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Design and analysis of PWM controller to reduce torque ripples in BLDC motor drive

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ABSTRACT

Low torque ripples are needed by the industrial loads. Torque ripples are produced in motor due to the commutation. The motor input current thus distorting from the ideal current waveform shape due to the motor inductance. So in one particular interval one phase current is decaying slowly and another phase current is increasing slowly. Due to this, the commutation ripples exists in the torque. Because of the brushless dc motor input supply current commutate at every 60 degrees interval, the magnetic field wave developing and revolving unequally. At every 60 degree the rotor position is observed, so the torque is not constant, ripples are existing in the torque curve which is undesirable. Hysteresis current controller and PWM control simulation models are given to reduce this type of torque ripples. The torque ripple reduction due to Hysteresis and PWM control methods are presented.

1. INTRODUCTION

Brushless Direct current motors (BLDCM) are electronically commutated motors which does not have the brushes. These are very popular because of more reliable, high life time, less maintenance and high efficiency etc. [1]. BLDC motors are widely used in hybrid electric vehicles [2]. Due to the interaction of magnetic fields of stator and rotor the torque is produced in BLDCM. Due to commutation and non trapezoidal back EMF the ripples are produced. For each 60^0, the new thyristor is on for conducting. The position of rotor is observed for every 60 degrees. So, six torque ripples are produced over one cycle. As the speed of the motor increases, then ripple frequency of torque ripple is also increases, which is undesirable [3]. This torque ripple makes the disturbances, oscillations, bearing damage that reduces performance and life time of motor. With ideal trapezoidal back EMF and rectangular currents, motor produces the constant torque.The motor inductance causes the stator current deviating from the ideal reference current waveform [4]. So in one particular interval one phase current is decaying slowly and another phase current is increasing slowly. During this interval, all three lines are conducting, that interval is called commutation interval [5]. The inverter in 120 degree mode is used for supplying for BLDC motor, which is shown in table. For one cycle of rotor position, there are six intervals each one having 60 degrees. In any one interval, two switches in ON position, i.e. two phases are in conduction. In consecutive interval also two phases are in conduction but only one phase is changing compared to first interval. So for every two consecutive commutation interval the conduction of current is changing from one phase to another phase. The conduction of current is changing from one phase to another phase six times [6]. Six torque ripples are produced for every 360^0.

This paper proposes Hysteresis and PWM control design models for reducing torque ripples and comparison is made with BLDC motor without controller. Operation and performance of open loop and closed loop BLDCM is presented.

2. MODELING OF BLDCM

BLDC motor equivalent diagram is shown in fig.1. It has three phase stator windings in star connection and rotor has permanent magnets. Motor winding have resistance and inductance. Three phase supply voltage is given to the Brushless dc motor which is as shown in fig.2. Trapezoidal back EMF is induced in the motor, the stator current and electromagnetic torque curves are observed from the simulink modeling. The triggering of thyristors according with rotor position is given in table1.The following assumptions are used to model a BLDC motor.

(i) The motor should be operated with the rated current with no saturation. (ii) Stator windings are balanced so it has equal phase resistances. (iii) Self inductance and mutual inductances are constant. (iv) Core losses are negligible. (v) Uniform air gap present between the stator and rotor. (viii) Ideal Semiconductor switches are used.

The modeling of motor is expressed by the following state equation.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \qquad (1)$$

