Real Time FPGA Implementation of Brushless DC Motor Control Using Single Current Sensor

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Abstract—In modern industry power consumption is becoming one of the most important constraints during the development phase of the product. In motor industry, significant part of the power consumption improvement can be done in motor control. Brushless dc (BLDC) motor drives are penetrating the market rapidly. Heating, ventilation and air conditioning (HVAC) systems use conventional motor drive technology and the machines found in these devices are characterized by low efficiency and high maintenance. BLDC motor drives are characterized by higher efficiency, lower maintenance and higher cost. This paper presents the analysis, design, and implementation of a cost-effective control technique for a low cost solution, six switch three-phase inverter brushless dc motor drive using single current sensor for current control. Various parameters defined optimization path for target drive solution. Also, basic framework for low cost BLDC control IC is presented. The controller is modeled and the concept is proven using simulator. Then the verification and feasibility study are done by using field-programmable gate array prototyping on the custom board made for this research. Final simulation results along with prototype operation measurements are presented as well.

I. INTRODUCTION

Energy consumption is becoming one of the major constraints in all electric motor driven systems (EMDS). In recent few decades all countries are challenged with high energy prices pressure. Both more developed and less developed countries are facing constant energy consumption growth trends along with industrial production rise. Motors are consuming over 40% of all global electricity [1]. In such circumstances, main goal is to control energy consumption increase of the above mentioned electric motors and drives.¹

Over 5 000 000 000 motors are built every year worldwide [2]. The fact is that the most of them are single phase induction motors or brushed DC motors. Single phase induction motors are characterized by low efficiency because of the ohmic loss in the rotor and due to the phase angle displacement between the stator current and back electromotive force (EMF). Brushed DC motors are characterized with demanding maintenance and servicing due to the presence of brushes [3][4]. From mentioned it is obvious that there is a huge potential for BLDC motors to replace both of these. Substitution of these inefficient motors with more efficient brushless dc (BLDC) motors will result in substantial energy savings. Besides the energy saving, BLDC motors have many other advantages over brushed DC motors and induction motors. Some of them are a high reliability, long operating life (no brush erosion), noiseless operation, better speed versus torque characteristics, sharp dynamic response, wider speed ranges and reduction of electromagnetic interference [3]. In addition, the ratio of delivered torque to the size of the motor is higher, making it useful in applications where space and weight are critical factors, especially in aerospace and automotive applications [2][3].

The BLDC motor, from the simulation and modeling perspective has linear relationship between current and torque, same as voltage and revolutions per minute (rpm). Commutation system itself is electronically controlled in comparison to mechanical commutation typical for brushed motors. Electromagnets and armature are static and the permanent magnets are moving. This solves the problem how to transfer the current to armature which is moving. To achieve this, old commutation system with brushes is replaced with an electronic controller which performs the power distribution the same way as on the brushed DC motor.

Over the last decade, ongoing improvements in power semiconductors and controller ICs as well as the permanent-magnet brushless motor production have made it possible to manufacture reliable cost-effective solutions for a broad range of adjustable speed applications [5].

One of steps needed to be made on the road towards massive usage of BLDC motors is achieving higher efficiency in motor driving and control. General classification of all permanent magnet (PM) motors can be made with respect to their back electromotor force (back EMF) waveforms. First group are PM AC synchronous (PMAC) motors with sinusoidal back EMF and second are brushless DC (BLDC) motors with trapezoidal back EMF. The second group, the analyzed one, is most often powered by a set of currents having a quasi square waveform. This is usually done by using full-bridge voltage source inverter. The switches could be
BJTs, MOSFETs, IGBTs, or MCTs. The decreasing cost and drastic improvement in performance of these semiconductor devices have accelerated the applications of BLDC motor drives [6].

Most of the academic work connected to BLDC motors can be divided in two areas, position detection and switching control [2][4][5][9][10]. The point of interest in this paper is switching control only. Timing for switching is obtained from Hall sensors. The research goal of this paper is to design a commutation IC for BLDC motors by using Hall sensors for rotor positioning and one current sensor for motor control.

II. BRUSHLESS DC MOTOR COMMUTATION LOGIC WITH HALL SENSOR INPUTS

In the area of the switching control, three-phase fully controlled bridge is the most common power processing architecture because, for the same total power, it takes fewer cables and connectors in comparison to two-phase or four-phase systems. The mass of used copper, in a two-phase or four-phase system is the same as in three-phase, but in either of those cases it requires four cables and connectors, rather than only three [7].

In Fig. 1 is shown three phase system with standard six switches. In Fig. 2 are shown typical waveforms for a three phase BLDC motor with trapezoidal flux distribution. In practice the back EMF induced per phase looks approximately like in Fig. 2, and it is constant for 120 degrees, and for next 60 degrees it changes linearly with rotor angle. In every 60 period only two phases are conducting and other phase is inactive.

