A Sensorless Control of Four Switch BLDC Motor Drive

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Abstract
This paper describes the analysis and design of a low cost three phase inverter brushless dc motor (BLDC) drive. The proposed method is a cost effective sensorless method employed for four switch BLDC motor. The absence of hall sensors give rise to a sensorless control in which the commutation instants are obtained from the zero crossing points (ZCP) of three voltage functions that are derived from the filtered stator terminal voltages $V_{ao}$ and $V_{bo}$. Hence phase shifters are not required that are common in conventional sensorless methods. The average terminal voltages are calculated using two low pass Butterworth filters. The phase currents are controlled using direct phase current (DPC) control scheme. The simulation results give the performance of developed sensorless technique.

Index Terms—Brushless DC (BLDC) motor drive, four-switch inverter, Sensorless control, phase shift.

I. Introduction.

Permanent-magnet Brushless DC (PMBLDC) motors with trapezoidal back emf finds a variety of applications in aerospace, automobiles, industries, military, computers, household products etc. due to higher efficiency, higher torque, higher power factor, increased power density, ease of construction, ease of control and ease of maintenance. The torque developed by a BLDC motor is constant as they are generated from trapezoidal back EMF and quasi square-wave currents. A conventional Brushless DC motor is excited by a six switch three phase inverter (SSTPI) where commutation is achieved through an inverter and a position sensor. So for each electrical cycle, three Hall-effect position sensors placed 120° apart on the stator provides the six commutation instants. Researchers are always conscious about their cost and are always exploring methods to bring in cost minimization. Cost effectiveness can be achieved either by reducing the number of power switches used in the inverter circuit, called topological approach or by proper designing of algorithms and their implementation in conjunction with a reduced component converter, called the control approach.

Fig. 1 Conventional six-switch three phase BLDC motor drive.

In this paper cost effectiveness is achieved by reducing the number of power switches, switching driver circuits, dc power supplies, total price and losses. A BLDC motor can be controlled by sensed control or sensorless control method. But for reducing the manufacturing cost a feasible sensorless method is developed by eliminating the position sensors. Also in harsh environments where these sensors cannot function reliably sensorless control is the only choice. In conventional six switch inverter topology a 30° phase delay is to be carried out between the zero crossing point of back emf and the commutation instant. In this aspect too four switch topology minimizes the cost by using the ZCP of three voltage functions, that coincide to six commutation instants rather than using complicated hardware’s to carry out phase shift. Theoretical analysis and simulations on MATLAB/SIMULINK
were conducted to demonstrate the feasibility of the proposed sensorless method.

II. Analysis of a FSTPI-BLDC motor drive.

The configuration of a four-switch three phase inverter (FSTPI) BLDC motor is shown in fig 2. The equivalent circuit of the four switch inverter Brushless DC motor drive is shown in figure 3.

The equation of a typical BLDC motor is represented as follows:

\[ V_{an} = R_i a + (L_s - M) \frac{d}{dt} (i_a) + e_a \]

\[ V_{bn} = R_i b + (L_s - M) \frac{d}{dt} (i_b) + e_b \]

\[ V_{cn} = R_i c + (L_s - M) \frac{d}{dt} (i_c) + e_c \]

Where \( V_{xn} \), \( R_i \), \( e_x \), \( L_s \), and \( M \) represents the phase voltages, resistances, phase currents, self inductances and mutual inductances of phase \( x \), respectively (\( x = a, b, c \)). The six operating modes for FSTPI BLDC motor drive are shown in fig.4.

A. Four-switch converter for BLDC motor drives.

In the four-switch configuration, the four switching status as shown in figure 5 are \((0, 0), (0, 1), (1, 0)\), and \((1, 1)\) where “0” means the lower switch is turned on and “1” means the upper switch is turned on. In the case of six-switch converter, the switching status \((0, 0)\) and \((1, 1)\) cannot supply the DC-link voltage to the load. So the current cannot flow through the load at these instants and hence they are regarded as zero vectors.
However, in the four-switch converter, current is flowing even at the zero-vectors as one phase of the motor is always connected to the midpoint of the dc-link capacitors. Moreover, the phase which is connected to the midpoint of dc-link capacitors is uncontrolled and only the resultant current of the other two phases flow through this phase during the switching status (0, 1) and (1, 0). This current is treated as zero if load is considered to be ideally symmetrical.

