Speed Performance of a BLDC Motor Employing PWM/PAM Control Techniques

Dr. T. Vamsee kiran¹, I.L.B.Sowjanya²

¹Professor & Head, Dept. of EEE, DVR & Dr. HS MIC College of Technology, Andhra Pradesh, India
²PG Student [PE&ED], Dept. of EEE, DVR & Dr. HS MIC College of Technology, Andhra Pradesh, India

ABSTRACT

Permanent magnet brushless DC motors finds wide applications in industries due to their high power density and ease of control. These motors are controlled using a three phase power semiconductor bridge. This paper deals with a novel control technique based on PWM & PAM control of brushless DC motor (BLDC). For inverter-controlled Brushless DC Motor (BLDC) drives, the inverter can be controlled by either Pulse-Width Modulation (PWM) technique with a constant DC link voltage or Pulse-Amplitude Modulation (PAM) technique. PAM modulates the inverter power devices using 120-degree modulation technique and controls the amplitude of the DC link voltage. The results show that Pulse amplitude modulation control improves the speed performance of BLDC motor at high speeds. The simulation results of BLDC motor drive with PWM & PAM control techniques are shown in the MATLAB/Simulink environment.

Key words: BLDC motor, pulse width modulation (PWM) & pulse amplitude modulation (PAM) techniques.

1. INTRODUCTION

Recently, permanent magnet brushless DC motors are widely used in many applications such as motors, sensors, actuators, etc [1]. Permanent magnet motors with trapezoidal back EMF and sinusoidal back EMF have several advantages over other motor types. when compared to the dc motors they need lower maintenance due to the elimination of the commutator. They also have high-power density that makes them ideal for high torque to weight ratio applications [2]. Compared to induction machines, they have lower inertia allowing for faster dynamic response to reference commands. Also, they are more efficient due to the permanent magnets which results in virtually zero rotor losses [3]. BLDC motors could become serious competitors to the induction motor for servo applications. The BLDC motor is becoming popular in various applications because of its high efficiency, high power factor, high torque, simple control and lower maintenance [4]. The major disadvantage with permanent magnet motors is their higher cost and relatively higher complexity introduced by the power electronic converter used to drive them.

Generally, the BLDC motor can be driven by either PWM or PAM techniques[5]. However the inverter of the BLDC motor drive system is controlled by the PWM scheme for varying the voltage. But, the PWM techniques can induce serious current and torque ripples for the ironless stator motor that will lead to very low inductance [6]. This paper shows that the PAM control is superior to the PWM control at high speeds and the speed performance of the motor is improved using PAM control. For PAM control, 120° commutation control is generally used and the dc link voltage is adjusted according to the error between the speed and its reference.

2. MATHEMATICAL MODELING OF BLDC MOTOR DRIVE

BLDC motor can be modelled in two ways: abc phase variable model and d-q axis model. The trapezoidal back EMF of a BLDC motor indicates that the mutual inductance between stator and rotor is non sinusoidal, therefore transforming to d-q axis does not provide any particular advantage, and so abc phase variable model is preferred. In the present model, the motor is assumed to be star connected with isolated neutral.

![Figure 1 Equivalent circuit of BLDC motor](image-url)
The following assumptions are made while doing the mathematical modeling:
- The motor is not saturated.
- Stator resistances of all windings are equal and self and mutual inductances are constant.
- Power semiconductor devices in the inverter are ideal.

From the assumptions made, the BLDC motor can be represented as,

\[
\begin{bmatrix}
\dot{v}_a \\
\dot{v}_b \\
\dot{v}_c \\
\end{bmatrix} =
\begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R \\
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
\end{bmatrix} +
\begin{bmatrix}
L - M & 0 & 0 \\
0 & L - M & 0 \\
0 & 0 & L - M \\
\end{bmatrix}
\frac{d}{dt}
\begin{bmatrix}
i_a \\
i_b \\
i_c \\
\end{bmatrix} +
\begin{bmatrix}
e_a \\
e_b \\
e_c \\
\end{bmatrix}
\tag{1}
\]

Where,
- \(L\) - Armature self-inductance [H]
- \(R\) - Armature Resistance [Ω]
- \(M\) - Mutual Inductance [H]
- \(v_a, v_b, v_c\) - Phase Voltages [V]
- \(i_a, i_b, i_c\) - Motor Input Currents [A]
- \(e_a, e_b, e_c\) - Motor Back-EMF’s [V]

The trapezoidal back-EMF’s of the motor can be represented as,

\[
E_k = \sum_k K_e \omega_{m} f_k(\theta r) \tag{1}
\]

The electromagnetic torque can be expressed as,

\[
T_e = T_L - j\frac{d\omega_m}{dt} + B\omega_m \tag{2}
\]

And,

\[
\frac{d\theta}{dt} = \frac{P}{2} \omega_m \tag{3}
\]

Where, \(k = a, b, c\).

