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Simulation and Performance Evaluation of Position Sensor and Sensorless Based Speed Control of BLDC Motor Using Hysteresis Band PWM Current Controller

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ABSTRACT

The paper presents the modeling, simulation & analysis of Speed Controller for a Brushless DC Motor. Performance comparison between a position sensor and sensorless based speed control is also presented in the paper. Hall effect Sensors have been used for position sensing and back emf based method has been used for determining the position of rotor in position sensorless scheme. The speed controller has been implemented by incorporating PI controller and hysteresis current controller in MATLAB Simulink. Hysteresis current controller was used to generate PWM pulses for inverter switches. IGBT based inverter was used for conversion of DC power to AC power.

Introduction

Brushless Direct Current (BLDC) motors also called Permanent Magnet DC Synchronous motors, have become popular, mainly because of their better characteristics and performance in comparison to other types of motors. The ratio of torque to the size of the motor is also higher, making it useful in applications where space and weight are critical factors [1]. In addition, position sensorless scheme has removed the Hall/Position sensors making the size and weight lesser. BLDC motor is a type of synchronous motor as the magnetic fields generated by the stator and rotor rotate at the same frequency. As the name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction motors. A few of these are [2]:

- Better speed versus torque characteristics
- High dynamic response
- Long operating life
- Noiseless operation
- High efficiency

Electronic commutation is the process of switching the current to flow through only two phases of motor for every 60 electrical degree rotation of the rotor. The power is supplied to the motor from a three-phase inverter, and the switching actions can be simply triggered by the use of signals from position sensors [3].

BLDC motors can be controlled in sensor or sensorless mode as shown in Fig. 1. The advantage of sensorless BLDC motor control is that the overall cost can be considerably reduced by removing the sensing part and the disadvantages are higher requirements for control algorithms and more complicated electronics [4].

In literature, pulse width-modulated (PWM) current controllers are used to maintain the actual currents flowing into the motor as close as possible to the rectangular reference values [5, 6]. In this paper hysteresis current controller based on a fixed hysteresis band is proposed to generate pulse width modulated signals for the switching of inverter.

Much research has been done on speed control based on position sensor as well as sensorless, but performance evaluation between them has not been found in literature [6-8]. In this paper, simulation for both the cases has been carried out and results are compared.

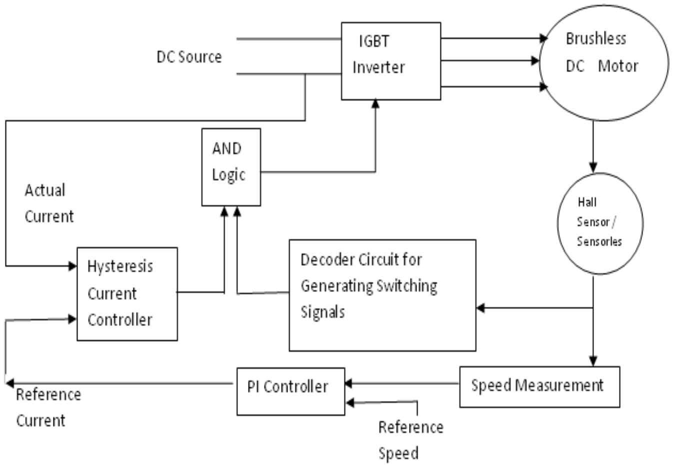

Figure 1 Block Diagram for BLDC motor Drives

Position sensor based speed control

Rotor position is sensed using Hall effect sensors embedded into the stator. Most BLDC motors have three Hall sensors embedded into the stator on the non-driving end of the motor. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the N or S pole

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respectively. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined.

Figure 2 shows an example of Hall sensor signals with respect to back-EMF and the phase current. On every 60 electrical degrees of rotation the Hall sensors changes the state. So, six steps are needed to complete one electrical cycle. However, one electrical cycle may not correspond to a complete mechanical revolution of the rotor. The number of electrical cycles to be repeated to complete a mechanical rotation is determined by the rotor pole pairs. For each rotor pole pair, one electrical cycle is completed. This sequence of conducting pair is essential to the production of a constant output torque.

