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Back EMF detection based sensorless speed control of brushless DC motor

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Abstract— Brushless Direct Current (BLDC) motor is one of the recent and notable developments in the evolution of special electrical machines due to its outstanding performance, lesser noise and energy efficiency. However the speed control of this motor is still a concern due to the presence of hall sensor. This paper proposes a method to control the speed of sensorless BLDC motor by estimating the back emf to generate the required pulses for the three phase inverter that feeds the motor. A controlled voltage source acts as the main source which is controlled by an adaptive Proportional Integral controller which is tuned for better speed control of the BLDC motor. The proposed system is modeled and simulated in MATLAB/SIMULINK for all possible scenarios and the results are analyzed. The results show that the proposed work is excellent in sensorless speed control of BLDC motors under all possible operating conditions.

Index Terms— Sensorless control, BLDC Motor, Back EMF detection, PI Controller.

I. INTRODUCTION

A Brushless DC (BLDC) motor is an electric motor that operates using direct current (DC) but does not have the traditional brushes and commutator found in brushed DC motors. Instead, BLDC motors use electronic commutation to control the direction and speed of the motor. BLDC motors are more efficient than brushed DC motors because they don't have the friction and wear associated with brushes and commutators. This leads to less heat generation and longer lifespan. Without brushes to wear out, BLDC motors require less maintenance over time. The Brushless DC (BLDC) motors are considered to be best choice for applications in robotics, computer disk driver and airplanes.

Speed control is an essential component in the smooth and effective operation of the BLDC motor. Various methods have been developed over the years for effective speed control of BLDC motor. Salah et al. (2009) discussed the development of a PM Brushless DC Motor Drive System for Underwater Applications. The system used a microcontroller for driving the power inverter bridge and a 6-slot/4-pole permanent magnet brushless motor with built-in Hall Effect sensors. This includes information on the hardware implementations and the successful generation of a proper driving sequence for the BLDC motor. Baszynski & Pirog (2014) presented a digital algorithm of a speed control of BLDC motor. The proposed method for measuring the rotational speed of motor is based on signals from the rotor's position sensor, allowing for increased measurement frequency and accurate results. Hingmire & Pimple (2018) performed simulation analysis of speed control of BLDC motor by controlling the input DC voltage using a PI controller while the secondary loop is used to generate switching pulses for the inverter using the signals obtained from hall sensors. However, all those aforementioned methodologies use a hall sensor which occupies additional space and the motor suffers the limitation of poor performance during high temperatures. This necessitated alternate mode of speed control without using a hall sensor, termed as sensorless control. Wang & Lee (2015) proposed a 12 – step sensorless drive for BLDC motor based on differences between back EMFs which are determined from disturbance observer structure. The disturbance observer structure is able to access the entire voltage profile. Chen et al. (2017) proposed a sensorless control approach for a high speed BLDC motor based on a flux linkage function which is independent of speed. The methodology is able to deliver robust sensorless operation up to 20,000 rpm. Chen & Liu (2020) made an analysis the impact of non-ideal back EMF on the position of the commutation point during sensorless operation. An optimal commutation method is proposed by comparing the fluctuations in square wave current driven electromagnetic torque with the one when commutating based on various other commutation points.

Although there are numerous research towards sensorless speed control of BLDC motor by researchers, those approaches involve complex mathematical modelling in sensorless operation. This work presented in this paper aims to minimize the complexities in mathematical modeling involved in sensorless speed control of BLDC motor.

II. PROPOSED METHODOLOGY

The block diagram of the proposed sensorless speed control of BLDC motor is shown in Figure 1.

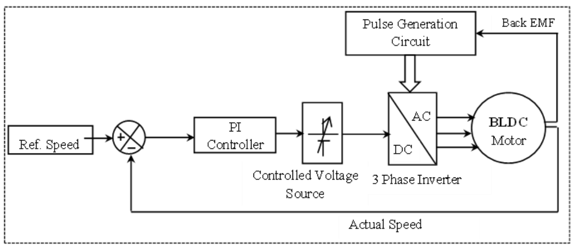

Figure 1 Block Diagram

The block diagram is composed of two sections. One is pulse generation circuit which performs sensorless operation and the other is the PI controller section which controls the speed of the BLDC motor by varying the input DC voltage to the inverter.

A. PULSE GENERATION CIRCUIT

The back EMF of the BLDC motor is sensed estimated of detecting the hall signals using hall sensor. The back EMF generated during the commutation of the motor phases is directly proportional to the motor's speed. The voltage across the windings of the motor and the current flowing through them are measured which is used for accurate estimation of the back EMF. Figure 2 shows the concept behind conversion of back emf of BLDC motor to corresponding hall signals.

