FPGA-Based Cooling Fan Control System for Automobile Engine using Sensorless BLDC Motor


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Abstract:
In this project FPGA is used as a controller to design the new sensorless brushless direct current (BLDC) motor control system of automobile engine cooling fan. This design uses back EMF zero crossing detection algorithm and hardware modular design approach, so that the precise calculation of motor rotor position and the moment of phase commutation in full speed can be gained, which makes the whole control system can work in the variety of adverse environment stably and accurately. This system has the good error tolerance for the outside interference and meets the requirements of reliable operation of the motor controller in vehicle engine cooling fan.

Keywords: Brushless DC (BLDC) motor, Sensorless Control, Zero Crossing Point (ZCP), Back EMF (BEMF) difference

I.INTRODUCTION
BLDC motors have emerged as the recent choice of researchers and scientists. Brushless DC motors are becoming more common in a variety of motor applications such as fans, pumps, appliances, robotic automation, and automotive drives. The size of the motor is higher, making it useful in applications where space and weight are critical factors[1]. In this type of DC motor, commutation is done electronically instead of using brushes. A BLDC motor drive system requires an inverter and a rotor position sensor to perform the commutation process. The motor which is powered by a rectangular current requires only six discrete rotor position [1]. It can be detected by using Hall sensors. There are several drawbacks when such types of position sensors are used. Reasons for their increased popularity are better speed versus torque characteristics, high efficiency, long operating life, and noiseless operation. In addition to these advantages, the ratios of torque delivered to these sensors increase the cost of the motor and reduce simplicity and reliability of the system due to the extra components and wiring. Especially, hall sensors increase the size of the motor and they are temperature sensitive since they are mounted inside. For these reasons, they limit the operation of the motor in practice. To overcome these disadvantages of using Hall sensor, lots of research is being done in sensorless drives. Various methods are implemented for sensorless driving of BLDC motor. These methods include detection of back EMF (BEMF) of the motor, detection of the conducting state of freewheeling diode in the unexcited phase[4], back EMF integration method, detection of stator third harmonic voltage components. Of the above mentioned methods, BEMF detection method is commonly used these days. In this method the zero crossing point (ZCP) of BEMF is determined and thereby the commutation point is determined. The BEMF of a motor can be detected when the motor starts running at high speed. BEMF of a motor cannot be detected directly. One well known method is terminal voltage detection method. The difference between the terminal voltage of the open phase and a virtual neutral point voltage which is created by connecting the three phases to a common point through a resistor is sensed. By monitoring the voltage difference, the zero crossing point (ZCP) can be detected and it is used to commutate a motor. Another method is that the ZCP is detected by matching the terminal voltage with the half of the DC link voltage. Both methods require low pass filters to eliminate the chopped pulses generated by PWM from the terminal voltage [4]. Virtual neutral induces electrical noise into the system which affects the system performance. This paper proposes a new sensorless drive scheme for a BLDC motor. Instead of detecting the ZCP of the open phase BEMF, the ZCP of the BEMF difference corresponds to the commutation point of a BLDC motor exactly and thus the optimal performance is guaranteed.

II.MODELLING
BLDC drive with sensor, consist of a BLDC motor, control circuit and Hall sensor for position information. By knowing the position information, inverter switches are commutated by generating PWM signals with the suitable duty ratio. Three Hall sensors are used for position detection of the BLDC motor. A general BLDC motor has three phase stator windings and is driven by an inverter which constitutes of six switches. Fig. 1 shows the equivalent circuit of a star connected BLDC motor and the inverter topology [2][3].

Figure1 Three phase inverter and BLDC Motor
The modeling is based on the following assumptions:
1. The motor is not saturated.
2. Stator resistances of all windings are equal and self and mutual inductances are constant.
3. Power semiconductor devices in the inverter are ideal.
4. Iron Losses are negligible.

The voltage equation of a BLDC motor can be expressed as:

\[
\begin{pmatrix}
V_a(t) \\
V_b(t) \\
V_c(t)
\end{pmatrix} =
\begin{pmatrix}
R_a I_a(t) \\
R_b I_b(t) \\
R_c I_c(t)
\end{pmatrix} +
\begin{pmatrix}
L_a \frac{d}{dt} I_a(t) \\
L_b \frac{d}{dt} I_b(t) \\
L_c \frac{d}{dt} I_c(t)
\end{pmatrix} +
\begin{pmatrix}
e_a(t) \\
e_b(t) \\
e_c(t)
\end{pmatrix}
\]

where
Va, Vb and Vc are the stator phase voltages; R is the stator resistance per phase; Ia, Ib and Ic are the stator phase currents; L is the self-inductance per phase and ea, eb and ec are the back electromotive forces.