The goal is to produce constant output power which means that the output torque should be constant. To achieve this, phase currents have to be quasi square, similar to currents in Fig. 2. For a star-connected motor, the whole working process can be switched into six modes, where, in every phase, two out of three phases are conducting, while third is open.

Commutation of BLDC motor is controlled electronically and the commutation sequence is generated using control logic. To produce proper commutation sequence which will turn the motor, it is important to know rotor position. Usually the rotor position is sensed using Hall sensors, resolvers or optical encoders. Each Hall sensor is positioned 120 electrical degrees apart from other and produces logical ‘1’ while North Pole of the rotor is crossing near it. In Fig. 2 lower graph shows the Hall sensor output for different rotor angle values.

Figure 3 Hall sensor outputs and phase voltages for proper commutation

Figure 4 BLDC motor and commutation logic with Hall sensor inputs
ideal case. From the first Kirchhoff’s first law for point
constant torque, the phase current should be square in
between, which protects voltage source from sharp current
peaks. Presented solution assumes current sensor on the
DC link side. From all presented implies that that single
current flows through the circuit and therefore it is
sufficient to control only that value to achieve proper
control. This is due to the fact that all 3 phases are
controllable and therefore one phase current can be
switched off.

As shown in Table II, two phase currents should be
controlled, by using the current sensor in DC link both
values could be controlled with one control module.

Based on switching sequences from Table II, the
current regulation using bipolar hysteresis current control
loop is implemented. Using Fig. 2 switching sequence
table is created for all six switches. After the minimization
process, equation for each switch as a function of Hall
signals are created. These functions are given with following
set of equations:

\[ SH_1 = \overline{ABC} + \overline{A}BC = \overline{A}C \] (5)
\[ SH_2 = \overline{ABC} + ABC = \overline{A}C \] (6)
\[ SH_3 = \overline{A}BC + ABC = \overline{A}B \] (7)
\[ SH_4 = \overline{ABC} + ABC = \overline{A}B \] (8)
\[ SH_5 = \overline{ABC} + \overline{A}BC = \overline{B}C \] (9)
\[ SH_6 = \overline{ABC} + \overline{A}BC = \overline{B}C \] (10)

Energyzing the proper phase coils based on the rotor
position is known as commutation logic. For every change
of the Hall signals different switching pattern should be
applied.

The voltage levels that should be applied on each phase
are shown in Fig. 3. The switching pattern for clockwise
rotation of the motor is given in Table I.

### Table I

<table>
<thead>
<tr>
<th>SWITCHES DRIVE PATTERN FOR CLOCKWISE DIRECTION</th>
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<tbody>
<tr>
<td>PHASE</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

Current flow from DC link towards motor phases is
the phase side if the aim is to exploit motor on the first
goal is to take care of power utilization from source, or on
for current sensing could be on DC link side if the main
flowing through two phases and DC link. Generally, place
in Table II, the phase currents due to the mismatch in the current
sensitivity of sensors [10]. To overcome these problems
authors [9][10] are choosing to use one current sensor in
DC link and applied hysterics current control is used.

Hysteresis current control achieves indirect voltage
control by monitoring the current through the load and
forcing it to stay within the predefined band-gap [8].

Fig. 5 shows the equivalent circuit of BLDC motor. The
typical mathematical model of the BLDC motor is
represented as follows:

\[
\begin{align*}
\dot{v}_{rm}(t) &= \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L \ 0 \\ 0 & L \\ 0 & 0 & L \end{bmatrix} \begin{bmatrix} \frac{d}{dt} i_a \\ \frac{d}{dt} i_b \\ \frac{d}{dt} i_c \end{bmatrix} + \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \\
\dot{v}_{em}(t) &= \begin{bmatrix} R_e & 0 & 0 \\ 0 & R_e & 0 \\ 0 & 0 & R_e \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L \ 0 \\ 0 & L \\ 0 & 0 & L \end{bmatrix} \begin{bmatrix} \frac{d}{dt} i_a \\ \frac{d}{dt} i_b \\ \frac{d}{dt} i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \\
\end{align*}
\]

where \( v_{em}, e_x, i_x \) and \( L \) represent the voltage, back EMF,
phase current and self-inductance of phase \( x \), respectively
(\( x = a, b, c \)). To drive the motor with maximum and
constant torque, the phase current should be square in
ideal case. From the first Kirchhoff’s first law for point \( n \):

\[ i_n + i_b + i_c = 0 \] (2)

Commutation sequence is driving switches in such
manner that one phase current should always be 0. If
phase C is OFF (2) becomes:

\[ i_a + i_b = 0 \] (3)

or

\[ i_a = -i_b = 0 \] (4)

