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Modelling and minimization of losses for brushless DC (BLDC) motor suitable for electric vehicular applications

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Abstract. This paper presents modelling and minimization of losses of a brushless DC (BLDC) motor. A modelling based approach is used for the simulation of the BLDC model which is helpful for electrical vehicular (EV) applications. This is achieved with the help of input current pulse width modulation (PWM) scheme for the inverter drive. The PWM switching for the inverter is based on Selective Harmonic Elimination (SHE) and the switching angles are obtained offline using Genetic Algorithm (GA). By removing certain lower order harmonics from the input current and thereby armature flux, the core losses for the BLDC machine are minimized. The proposed method thus reduces total harmonic distortion (THD) from the input current. Also the power requirement for the proposed switching based model is much lesser than the existing switching schemes. The usefulness of the proposed scheme is demonstrated through simulation and experimental results.

Keywords: brushless DC (BLDC) motor, loss minimization, selective harmonic elimination (SHE), genetic algorithm (GA)

1 Introduction

Brushless DC (BLDC) motors have been widely accepted for use in various industries, automation as well as domestic appliances due to their higher efficiency, ruggedness and high power density. BLDC motors require lower maintenance due to the lack of mechanical commutator[11]. The most important drawback of BLDC motor is high initial cost and relative higher complexity due to electronic commutation. BLDC motors with trapezoidal back electromotive force (EMF) characteristics requires six discrete rotor position sensors for driving the inverter as they are used to trigger the semiconductor switches. These switchings accounts for some switching losses for the BLDC drive. In BLDC motors, core losses accounts for the major losses for the machine and hence proper design considerations is essential[1]. Online loss minimization by injecting stator current is studied in [4]. Flux weakening of BLDC machines for constant power operation at higher speeds for adjustable speed drive applications is studied in [3, 9, 14]. Efficiency improvements through using both axial and radial flux also have been studied[10]. 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 shown. 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[13]. Core loss determination using finite element model[7] has been proposed but the calculation becomes hectic when harmonics are considered. Switching techniques for BLDC motor torque ripple reduction is proposed previously using microcontroller[2]. The PWM based switching reduces

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the associated torque ripple for BLDC motors which is an added advantage. In the recent past, sensorless position control strategies for BLDC motor control have been adopted out of which Hybrid sliding mode control[15], I-f starting sequence and real time flux estimation based control[8], hysteresis comparator[5] and for high speed applications[6] are of great relevance for online applications. However, current switching based loss minimization for BLDC drive is not available in literatures.

In the proposed control, the authors present an ideal loss modelling approach to predict the losses due to harmonics and reducing them by phase current waveform switching. The harmonic elimination based switching effectively eliminates some lower order harmonics which will reduce the harmonics generated by the stator flux. Also, the switching losses and conduction losses are minimized by using a constraint to the proposed switching. This will also ensure that the BLDC motor to have minimal core losses. Fig. 1 shows the star connected equivalent circuit of a BLDC motor connected to an inverter.

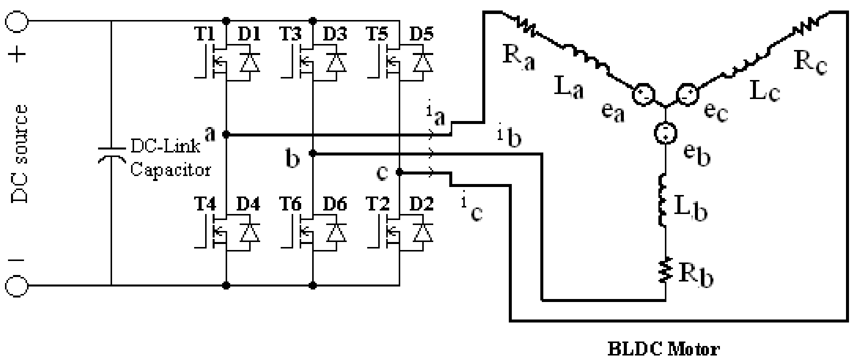

Fig. 1: Star connected equivalent circuit of a BLDC motor connected to an inverter

2 BLDC motor model

The three phase voltage equations from the equivalent circuit of Fig. 1 for the BLDC motor can be written as [11],

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

where, v is the stator voltage, i is the phase current, R and L are the stator resistances and inductances respectively and e is the back emf. The above quantities are defined for three phases $a-b-c$. The mechanical dynamic equation for the motor can be given as

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

where, $T_{em}(t)$ is developed electromagnetic torque, $\omega(t)$ is the rotor angular velocity, B is viscous friction constant, J is the rotor moment of inertia and T_L is the load torque.

