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Modelling and Simulation of Cost Effective Sensorless Drive for Brushless DC Motor

Debjyoti Chowdhury\textsuperscript{a}, Madhurima Chattopadhyay\textsuperscript{a}, Priyanka Roy\textsuperscript{b}

\textsuperscript{a}Heritage Institute of Technology, Kolkata-107
\textsuperscript{b}Netaji Subhash Engineering College, Kolkata-152

Abstract

This paper deals with a new commutation approach to achieve the sensorless drive of permanent magnet BLDC motor over the conventional six switch commutation circuitry. In the simulation model, we have introduced four switch three phase Brushless DC (BLDC) motor drive in which the rotor position is estimated using back EMF detection technique. In sensorless concept, the electronic commutation circuit plays an important role to drive motors because of their non-self commutating nature. In this work, power electronics based inverter along with logical circuitry has been employed in order to perk up the sensorless technique of BLDC motor. This driving procedure is always advantageous over sensored drives of BLDC motors, which come with bulky module using Hall-effect position sensors to detect the rotor position. Thus, this sensorless performance not only reducing the hardware complexity but also minimizes the consumption of power by associated circuitry. The effectiveness of the design is demonstrated through simulation results. The performance of this design is first evaluated by MATLAB based SIMULINK platform which gives a satisfactory result. Finally, this study helps us to develop a real time implementation of cost effective drive without hall sensors for BLDC motor.

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Keyword: Four Switch Inverter, back EMF, RC network, Sensorless, Brushless DC motor, Hall effect Six Switch Inverter;

1. Introduction

The usage of BLDC motors has increased because of its simple construction, relatively high reliability, low electromagnetic pollution and high power density\cite{1} for which they are extensively used in servo and low power drive systems\cite{2}. Over past few decades, the performance of these motors has significantly increased due to rapid development in power electronics and various commutation techniques. Four Switch Three phase sensorless drive provides reduced space management compared to the conventional six switch inverter circuit\cite{3}. In sensorless technique, the motor parameter i.e. stator back EMF is used to detect the instantaneous position of rotor. Back EMF detection technique has been proved as a significant improvement of the conventional sensored methods. BLDC motors exhibit two different types of back EMF waveforms a) trapezoidal and b) sinusoidal.

* Debjyoti Chowdhury. Tel.: +919474644186
E-mail address: djbabai.debjyoti@gmail.com
The back EMF waveform changes its phase every time when the rotor of the motor crosses the stator coil in front of it. The back EMF waveforms thus generated from the motor stator are made to go through a zero crossing detector (ZCD) [5]. The output of the ZCD is a square wave pulse and it is generated every time when the back EMF pulse changes its phase. These square wave pulses hence generated are similar to a hall sensors output and so are used to commute the motor. Square wave pulses from each of the stator windings are fed back to the control logic from motor to achieve commutation.

Hence, in this paper a position sensorless BLDC control scheme with Four Switch Inverter is proposed. This three phase inverter with four switches is advantageous over conventional scheme as it reduces the number of switches and freewheeling diodes as well as electromagnetic conduction losses [4]. The working principle of a Four Switch Inverter (FSI) is based on sensing the un-controlled phase C to commute the other two phases. Basically, two types of sensorless control technique can be found in the literature, i) the first type is the position sensing using back EMF of the motor, and the second one is ii) position estimation using motor parameters, terminal voltages and currents. The second type scheme usually needs Digital Signal Processors to do the complicated computation, and the cost of the system is relatively high. The position information is obtained from the zero crossing of the output voltages of the controlled phases.

The paper arrangement is as follows. The introduction is given in Section 1. In Section 2, we have described the mathematical model of the BLDC motor drive system using Four Switch control approach compared with traditional six switch strategy. Section 3 puts forwards the simulation model of the proposed inverter design in MATLAB/SIMULINK based platform. Finally, Section 4 concludes the work with the essence of final outcome of this simulation study by means of real time experimental results.