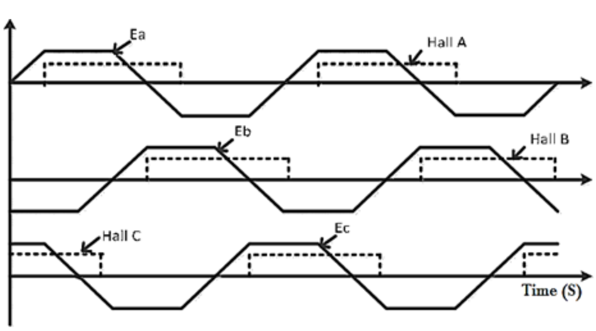

Figure 2 Hall signal generation from back emf of BLDC motor

After estimation of the back EMF of BLDC motor, the commutation signals or hall signals are estimated for the three phases. To determine the commutation signals, the trapezoidal back EMF is split into 6 modes of operation with 60 degrees for each mode.

The commutation function for each mode is defined using Equations (1) to (5).

$$\text{Mode I \& IV : } CF(\theta)1 = \frac{\widehat{e_{bc}}}{\widehat{e_{ca}}} \quad (1)$$

$$\text{Mode I \& IV : } CF(\theta)2 = \frac{\widehat{e_{ab}}}{\widehat{e_{bc}}} \quad (2)$$

$$\text{Mode I \& IV : } CF(\theta)3 = \frac{\widehat{e_{ca}}}{\widehat{e_{ab}}} \quad (3)$$

The commutation function for the mode conversion from mode 6 to 1 is represented by the fractional equation consisted of the numerator ($\widehat{e_{bc}}$) having a constant negative magnitude and the gradually decreasing denominator ($\widehat{e_{ca}}$). Before mode change, this commutation function instantaneously changes from negative infinity to positive infinity and this moment is considered as the position signal so that this feature can be certainly distinguished from noises by selecting a relevant threshold magnitude.

The switching sequences are determined based on the look up table as presented in Table 1.

Table 1 Switching configuration

Hall Signals			Switching Configuration					
A	B	C	S1	S2	S3	S4	S5	S6
0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	1	1	0
0	1	0	0	1	1	0	0	0
0	1	1	0	1	0	0	1	0
1	0	0	1	0	0	0	0	1
1	0	1	1	0	0	1	0	0
1	1	0	0	0	1	0	0	1
1	1	1	0	0	0	0	0	0

B. PI CONTROLLER

This is another important section in the proposed work. While back EMF observer , estimation of hall or commutation signals and consequent switching pulse generation contributes for the sensorless operation of BLDC motor, the PI controller is used to control the speed of BLDC motor by controlling the input DC voltage to the three phase inverter. The PI controller produces an output which is proportional to error and integral of the error as given in Equation (4).

$$u(t) = K_p e(t) + K_i \int e(t)dt \qquad (4)$$

where e(t) is the speed error, u(t) is the DC voltage to the three phase inverter, K_p and K_i are proportional and integral gain vales of the controller.

III. SIMULATION AND RESULTS

The proposed sensorless speed control methodology was implemented in a test system with specification for BLDC motor as presented in Table 2. All the components are modeled based on SimPowerSystem toolbox in MATLAB/ SIMULINK. The results are obtained using an Intel i5-4210U CPU @ 1.70 GHz processor, 4GB RAM.

Table 2 Parameters of BLDC Motor

Parameter Name	Value
Rated Voltage	180v DC
Rated Speed	2100 rpm
Voltage Constant	85.71 (V_peak L-L/krpm
Torque Constant	0.84
Stator Phase Resistance (Rs)	0.7Ω
Stator Phase Inductance (Ls)	2.72 mH
Flux Linkage	0.105

To illustrate the effectiveness of the proposed approach, the system is simulated under different operating conditions. The operating conditions include different set speed and different loading conditions and the results are discussed in this section.

A. Case (i) – No Load Condition

In this condition, the motor is set to run under no load. The speed control is performed for set speeds of 1500 rpm. The gain parameters of the PI controller are set as Kp=0.0025 and Ki=10. The simulation is run for a time period of 1 second. The hall signal generated by the proposed method in comparison with actual hall signal is shown in Figure 3.