The back EMF (a phase) can be described as

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

where, k_e is the per-phase back emf constant The voltage equation in Laplace domain can be obtained from Eqs. (1) and (2) for phase a as

$$V_{an}(s) = R_aI_a(s) + L_asI_a(s) + k_e\Omega(s). \tag{4}$$

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

$$I_a(s) = \frac{V_{an}(s) - K_e\Omega(s)}{R_a + sL_a}. \quad (5)$$

The electromagnetic torque T_{em} can be expressed as

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

3 Prediction of the losses for a BLDC motor

For a trapezoidal emf BLDC machine considered, the phase current waveforms considering 120 degree switching with PWM are shown in Fig. 2.

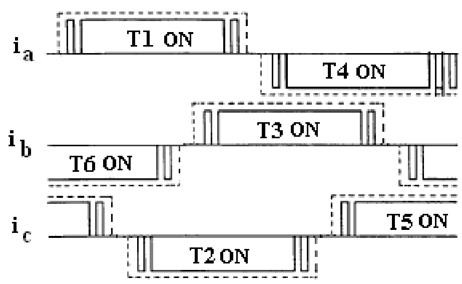

Fig. 2: PWM switching of phase current waveform

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

$$I_a = \frac{2\sqrt{3}I}{\pi}\left(\sin\omega t + \frac{1}{5}\sin 5\omega t + \frac{1}{7}\sin 7\omega t + \cdots + n^{th} term\right). \quad (7)$$

The harmonic spectrum for Eq. (7) is shown in Fig. 3. The phase current of BLDC motor for 120° contains harmonics as evident from Fig. 3. It is thus apparent that by eliminating the harmonics from the phase current waveform, the core losses can be minimized, thus higher efficiency in the given speed range can be achieved. 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 said harmonics and one switching is used for adjustment of the fundamental component of the current. This process of selective harmonic elimination based PWM is employed using a PIC based microcontroller PIC18F452 in experimental study. The angles for switching are found using Genetic Algorithm (GA) based offline calculation. Fig. 3 shows the current harmonic spectrum for the system with conventional switching and after removal of 5th and 7th harmonics using GA.

3.1 Hysteresis loss

The core losses of a soft ferromagnetic material can be subdivided into the hysteresis and eddy current losses. The hysteresis loss is due to the reversal of magnetisation of the armature core. The core undergoes one complete cycle of magnetic reversal after passing under one pair of poles. Hysteresis loss is given by well known Steinmentz equation expressed as

$$W_h = k_h B_{\max}^{\alpha} f, \quad (8)$$

where f is the fundamental supply frequency, is the maximum flux density of the stator core. K_h is the hysteresis constant along with α can be derived from the $W_h - B_{\max}$ curve derived experimentally from

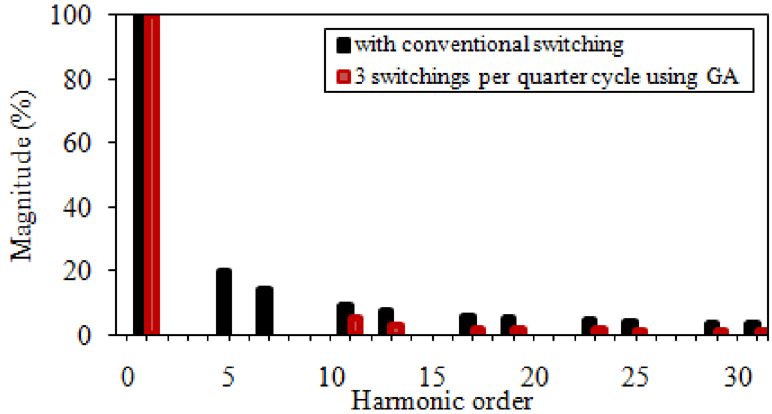

Fig. 3: Current harmonic spectrum for 120o conduction mode

single sheet dc tests. Where, the induction waveform cause minor loop hysteresis loss, the above expression can be corrected as [15],