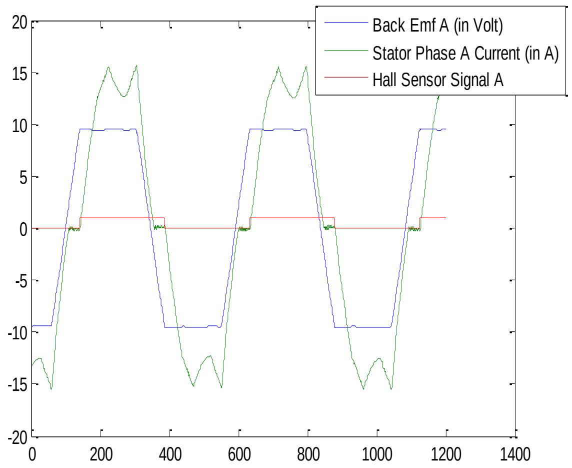

Figure 2 Relation between back EMF voltage, phase currents and Hall sensors

The Hysteresis current controller contributes to the generation of the switching signals for the IGBTs of inverter. Hysteresis-band PWM is basically an instantaneous feedback current control method of PWM where the actual current continuously track the reference current within hysteresis-band. When the current exceed upper band limit the switching signal will be zero (low) so that current can be decreased. As the current exceed the lower band limit, the switching signal will be one (high) so that current can be increased.

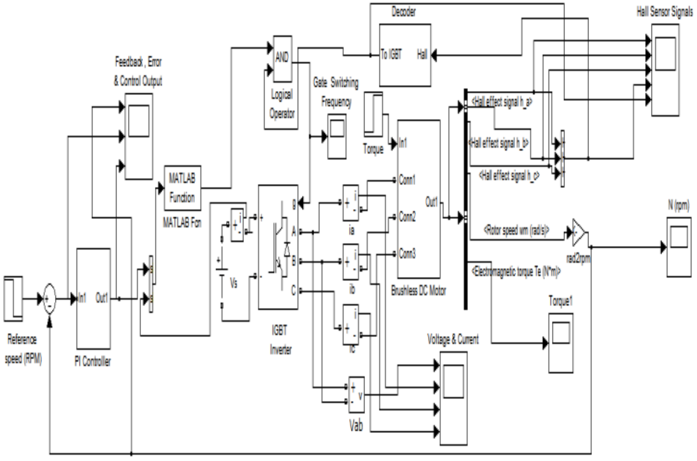

Figure 3 SIMULINK model for Brushless Motor Drive

A three phase BLDC motor equation can be represented as:-

$$v_a = i_a.R_a + L_a\frac{di_a}{dt} + M_{ab}\frac{di_b}{dt} + M_{ac}\frac{di_c}{dt} + e_a \quad \text{-(1)}$$

$$v_b = i_b.R_b + L_b\frac{di_a}{dt} + M_{ba}\frac{di_a}{dt} + M_{bc}\frac{di_c}{dt} + e_b \quad \text{-(2)}$$

$$v_c = i_c.R_c + L_c\frac{di_c}{dt} + M_{ca}\frac{di_a}{dt} + M_{cb}\frac{di_b}{dt} + e_c \quad \text{-(3)}$$

Table 1: Ratings and parameters of the BLDC motor

Rated Power	500 Watts
No. of Poles	16
No. of Phases	3
Type of Connection	Star
DC Voltage (Vs)	24
Rated Speed	2500 RPM
Rated Torque	1.9 N-m
Resistance / Phase	0.3 Ohm
Self Inductance	2.5 mH
Mutual Inductance	1.2 mH
Moment of Inertia	1271 x 10 -7 kg-m/sec2

Where

R: Stator resistance per phase, assumed to be equal for all phases

M: Mutual inductance between the phases.

ea, eb , ec : Back EMF of phase a , b and c respectively

The MATLAB/SIMULINK model based on mathematical equations 1 – 3 and with parameters given in table 1 was modelled as shown in the figure 3.

The MATLAB function block in the figure is the hysteresis current controller. The actual current and the reference current were compared and the hysteresis band was set at 5%.

The Hall sensor switches deliver digital pulses that can be decoded into the desired three-phase switching sequence as shown in table 2.