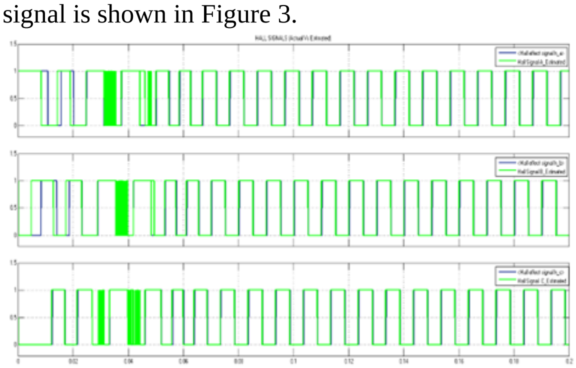

Figure 3 Generated Hall Signal

Under this operating condition, for the set speed of 1500 rpm, the BLDC motor reaches the steady state value in 0.072 seconds. The steady state error is found to be very less, ie., equal to 0.65 rpm (0.043%). The speed overshoot is observed as 456 rpm which is only about 30% of the required speed and lasts only for a period of few microseconds. Hence by evaluating these parameters, the proposed system is found to be efficient in controlling the speed of sensorless BLDC motor. The comparison between actual speed and set speed for the BLDC motor are depicted in Figure 4.

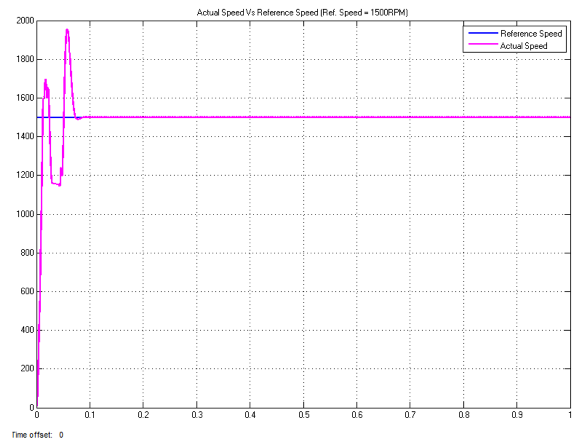

Figure 4 Speed Characteristics for reference speed of 1500 rpm under no load

B. Case (ii) – Constant Load Condition

In this case, the motor is set to operate at constant load. The load torque is fixed at 1.5 Nm throughout the simulation. Since, the load is increased, the input voltage need to be increased to run at 1500 rpm compared to that of no load in previous case.

Under this operating condition, for the set speed of 1500 rpm, the speed of BLDC motor reaches the steady state value at 0.048 seconds and the steady state error for this reference speed is found to be 1.3 rpm (0.087%). The speed curve reaches an overshoot of 2497 rpm (for a fraction of milliseconds) before reaching the steady state condition at 0.048 seconds. The comparison between actual and reference speed for this operating condition are given in Figure 5.

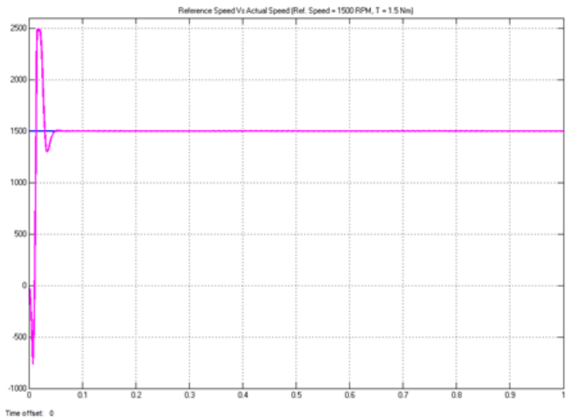

Figure 5 Speed Characteristics for reference speed of 1500 rpm at load torque of 1.5 Nm

C. Case (iii) – Varying Load Condition

In real time industrial applications of BLDC motor, the load is necessarily not constant always. The load on a BLDC motor in an industrial application can vary depending on the specific application and requirements. Many industrial processes involve variable loads where the motor needs to adapt to changes in torque or speed. Examples include conveyor systems with varying loads, pumps, and fans with changing flow rates. The design and selection of a BLDC motor for a specific industrial application should take into account the expected load conditions. Hence, in-order to reflect this possible load variation in the proposed speed control technique, in this operating condition, two different loads are set at different timings. The impact of the proposed method in speed characteristics when there is a sudden raise or decrease in load is analyzed in this section.

In this case, the load torque of the BLDC motor is set as 0.75 Nm as the initial condition (t=0 sec). At t=0.3 sec., the load torque is increased to 1.5 Nm and at 0.7 sec., it is decreased to 0.5 Nm. This operating condition is tested for reference speed of 1500 rpm. The variation in load will be reflected in the stator load current of the BLDC motor. The electromagnetic torque and stator current of the BLDC motor against the reference set torque are shown in Figure 6.