$$W_h = k_h B_{\max}^{\alpha} f K(B_{\max}), \tag{9}$$

where, $K(B_{\max}) = 1 + \frac{0.65}{B_{\max}} \sum_{i=1}^{n} \Delta B_i$ and is the change in flux density in the minor loop. Taking harmonic components into account for a three phase balanced system without minor loop losses, expression Eq. (8) can be modified as,

$$W_h = k_h B_{\max}^{\alpha} f_1 + k_h B_{5\max}^{\alpha} f_5 + k_h B_{7\max}^{\alpha} f_7 + \cdots + n^{th}\text{term}. \tag{10}$$

As evident from Eq. (9), the hysteresis loss component of core loss can be minimized by removing the harmonic frequency components that adds to the total incurred losses.

3.2 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 emf 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 is given by relation Eq. (11),

$$W_e = K_e B_{\max}^2 f^2. \tag{11}$$

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

$$W_e = K_e B_{\max}^2 f_1^2 + K_e B_{5\max}^2 f_5{}^2 + K_e B_{7\max}^2 f_7{}^2 + \cdots + n^{th} term. \tag{12}$$

As evident eddy current losses contain harmonic terms similar to the hysteresis losses. 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 an 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.

3.3 Copper loss

Copper loss for general switching per phase can be expressed as

$$W_{cu} = I_{\text{rms}}^2 R_a \text{ Watts}. \tag{13}$$

With increased number of switchings for a selective harmonic based PWM waveform as shown in Fig. 3, the expression for rms value of phase current will get minimized for a particular set of operating condition and thus the losses can be minimized.

3.4 Conduction and switching losses

On state conduction loss across a switch can be determined from the on state voltage drop $V_{\min}$ and the on state current $I_{\max}$. For 120° conduction mode operation for the inverter, the conduction loss W_{cond} can be given as,

$$W_{\text{cond}} = 2V_{\min}I_{\max} \text{ Watts.} \tag{14}$$

This loss can be added as a compensation term with the copper loss model as both the losses are dependent on conduction.

The average switching losses on the contrary are dependent on the switching frequency $f_{\text{switching}}$ and dependent on the switch on and switch off times of the semiconductor switch.

$$W_{\text{switch}} = \frac{V_{\min}I_{\max}}{6}(T_{\text{on}} + T_{\text{off}})f_{\text{switching}} \text{ Watts.} \tag{15}$$

For the experimental setup used, the switching loss taking 10 kHz frequency for the semiconductor MOSFET 2SK727 and 120° conduction mode, where, on and off times are 1 μs and 1.5 μs respectively,

$$W_{\text{switch}} = \frac{50 \times 10}{6}(2.5 \times 10^{-6})10 \times 10^3 \approx 2 \text{ Watts.} \tag{16}$$

Thus, a standoff is made to lower the switching losses by keeping only three switchings per quarter cycle while minimizing the harmonics and thereby the core losses.

For calculating the switching angles for the inverter, offline Genetic Algorithm (GA) is chosen. The optimum switching angles are computed using GA which will contribute to minimum current distortion, keeping selected harmonics within the allowable limits. The objective function $f(\alpha)$ therefore chosen to minimize the harmonics is the total harmonic distortion of the phase current which is given as

$$f(\alpha) = \frac{\sqrt{\sum_{n=5}^{\infty} I_n^2}}{I_1}. \tag{17}$$

$$\begin{aligned} \text{Subject to } & 0 < \alpha_1 < \alpha_2 < \alpha_3 < (\pi/2), \\ & a_1 = M, \\ & k_5(a_5 - \in_5)^2 + k_7(a_7 - \in_7)^2 \leq \in, \end{aligned}$$

where n is the harmonic order corresponding to the harmonics to be minimized. This equation is constrained by the criterion that the minimization is to be done following the switching angles to be generated within 0 to $\pi/2$ degrees. $\in$ is the error limit for acceptable minimization for harmonics and k_5, k_7 are the constants which represent the burden for minimizing the 5th and 7th harmonics respectively. The flowchart for the GA based switching is shown in Fig. 4. The obtained switching angles are stored in the microcontroller memory for online switching of the BLDC motor.