\(\theta r\) is the rotor electrical position.

\(f_k(\theta r)\) represents the back EMF as a function of rotor.

\(K_e\) is the back EMF constant, \(\omega_m\) is the mechanical speed of the rotor, \(J\) is the rotor inertia, \(B\) is the friction coefficient, \(P\) is the no. of rotor poles.

When a brushless dc motor rotates, each winding generates a voltage known as electromotive force or back EMF, which opposes the main voltage supplied to the windings. The polarity of the back EMF is opposite to the energized voltage. The stator has three phase windings, and each winding is displaced by 120 degrees. The windings are distributed so as to produce trapezoidal back EMF. The principle of the BLDC motor is to energize the phase pairs that produce constant torque. The three phase currents are controlled to take a quasi-square waveform in order to synchronize with the trapezoidal back EMF to produce the constant torque. The simulink model of a BLDC motor contains current generator, speed generator and EMF generation blocks. Figure 2 shows the mathematical model of BLDC motor in MATLAB/Simulink.

*Figure 2 Simulink Model of a BLDC Motor*
3. CLOSED LOOP CONTROL OF BLDC MOTOR

A precise speed control of BLDC 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 reference speed is important keeping insensitivity to the parameter variations. In order to achieve high performance, conventional control schemes are employed. At present the conventional PID controller handles these control issues. Moreover conventional PID controller is very sensitive to step change of command speed, parameter variation and load disturbances. 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.

The difference between the actual and required speeds is given as input to the controller. Based on this data PID controller controls the duty cycle of the PWM pulses that correspond to the voltage amplitude required to maintain the desired speed. When employing 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. 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.

![Figure 3](image)

**Figure 3** Closed loop speed control of BLDC motor

4. PULSE WIDTH MODULATION CONTROL OF BLDC MOTOR

PWM is the most popular method for producing a controlled output for inverters. They are quite popular in industrial applications. Pulse width modulation (PWM) is a technique where the duty ratio of a pulsating waveform is controlled by another waveform. The interaction between the reference waveform and the carrier waveform give the opening and closing times of the switches. PWM is commonly used in applications like converters, motor speed control, audio amplifiers etc. For example, it is used to reduce the total power delivered to a load without losses, which normally occurs when a power source is limited by a resistive element. Figure 4 shows the conventional PWM control of a BLDC motor drive. The drive consists of a diode bridge rectifier, IGBT based voltage source inverter, PWM controller, and switching logic from the Hall Effect signals. A voltage source inverter is used to feed a BLDC motor. The exact position of rotor at every instant is obtained with the help of hall sensors mounted on stator. Fig. 4 shows the block diagram for closed loop control of a BLDC motor with pulse width modulation inverter control. From the hall signals the switching logic is determined to provide triggering pulses to the inverter switches. The actual and reference is compared to produce an error signal, which is then fed to the PID controller, generated control signal will then modify the speed accordingly.

![Figure 4](image)

**Figure 4** Block diagram for PWM inverter control of BLDC motor
The switching pulses for the voltage source inverter are obtained using pulse width modulation (PWM) method. The gating signals are generated by comparing a rectangular reference signal of the amplitude $A_r$, with triangular carrier wave of amplitude $A_c$. The frequency of the carrier wave determines the fundamental frequency of output voltage. By varying $A_r$ from 0 to $A_c$, the pulse width can be varied from 0 to 100 percent. The ratio of $A_r$ to $A_c$ is the control variable and defined as the modulation index. The number of pulses per half cycle depends on carrier frequency. Figure 5 shows the generation of gate pulses using pulse width modulation technique in MATLAB/Simulink.