**Table I** indicate the detailed current equations from their corresponding operating modes. Due to the characteristics of BLDC motor, only two phases need to be controlled by the four switches using the hysteresis current control method during conducting intervals. Also at each operating mode, only two phases are conducting and the other phase remains silent or inactive. However, in the four-switch converter based on the four switching vectors as shown in figure 6, the generation of 120° conducting and a 60° non-conducting current profiles is inherently difficult. That means the conventional PWM schemes employed for four switch induction motor drives cannot be directly applied to BLDC motor drives. This led to the development of a new control scheme called Direct Current Controlled PWM scheme.

### B. Direct current controlled PWM scheme.

Under a balanced condition, the three-phase currents will satisfy the following condition:
\[ I_a + I_b + I_c = 0 \]  
(2)
This can also be written as
\[ I_c = -(I_a + I_b) \]  
(3)
In an ac induction motor drive, at any instant there are always three phase currents flowing as:
\[ I_a \neq 0; I_b \neq 0; I_c \neq 0 \]  
(4)
But from Fig. 4, for a BLDC motor (4) is not valid anymore. Table I indicate the detailed current equations from their corresponding operating modes. Due to the characteristics of BLDC motor, only two phases need to be controlled by the four switches using the hysteresis current control method during
Table I
Detailed current equations from the operating modes of BLDC motor.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Conditions</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode I (0°&lt;θ&lt;30°)</td>
<td>$I_b + I_c = 0$ and $I_a = 0$</td>
<td></td>
</tr>
<tr>
<td>Mode II (30°&lt;θ&lt;90°)</td>
<td>$I_a + I_b = 0$ and $I_c = 0$</td>
<td></td>
</tr>
<tr>
<td>Mode III (90°&lt;θ&lt;150°)</td>
<td>$I_a + I_c = 0$ and $I_b = 0$</td>
<td></td>
</tr>
<tr>
<td>Mode IV (150°&lt;θ&lt;210°)</td>
<td>$I_b + I_c = 0$ and $I_a = 0$</td>
<td></td>
</tr>
<tr>
<td>Mode V (210°&lt;θ&lt;270°)</td>
<td>$I_a + I_b = 0$ and $I_c = 0$</td>
<td></td>
</tr>
<tr>
<td>Mode VI (270°&lt;θ&lt;330°)</td>
<td>$I_a + I_c = 0$ and $I_b = 0$</td>
<td></td>
</tr>
</tbody>
</table>

each operating mode. Hence this scheme is called the Direct Current Controlled PWM scheme. This is shown in table I.

Table II
Switching sequences of four switch converter

<table>
<thead>
<tr>
<th>Modes</th>
<th>Active Phases</th>
<th>Silent Phases</th>
<th>Switching Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode I</td>
<td>Phase B and C</td>
<td>Phase A</td>
<td>S4</td>
</tr>
<tr>
<td>Mode II</td>
<td>Phase A and B</td>
<td>Phase C</td>
<td>S1 and S4</td>
</tr>
<tr>
<td>Mode III</td>
<td>Phase A and C</td>
<td>Phase B</td>
<td>S1</td>
</tr>
<tr>
<td>Mode IV</td>
<td>Phase B and C</td>
<td>Phase A</td>
<td>S3</td>
</tr>
<tr>
<td>Mode V</td>
<td>Phase A and B</td>
<td>Phase C</td>
<td>S2 and S3</td>
</tr>
<tr>
<td>Mode VI</td>
<td>Phase A and C</td>
<td>Phase B</td>
<td>S2</td>
</tr>
</tbody>
</table>

C. Current regulation.

Current is regulated to obtain the required quasi-square waveform. Based on the switching sequences shown in table II, the current regulation is brought out by hysteresis current control scheme. The switching sequence and corresponding current flow during the six operating modes are depicted in Fig. 7. The current regulation and detailed switching sequences are explained in Fig. 8. The torque and speed control loop from which the required reference torque is obtained gives the reference current value. This is represented by the bold line. A smaller band causes higher switching frequency and lower torque ripple. Therefore, the upper and lower bands for hysteresis control are fixed based on these values.
Fig. 7. Direct current controlled PWM strategy for modes: (a) S₃, (b) S₁ & S₄, (c) S₁, (d) S₄, (e) S₁, (f) S₁ & S₂

Case 2: Iₐ < 0

Iᵣ Interval : Iₐ > UL; S₂ is ON
IIᵣ Interval : Iₐ < (LL); S₂ is OFF
IIIᵣ Interval : LL < Iₐ < UL and d/dt(Iₐ) > 0; S₂ is ON
IVᵣ Interval : LL < Iₐ < UL and d/dt(Iₐ) < 0; S₂ is OFF

The same explanation can be given to phases B and C. Based on the current regulation, the voltage and current equations during the various modes are as shown in Table III.