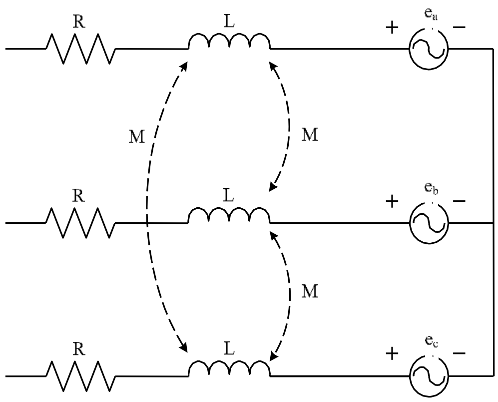

Figure 1. Equivalent circuit of BLDCM

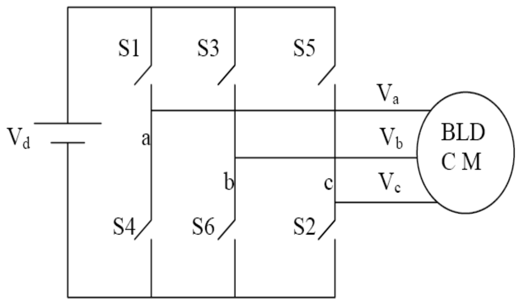

Figure 2. Inverter supplies BLDCM

Table 1. Triggering of thyristors with rotor position

θ_{ele}	Switches ON
0^0-60^0	S1 and S6
60^0-120^0	S1and S2
120^0-180^0	S2 and S3
180^0-240^0	S3 and S4
240^0-300^0	S4 and S5
300^0-360^0	S5 and S6

Since the motor in star connected isolated neutral, i.e. $i_a + i_b + i_c = 0$, then equation (1) becomes

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad (2)$$

where

$$E_a = K_e * f_a(\theta) * \omega_m \quad (3)$$

$$E_b = K_e * f_b(\theta) * \omega_m \quad (4)$$

$$E_c = K_e * f_c(\theta) * \omega_m \quad (5)$$

$$E_P = K_e * \omega_m \quad (6)$$

Due to the interaction between the stator winding currents and rotor magnetic field, the electromagnetic torque of brushless dc motor is produced. The expression used for electromagnetic torque is specified by

$$T_e = \frac{E_a * I_a + E_b * I_b + E_c * I_c}{\omega_m} \text{ N-m} \quad (7)$$

where K=a, b, c

I_K is K^{th} phase current
E_K is the back emf of K^{th} phase
T_e is electromagnetic torque
ω_m is the mechanical speed of the motor
J is rotor inertia
B is damping constant
R is the resistance per phase
L is self inductance per phase
M is mutual inductances between the two phases
K_e is the back-EMF constant
P is the number of poles.

From the above equations we obtained modeling of BLDC motor using MATLAB/SIMULINK which is shown in fig.3.

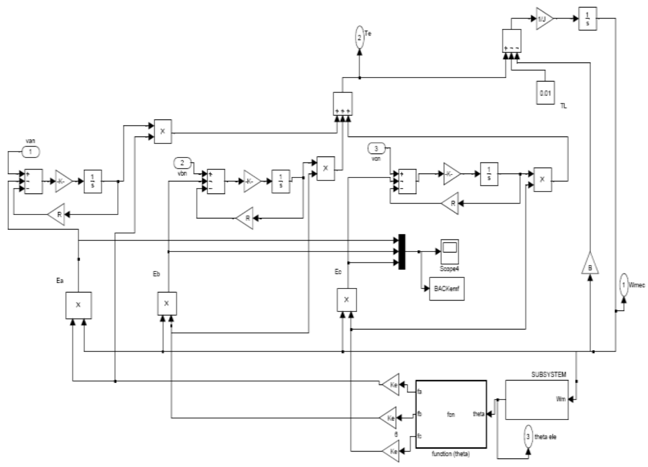

Figure 3. Simulation of BLDC motor modeling

The variation of back EMF with rotor position is given in table2.

Table 2. Relation between the back-EMF and rotor position

$\theta_{electrical}$	E_a	E_b	E_c
0^0-60^0	$((6/\Pi)*\theta-1)*E_p$	E_p	$-E_p$
60^0-120^0	E_p	$(3-(6/\Pi)*\theta)*E_p$	$-E_p$
120^0-180^0	E_p	$-E_p$	$(6/\Pi)*\theta-5$
180^0-240^0	$(7-(6/\Pi)*\theta)*E_p$	$-E_p$	E_p
240^0-300^0	$-E_p$	$((6/\Pi)*\theta-9)*E_p$	E_p
300^0-360^0	$-E_p$	E_p	$(11-(6/\Pi)*\theta)*E_p$

2.1 Bldc motor without controller

Motor rotor position can be detected by using hall sensors. With the rotor position, the switching pulses are given to the inverter, which supplies the BLDC motor is as shown in fig.4.