2. Mathematical Model of the system

2.1. Modelling of the BL DC motor

A BLDC motor has three stator phase windings connected in star fashion. Permanent Magnets (PMs) are mounted on the rotor. Fig.1 shows the equivalent circuit of a BLDC motor and Fig. 2 illustrates the relationship between the back EMF waveform of an ideal BLDC motor and the armature current, where E, I denotes the amplitude of back EMF and current respectively. The currents should have a rectangular waveform and must be in phase with the corresponding phase back EMF [5].

The windings of a BLDC motor can be modeled as a series circuit consisting a resistance R, an inductance L and a speed dependant voltage source \([6,7]\), which is known as the back EMF. While designing a BLDC motor, a few parameters such as induced current in the rotor due to stator harmonics fields, iron and stray losses are neglected. Self and mutual inductances are considered constant. The motor has three phases with the following voltages, described in Eq. 1, Eq. 2 and Eq. 3.

\[
V_A = R_s I_A + \frac{d}{dt} F_A + E_A \quad (1)
\]

\[
V_B = R_s I_B + \frac{d}{dt} F_B + E_B \quad (2)
\]

\[
V_C = R_s I_C + \frac{d}{dt} F_C + E_C \quad (3)
\]

where \(V_A, V_B, V_C\) are three phase stator voltages, \(R_s\) is resistance of stator winding, \(I_A, I_B, I_C\) are three phase stator currents, \(E_A, E_B, E_C\) are three phase back EMF and \(F_A, F_B, F_C\) are stator flux linkages.
Here \( L \) self inductance of the stator winding; \( M \) mutual inductance of stator winding. If \( L \) self-inductance and mutual inductance around the air gap are constant, there will be a direct relation between the applied source voltage to the phase terminals (V) and the induced back EMF (E) \[8\].

\[
E \propto V
\]

According to the working principle of BLDC motor, only two phases are conducting at a time while the third phase is floating in running mode \[9\], so Eq.4 reduces to the following:

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c \\
\end{bmatrix} = R_s \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1 \\
\end{bmatrix} \begin{bmatrix}
I_a \\
I_b \\
I_c \\
\end{bmatrix} + \begin{bmatrix}
L - M & 0 & 0 \\
0 & L - M & 0 \\
0 & 0 & L - M \\
\end{bmatrix} \begin{bmatrix}
\frac{d}{dt} I_a \\
\frac{d}{dt} I_b \\
\frac{d}{dt} I_c \\
\end{bmatrix} + \begin{bmatrix}
E_a \\
E_b \\
E_c \\
\end{bmatrix}
\]

(4)

The above Eq.6 provides the electrical transfer function of a BLDC motor.  

2.2. Modelling of uncontrolled Phase current based FSTPI

A BLDC motor conventionally is driven by a three-phase inverter with six-step commutation logic in both six switch and four switch analogy. Fig.1 shows the proposed design for the Four Switch Three Phase inverter (FSTPI), and the conventional Six Switch Inverter (SSI) is shown in Fig.2 \[10\].

![Fig.3 Four Switch Three Phase Inverter](image)

![Fig.4 Six Switch Three Phase Inverter](image)

In four switch inverter as shown in Fig.3, the phase C instead of being connected to \( V_{cc}/2 \) is connected to the midpoint of a RC-network.