4 Simulation and experimental results

A simulation study for the proposed loss minimization scheme was carried out using MATLAB/Simulink R2014b. To validate the simulation results obtained, an experimental study was also conducted using an experimental BLDC motor whose complete specification 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. A PIC micro-controller is used for generating harmonic elimination based PWM for the BLDC driver.

The switching angles for the PWM are calculated offline and are stored in the micro-controller for online use. Fig. 5 shows the simulated model of the BLDC motor drive system. The BLDC motor is modeled using the equations as discussed in section 2 of the paper.

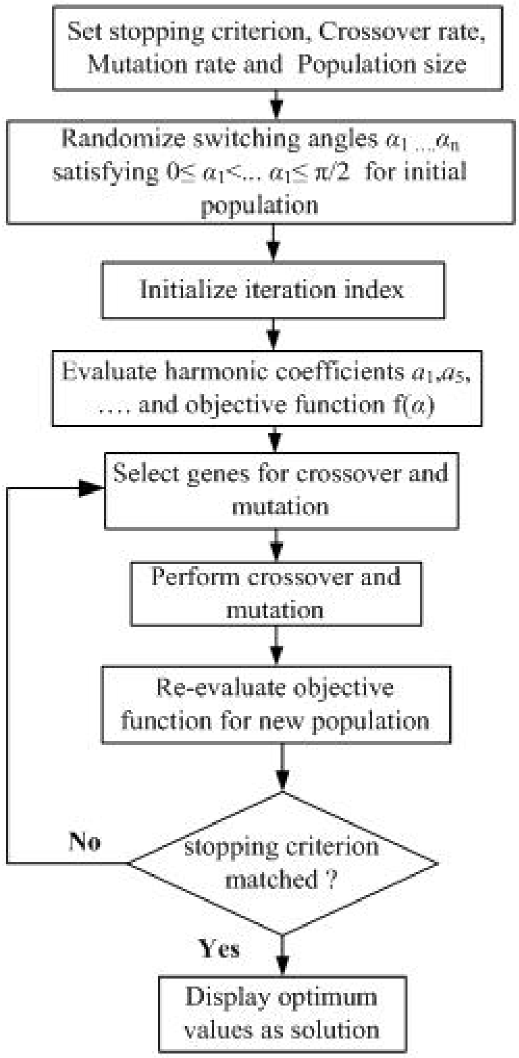

Fig. 4: Flowchart for genetic algorithm (GA) based switching calculation

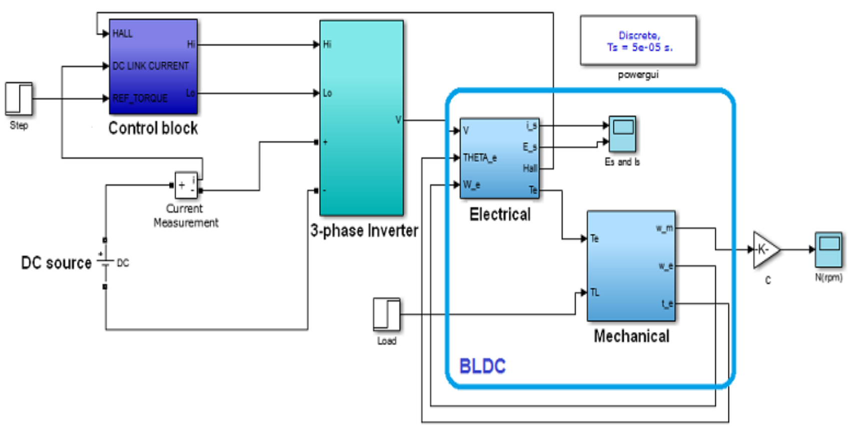

Fig. 5: Simulation block for the proposed scheme using MATLAB/Simulink

Table 1: BLDC specifications

Rated Power	Rated Voltage	Rated Speed	Poles	Resistance	Inductance
350W	48V	450 r/min	12	2.5 Ω	11.2 mH

