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Sensorless Speed Control of FSTPI Fed Brushless DC Motor Drive Using Terminal Voltage Sensing Method

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Abstract: This study presents the design to control the speed of permanent magnet brushless DC motor using Sensorless Method. In conventional operation hall sensors are used to detect the position of the rotor windings and according to which the six switches of the voltage source inverter are gated. In Sensorless Method, zero crossing point of back-emf of line voltage differences are measured which will give the information about the phase which is to be energized. The zero crossing instant of back-emf waveforms is estimated indirectly from the measurement of three terminal voltages of the motor, from which correct commutation instants of the six switches are estimated. A Direct Phase Current Control Method is used to control the phase currents in four switches. Cost reduction is achieved by elimination of three hall effect position sensors and the numbers of power switches are reduced to four instead of six. An algorithm for four switch topology is developed with the third winding connected to the neutral of the supply line and performance of the developed sensorless technique is demonstrated by simulation. The hardware implementation is done by using PIC16F877 and the voltage and virtual hall signals are verified.

Key words: Brushless DC motor, four switch inverter, sensorless control, back-emf, implementation

INTRODUCTION

A Brushless DC motor (BLDC) is a PM synchronous electric motor which is powered by Direct-Current electricity (DC) and has an Electronically Controlled Commutation System, instead of a Mechanical Commutation System with brushes. In such motors, current and torque, voltage and rpm are linearly related. The permanent magnet Brushless DC (BLDC) motors are increasingly used in computer, automotive, industrial and household equipments because of its high power density, compactness, high efficiency, low maintenance and ease of control. BLDC motor is inherently electronically controlled and requires six commutation points per cycle. (Pillay and Krishnam, 1988; Lin *et al*., 2007; Lee *et al*., 2003).

A BLDC motor needs Quasi-square current waveforms which are synchronized with the back-emf to generate constant output torque with 120° conduction and 60° non-conducting regions. Also, at every instant only two phases are conducting and the other phase is inactive. In the four-switch converter, the generation of 120° conducting current profiles is inherently difficult (Niasar *et al*., 2008b; Miller, 1989).

Manufacturing cost of a BLDC motor drive can be reduced more by elimination of position sensors and by developing feasible sensorless methods. Sensorless control is the only choice for some applications where hall sensors cannot function reliably because of harsh environments. The sensorless technique utilizing back-emf voltage include: terminal voltage sensing, third harmonics sensing and freewheeling diode conduction current sensing (Niasar *et al*., 2008a, 2007; Johnson *et al*., 1999). Due to lower cost, simplicity and ease of implementation sensorless techniques based on back-emf methods are most commonly used.

In a typical three phase star wound BLDCM utilizing six step commutations, the current flow take place in only two phase windings at any one time. This leaves third phase winding available for commutation timing by sensing back-emf (Niasar *et al*., 2009). Commutation timing is determined when the unexcited phase back-emf reaches its zero potential points. This is called the "Zero crossing".

ANALYSIS OF FSTPI-BLDC MOTOR DRIVE

The typical mathematical model of the BLDC motor is represented as follows:

$$\begin{bmatrix}V_a\\V_b\\V_c\end{bmatrix}=\begin{bmatrix}R&0&0\\0&R&0\\0&0&R\end{bmatrix}\times\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix}+\begin{bmatrix}L-M&0&0\\0&L-M&0\\0&0&L-M\end{bmatrix}\frac{d}{d_t}\begin{bmatrix}i_a\\i_b\\i_c\end{bmatrix}+\begin{bmatrix}e_a\\e_b\\e_c\end{bmatrix}\qquad(1)$$

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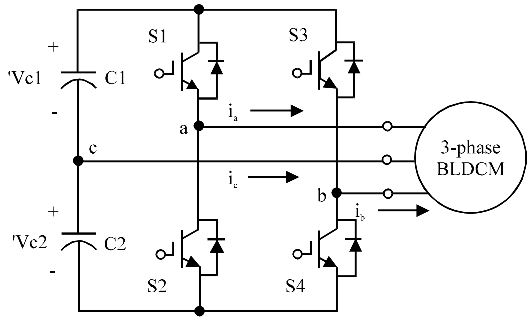