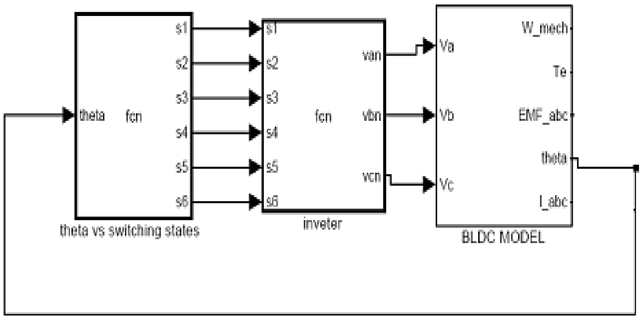

Figure 4. Simulink diagram of BLDC motor without controller

3. CLOSED LOOP OPERATION OF BLDC MOTOR

The error due to actual and reference speed is giving to Proportional-Integral controller (PI). The reference torque is limited with PI controller. When two phases are conducting, the reference current magnitude (I_S) can be obtained. From the rotor position and I_S, the reference currents can be generated. The controller compares the three-phase reference currents and actual currents and it working so as to limit the actual current within hysteresis band. The closed loop operation of BLDC motor is shown in fig5.

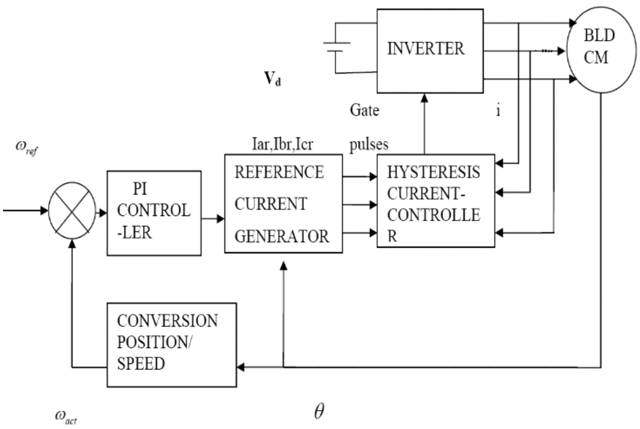

Figure 5. Closed loop operation of BLDC motor drive

3.1 Hysteresis current controller

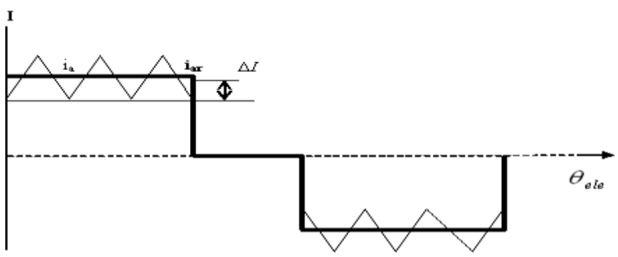

Figure 6. Hysteresis current controller

Hysteresis current controller compares the actual and reference currents. The commutations are obtained by comparing actual and reference rectangular currents. The actual currents controlled by hysteresis current controller which is shown in the fig 6.

According to error, to limit the actual currents around the hysteresis band switches to be on/off are given in table 3.