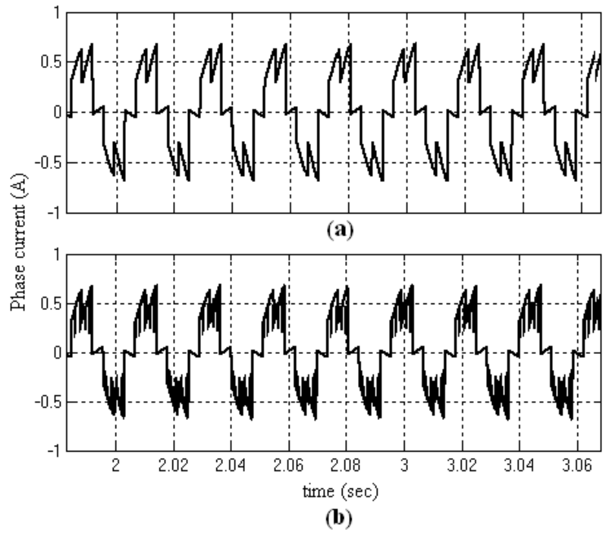

Fig. 6: Phase current waveform for (a) with conventional switching and (b) with proposed switching

The simulated waveform for the phase current for normal phase current with conventional switching is shown in Fig. 6(a) and with proposed switching is shown in Fig. 6(b) at 450 rpm.

Fig. 7 shows the variation of the current with step change in load torque from 2 Nm to 5 Nm at 450 rpm speed.

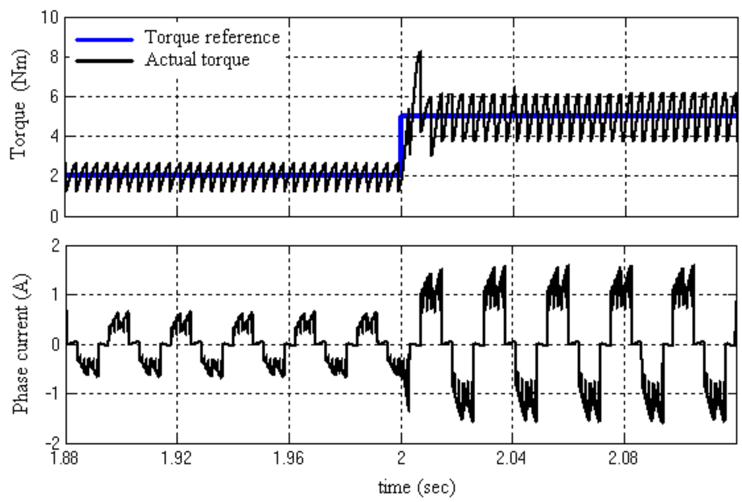

Fig. 7: Variation of BLDC motor current with step change in load torque

Similar phase current waveform is obtained with the experimental laboratory setup shown in Fig. 8. The experimental waveforms are stored using a Tektronix make digital storage oscilloscope TDS 2022B. With the proposed switching, the current obtained is shown in Fig. 9(a). Fig. 9(b) shows the experimental phase current with the load torque.

The input power versus motor speed at no-load and rated load is plotted to justify the lower power requirement for the proposed SHE based PWM control. As observed from the plot of Fig. 10, the power consumption with proposed control decreases than existing switching control schemes.

