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Efficiency Optimized Brushless DC Motor Drive based on Input Current Harmonic Elimination

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ABSTRACT

This paper describes efficiency improvement of a position sensorless brushless dc motor with improved pulse width modulation scheme for the inverter compared to existing ones. This is based on Selective Harmonic Elimination. The proposed method reduces Total Harmonic Distortion from the input current and armature flux and thereby reducing the core losses. Also the power requirement with the proposed switching technique is much lesser than the existing switching scheme. The effectiveness of the proposed scheme is demonstrated through simulation and experimental results.

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1. INTRODUCTION

Brushless DC (BLDC) motors have been widely used in various industries, automation and appliances due to their higher efficiency, improved ruggedness and power density. Brushless DC (BLDC) motors with trapezoidal back electromotive force (EMF) characteristics requires six discrete rotor position information for the inverter as they are used to trigger the switches, here metal oxide semiconductor field effect transistor (MOSFET). Brushless DC motors require lower maintenance due to the lack of mechanical commutator and they have high power density. For these reasons they are ideal for high torque to weight ratio applications [1]. The most important drawback of BLDC machine is high initial cost and relative higher complexity due to the converter part. Reducing losses through the injection of proper direct axis current in the stator winding is also present [2]. The control algorithm determines the optimal direct axis current according to the operating speed and loading conditions. Efficiency improvement through using both axial and radial flux also has been studied [3]. Utilizing both radial and axial gaps can increase the effective area for torque generation and the fill-factor for the coil winding. By optimizing core and permanent magnet to minimize the electromagnetic loss while maintaining the same level of torque, the magnetic saturation of the core is also reduced. The iron loss can be reduced by the flux-weakening control [4]-[6]. To reduce the air gap flux by the demagnetizing effect due to the d-axis armature reaction, d-axis current is controlled. Optimal control method of armature current vector is proposed in order to minimize the controllable losses [7]. Switching techniques for BLDC motor torque ripple reduction is proposed previously using microcontroller [8]. FPGA based PWM is also presented in [9]. Also Fuzzy logic based speed control is discussed in [10]. In the proposed control, the phase current waveform is switched effectively to eliminate some lower order harmonics which will reduce the harmonics generated by the stator flux. This will also ensure that the BLDC to have minimal core losses. Figure 1 shows the equivalent circuit of a BLDC motor.

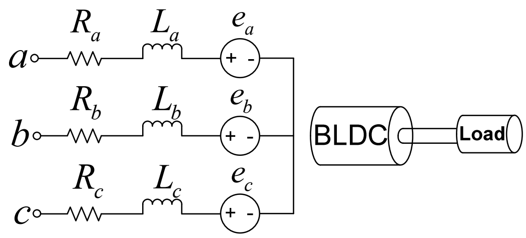

Figure 1. Equivalent circuit of a BLDC motor

2. BLDC MOTOR MODEL

The three phase voltage equations from the equivalent circuit of Figure 1 for the BLDC motor can be written as,

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{pmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{pmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{pmatrix} L_a & 0 & 0 \\ 0 & L_b & 0 \\ 0 & 0 & L_c \end{pmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_b \end{bmatrix} \tag{1}$$

Where, v = stator voltage, R = stator resistance, i = stator current, L= stator inductances and e= back emf.

The above quantities are defined for three phases *a-b-c.* The mechanical dynamic equation for the motor can be given as,

$$T_{em}(t) = \omega(\mathrm{t})B + J\frac{d\omega}{dt} + T_L(t) \tag{2}$$

Where, T_{em} (t) = developed electromagnetic torque, ω (t) = rotor angular velocity, B = viscous friction constant, J = rotor moment of inertia and T_L = load torque.

The back EMF (*a* phase) can be described as,

$$e_a = k_e \omega(t) \tag{3}$$

Where, k_e = per-phase back EMF

The voltage equation in Laplace domain can be obtained from (1) and (2) for phase *a* as,

$$V_{an}(s) = R_a I_a(s) + L_a s I_a(s) + k_e \omega(s) \tag{4}$$

From (4), the phase current can be given as,

$$I_a(s) = \frac{V_{an}(s) - K_e \omega(s)}{R_a + sL_a} \tag{5}$$

The electromagnetic torque T_{em} can be expressed as,

$$T_{em} = \frac{(e_a i_a + e_b i_b + e_c i_c)}{\omega} \tag{6}$$

3. PROPOSED SHE PWM BASED LOSS MINIMIZATION

For a Trapezoidal emf machine considered, the back emf and phase current waveforms for phase *a* considering 120° switching are given in Figure 2(a) for normal switching and Figure 2(b) for PWM switching required for speed control applications.