Fig. 1: Four switch inverter BLDC motor drive and equivalent circuit of BLDC motor

Where:

V_a-V_c = The stator phase winding voltages of phase a, b and c, respectively

e_a-e_c = The back-emfs of phase a, b and c, respectively

i_a-i_c = The phase currents of phase a, b and c, respectively

L and M = Self and mutual inductance per phase of the BLDC motor, respectively

In the Four-Switch Three Phase Inverter (FSTPI) as shown in Fig. 1, the generation of 120 conducting current profiles is inherently difficult. Hence, the Direct Phase Current (DPC) Control Method is used. Therefore, the currents of phase A and B in modes 2 and 5 are controlled independently and the current profiles are the same as the currents of a conventional six-switch inverter BLDC motor drive. The current and back-emf profiles of a BLDC motor is shown in Fig. 2.

A BLDC motor needs quasi square current waveforms which are synchronized with the back-emf to generate constant output torque. Also, at every instant only two phases are conducting and another phase is inactive. However, in the four-switch inverter, the generation of 120° conducting current profiles is inherently difficult due to its limited voltage vectors. It means that conventional PWM schemes for the four-switch induction motor drive cannot be directly used for the BLDC motor drive. Hence, in order to use four-switch inverter topology for the three-phase BLDC motor, a new control scheme named Direct Current Controlled PWM which has been developed by Lee *et al.* (2003) is employed. The two-phase currents need to be directly controlled using the Hysteresis Current Control Method by four switches. Hence, it is called the Direct Current Controlled PWM scheme.

Table 1 summarized the switching sequences in all six modes. The only difference between four-switch and six switch topologies is imbalance in phase and line to line stator voltages. This leads to shifting the neural point in the BLDC motor. It must be paid more attention in case of using the sensorless techniques.

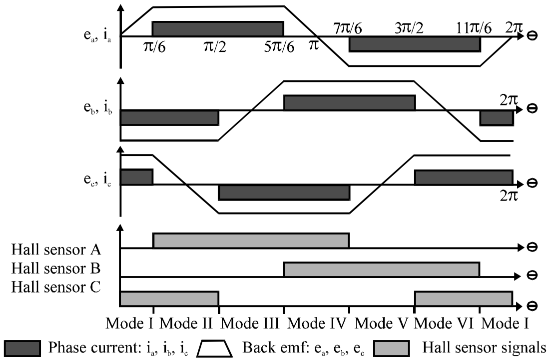

Fig. 2: Current and back-emf of a BLDC motor

Table 1: Switching sequences of the FSTPI-BLDC drive

Modes	Active phases	Silent phases	Switching devices
I	Phase B and C	A	S4
II	Phase A and B	C	S1 and S4
III	Phase A and C	B	S1
IV	Phase B and C	A	S3
V	Phase A and B	C	S2 and S3
VI	Phase A and C	B	S2

SENSORLESS METHOD BASED ON TERMINAL VOLTAGE SENSING

The terminal voltage equations of the four-switch inverter BLDC motor with respect to point O (natural ground in the middle point of DC bus) can be expressed as follows:

$$V_{a0} = RI_a + L\frac{di_a}{dt} + e_{an} + V_{no} \tag{2}$$

$$V_{b0} = RI_b + L\frac{di_b}{dt} + e_{bn} + V_{no} \tag{3}$$

$$0 = RI_c + L\frac{di_c}{dt} + e_{cn} + V_{no} \tag{4}$$

Because the drive employs the Direct Current Control Method, the motor adopts 120° conducting mode and only two phases are energized at one time. So, the current in the two phases has the same amplitude and opposite direction while in the third phase, the current is zero. As shown in Fig. 3, in the four-switch inverter topology, phase voltages V_{ao} and V_{bo} are at a phase difference of 60°. It results V_{ao} and $-V_{bo}$ are 30° phase lag respect to e_{an} and e_{cn}, respectively. Moreover, V_{ba} voltage (or V_{bo}- V_{ao}) vector has 30° delay respect to e_{cn}. It means that the zero crossing points of V_{ao} and $-V_{bo}$ can be used to commutate the current in phase A and C and also while two voltages V_{ao} and V_{bo} become equal together, two commutation instants of phase B may be detected. Due to PWM control of the inverter, stator terminal voltages V_{ao} and V_{bo} contains high frequency switching signals and thus detection of the zero crossings of three line voltages is difficult. Hence, two low pass filters should be used to eliminate high frequency harmonics.