![Figure 5 Simulink Model of Pulse Width Modulation Technique](image)

**5. PULSE AMPLITUDE MODULATION**

Unlike the Amplitude modulation which varies the amplitude of the carrier signal on both sides from the mean position, the PAM modulation varies the amplitude of the pulses only at a single side. Simply the top of the pulses are modulated corresponding to the message signal. In this paper the PAM is generated from a pure sine wave modulating signal and a square wave generator which produce the carrier pulses and a PAM modulator circuit. In pulse amplitude modulation the amplitudes of the pulses are varied in accordance with the modulating signal.

![Figure 6 Block diagram of the BLDC Motor drive with PAM control](image)

Figure 6 shows the block diagram of inverter controlled BLDCM drives. As shown in Fig 6 for PWM control, PWM generator block results in commutation signals to control power devices via driver circuit. The commutation control signals are generated in accordance with the back-EMF waveforms detected by the terminal voltage sensing circuit. Moreover, for PAM control, the PAM generator gives the DC link voltage reference to PAM converter to adjust its output.

For PWM control, the DC-link voltage is fixed and duty ratio is controlled by the speed and load conditions. For PAM control, 120 degree commutation control is used in general and the DC link voltage is adjusted according to the error between speed and its reference. PAM control results in low switching losses and requires an extra circuit to change the DC link voltage. Moreover PAM has been shown to be superior to PWM method. Because of PWM period interruption caused by commutation and limitation of the resolution of PWM generator, the performance of PWM-
controlled BLDCM drives gives more torque ripple. It becomes more relevant at high speed region. In general voltage source inverter is used to adjust DC-link voltage and combined with conventional PWM method, called PAM/PWM method, to control the adjustable speed drives. Figures 7 – 9 indicates control signals for PAM, generation of PAM signals and closed loop speed control of BLDC motor with PAM control.

![Diagram](image1)

**Figure 7** Control signals for PAM, 120° commutation

![Diagram](image2)

**Figure 8** Generation of pulse amplitude modulated signals in Simulink
6. RESULTS & DISCUSSIONS

The simulation results of BLDC motor performance can be evaluated under various input parameters in MATLAB/SIMULINK environment.

Simulation of Brushless DC motor with pulse width modulation & PAM control has been observed and the result is shown in the Figure 10 - 14. The reference speed is set at 2000 rpm and the corresponding rotor speed is shown in Figure 11 for the load torque disturbances shown in Figure 10.
When a step load is suddenly applied, there is a small change in speed, but the controller recovers the speed to set value and the motor reaches to steady state speed at 0.6 sec. Figure 12 - 16 shows the speed response of a BLDC motor using PAM control for different load torques. It can be observed that the drive operating with PAM control resulted in maintaining constant speed even at load torque fluctuation.

![Figure 12 Speed Response of PAM for Load Torque disturbance 1](image1)

The PWM controlled BLDC drive is tested for different load torque fluctuations.

![Figure 13 Load Torque Disturbance 2](image2)

![Figure 14 Rotor Speed for Load Torque Disturbance 2 using PAM](image3)
From the figures it can be observed that the speed error can be decreased and the speed performance is also improved using PAM method. Figure 17 and 18 show the back EMF’s and currents of phases a, b, c for a BLDC motor.

![Figure 15 Load Torque Disturbance 3](image1)

![Figure 16 Rotor Speed for Load Torque Disturbance 3 using PAM](image2)

![Figure 17 Trapezoidal Shaped Back EMF](image3)
7. CONCLUSIONS

In this paper closed loop PAM control of BLDC motor is modelled and simulated. Feedback signals from the BLDC motor representing speed and position are utilized to get the driving signals for the inverter. Also the detailed comparison of the PWM and PAM control for BLDC motor is presented.

It has been shown that the proposed PAM control is superior to the PWM control for providing good speed performance at high speed by applying different load torques i.e., the speed oscillations are minimized using closed loop PAM control. Here the tuning of PID controller has done manually and this can be further extended by using optimization techniques.

APPENDIX

<table>
<thead>
<tr>
<th>BLDC motor specifications</th>
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<tbody>
<tr>
<td><strong>Parameters</strong></td>
</tr>
<tr>
<td>No. of pole pairs</td>
</tr>
<tr>
<td>Supply voltage</td>
</tr>
<tr>
<td>Torque constant</td>
</tr>
<tr>
<td>Back-EMF constant</td>
</tr>
<tr>
<td>Moment of inertia</td>
</tr>
<tr>
<td>Damping constant</td>
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REFERENCES