Table III
Voltage and current equations after current regulation

<table>
<thead>
<tr>
<th>Modes</th>
<th>( \frac{di_a}{dt} &gt; 0 )</th>
<th>( \frac{di_a}{dt} &lt; 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode I</td>
<td>( \frac{di_a}{dt} = -\frac{R}{L} i_a + \frac{1}{2L} (\psi_a - \epsilon_a) )</td>
<td>( \frac{di_a}{dt} = -\frac{R}{L} i_a - \frac{1}{2L} (\psi_a + \epsilon_a) )</td>
</tr>
<tr>
<td>Mode II</td>
<td>( \frac{di_a}{dt} = \frac{R}{L} i_a + \frac{1}{2L} (\psi_a - \epsilon_a) )</td>
<td>( \frac{di_a}{dt} = -\frac{R}{L} i_a - \frac{1}{2L} (\psi_a + \epsilon_a) )</td>
</tr>
<tr>
<td>Mode III</td>
<td>( \frac{di_a}{dt} = \frac{R}{L} i_a + \frac{1}{2L} (\psi_a - \epsilon_a) )</td>
<td>( \frac{di_a}{dt} = -\frac{R}{L} i_a - \frac{1}{2L} (\psi_a + \epsilon_a) )</td>
</tr>
<tr>
<td>Mode IV</td>
<td>( \frac{di_a}{dt} = \frac{R}{L} i_a + \frac{1}{2L} (\psi_a - \epsilon_a) )</td>
<td>( \frac{di_a}{dt} = -\frac{R}{L} i_a - \frac{1}{2L} (\psi_a + \epsilon_a) )</td>
</tr>
<tr>
<td>Mode V</td>
<td>( \frac{di_a}{dt} = \frac{R}{L} i_a + \frac{1}{2L} (\psi_a - \epsilon_a) )</td>
<td>( \frac{di_a}{dt} = -\frac{R}{L} i_a - \frac{1}{2L} (\psi_a + \epsilon_a) )</td>
</tr>
</tbody>
</table>

Fig. 8. Switching sequence for current regulation

Considering phase A, we can take two cases as follows:

Case 1: Iₐ > 0

Iᵣ Interval : Iₐ < Lower Limit (LL); S₁ is ON
IIᵣ Interval : Iₐ > Upper Limit (UL); S₁ is OFF
IIIᵣ Interval : LL < Iₐ < UL and d/dt(Iₐ) > 0; S₁ is ON
IVᵣ Interval : LL < Iₐ < UL and d/dt(Iₐ) < 0; S₁ is OFF

Based on the current regulation, the voltage and current equations during the various modes are as shown in Table III.

The same explanation can be given to phases B and C.
D. Back EMF compensation.

While examining modes II and V, it’s seen that the active phases are phases A and B and the silent phase is phase C. That means, it’s expected that the current through phase C is zero. But the back emf of phase causes an unexpected current to flow through phase C thereby distorting the actual currents in phases A and B. Therefore, while considering the direct current controlled PWM scheme, the back emf compensation problem should also be considered. Fig.9 illustrates the back emf compensation. In Fig.9 (a), the current through phases A and B are same. Therefore any one current need to be sensed, either the current through phase A or that through phase B. If the current through phase A is sensed, then, the switching signal of S1 is determined independently and that of S4 depends on the S1 signal. So phase A current can be regarded as a constant current source. In this case, the current through phase B will be distorted due to the back emf of phase C.

III. Sensorless control of FSTPI BLDC motor drive.

Terminal voltages of a BLDC motor in the four switch inverter with respect to the mid-point of DC bus as shown in Fig 3 are:

\[ V_{ao} = R_i + L_i \frac{d}{dt}(i_a) + e_a + V_{no} \]
\[ V_{bo} = R_i + L_i \frac{d}{dt}(i_b) + e_b + V_{no} \]
\[ V_{co} = R_i + L_i \frac{d}{dt}(i_c) + e_c + V_{no} = 0 \] (5)