The MATLAB/SIMULINK model based on switching logic was modelled as shown in figure 4

Table 2: Generation of Switching Sequence from Hall Sensor signals

Hall Sensor Signals			Switching Sequence for IGBT Switches					
H_1	H_2	H_3	S_1 (a+)	S_2 (a-)	S_3 (b+)	S_4 (b-)	S_5 (c+)	S_6 (c-)
1	0	0	1	0	0	1	0	0
1	0	1	0	0	0	1	1	0
0	0	1	0	1	0	0	1	0
0	1	1	0	1	1	0	0	0
0	1	0	0	0	1	0	0	1
1	1	0	1	0	0	0	0	1

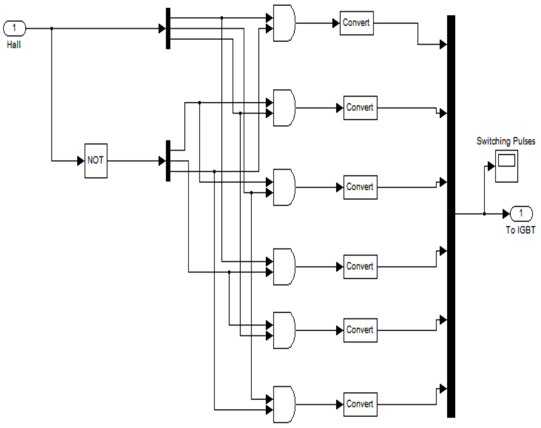

Figure 4 SIMULINK model for generation of switching sequence from Hall Sensor signals

Position sensorless based speed control

In the excitation of a three-phase BLDC motor, except for the phase-commutation periods, only two of the three phase windings are conducting at a time and the non conducting phase carries the back-EMF. Amongst the categories the most popular category is based on back electromotive forces or back- EMF's. The most cost efficient method to obtain the commutation sequence in star wound motors is to sense back-EMF of non conducting phase.

The phase current and back-EMF are aligned to generate constant torque. The current commutation point can be estimated by the zero crossing point (ZCP) of back-EMFs and a 30° phase shift, using a six-step commutation scheme through a three-phase inverter for driving the BLDC motor. The conducting interval for each phase is 120 electrical degrees. Therefore, only two phases conduct current at any time, leaving the third phase floating/silent. In order to produce maximum torque, the inverter should be commutated every 60° by detecting zero crossing of back-EMF on the floating coil of the motor , so that current is in phase with the back-EMF. The technique of delaying 30° (electrical degrees) from zero crossing instant of the back-EMF is not affected much by speed changes. To detect the ZCPs, the phase back-EMF should be monitored during the silent phase (when the particular phase current is zero) and the terminal voltages should be low-pass filtered first.

The terminal voltage of the opened or floating phase is given by equation (4):

$$V_C = e_C + V_N = e_C + \frac{V_{CE} - V_F}{2} - \frac{e_A + e_B}{2} \qquad (4)$$

As the back-EMF of the two conducting phases (A and B) have the same amplitude but of opposite sign the terminal voltage of the floating phase results in equation (5)

$$e_A = -e_B \Rightarrow V_C = e_C + \frac{V_{CE} - V_F}{2} \qquad (5)$$

The SIMULINK model based on the mathematical equations as described above is designed in MATLAB/SIMULINK for sensorless scheme is shown in the Figure 5.

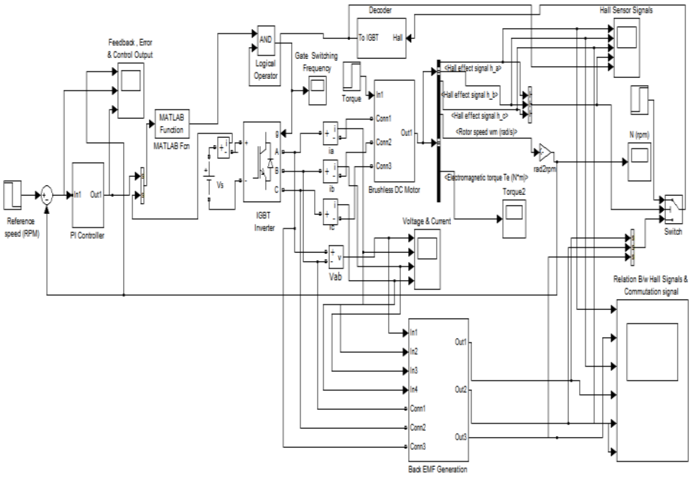

Figure 5. SIMULINK model for Position Sensorless (Back EMF) based Brushless Motor Drive

Performance Evaluation between Position Sensor and sensorless based speed control

In literature, researchers have discussed speed control of BLDC motor separately for position sensor and position sensorless based drive. So it is difficult to analyze torque generation, ripples in speed and torque for both methods together.

Here, the performance evaluation has been done and results are shown and discussed for both the cases.