From Figure 2(a) the harmonic currents can be obtained as,

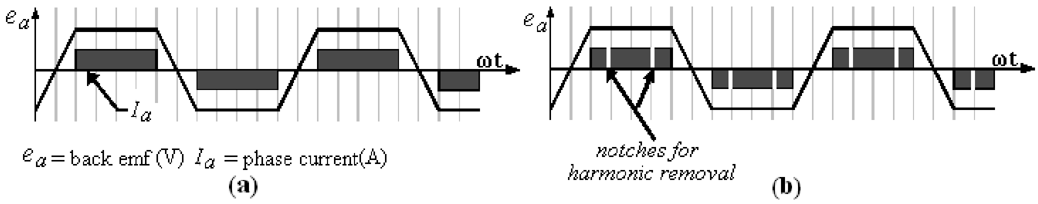

Figure 2. Phase current waveform for 120° conduction mode **(a)** normal switching **(b)** PWM switching

The corresponding expression for the current waveform for 120° conduction mode can be given as,

$$I_a = \left(\frac{4I}{\pi}\right)[\cos\alpha\sin\omega t + \frac{1}{3}\cos 3\alpha\sin 3\omega t + \frac{1}{5}\cos 5\alpha\sin 5\omega t + \frac{1}{7}\cos 7\alpha\sin 7\omega t....] \quad (7)$$

Putting $\alpha = 30^{\circ}$ in equation (7), the harmonic spectrum can be given in Figure 3.

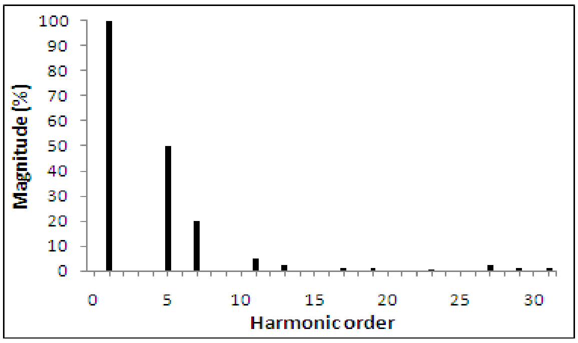

Figure 3. Harmonic spectrum for 120° conduction mode for normal phase current waveform

Using the proposed switching with removal of 5th and 7th harmonics as shown in the proposed Selective Harmonic Elimination based (SHE) PWM switching of Figure 2(b), the harmonic spectrum can be shown in Figure 4.

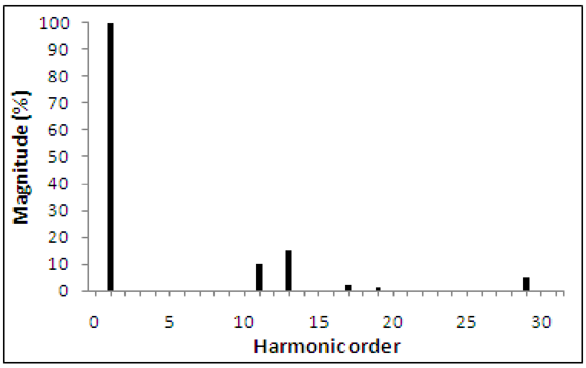

Figure 4. Harmonic spectrum for 120° conduction mode for SHE-PWM phase current waveform

The phase current of BLDC motor for 120° contains harmonics as evident from Figure 2(a). It is reasonably apparent that by eliminating the current harmonics, the core losses can be minimized, thus higher efficiency in the given speed range can be obtained. For removal of 5th and 7th harmonics from the waveform, three switchings are performed per quarter cycle of the current waveform. Of the three switchings, two are used for elimination of the 5th and 7th harmonics and one switching is used for adjustment of the fundamental. This process of selective harmonic elimination based PWM is employed using a PIC based microcontroller PIC18F452. The block diagram of the experimental setup is shown in Figure 5.