From Fig. 1 and Fig. 5, it is clear that this is the current
flowing through two phases and DC link. Generally, place
for current sensing could be on DC link side if the main
goal is to take care of power utilization from source, or on
the phase side if the aim is to exploit motor on the first
place. Current flow from DC link towards motor phases is
not ideally equal, because typically there is capacitor in
between, which protects voltage source from sharp current

### Table II

<table>
<thead>
<tr>
<th>MODES</th>
<th>CURRENT EQUATIONS ACCORDING TO THE OPERATING MODES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode I (0°&lt;\theta&lt;30°)</td>
<td>( i_a + i_b = 0 ) and ( i_c = 0 )</td>
</tr>
<tr>
<td>Mode II (30°&lt;\theta&lt;60°)</td>
<td>( i_a + i_b = 0 ) and ( i_c = 0 )</td>
</tr>
<tr>
<td>Mode III (90°&lt;\theta&lt;150°)</td>
<td>( i_a + i_b = 0 ) and ( i_c = 0 )</td>
</tr>
<tr>
<td>Mode IV (150°&lt;\theta&lt;210°)</td>
<td>( i_a + i_b = 0 ) and ( i_c = 0 )</td>
</tr>
<tr>
<td>Mode V (210°&lt;\theta&lt;270°)</td>
<td>( i_a + i_b = 0 ) and ( i_c = 0 )</td>
</tr>
<tr>
<td>Mode VI (270°&lt;\theta&lt;330°)</td>
<td>( i_a + i_b = 0 ) and ( i_c = 0 )</td>
</tr>
</tbody>
</table>

### Table III

<table>
<thead>
<tr>
<th>MODES</th>
<th>SWITCHEES SWITCHEAD SEQUENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode I (0°&lt;\theta&lt;30°)</td>
<td>B C A S_{AC}, S_{BC}</td>
</tr>
<tr>
<td>Mode II (30°&lt;\theta&lt;60°)</td>
<td>B C A S_{BC}, S_{AC}</td>
</tr>
<tr>
<td>Mode III (90°&lt;\theta&lt;150°)</td>
<td>A C B S_{AB}, S_{BC}</td>
</tr>
<tr>
<td>Mode IV (150°&lt;\theta&lt;210°)</td>
<td>B C A S_{AC}, S_{BC}</td>
</tr>
<tr>
<td>Mode V (210°&lt;\theta&lt;270°)</td>
<td>A B C S_{AB}, S_{AC}</td>
</tr>
<tr>
<td>Mode VI (270°&lt;\theta&lt;330°)</td>
<td>A C B S_{AC}, S_{BC}</td>
</tr>
</tbody>
</table>
where $\text{SH}_i$ are switching signals as functions of Hall signals. These equations are giving function for each switch to be active in a mode defined in Table III. These signals must be additionally controlled with output of the current hysteresis in order to create quasi-square current shape for each mode. This control is applied to two switches in each mode as shown in Table III.

### B. Hysteresis Current Control

The strategy of this control is to keep current value within the predefined band-gap. In elaborated case this is achieved by observing the DC link current value.

Presented assumes bipolar hysteresis current control. For better understanding of this control mode, it is easiest to analyze example with switching Mode II where switches S1 and S4 should be controlled. In this mode $i_a$ and $i_c$ are flowing and $i_e$ is zero. Then, every mode is divided into two different sub modes, one in which S1 and S4 are turned ON, and the other in which the S1 and S4 are switched OFF and the freewheeling diodes D2 and D3 are conductive. When the switches are ON, the current is rising up to the moment when the current reaches upper limit $UL$. In that moment the S1 and S4 are switched OFF and the current level is falling helped by D2 and D3. In this sub mode when switches are off and the current is flowing through the diodes, negative DC link voltage is applied to phase and current is decreasing. According to the active mode and the current sensor readings control signals are created for all switches. For every rotor position there is operating mode defined in Table III. In each mode current level is observed, and if the current is less than LL, generated control signal allows the switches to operate as defined in Table III.