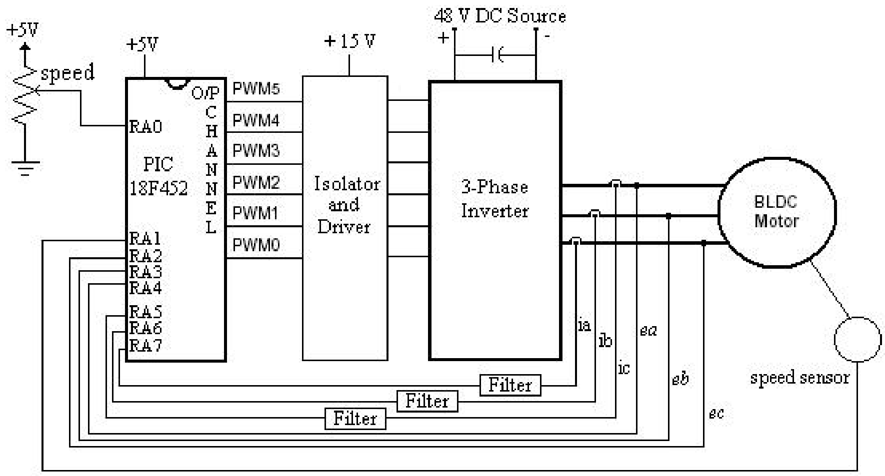

Fig. 8: Experimental setup of the proposed scheme

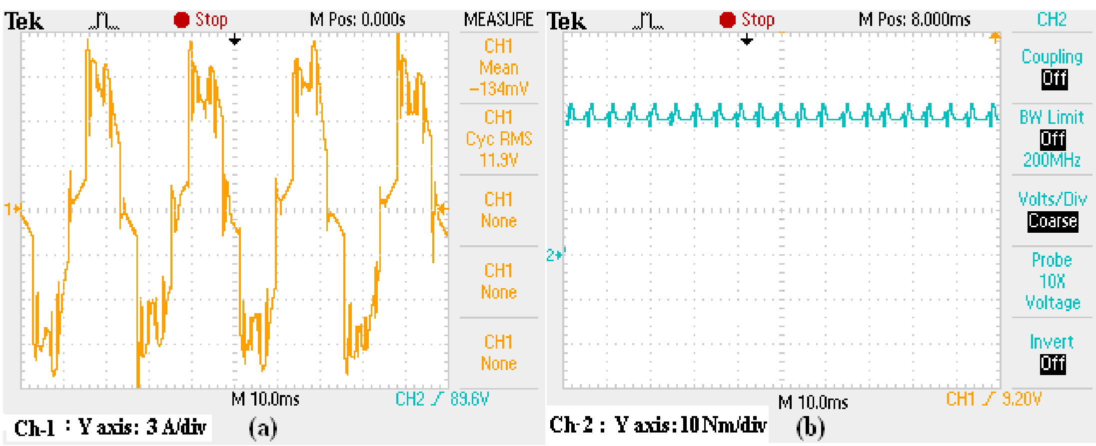

Fig. 9: Experimental waveform for proposed switching (a) current and (b) current with torque

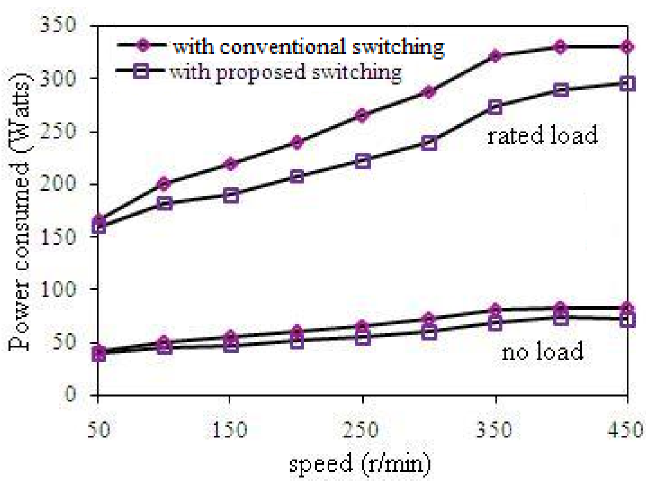

Fig. 10: Power consumed by the motor at different loads as a function of motor speed

5 Conclusion

A simple model based loss minimization scheme for BLDC motor and drive system is proposed in this paper. The optimization is realized by eliminating unwanted lower order harmonics for the motor current and thereby decreasing the core and copper losses. SHE based PWM is used for this purpose. The switching angles for the harmonic elimination are calculated offline using GA and then stored in the microcontroller memory for online applications. The simulation and experimental results confirm the suitability of the proposed scheme which can be useful in driving electric vehicles.

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