This paper describes a simpler way to control the speed of PMBLDC motor using a closed loop control method. The performance of the PMBLDC system is simulated. The speed is regulated by PI controller. SimuLink is utilized, with MATLAB to get a reliable and flexible simulation. In order to highlight the effectiveness of the speed control method used, the studies are conducted at two different load torques and the corresponding speed regulation is recorded using MATLAB/SimuLink. The method proposed suppresses torque oscillations. This drive has high accuracy, robust operation from near zero to high speed.

**ABSTRACT**

This paper presents a simple way to control the speed of PMBLDC motor using a closed loop control method. The performance of the PMBLDC system is simulated. The speed is regulated by PI controller. SimuLink is utilized, with MATLAB to get a reliable and flexible simulation. In order to highlight the effectiveness of the speed control method used, the studies are conducted at two different load torques and the corresponding speed regulation is recorded using MATLAB/SimuLink. The method proposed suppresses torque oscillations. This drive has high accuracy, robust operation from near zero to high speed.

**KEYWORDS** Hall position sensors, permanent magnet brushless DC motor, BLDC motor, closed loop speed control, PI controller.

**I. INTRODUCTION**

Latest advances in permanent magnet materials, solid state devices and micro electronics have resulted in new energy efficient drives using Permanent magnet brushless DC motors (PMBLDCM). Brushless DC motors are very popular in a wide array of applications in industries such as appliances, automotive, aerospace, consumer, medical, industrial automation for its reliability, high efficiency, high power density, low maintenance requirements, lower weight and low cost. As the name implies, BLDC motors do not have brushes for commutation. Instead they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors, like better speed-torque characteristics, high dynamic response, high efficiency, noiseless operation and wide speed ranges. Torque to weight ratio is higher enabling it to be used in applications where space and weight are critical factors [1]. A BLDC motor finds numerous applications in motion control. A BLDC motor has windings on stator and alternate permanent magnets on rotor. Electronic commutation of stator windings is based on rotor position with respect to the stator winding [1]. A new generation of microcontrollers and advanced electronics has overcome the challenge of implementing required control functions, making the BLDC motor more practical for a wide range of uses [2], [3], [4]. In this method the speed is controlled in a closed loop by measuring the actual speed of the motor. The error in the set speed and actual speed is calculated. A Proportional plus Integral (PI) controller is used to amplify the speed error and dynamically adjust the PWM duty cycle. When using PWM outputs to control the six switches of the three-phase bridge, variation of the motor voltage can be got by varying the duty cycle of the PWM signal. For low-cost, low-resolution speed requirements, the Hall signals are used to measure the speed feedback.

**II. TYPES OF CONTROL TECHNIQUES OF PMBLDC MOTOR**

Though various control techniques are discussed in [5] basically two methods are available for controlling PMBLDC motor. They are sensor control and sensorless control. To control the machine using sensors, the present position of the rotor is required to determine the next commutation interval. Motor can also be controlled by controlling the DC bus rail voltage or by PWM method. Some designs utilize both to provide high torque at high load and high efficiency at low load. Such hybrid design also allows the control of harmonic current [6].

In case of common DC motors, the brushes automatically come into contact with the commutator of a different coil causing the motor to continue its rotation. But in case of BLDC motors the commutation is done by electronic switches which need the rotor position. The appropriate stator windings have to be energized when rotor poles align with the stator winding. The BLDC motor can also be driven with predefined commutation interval. But to achieve precise speed control and maximum generated torque, brushless commutation should be done with the knowledge of rotor position. In control methods using sensors, mechanical position sensors, such as a hall sensor, shaft encoder or resolver have been utilized in order to provide rotor position information. Hall Position sensors or simply Hall sensors are widely used and are popular. Three phase windings use one Hall Sensors each. They provide three overlapping signals giving a 60° wide position range. Whenever the magnetic poles pass near the sensors, they either give a high or low signal, indicating North or South Pole is passing the pole. The accurate rotor position information is used to generate precise firing commands for power converter. This ensures drive stability and fast dynamic response. The speed feedback is derived from the position sensor output signals.
Between the two commutation signals the angle variation is constant as the Hall Effect Sensors are fixed relative to the motor, thus reducing speed sensing to a simple division. Usually speed and position of a permanent magnet brushless direct current motor rotor is controlled in a conventional cascade structure. The inner current control loops runs at a larger width than the outer speed loop to achieve an effective cascade control [7].