The commutation instants are exactly 30° phase shifted from the zero crossing points of the back emf. However, creating a 30° phase shift results in more hardware or complicated software that can lead to computational errors. Therefore a novel position sensorless method is developed based on the line voltages of BLDC motor.
In a four-switch inverter topology, as shown in Fig.11, terminal voltages $V_{ao}$ and $V_{bo}$ are oriented 60° together. That means $V_{ao}$ and $-V_{bo}$ lag 30° with respect to $e_{an}$ and $e_{cn}$ respectively. Moreover, voltage $V_{bo}-V_{ao}$ also lag 30° with respect to $e_{an}$. This means that the zero crossing points of $V_{ao}$, $V_{ba}$ and $-V_{bo}$ can be used to commutate the currents in phase A, B and C respectively. Thus the three voltage functions (VF) derived from the two terminal voltages $V_{ao}$ and $V_{bo}$ are:

$$V_{Fa} = V_{ao}$$
$$V_{Fb} = V_{ba} = V_{bo} - V_{ao}$$
$$V_{Fc} = -V_{bo}$$

![Fig.12. Voltage function and phase back emf voltages of FSTPI-BLDC motor drive.](image)

Fig.12 shows the waveforms of voltage functions and phase back emf voltages of BLDC motor drive. Zero crossings of VFs are detected using simple comparator circuits, and the virtual Hall sensor signals $V_{Ha}$, $V_{Hb}$ and $V_{Hc}$ are generated that can be used for current commutation. The virtual Hall sensor signals and the corresponding operation modes are summarized in table IV.

<table>
<thead>
<tr>
<th>Table IV</th>
<th>Commutation logic from voltage functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Function</td>
<td>$V_{Fa}$</td>
</tr>
<tr>
<td>$V_{Fa}$</td>
<td>Positive</td>
</tr>
<tr>
<td>$V_{Fb}$</td>
<td>Negative</td>
</tr>
<tr>
<td>$V_{Fc}$</td>
<td>Positive</td>
</tr>
<tr>
<td>$V_{Fe}$</td>
<td>Negative</td>
</tr>
<tr>
<td>$V_{Fg}$</td>
<td>Positive</td>
</tr>
<tr>
<td>$V_{Ff}$</td>
<td>Negative</td>
</tr>
</tbody>
</table>

IV. Simulation results.

The implementation of four-switch brushless dc motor drive system in simulink is shown in Fig.13.

![Fig.13. Simulink model of sensorless controlled FSTPI-BLDC motor.](image)

This is a high torque low speed motor with load torque as 0.5[Nm], reference speed as 100[rpm] and DC bus voltage as 60[v]. The rated BLDC motor parameters are listed in table V.

<table>
<thead>
<tr>
<th>Table V</th>
<th>Motor Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_r$</td>
<td>425 [W]</td>
</tr>
<tr>
<td>$T_e$</td>
<td>10 [N.m]</td>
</tr>
<tr>
<td>$R$</td>
<td>0.71[Ω]</td>
</tr>
<tr>
<td>$J$</td>
<td>2e-4 [Kg.m²]</td>
</tr>
<tr>
<td>$I_f$</td>
<td>2.72 [mA]</td>
</tr>
<tr>
<td>$K_f$</td>
<td>1.194 [N.m/A]</td>
</tr>
<tr>
<td>$K_e$</td>
<td>0.5218 [V.pm]</td>
</tr>
</tbody>
</table>

The main blocks used are Speed control block, Current control block, Power inverter block, BLDC motor block and Zero crossing detector block. The speed control block generates the reference current. The direct phase current control (DPC) scheme is employed in the current control block where the currents of two phases A and B are regulated through two independent current regulators. Proper phase voltages and terminal voltages are generated by the power inverter block and are applied to the BLDC motor block and Zero crossing detector block respectively using the developed duty cycle. Two second order low pass filters are used to eliminate the high frequency components. Virtual position Hall signals for sensorless control are then generated from the zero crossing points of voltage functions within the zero crossing detector block. Fig.14 shows the back emf waveforms of phase A, phase B and phase C. The rectangular phase currents are shown in Fig.15. Fig.16 shows the estimated operation modes and Virtual Hall Sensor signals $V_{Ha}$, $V_{Hb}$ and $V_{Hc}$. 
V. Conclusion.

A four-switch converter topology is introduced in this paper where cost saving is achieved by reducing the number of inverter power switches and also by eliminating the position Hall-effect sensors and phase shifters. The measured terminal voltages yields the virtual Hall signals for current commutation thereby giving a sensorless control. Simulation validates the proposed sensorless method. The main advantages of the proposed method are:

- Simplification of power conversion circuit.
- Using four switch inverter, all the six commutation instants can be detected.
- This method can be applied to permanent magnet synchronous motors as it is independent of back emf waveforms.
- Phase shifters are not required as the virtual hall sensors immediately follows the commutation instants.

Therefore, the implementation of the proposed method is easier and less expensive than other sensorless methods.

References.