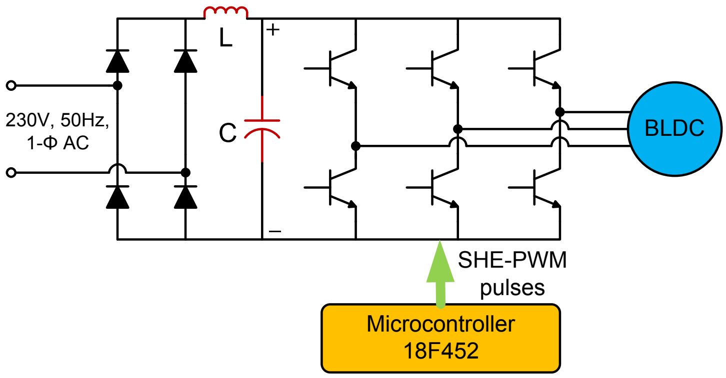

Figure 5. Block diagram of the experimental setup

Hysteresis Loss:

This loss is due to the revarsal of magnetisation of the armature core. The core undergoes one complete cycle of magnetic revarsal after passing under one pair of poles. Hysteresis loss is given by well known Steinmentz equation expressed as,

$$W_h = K_h B_{\max}^{1.6} f \text{ Watts} \tag{8}$$

Where f = Fundamental frequency, $B_{\max}$ is the maximum flux density of the stator core and K_h = Hysteresis constant. Taking harmonic components into account for a three phase balanced system, (8) can be modified as,

$$W_h = K_h B_{\max}^{1.6} f + K_h B_{5\max}^{1.6} f_5 + K_h B_{7\max}^{1.6} f_7 + ...n^{th} term \tag{9}$$

Eddy Current loss:

When permanent magnet rotor of the BLDC motor rotates, flux linkage changes in stator armature core. Thus according to the laws of electromagnetic induction an e.m.f is induced in the core body which sets up large current in the core due to its small resistance. The power loss due to the flow of this current is known as eddy current loss. The eddy current loss per unit core volume W_e is given by relation (10),

$$W_e = K_e B_{\max}^2 f^2 \text{ Watts} \tag{10}$$

Again, taking harmonic components in account (10) can be modified as,

$$W_e = K_e B_{\max}^2 f^2 + K_e B_{5\max}^2 f_5^2 + K_e B_{7\max}^2 f_7^2 + ...n^{th} term \tag{11}$$

As evident from equation (9) and (11), both the losses contain harmonic terms. Removal of the 5th and 7th order harmonics from the phase current will ensure reduced harmonic content in the induced flux linkages. Removal of these harmonics from the phase current will contribute to a induced flux waveform with minimal core losses. Consequently, the input power requirement for the BLDC motor will diminish.

With the removal of lower order harmonics in phase current waveform, the torque pulsation also gets reduced.

4. RESULTS AND DISCUSSION

A simulation study for the proposed scheme was carried out using *MATLAB/Simulink R2012b*. To validate the simulation, an experimental study was also conducted using an experimental BLDC motor. The complete specification of the motor is provided in Table 1. The required 48V DC for the BLDC motor is obtained through a single phase diode bridge rectifier module. The DC voltage is filtered with a LC filter before it is fed to the three phase inverter driver. The PIC microcontroller is used for generating SHE based PWM for the BLDC driver. The switching angles for the PWM are calculated offline and are stored in the microcontroller for online use.

Table 1. BLDC specifications

Parameters	Specifications/Ratings
Motor type	Surface Permanent Magnet type
Rated Power	350W
Rated Voltage	48V
Rated Speed	450 r/min
No. of poles	12
Winding	3-phase star connected
Resistance	2.5 Ω
Inductance	11.2 mH

The simulated waveform for the phase current for normal phase current is shown in Figure 6(a) and with proposed switching is shown in Figure 6(b).