Various sensorless methods for BLDC motors are analyzed in [8-18]. Modeling of BLDC is given in [3]. [8] proposes a speed control of brushless drive employing PWM technique using digital signal processor. A PSO based optimization of PID controller for a linear BLDC motor is given in [9-10]. Speed Control of BLDC based on CMAC & PID controller is explained in [11]. Direct torque control and indirect flux control of BLDC motor with non sinusoidal back emf method controls the torque directly and stator flux amplitude indirectly using d-axis current to achieve a low-frequency torque ripple-free control with maximum efficiency [12-13]. Direct back EMF detection method for sensorless control is given in [14]. [15] Proposes a novel architecture using a FPGA-based system. Fixed gain PI speed controller has the limitations of being suitable for a limited operating range around the operating point and having overshoot. To eliminate this problem a fuzzy based gain scheduled PI speed controller is proposed in [16]. A new module structure of PLL speed controller is proposed by [17]. A fixed structure controller (PI or PID) using time constrained output feedback is given in [18]. The above literature does not deal with reduction of speed oscillations in PMBLDC drive. This paper deals with control methods to reduce speed oscillations.

To control a system, by any of these methods an accurate mathematical model of the complete system is required.

III. MATHEMATICAL MODEL OF THE PMBLDC MOTOR

The circuit model of PMBLDC motor is shown in Fig 1.

![Motor Circuit Model](image)

The voltage equations of the BLDC motor are as follows:

\[
V_a = R_i + \frac{d}{dt}(L_{ia}i_a + L_{ib}i_b + L_{ic}i_c) + \frac{d\lambda_{ia}}{dt}(\Theta)
\]

\[
V_b = R_i + \frac{d}{dt}(L_{ib}i_b + L_{ib}i_b + L_{ic}i_c) + \frac{d\lambda_{ib}}{dt}(\Theta)
\]

\[
V_c = R_i + \frac{d}{dt}(L_{ic}i_c + L_{ic}i_c + L_{ic}i_c) + \frac{d\lambda_{ic}}{dt}(\Theta)
\]

In balanced system the voltage equation becomes

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} =
\begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} +
\begin{bmatrix}
L_{ia} & 0 & 0 \\
0 & L_{ib} & 0 \\
0 & 0 & L_{ic}
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix} + \frac{1}{L}
\begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix}
\]

The mathematical model for this motor is described in Equation (1) with the assumption that the magnet has high sensitivity and rotor induced currents can be neglected [3]. It is also assumed that the stator resistances of all the windings are equal. Therefore the rotor reluctance does not change with angle. Now

\[
L_a = L_b = L_c = L
\]

\[
L_{ab} = L_{bc} = L_{ca} = M
\]

Assuming constant self and mutual inductance, the voltage equation becomes

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} =
\begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} +
\begin{bmatrix}
L_{ia} & 0 & 0 \\
0 & L_{ib} & 0 \\
0 & 0 & L_{ic}
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix} + \frac{1}{L}
\begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix}
\]

In state space form the equation is arranged as

\[
\frac{d}{dt}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{L} & 0 & 0 \\
0 & \frac{1}{L} & 0 \\
0 & 0 & \frac{1}{L}
\end{bmatrix}
\begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix} + \frac{1}{L}
\begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix}
\]

The electromagnetic torque is given as

\[
T_e = (e_a i_a + e_b i_b + e_c i_c) / \omega_r
\]

The equation of motion is given as

\[
\frac{d}{dt}\omega_r = (T_e - T_L - B \omega_r) / J
\]

IV. BLDC MOTOR SPEED CONTROL

In servo applications position feedback is used in the position feedback loop. Velocity feedback can be derived from the position data. This eliminates a separate velocity transducer for the speed control loop. A BLDC motor is driven by voltage strokes coupled by rotor position. The rotor position is measured using Hall sensors. By varying the voltage across the motor, we can control the speed of the motor. When using PWM outputs to control the six switches of the three-phase bridge, variation of the motor voltage can be obtained by varying the duty cycle of the PWM signal.

