Kp	Decrease	Increase	Small Change	Decrease
Ki	Decrease	Increase	Increase	Eliminate
Kd	Small Change	Decrease	Decrease	Small Change

Table 1: Characteristics of a PID Controller

The tuning of the PID controller can be done using trail and error method or using Ziegler Nicholas method. For low cost, low resolution speed requirements the hall sensors can be used to measure the speed feedback for a BLDC motor. The PID controller incorporates with the control scheme for the speed of the motor and provides a signal to the PWM inverter.

$$Speed\ Error = Desired\ Speed - Current\ Speed$$

$$Integral\ Error = Integral\ Error + Speed\ Error$$

V. SIMULATION MODEL AND RESULTS

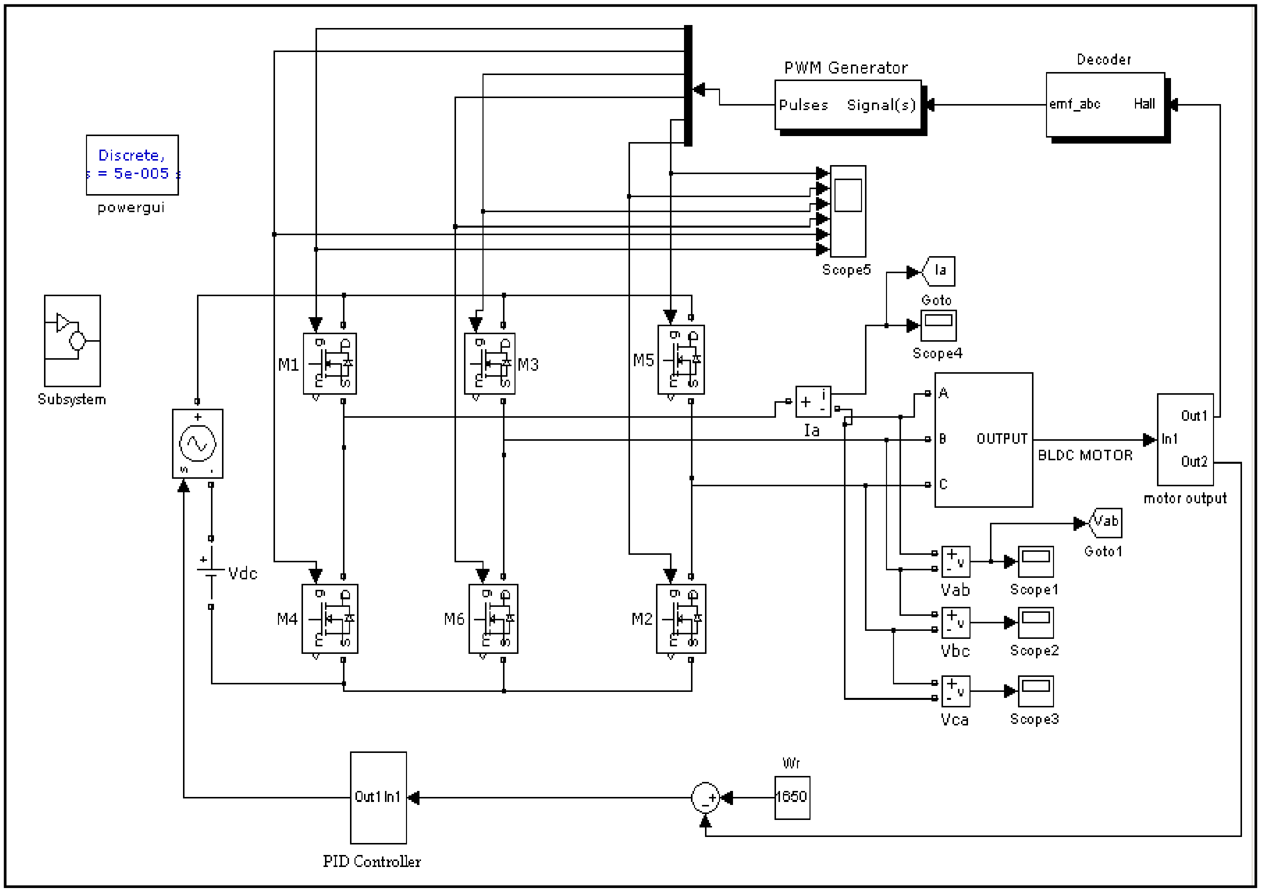
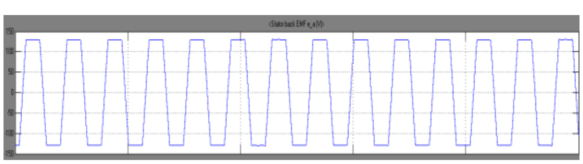


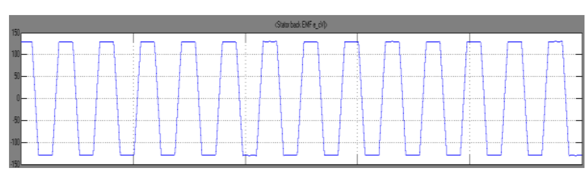
Fig 7: Simulink Model of a BLDC Motor using PWM sensor control

