Role Of Bldc Motor Drives In Vehicular Applications


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ABSTRACT

This paper describes the performance of Brushless DC motor (BLDC) drive system. BLDC motors are widely used in applications which require a wide range of speed and torque control as of its reduced inertia, quick response, improved reliability, and maintenance free. This paper also explains the role of BLDC motor drive for electric vehicle operation. It is based on the function relationship between the Hall sensor logics and currents that must be supplied to each phase of the motor. The controller is successfully simulated by means of Matlab/Simulink and simulation result shows that the digital controllers have a simpler circuit and have better speed performance than a conventional controller.

KEYWORDS: Brushless DC motor (BLDCM), Electric Vehicles (EVs), Hall sensors, Microcontroller.

INTRODUCTION

The electric motor technology comprises construction of machines, materials, electronics, sensors and control technologies. A proper converter and control techniques must be developed for different kind of motors to produce a high-performance drive. The significant aspect of converter design is the converter efficiency and its fast response. The third harmonic and its consistent multiples component are removed in the output due to the feature three phase power system used in DC drive systems. Relating 1-phase system with that of 3-phase, the ripple voltage is considerably less. The difficulty with the induction motor is its poor efficiency at lesser loads. This can be conquer by working the motor at optimized effectiveness at every load. Different techniques are available for this purpose [1,2].

Present world is facing a lot of dissimilar crisis produced by great oil prices and outdated designs which have encouraged the hunt for more effective road vehicles, probably based on atmosphere friendly sources situated in politically steady areas. This has run to the growth of electric vehicles [3]. Compared with a DC motor, the BLDC motor uses an electric commutator relatively than a mechanical commutator, so it is extra reliable than the DC motor. In a BLDC motor, rotor magnets generate the rotor magnetic flux, so the BLDC motors reach advanced efficiency [4]. It has become feasible because of their larger performance in terms of great efficiency, fast response and weight, accurate control, increased reliability, less maintenance, brushless assembly and reduced dimension, high torque to motor weight ratio, and thermal over & under load protection [5, 6, 7].

New developments in battery technology, system integration, aerodynamics, research and development by vehicle manufacturers have direction to the production of electric vehicles that can play a practical role on city streets. An aircraft, automobile, scooter, and cycle can be developed using electric vehicle technology. For example, an electric car is shown in Figure 1.
The high-performance, small-diameter magnetic rotors decrease the inertia of armature, permitting immense acceleration rates, a drop in rotational losses, and smoother servo characteristics. This finest motor response also agrees for more constant speeds, immediate speed regulation, and a softer drive system. Speed torque characteristics of BLDC motor are shown in Figure 2.

I. Block diagram of the control system:

Many of the problems related with brushes such as radio frequency interference and sparks are the potential sources of power loss that must be eliminated. It is inevitable to accept the role of accurate modelling of the electric drive system to achieve desired performance. The increasing load and line disturbances create considerable difficulties in performing speed control of such drives.

So, the design of the motor drive system usually requires a time-consuming trial and error process and may fail to optimize the performance. The design of BLDC motor drive involves some difficult processes such as modelling, control scheme, parameters tuning, simulation and real time implementation. Based on earlier linear system studies, the controller parameters of Proportional Integral Derivative (PID) controller are easy to determine and simple to resolve. On the other hand, for a nonlinear model such as BLDC motor drive system, the performance of the Proportional Integral (PI) controller becomes poor and difficult to establish the controller parameters.