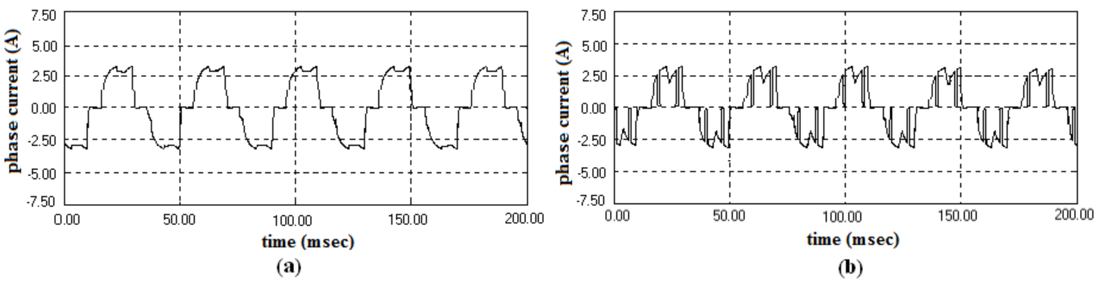

Figure 6. Simulated waveform for phase current for speed reference of 450 rpm for 120^{o} conduction mode for **(a)** normal switching **(b)** proposed SHE PWM switching

Similar phase current waveform was obtained with the experimental setup. The experimental waveforms were stored using a Tektronix make digital storage oscilloscope. The normal phase current is shown in Figure 7(a) and with proposed switching is shown in Figure 7(b).

The input power versus motor speed at no-load is plotted to justify the lower power requirement for the proposed SHE-PWM control. As observed from the plot of Figure 8, with the proposed control, the power requirement decreases than existing switching control scheme. A 20% reduction of power requirement can be observed at rated speed in the proposed switching scheme which is of much relevance.

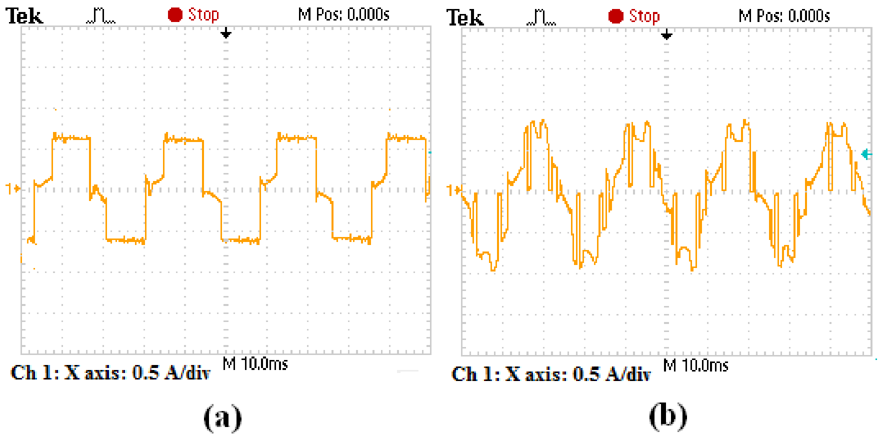

Figure 7. Experimental waveform for phase current for speed reference of 450 rpm for 120° conduction mode for **(a)** normal switching **(b)** proposed SHE PWM switching

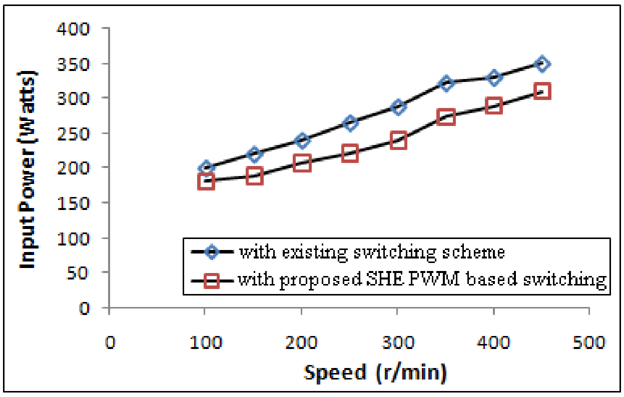

Figure 8. Plot for input power vs motor speed

5. CONCLUSION

A simple efficiency optimization scheme for BLDC drive system is proposed. The efficiency optimization is realized by eliminating unwanted lower order harmonics for the motor current and thereby reducing torque pulsations. Selective Harmonic Elimination based PWM is employed for this purpose which reduces the converter switching losses. The simulation and experimental results sum up the suitability of the proposed scheme.

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