The speed and torque of the motor depend on the strength of the magnetic field generated by the energized windings of the motor, which depend on the current through them. Hence adjusting the rotor voltage and current will change motor speed.
Commutation ensures only proper rotation of the rotor. The motor speed depends only on the amplitude of the applied voltage. This can be adjusted using PWM technique. The required speed is controlled by a speed controller. This is implemented as a conventional proportional-Integral controller. The difference between the actual and required speeds is given as input to the controller. Based on this data PI controller controls the duty cycle of the PWM pulses which correspond to the voltage amplitude required to maintain the desired speed. When using PWM outputs to control the six switches of the three-phase bridge, variation of the motor voltage can be achieved easily by changing the duty cycle of the PWM signal.

In case of closed loop control the actual speed is measured and compared with the reference speed to find the error speed. This difference is supplied to the PI controller, which in turn gives the duty cycle. PMBLDC motor is popular in applications where speed control is necessary and the current must be controlled to get desired torque. Figure 4 shows the basic structure for closed loop control of the PMBLDC motor drive. It consists of an outer speed control loop, an inner current control loop for speed and current control respectively. Speed loop is relatively slower than the current loop.

V. PMBLDC MOTOR FED FROM A VOLTAGE SOURCE INVERTER

Schematic diagram of a three level voltage source inverter fed PMBLDC motor is shown in Fig.5. This is a closed loop control circuit using 3 Hall Sensors. MOSFETs are used as switching devices here. To control the speed of the motor the output frequency of the inverter is varied. To maintain the flux constant the applied voltage is varied in linear proportion to the frequency. The MATLAB simulation is carried out and the results are presented.

![Fig.2: PWM Speed Control](image1)

![Fig.3: Schematic of a Speed Controller](image2)

![Fig.4: Closed Loop Speed Control](image3)
A precise speed control of PMBLDC motor is complex due to non-linear coupling between winding currents and rotor speed. Also the non-linearity present in the developed torque due to magnetic saturation of the rotor alleviates this problem. For very slow, medium, fast and accurate speed response, quick recovery of the set speed is important keeping insensitivity to the parameter variations. In order to achieve high performance, many conventional control schemes are employed. Moreover conventional PI controller is very sensitive to step change of command speed, parameter variation and load disturbances. With higher frequency switching, the PMBLDC motor rotates at a higher speed. But without the strong magnetic field at stator, the rotor fails to catch up the switching frequency because of weak pull force. Speed of BLDC motor is indirectly determined by the applied voltage magnitude. Current in the winding is increased by increasing the voltage. This produces stronger magnetic pull to align the rotor’s magnetic field faster with the induced stator magnetic field. The rotational speed or the alignment is proportional to the voltage applied to the terminals. The torque pulsation is very high as the step size is reduced.

VI. SIMULATION RESULTS

With the help of the designed circuit parameters, the MATLAB simulation is done and results are presented here. Speeds are set at 2000 rpm and 1800 rpm and the load torque disturbances are applied at time \( t = 1 \text{ sec} \). The speed regulations are obtained at two different set speeds and the simulation results are shown. The waveforms of the back EMF are shown in Fig.6. From Fig.7 it can be seen that the phasor voltages are displaced by 120°. The stator current waveforms are shown in Fig 8. They are quasi sinusoidal in shape and displaced by 120°.
Case 1: Set Speed = 2000 rpm

Case 2: Set Speed = 1800 rpm
Figures 9 and 11 show the load torque disturbances applied at time $t=1$ sec for the set speeds 2000 rpm and 1800 rpm respectively. From Figures 10 and 12 it can be seen that the closed loop system brings the speed to the normal value by adjusting the input voltage of the inverter.

VI. CONCLUSION

Closed loop controlled VSI fed PMBLDC motor is modeled and simulated. Feedback signals from the PMBLDC motor representing speed and position are utilized to get the driving signals for the inverter switches. The simulated results shown are at par with the theoretical predictions. The simulation results can be used for implementation of PMBLDC drive. The speed oscillations are minimized using closed loop system.

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