#### TABLE IV

<table>
<thead>
<tr>
<th>Modes</th>
<th>Current level</th>
<th>Switching devices ON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode I (0°&lt;θ&lt;30°)</td>
<td>$\frac{di}{dt} &gt; 0$, $i_b &gt; -HL$ and $i_e &lt; HL$</td>
<td>S4, S3</td>
</tr>
<tr>
<td></td>
<td>$\frac{di}{dt} &lt; 0$, $i_b &lt; -LL$ or $i_e &gt; LL$</td>
<td>none</td>
</tr>
<tr>
<td>Mode II (30°&lt;θ&lt;90°)</td>
<td>$\frac{di}{dt} &gt; 0$, $i_e &lt; HL$ and $i_b &gt; -HL$</td>
<td>S1, S4</td>
</tr>
<tr>
<td></td>
<td>$\frac{di}{dt} &lt; 0$, $i_a &gt; LL$ or $i_b &lt; -LL$</td>
<td>none</td>
</tr>
<tr>
<td>Mode III (90°&lt;θ&lt;150°)</td>
<td>$\frac{di}{dt} &gt; 0$, $i_a &lt; HL$ and $i_b &gt; -HL$</td>
<td>S1, S6</td>
</tr>
<tr>
<td></td>
<td>$\frac{di}{dt} &lt; 0$, $i_a &gt; LL$ or $i_b &lt; -LL$</td>
<td>none</td>
</tr>
<tr>
<td>Mode IV (150°&lt;θ&lt;210°)</td>
<td>$\frac{di}{dt} &gt; 0$, $i_b &lt; HL$ and $i_e &gt; -HL$</td>
<td>S5, S6</td>
</tr>
<tr>
<td></td>
<td>$\frac{di}{dt} &lt; 0$, $i_b &gt; LL$ or $i_e &lt; -LL$</td>
<td>none</td>
</tr>
<tr>
<td>Mode V (210°&lt;θ&lt;270°)</td>
<td>$\frac{di}{dt} &gt; 0$, $i_b &lt; HL$ and $i_e &gt; -HL$</td>
<td>S2, S3</td>
</tr>
<tr>
<td></td>
<td>$\frac{di}{dt} &lt; 0$, $i_b &gt; LL$ or $i_e &lt; -LL$</td>
<td>none</td>
</tr>
<tr>
<td>Mode VI (270°&lt;θ&lt;330°)</td>
<td>$\frac{di}{dt} &gt; 0$, $i_e &lt; HL$ and $i_b &gt; -HL$</td>
<td>S2, S5</td>
</tr>
<tr>
<td></td>
<td>$\frac{di}{dt} &lt; 0$, $i_e &gt; LL$ or $i_b &lt; -LL$</td>
<td>none</td>
</tr>
</tbody>
</table>

This control is applied to two

**FIGURE 6 Hysteresis current control**

If the current level is higher than $UL$, generated control signal turns OFF all switches and turns the converter in sub mode in which the diodes are conductive. This control is given in Table IV.

#### III. SIMULATION AND EXPERIMENTAL RESULTS

In order to verify concept and create model for the implementation of the system PSIM simulation environment is created. The simulation PSIM model for Anaheim BLY173S-24V-4000 motor is created, the same model that is used in real system. The simulated speed is 3000 rpm, since the nominal motor speed is 4000 rpm.

For prototype implementation, custom control FPGA based board is developed – Xilinx Virtex6 and ADC converters on it, inverter board with six power FETs and the current sensor board with four sensors for each phase and DC link. Together these three boards are forming emulation platform which main purpose is ASIC prototyping, but it can also be used for different algorithm development and it has teaching potential as well.

The control algorithm from the simulation is successfully transferred to the emulation platform. The obtained results are matching the simulation results. With that, the validity of proposed model is proven. Performance of the implemented control is acceptable even for the commercial use, so this solution can be the basis for development of low cost IC. In addition to hysteresis current control, PWM is implemented to make control of the speed more efficient.

In Fig. 7 are shown simulation results of applied control. Three phase currents and torque characteristics are shown. As can be seen the expected quasi square current shape is derived using hysteresis current control.

In Fig. 8 are shown control board connected on top of inverter board. These two together with board with current sensors were used for implementation of control algorithm and concept validation. Table V is showing resource utilization of Virtex6 and it can be seen that there is big percent of resources still available, which means that this platform is good enough even for the development of complex control algorithms such as sensor less motor control. Since potential IC would not consume much silicon area this solution must be sorted in low price group.

#### TABLE V

<table>
<thead>
<tr>
<th>VIRTEX6 UTILIZATION SUMMARY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slice Logic Utilization</td>
</tr>
<tr>
<td>Number of Slice Registers</td>
</tr>
<tr>
<td>Number of Slice LUTs</td>
</tr>
<tr>
<td>Number used as Memory</td>
</tr>
<tr>
<td>Number of occupied Slices</td>
</tr>
</tbody>
</table>
CONCLUSION

In this paper conventional six switch converter topology is studied to analyze the potential for the realization of low cost solutions that can meet the highest commercial requirements. For this purpose emulation and prototyping platform that were developed and validated. All of these, concerning the components that are used, have potential to be used for further development of control algorithms. The six switch three-phase inverter brushless dc motor drive, using single current sensor for current control, is designed and implemented. From the presented results can be noted that developed control has potential to be widely used in low cost applications and the fact that whole control is implemented using FPGA gives the potential for IC production.

REFERENCES