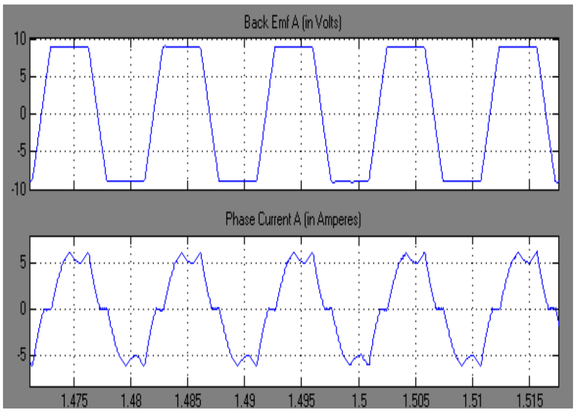

Fig. 6 Back EMF and Phase Current Waveform

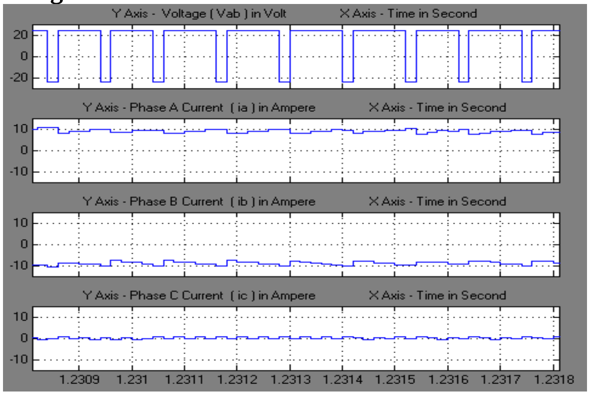

Fig. 7 Generation of PWM signals by Hysteresis controller

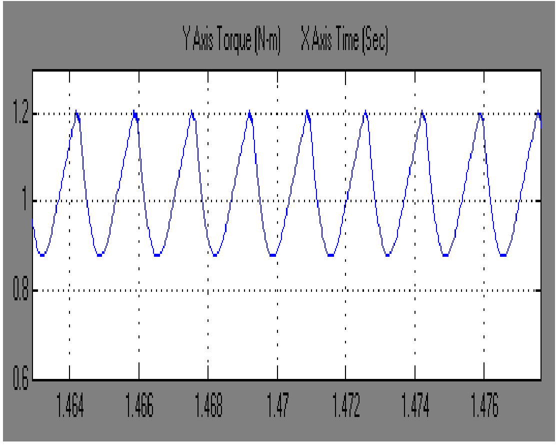

Fig. 8 Torque Ripple due to commutation (Position Sensor)

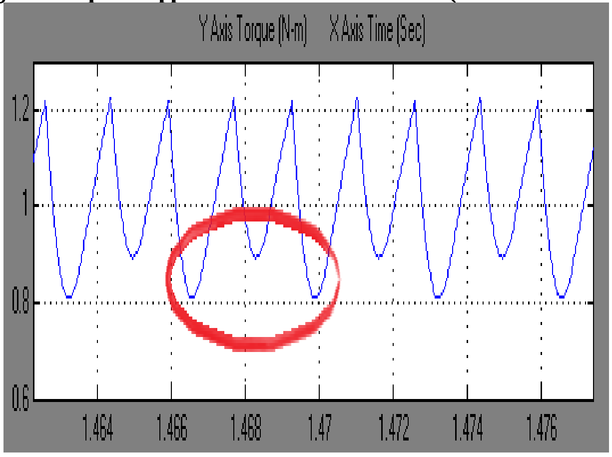

Fig. 9 Torque Ripple due to commutation (Position Sensorless)

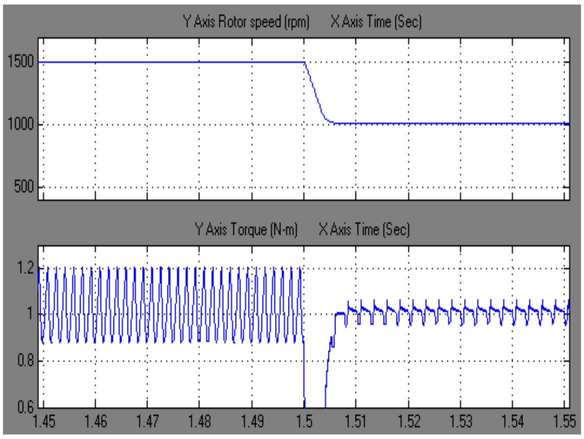

Fig. 10 Speed Change , Torque Ripple (Position Sensor)