In a four-switch inverter topology as shown in Fig. 1, the terminal C is connected to the middle point of DC bus (point O), with point O as reference, Fig. 4 shows the three line voltage waveforms, V_{ao}, V_{ba} and $-V_{bo}$. Zero Crossing Points (ZCPs) of these voltages lag 30° from ZCPs of phase back-emf voltages so they coincident with the commutation instants. Therefore, by detecting the zero crossing points of three line voltages, six commutation points are obtained. Three line voltages are derived from terminal voltages V_{ao} and V_{bo}. They have higher magnitude compared to back-emf voltages (√3 times phase voltages plus drop voltage on the stator impedance).

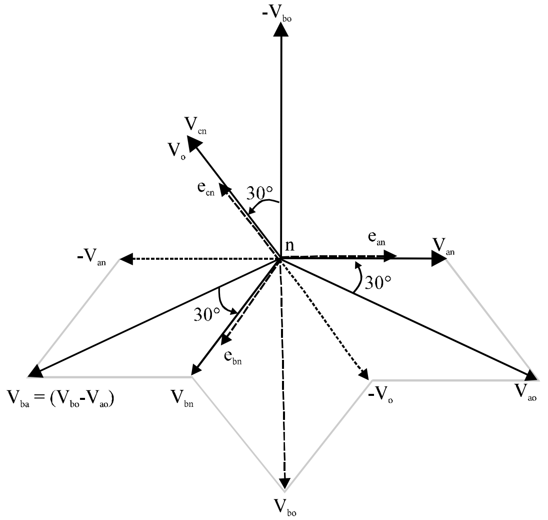

Fig. 3: Stator line to line voltage vectors of FSTPI BLDC motor drive

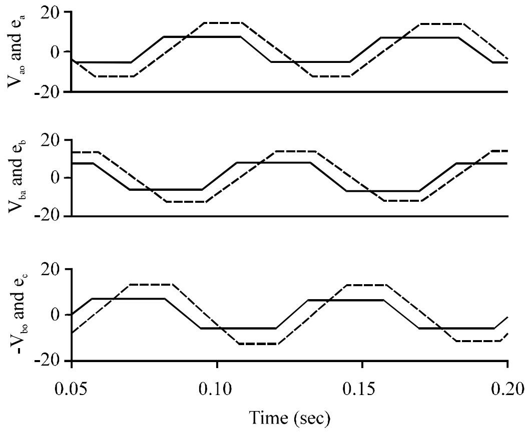

Fig. 4: Stator line and phase back-emf voltage

SIMULATION

In this study, the performance of the Developed Sensorless algorithm is developed and simulated using MATLAB Simulink. Employed BLDC motor is a low speed motor that has got 16 poles and has been designed for electric bicycle applications. In sensorless control scheme, control is achieved via terminal voltage sensing. The three voltage functions are used to get the commutation points. A voltage divider circuit is used first, it is followed by low pass filter (second order Butterworth) and then zero crossing detection circuits are used to get the virtual hall signals.

The gate signals are obtained as required exactly as per the switching sequence of four switch topology. Each switch has a 120° conducting period. Virtual hall signals are derived from three line voltages that are some delay from real ones because of voltage drop present in the stator impedance. Figure 5 shows the overall simulation diagram of the sensorless-controlled, four-switch inverter BLDC motor drive obtained through Simulink. A high-torque, low-speed BLDC motor with 16 poles is used for simulation and its parameters are given in Table 2. The zero crossing detectors detect the ZCPs of the voltage functions and then develop virtual position hall signals for sensorless control. Two second-order Butterworth low-pass filters with pass band frequency of 700 rad sec^{-1} are used to eliminate the high-frequency components of PWM voltages (Fig. 6). Figure 7 shows the estimated operation mode, voltage signals and phase currents where the phase currents are