Every commutation series has one of the windings energized to positive power, the second winding is negative and the third is in a non-energized circumstance. Torque is formed because of the interface between the magnetic fields created by the stator coils and the permanent magnets. Ideally, the peak torque occurs when these two fields are at 90 degrees to every other and falls off as the fields move about mutually [13]. To keep the motor running, the magnetic field produced by the windings should shift position, as the rotor moves to catch up with the stator fields. The block diagram of BLDC drive system is shown in Figure 3. It contains three phase inverter, position sensors, signal conditioner and a digital controller. The inverter with the position sensor arrangement is functionally like the commutator of a dc motor. Electronically the commutation of a BLDC motor is controlled. The stator windings must be energized in arrangement to rotate the motor. Rotor position must be known to switch the winding in order. The BLDC motors though create a high-quality performance at superior speeds, can result into a torque pulsation particularly at low speeds.
Also, the commutation torque ripple may become prominent if the switching of the devices is not taken care properly [8]. The three-phase inverter supply is given to the BLDC motor. Hall Effect sensors are used to measure the rotor position. The rotor speed and the signal as of the current sensing resistor are opposite [12]. This error is then approved through PI controller to generate the PWM for all the six switches of the inverter, which are in sequence stimulated by the shaft position sensors. As the motor is of the brushless dc type, the waveforms of the armature currents are quasi-square. The control approach also allows regenerative braking, which is very important in many applications, like electric vehicles, where energy return to the battery pack.

To apply the brakes, stator magnetic field is reversed [15]. This action is accomplished through the inversion of the signals given by the position sensor. The position sensor differentiates six positions each one 360 electric degrees. During motor operation, the rotor moves clockwise. When the brake signal is applied, the stator field is reversed 180 electric degrees. These actions create an immediate change in the direction of the torque, making a fast reduction of the speed of the motor, which begins to return its energy to the dc link.

The BLDC motor senses the location of the rotor by means of Hall sensors. Three sensors are needed for position information. With three sensors, six probable commutation orders can be found. In the sensor system, three Hall sensors are positioned inside the motor, spaced 120 degrees apart. Each Hall sensor provides either a High or Low output based on the polarity of magnetic pole close to it. Rotor position is determined by evaluating the outputs of all three Hall sensors. Based on the output from hall sensors, the voltages to the three phase motor are switched. The torque and speed of motors are achieved by the microcontroller. An adequate volume of processing power is essential to solve the algorithms needed to produce Pulse Width Modulated (PWM) outputs for the motor.

By changing the voltage across the motor, one can switch the speed of the motor. When using PWM outputs to control the six switches of the three-phase bridge inverter, variation of the motor voltage can be attained by varying the duty cycle of the PWM signal. The three-phase BLDC speed control is done by using both open loop and closed loop configurations. Open loop control is used to control the speed of the motor by honestly controlling the duty cycle of the PWM signal to drives the motor-drive circuitry. Closed loop control sets the speed of the motor by directly controlling the duty cycle of the PWM signals that drives the motor.

The main difference between the two control systems is that the open-loop control considers only the speed control input to update the PWM duty cycle, but, the closed-loop control reflects both speed-input control and actual motor speed for updating the PWM duty cycle. A PID controller is a closed-loop control implementation which is widely used and is most commonly used as a feedback controller.

The motor speed is designed by chasing the time between consecutive Hall sensor actions, which signifies a part of the mechanical cycle of the motor. In a 3-phase BLDC motor control, one electrical cycle includes six Hall states as well as, depending on the number of poles pairs in the motor, the electrical angle measured between consecutive Hall state variations can be decoded to a mechanical angle.

### II. Dynamic model of the BLDC motor:

Figure 4 shows the BLDC motor is fed by PWM controlled voltage source inverter (VSI). The speed is controlled by adjusting the stator voltage of the BLDC motor. The model of BLDC motor is developed by means of the hypothesis that there is no power loss in an inverter, and then the voltage of the stator winding can be stated as,

\[
U_a = R_d i_a + L_d (di_a/dt) + M_a (di_b/dt) + M_{ac} (di_c/dt) + e_a \tag{1} \\
U_b = R_b i_b + L_b (di_b/dt) + M_b (di_a/dt) + M_{bc} (di_c/dt) + e_b \tag{2} \\
U_c = R_c i_c + L_c (di_c/dt) + M_c (di_a/dt) + M_{bc} (di_b/dt) + e_c \tag{3}
\]

Where, \( R_a, R_b, R_c \) resistance of the stator winding,
La, Lb, Lc: Self-inductance of the stator winding,
Mab, Mba, Mac: Mutual inductance of the stator winding,
e_a, e_b, e_c: Back emf of the motor,

Back emf e is derived from the angular velocity of the rotor

\[
\begin{bmatrix}
e_a \\ e_b \\ e_c
\end{bmatrix} = \begin{bmatrix}
f_a(\theta) \\ f_b(\theta) \\ f_c(\theta)
\end{bmatrix}
\]

\[E = k_e E\]

Where \(K_e\) is back-EMF constant, \(f_a(\theta), f_b(\theta),\) and \(f_c(\theta)\) are functions of rotor position.