A Matlab Simulation model of a Brushless DC motor is shown in the figure where the reference speed is set at 1650 rpm and the load torque disturbance is applied for the duration of 0.05 seconds. A subsystem is shown which corresponds to the Total Harmonic Distortion which is improved using PWM technique. PWM generator is also used to vary the speed of the motor. Hall Effect sensors are used to sense the position of the rotor for controlling of the speed of the rotor. A De-multiplexer is used after the PWM Generator for the gate pulses which are given to the IGBT's for their operation. A BLDC motor is used where the outputs are divided into two parts; one of the output is the input to the error in the speed i.e. the actual speed while the other output is input to the Hall sensors with the help of which an emf is generated whose output signal is given as input to the PWM pulse generator, where de-multiplexer is used for the gate signal of the IGBT. A PID controller is used for the closed loop speed control of the motor. The outputs of the different factors of the simulation model are obtained using scope and the waveforms obtained are shown below where the phase voltages are displaced at an angle of 120° from each other.

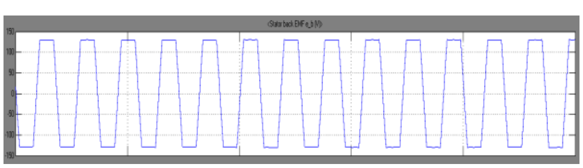
Back emf A



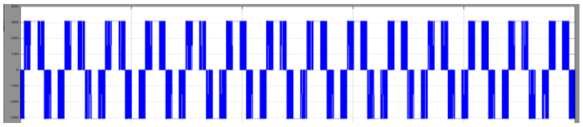
Back emf C



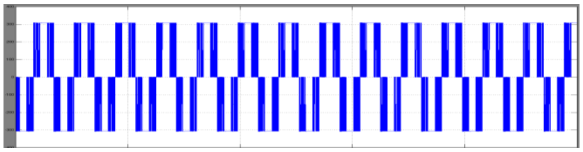
Back emf B



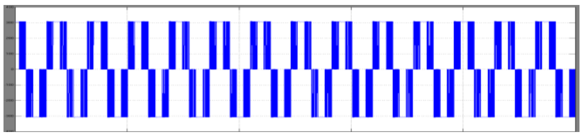
Phase voltage A



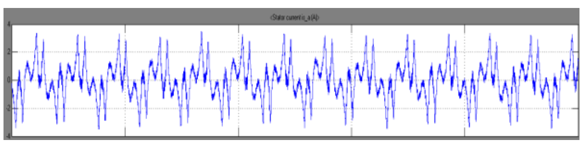
Phase voltage B



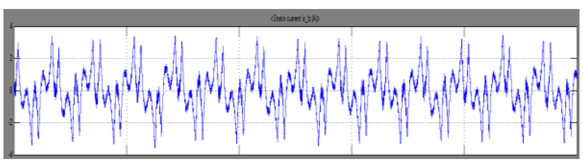
Phase voltage C



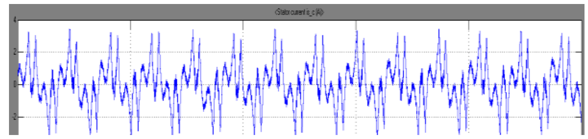
Phase current A



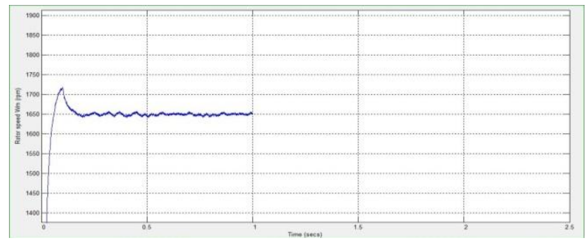
Phase current B



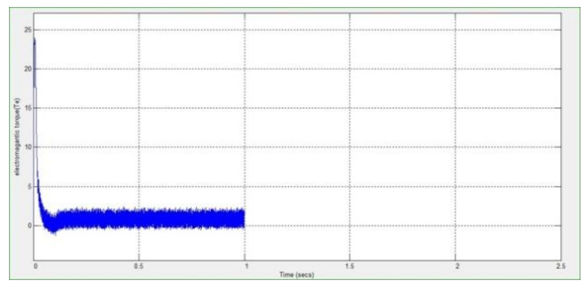
Phase current C



Speed in rpm



Electromagnetic Torque



VI. CONCLUSION

The paper presents modeling and simulation analysis of a closed loop PID controlled Brushless DC motor with PWM control technique. The developed model for a BLDC motor drive which is a VSI fed motor drive offers efficient and cost effective implementation aspects for controlling a PMBLDC motor drive system. The speed control of BLDC motor is done using PID controller and the speed of the motor remains constant irrespective of the load torque applied to the motor. The results for different conditions have been presented and analyzed for a PMBLDC motor.

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