Table 2: Machine parameters

Parameters	Values
Pn	425 W
Tn	10 Nm
R	0.64 Ω
Ls	1.0 mH
Kf	1.194 Nm A^{-1}
Zp	16 pole
ωn	700 rad sec^{-1}
J	5e-4 kg m^2
M	0.25 mH
Ke	0.0667 V rpm^{-1}

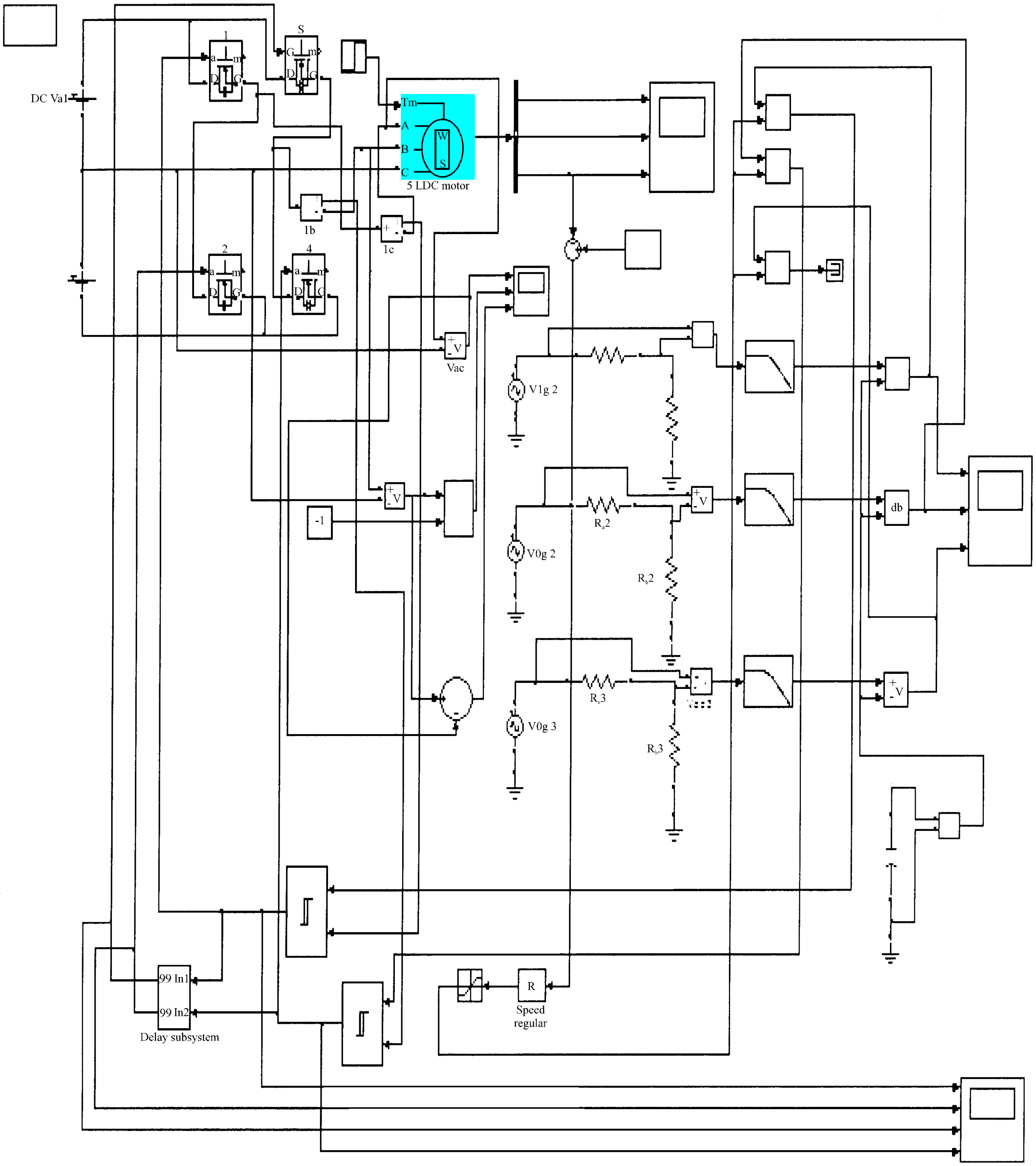

Fig. 5: Simulation circuit

rectangular. The filtered terminal voltages are used to determine the voltage functions. There are some glitches occurs in the current waveform due to the position estimation error.