BEMF equation of each phase should be as follows:

\[
e_a = K_e f_a (\theta_e) \omega
\]
\[
e_b = K_e f_b (\theta_e - 2\pi /3) \omega
\]
\[
e_b = K_e f_c (\theta_e + 2\pi /3) \omega
\]

where
Kw is back EMF constant of one phase [V/rad.s-1],
\(\theta_e\) - electrical rotor angle [° el.],
\(\omega\) - rotor speed [rad.s-1].

The back EMF is a function of rotor position which is represented as fa(\(\theta_e\)), fb(\(\theta_e\)), fc(\(\theta_e\)) with limit values between -1 and +1

Accordingly fb (\(\theta_e\)) and fc (\(\theta_e\)) can be designed.

Total torque output can be represented as summation of each phase.

Total torque output is given by

\[
T_e = \frac{e_a I_a + e_b I_b + e_c I_c}{\omega}
\]

where
Te is total torque output [Nm],
Also,
\(T_e = J \frac{d}{dt} \omega_m + B \omega_m + T_L\)

where
TL - Load torque [Nm],
J - Inertia of rotor and coupled shaft [kgm2],
B - Friction constant [Nms.rad-1].
The electrical rotor angle is equal to the mechanical rotor angle multiplied by the number of pole pairs p:

\[
\Theta_e = p / 2 \Theta_m
\]

where
\(\Theta_m\) is mechanical rotor angle [rad].

The block diagram of the proposed system consisting of Inverter, DC Supply, BLDC Motor, FPGA, ZCD, Opto coupler, Driver circuit is shown below in Figure 1.

When DC supply is given to the inverter, it converts DC supply to AC supply which is then given to the windings in the BLDC Motor according to the control signals from FPGA. In the windings of the BLDC motor, when the AC supply is given it excites only two phases at a time and the other phase remains unexcited. The ZCD detects the two excited phase by sensing its BEMF (i.e, by comparing input signal with the reference signal) and gives input to the FPGA controller. The FPGA controller controls the switches in the inverter for the continuous rotation of BLDC motor. Opto coupler is used to isolate high power and low power circuit which in turn eliminate short circuiting. Driver circuit is used to provide the necessary gate pulse to the switches in the inverter.

III. SIMULATION AND RESULTS

This section presents the aspects of continuous sensorless operation. This sensorless method is simulated in MATLAB/SIMULINK.

Figure 3. Simulation of BLDC with sensors

A three-phase motor is fed by a six step voltage inverter. The inverter is a MOSFET bridge of the SimPower Systems library. A speed regulator is used to control the DC bus voltage. The inverter gates signals are produced by decoding the Hall Effect signals of the motor. The three-phase output of the inverter is applied to the PMSM block's stator windings. The load torque...
applied to the machine's shaft is first set to 0 and steps to its nominal value (5 N.m) at t = 3 s. Observe the saw tooth shape of the motor currents. That's caused by the DC bus which applies a constant voltage during 120 electrical degrees to the motor inductances. The initial current is high and decreases during the acceleration to the nominal speed. When the nominal torque is applied, the stator current increases to maintain the nominal speed. The saw tooth waveform is also observed in the electromagnetic torque signal $T_e$. However, the motor's inertia prevents this noise from appearing in the motor's speed waveform. Change the "Back EMF flat area" of the motor from 120 to 0 and observe the waveform of the electromotive force.

The below waveform shows the rotor speed of the BLDC Motor.

![Figure 5 output waveform of rotor speed](image)

### Table 1 Hall output

<table>
<thead>
<tr>
<th>PHASE SEQUENCE</th>
<th>0-60</th>
<th>60-120</th>
<th>120-180</th>
<th>180-240</th>
<th>240-300</th>
<th>300-360</th>
</tr>
</thead>
<tbody>
<tr>
<td>HALL A</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>HALL B</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>HALL C</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 2. Switching sequence

<table>
<thead>
<tr>
<th>SWITCHING STATE</th>
<th>S3,S2 ON</th>
<th>S4,S3 ON</th>
<th>S4,S5 ON</th>
<th>S6,S5 ON</th>
<th>S1,S6 ON</th>
<th>S1,S2 ON</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHASE A</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>PHASE B</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>PHASE C</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>-1</td>
</tr>
</tbody>
</table>

### IV. CONCLUSION

In this project a review of position control methods for BLDC motors has been presented. The fundamentals of various techniques have been introduced; mainly back EMF schemes and estimators, as a useful reference for preliminary investigation of conventional methods. Advances in the position control and applications were also discussed. From the above discussion, it is obvious that the control for BLDC motors using position sensors, such as shaft encoders, resolvers or Hall Effect probes, can be improved by means of the elimination of these sensors to further reduce cost and increase reliability. Furthermore, sensor less control is the only choice for some applications where those sensors cannot function reliably due to harsh environmental conditions and a higher performance is required.

### V. REFERENCES