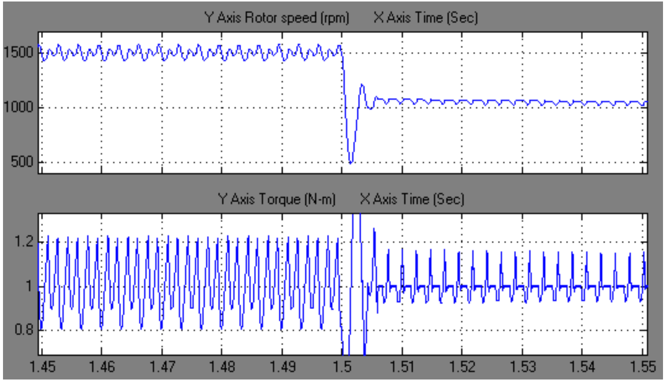

Fig. 11 Speed Change , Torque Ripple (Position Sensorless)

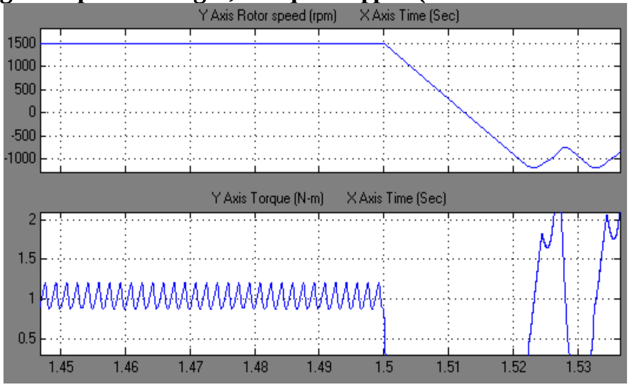

Fig. 12 Speed Reversal , Torque Ripple (Position Sensor)

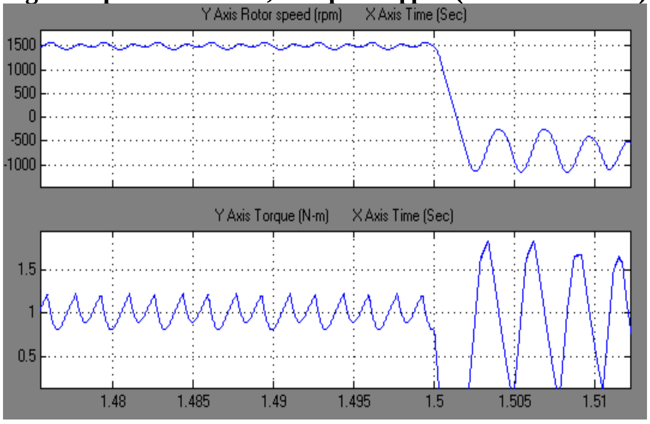

Fig. 13 Speed Reversal , Torque Ripple (Position Sensorless)

Simulated back EMF and current waveform is shown in figure 6. The results shown in figure 6 were used for generating commutating signals for back EMF based speed control. Figure 7 shows the generation of pulse width modulated (PWM) signals based on hysteresis controller. It is observed that when the current is exceeding its reference value by 5%, the PWM signal is low (0) and when the current is lower than the reference, then PWM signal is high (1). Hysteresis controller makes the current to follow the reference rectangular shape. A comparison between torque generations has been shown in figure 8 and 9. In the case of position sensorless control, it was observed that the ripple in torque is more as compared to the position sensor based control as highlighted by a red circle. In the case of Back EMF based speed control, more torque ripple generation is obvious as the torque ripple occurs due to the commutation of phases currents.

Figure 10 and 11 also shows a comparison for speed change. Here also it was observed that the ripple in position sensorless control is higher by 33%.

Figure 12 and 13 show reversal of speed and corresponding torque generation.

Conclusion

The transient and dynamic analysis of the Brushless DC motor with Hall effect sensor signals for position determination as well as back EMF based position sensorless methods for speed control have been presented in the paper. Performance evaluation for both the cases has been done and results are discussed. It can be observed that the ripple in speed and torque is higher in position sensorless control while all the parameters are kept same. Though position sensorless control will decrease the cost by eliminating the position sensing element, the performance of BLDC motor can decrease with same parameters. Hence in the development of sensorless controller one has to optimize between the performance and cost.

VI. Acknowledgements

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