Due to PWM control of the inverter, stator terminal voltages V_{ao} and V_{bo} contains high frequency switching signals and thus detection of the zero crossings of three line voltages is difficult. Hence, two low pass filters should be used to eliminate the high frequency harmonics and to calculate the average line voltages.

In the current control block, as shown in Fig. 5, the currents of phase A and B are regulated via two independent hysteresis current controllers and so will have balanced square-shape waveforms for the phase

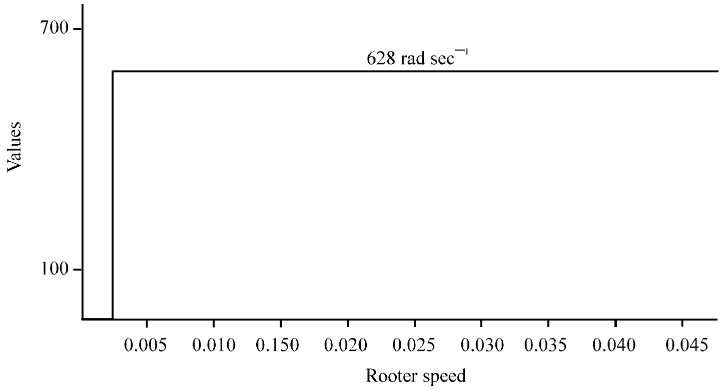

Fig. 6: Rotor speed

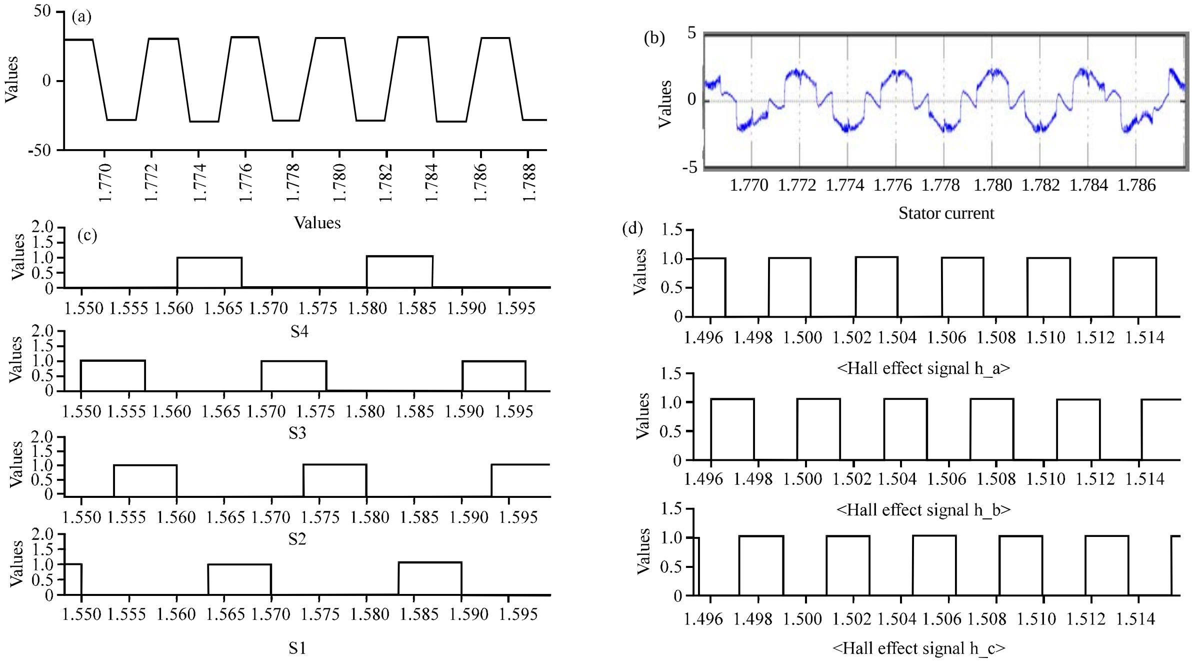

Fig. 7: a) Back-emf; b) stator currents of phase C; c) gate signals and d) virtual hall signals of FSTPI-BLDC motor drive

currents. Current control block the switching signals of the inverter. In this block, the phase and line PWM voltages are generated and are applied to the BLDC Motor Model. Moreover, the PWM voltages V_{ao} and V_{bo} are analyzed to detect the commutation points and generate the virtual hall sensors signal.