The trapezoidal shape functions with limit values between +1, -1

\[f_a(\theta) = \begin{cases}
\left(\frac{\pi}{6}\right) \theta & \theta < 0 \\
\frac{\pi}{6} & 0 \leq \theta < 5\pi \\
\frac{5\pi}{6} & 5\pi \leq \theta < 7\pi \\
\frac{7\pi}{6} & 7\pi \leq \theta \leq 2\pi
\end{cases}\]

The torque of the BLDC motor is derived from the back emf, stator current and speed

\[T_{em} = (e_a i_a + e_b i_b + e_c i_c) / \omega_m\]

Then, electromagnetic torque is written as

\[T_e = T_L + J \frac{d\omega_m}{dt} + \beta \omega_m\]

Where

- \(T_L\) - Load torque (Nm)
- \(J\) - Inertia of the rotor and coupled shaft (kg\cdot m^2)
- \(\beta\) - Dynamic frictional torque constant (Nm\cdot s\cdot rad^{-1})

From the above equations model of BLDC motor can be developed.

III. Design flow of BLDC motor drive system:

To control the speed of drive precisely without operator involvement, a speed control system that relies upon a controller is essential.

The speed control system accepts the actual motor speed by a speed sensor as input. Figure 5 clearly shows the work flow diagram of controller.
Fig. 5: Control flow of the whole system

The controller compares the actual speed and the set speed and provides an output, which decides the duty cycle of PWM pulses applied to the MOSFET based VSI fed PMBLDCM drive system. The controller is a part of the entire control system, and the whole system is analysed for selecting the proper controller. The following factors should be considered when selecting a controller.

(i) Type of sensor and speed range
(ii) Type of output required
(iii) Control algorithm needed
(iv) Type of outputs required for the specific functions

IV. Simulation And Results:
The simulations are carried out using MATLAB. The ratings of BLDC motor are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Rating of BLDC motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of motor</td>
</tr>
<tr>
<td>Stator voltage</td>
</tr>
<tr>
<td>Power rating</td>
</tr>
<tr>
<td>Speed</td>
</tr>
<tr>
<td>No. of poles</td>
</tr>
<tr>
<td>No. of turns</td>
</tr>
<tr>
<td>Degree</td>
</tr>
</tbody>
</table>

Figure 6, shows the controller circuit of the system. Protection safety fuse is used because the motor draws more current during starting. So, protection 5A fuse is used. During load fluctuation, the motor draws more current. The control circuit consists of a controller and a gate drive circuit for the generation of pulses of required frequency which is 10 KHz. The internal timer is used as a clock to control the timing and counter is used for counting the pulses from the proximity sensor.
In open-loop control, the duty cycle of the PWM signal controls the ON time of the IGBTs in the half bridges of the motor drive circuit and this, in turn, controls the average voltage supplied from corner to corner of the motor windings. Table 2 illustrates the sample experimental standards of duty cycle and actual speed in rpm for open-loop control.

**Table 2:** Values of duty cycle & actual speed in rpm for open-loop control

<table>
<thead>
<tr>
<th>Duty cycle</th>
<th>Actual speed</th>
</tr>
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<tbody>
<tr>
<td>20</td>
<td>490</td>
</tr>
<tr>
<td>30</td>
<td>789</td>
</tr>
<tr>
<td>40</td>
<td>1123</td>
</tr>
<tr>
<td>50</td>
<td>1514</td>
</tr>
<tr>
<td>60</td>
<td>1946</td>
</tr>
<tr>
<td>70</td>
<td>2117</td>
</tr>
</tbody>
</table>

In closed-loop operation, the desired speed is given by the operator of the system and the system recompenses the voltage offered to the motor to obtain the authentic speed.