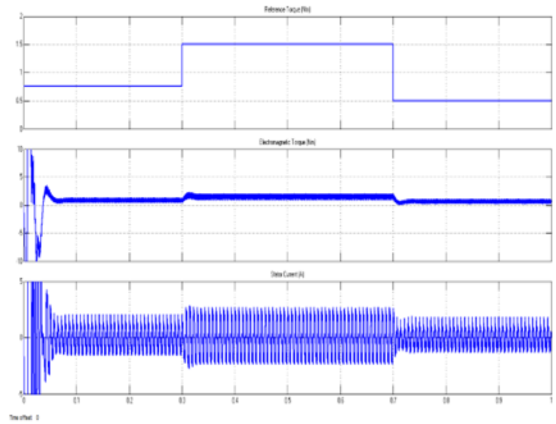

Figure 6 Stator Current of BLDC motor showing load variation

Initially when the load is 0.75 Nm, the actual speed of BLDC motor reaches steady state value at 0.1 seconds. At 0.3 seconds when the load is increased to 1.5 Nm, due to sudden increase in load, the speed drops to 1471 rpm and recovers back in 0.015 seconds to reach the steady state speed of 1500 rpm again. Also when the load is suddenly dropped to 0.5 Nm at 0.7 seconds, due to sudden loss of load, the speed slightly increases up to 1540 rpm and again recovers in 0.016 seconds to reach the required speed of 1500 rpm. This means that whenever there is any increase or decrease in load, the change in speed in less than 3% and it recovers back to steady state speed in quick time. The speed characteristic under this operating condition is presented in Figure 7.

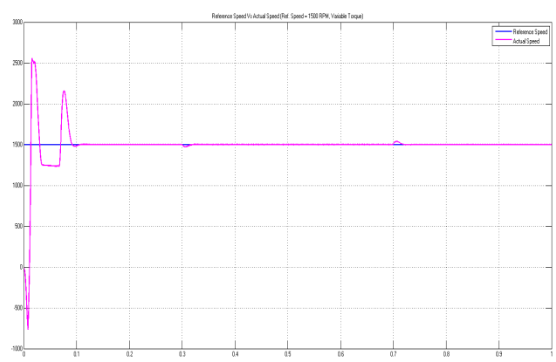

Figure 7 Speed Characteristics for reference speed of 1500 rpm at variable load torque

D. Case (iv) – Varying reference speed

In general, for any application, there might be requirements to reduce or increase speed of BLDC motor for same load. To include this scenario in the analysis, the load ix fixed to a constant value and the required operating speed or reference speed is varied in this operating condition. The load torque is fixed at 1.5 Nm; the reference speed is varied such that the initial speed is 1500 rpm, which is increased to 2100 rpm at 0.3 seconds and then again decreased to 1800 rpm at 0.7 seconds. The simulation is carried out for 1 second.

Under this operating condition, as in previous cases, the back EMF detection based controller produces the switching pulses required for three phase inverter and are responsible for sensorless operation. The PI controller controls the input DC voltage to control the speed of the BLDC motor.

The comparison between actual speed and required or reference speed of BLDC motor under this operating condition is shown in Figure 8.

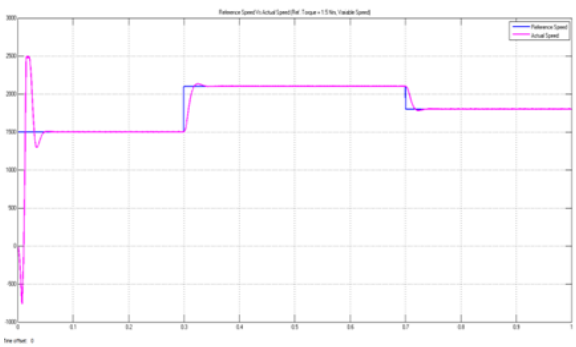

Figure 8 Speed Characteristics of BLDC motor for varying reference speed

It is observed that the motor attains initial steady state speed of 1500 rpm at 0.05 seconds and when the required speed is increased to 2100 rpm at 0.3 seconds, the actual speed gradually increases and reaches the steady state speed of 2100 rpm at 0.335 seconds. When the required speed is suddenly reduced to 1800 rpm at 0.7 seconds, the speed of BLDC motor gradually decreases and attains the required 1800 rpm at 0.725 seconds. In both the occasion of change in reference speed, the BLDC motor takes only 0.035 and 0.025 seconds to reach the required steady state value.

IV. CONCLUSION

In this paper, a sensorless speed control technique for BLDC motor based on back EMF estimation and PI controller is presented. The back EMF is estimated using measured voltage and current of the BLDC motor and the hall signals from back emf of BLDC motor which eliminates the need of a hall sensor. From the hall signals, based on switching logic lookup table, the switching pulses required for the three phase inverter thereby eliminating logical circuits. The PI controller controls the input DC voltage to the inverted depending on the speed requirement.

The proposed method is implemented on a test system and the simulation results under various operating conditions have proved the efficiency of the proposed approach for the speed control of BLDC motor.

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