HARDWARE IMPLEMENTATION

A block diagram of FSTPI Fed Permanent Magnet Brush less DC Motor sensorless speed control is shown in the Fig. 8. The controller used is PIC16F877. PC interfacing is done using RS232 in visual basic platform.

The FSTPI drives are used to control the speed of the motor by varying the supply voltage to the motors. The MOSFET is switched with very high speed with the help of PWM waves. The PWM waves are generated by using PIC microcontroller.

The PWM time period and duty cycle is controlled by the software. Technology that is used in PIC16F877 is flash technology, so that data is retained even when the power is switched off. Easy programming and erasing are other features of PIC 16F877. The motor speed depends only on the amplitude of the applied voltage; the amplitude of the applied voltage is adjusted by using the PWM technique (Fig. 9).

The voltage and virtual hall signal outputs are taken under two conditions as one in lower speed region around 450 rpm and other at high speed region around 1000 rpm. The voltage and virtual hall signals are

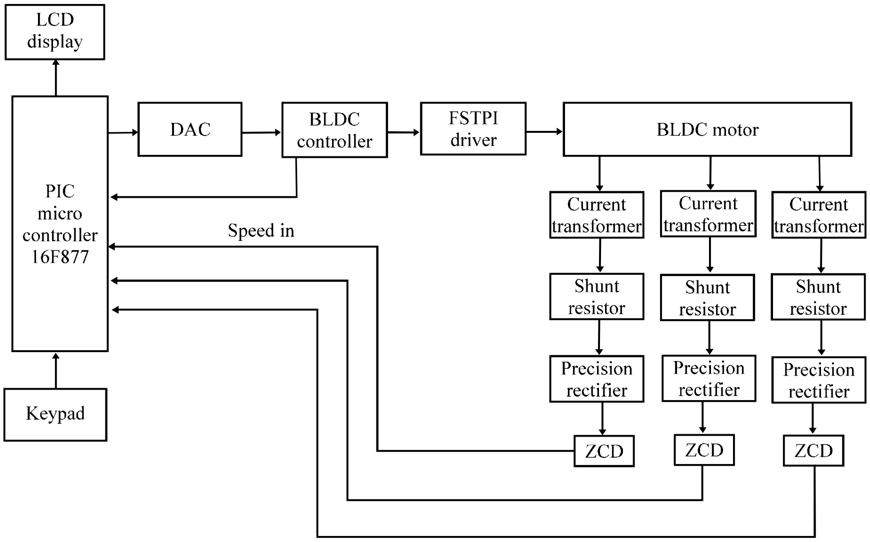

Fig. 8: Block diagram of PMBLDC Drive System

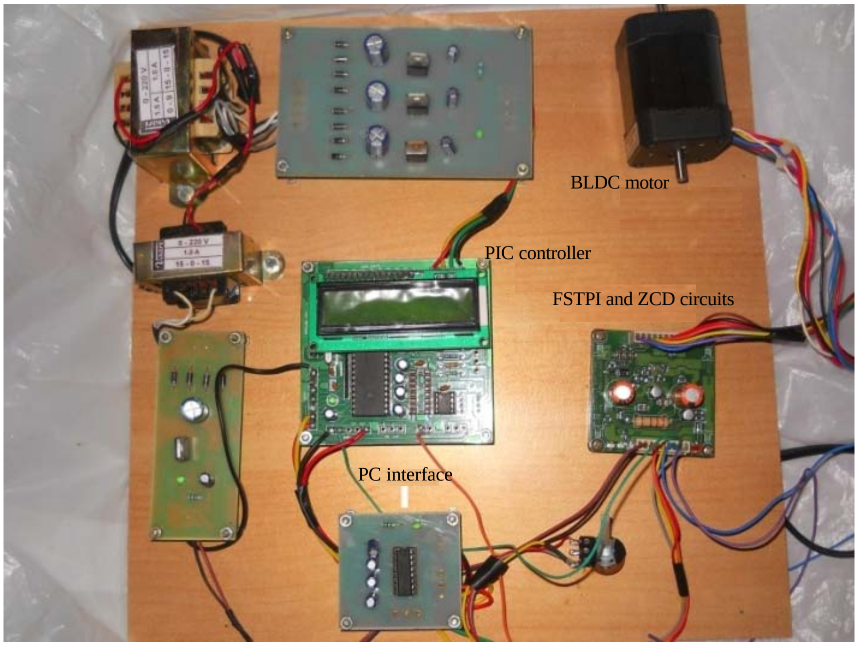

Fig. 9: Hardware implementation setup

shown in Fig. 10. Voltage and virtual hall signal are shown at 450 rpm. The voltage has a magnitude of 5.6 V.

For the operating speed of 1000 rpm the voltage magnitude also increased with speed and has a magnitude of 25.6 V. The virtual hall signal magnitude also increased. This implies that by using voltage control the speed of BLDC motor can be varied.