In the primary part of the closed loop, the preferred speed is delivered as of an external potentiometer by the A/D converter. The A/D converter founds a software assessment called Reference Speed. The subsequent part of the closed-loop system is the calculated speed, which is used to increase or decrease the output voltage of the motor depending on the calculated error among the desired speed and the measured speed. The proportional value $K_p$ is set to 0.30 and $K_i$ is set to 0.20 for the closed loop control of the motor. Table 3 is evidence for the experimental values of set speed and actual speed in rpm for closed-loop control.

**Table 3:** set speed and actual speed of motor

<table>
<thead>
<tr>
<th>Set Speed</th>
<th>Actual Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>301</td>
</tr>
<tr>
<td>600</td>
<td>592</td>
</tr>
<tr>
<td>900</td>
<td>903</td>
</tr>
<tr>
<td>1200</td>
<td>1245</td>
</tr>
<tr>
<td>1500</td>
<td>1521</td>
</tr>
<tr>
<td>1800</td>
<td>1808</td>
</tr>
<tr>
<td>2200</td>
<td>2100</td>
</tr>
</tbody>
</table>
Figure 7 shows the Simulink block of inverter. The application voltage source inverter (VSI) has been the main control component of the AC drive industry for more than 50 years. Kassakian et al. (1991) presented the switching concept of power converters and how it is used to convert electrical power with high efficiency. The VSI is widely used for inverter converters because they naturally behave as voltage sources as required by variable speed industrial drive applications, such as which is one of the most popular applications of inverters. Nowadays low cost, high power devices are highly available and it is possible to use PWM scheme to enhance the VSI performance. Thus, the VSI drive predominantly used in the AC drive system.

The latest developments also made in PWM algorithm for the VSI for achieving the fast response high-performance AC drives.

Figure 8 shows the line to line voltage response of BLDC motor drive using PI controller for the reference speed of 1500 RPM. From 0 to 2.5 sec, the voltage is maintained at 220 V. Then, due to the load change, the voltage increases to 245 V which is clearly depicted.

Figure 9: Simulation response of stator current and back emf
Figure 9 shows the stator current and back EMF response of BLDC motor drive using for reference speed of 1500 RPM. At the initial stage, there is a slight deviation in the stator current then, the stator current settles. At 0.5 sec, due to load disturbance, there is a change in the speed response. The stator current quickly settles after a deviation. The stator current is observed to be 2.5A after the load disturbances.

![Simulation response of torque](image1)

**Fig. 10:** Simulation response of torque.

![Simulation response of speed](image2)

**Fig. 11:** Simulation response of speed

Figure 10 and Figure 11 shows simulation response Torque and speed of BLDC motor drive. At 0.5 sec, the deviation in the torque due to the load change is clearly observed. But the torque settles quickly after 0.5 seconds.

**Conclusion:**

The crucial characteristics of motor in electric vehicle are accurate speed and stability during load change. The BLDC motor drive is suitable for electric vehicle to operate in a wide speed range and frequent load changing condition. Simulation results justify effectively the drive designs. There are various approaches for creating the simulation models of motor drives. The construction, working, speed control and the state space model for the simulation analysis of BLDC motor is discussed in detail. The mathematical model of BLDC motor drive system for Matlab/Simulink platform is presented. The generated PWM signals for driving the power inverter bridge for BLDC motor have been successfully tested and the speed of the motor is constant which is set by controller circuit. This simple PI controller based speed control method with BLDC motor found to be efficient and the results are promising. PI controller produces better transient response, negligible overshoot, smaller settling time and rise time than other controllers. Further, the controller provides low torque ripples and high starting torque. The control and power circuit utility must properly satisfy the vehicular application requirements.

**REFERENCES**