![Fig.5 Four switch subsystem.](image)

The power circuit of the FSTPI fed BLDC motor drive is shown in Fig.5. The circuit consists of four switches IGBT_1, IGBT_2, IGBT_3, IGBT_4 and a pair of RC-network. The power circuit is the four switch three phase inverter. Two phases A and B are connected to the two legs of the inverter, while the third phase C is connected to the center point of the RC-network. The four power switches are denoted by the binary variables \( S_1 \) to \( S_4 \), where the binary ‘1’ corresponds to an ON state and the binary ‘0’ corresponds to an OFF state. The states of the upper switches (IGBT_2, IGBT_4) and lower switches (IGBT_1, IGBT_3) of a leg are complementary that is \( S_3 = 1 - S_4 \) and \( S_1 = 1 - S_2 \).
The terminal voltages $V_{as}$, $V_{bs}$, and $V_{cs}$ of a 3-phase Y-connected BLDC Motor can be expressed as the function of the states of the upper switches as follows:

$$
V_{as} = \frac{V_c}{2} (4S_2 - 2S_4 - 1) \quad (6)
$$

$$
V_{bs} = \frac{V_c}{2} (-2S_2 + 4S_4 - 1) \quad (7)
$$

$$
V_{cs} = \frac{V_c}{2} (-2S_2 - 2S_4 + 2) \quad (8)
$$

where $V_{as}$, $V_{bs}$, $V_{cs}$ are the inverter output voltages, $V_c$ is the voltage across one RC-network, $V_{dc}$ is the voltage across the pair of RC-networks ($V_c/2 = V_{dc}$).

The control scheme shown in Fig.6 can be implemented as an algorithm for real time application.

![Algorithm for logical control of sensorless drive](image1)

![MATLAB/SIMULINK model of commutation logic using zero crossing detector](image2)
From Fig. 8 it can be inferred that current waveform of phase C can never be held at zero like that of Phase A and B[12]. This introduces additional disturbance in phase currents of A and B. BLDC motors driven by BEMF detection analogy need quasi-square waves to drive the gates having 120° conducting and 60° non-conducting regions. The waveforms have to be synchronized with the Back EMF to obtain a constant steady torque output [13]. The working of the FSTPI is divided into six different modes depending on which phases are active and number of conducting switches, as shown in TABLE I.

| Switching states | Output voltages |
|------------------|-----------------|
|                  | $V_a/3$        | $V_b/3$        | $2V_c/3$       |
| $S_2$ $S_4$      | $-V_a$         | $V_b$          | $0$            |
| $V_a/3$          | $V_b/3$        | $-2V_c/3$      |

3. Simulation Results

In this part a position sensorless control scheme for FSTP inverter to drive the BLDC motor has been explained with the simulation results. Fig. 9 shows the MATLAB/SIMULINK model of the BLDC motor driven by a FSTP inverter. The following section represents the simulation results when a BLDC motor is driven by a Four Switch three phase inverter drive[14].

Fig. 8 Phase current waveforms when a BLDC motor is driven by FSTP inverter.

Fig. 9 MATLAB/SIMULINK model with motor load
4. Conclusion

In this paper, the simulation results helped the development of real time implementation shown in Fig.13. The results give the same outputs (stator currents, back EMF) as we obtained from simulation on MATLAB/SIMULINK. In this project the rotor position is detected with the help of back EMF in sensor less four switching technique. This system shows significant output at very high rpm, but shows some nonlinearity at lower rotational speeds. Here we have developed an instrumentation scheme which has innovativeness of sensor less technique based on four switch commutated method. This study has been carried out in MATLAB based SIMULINK platform and the output waveform are compared with the conventional SSI.

![Fig.10 RPM output waveform for FSTPI](image1)

![Fig.11 RPM output waveform for SSTPI](image2)

The above waveforms shown in Fig.10 and Fig.11 are output rpm waveforms of a BLDC motor driven by FSTPI and SSTPI respectively. The waveforms from both the figures show enough similarity, thus stating the proposed FSTPI can serve as a viable replacement for the commonly used Six Switch inverter.

![Fig.12 Stator current waveforms of a FSTP inverter driven BLDC](image3)
## Appendix

### TABLE II

| Rated Voltage(V) | Rated Speed(rpm) | Rated Current(mA) | Torque Constant (mNm/A) | Life(hours) |
|------------------|------------------|-------------------|-------------------------|-------------|
| 12               | 5400             | 110               | 14.5                    | 50,000      |

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