Simulation results are obtained as shown in Fig. 6 and 7. The actual speed is following the reference speed. The gate signals and the virtual hall signals produced are delayed in the manner such that the rotor windings are energized in sequence.

Using the PIC controller the DSO outputs of voltages and virtual hall signals are obtained at two speed regions as ,one in low speed region around 450 rpm and other at high speed region 1000 rpm. The results shows that the speed of the motor is proportional to the voltage applied.

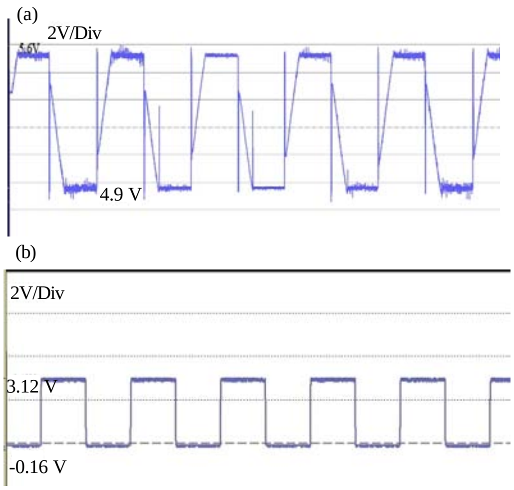

Fig. 10: Voltage and virtual hall sensor output at 450 rpm

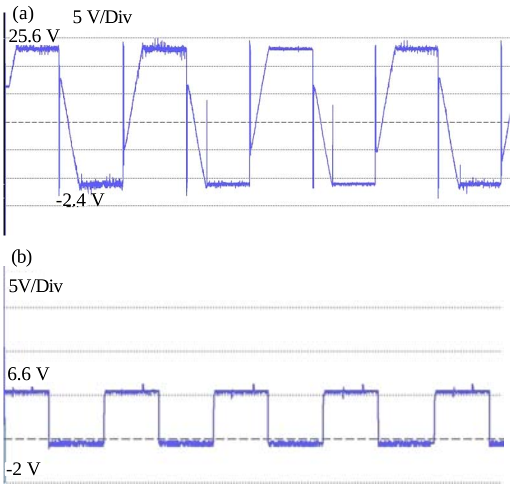

Fig. 11: Voltage and virtual hall sensor output at 1000 rpm

CONCLUSION

Sensor less control is the only choice for some applications where those sensors cannot function reliably due to harsh environmental conditions and a higher performance is required. For low-cost applications, the implementation of the proposed method is easier and less expensive than that of other methods even with the sensorless methods based on back-emf voltage. Therefore, it is a more attractive and cost-effective method. If the losses are reduced the efficiency is increased and very useful in aerospace applications. The ratio of torque delivered to the size of the motor is higher, making it useful in applications where space and weight are critical factors. The speed variation is very smooth. So, this can be used where position and accuracy is very important like in medical applications.

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