Table 3. Relation between error switches to be ON/OFF

Error($\Delta I = i_{ar} - i_a$)	Switches	Voltage
$(i_{ar}-i_a) > \Delta I$	T_1 ON T_4 OFF	Van=Vd/2
$(i_{ar}-i_a) < -\Delta I$	T_1 OFF T_4 ON	Van= -Vd/2
$(i_{br}-i_b) > \Delta I$	T_3 ON T_6 OFF	Vbn=Vd/2
$(i_{br}-i_b) < -\Delta I$	T_3 OFF T_6 ON	Vbn= -Vd/2
$(i_{cr}-i_c) > \Delta I$	T_5 ON T_2 OFF	Vcn=Vd/2
$(i_{cr}-i_c) < -\Delta I$	T_5 OFF T_2 ON	Vcn= -Vd/2

3.2 Pwm controller

Pulse width modulation control involves making the pulses of continuous supply voltage of converter to effect on the current for each switch. In this method the actual values of three phase currents are measured and compared to the reference currents. The generated error signals are compared to the repeating sequence of fixed frequency and amplitude. The PWM is implemented because the chopping frequency is a fixed parameter, acoustic and noise is relatively easy to filter. The PWM control Simulink model is shown in fig7.

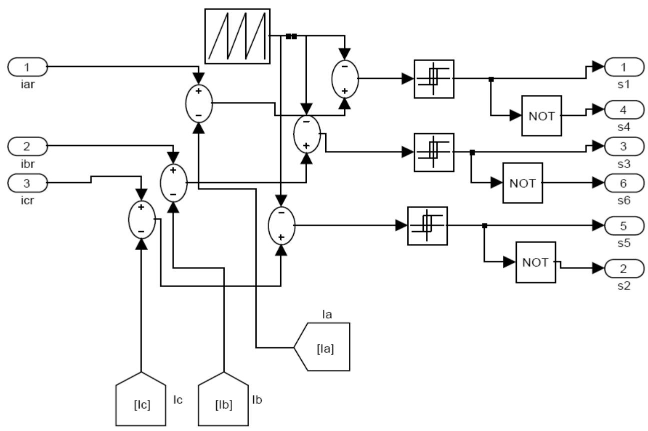

Figure 7. PWM control Simulink model

4. SIMULATION RESULTS

The simulation result of rotor position of BLDC motor is as shown in the fig8.

The trapezoidal back EMF of BLDC motor simulation result is as shown in the fig 9. Ea, Eb and Ec are the back EMF's which is differentiated in the three different lines.

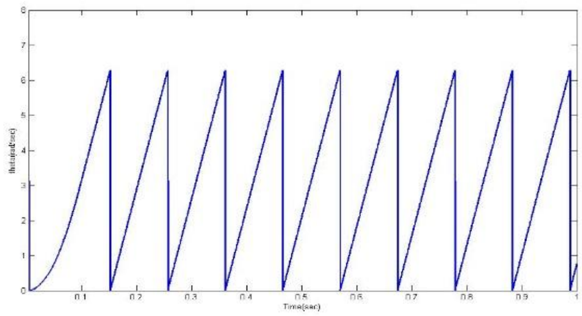

Figure 8. Rotor position of BLDC motor

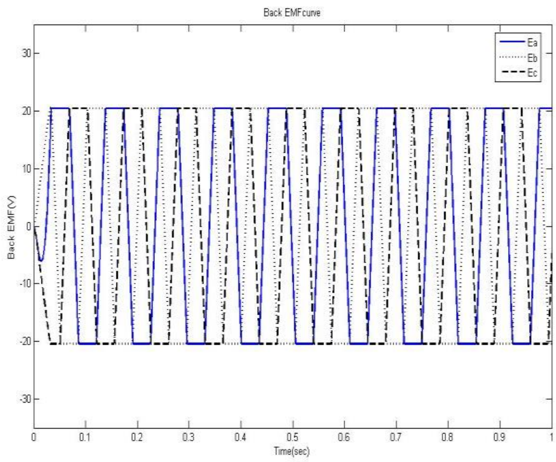

Figure 9. Back EMF of BLDC motor

The simulation result of Mechanical speed of BLDC motor is as shown in the fig 10.

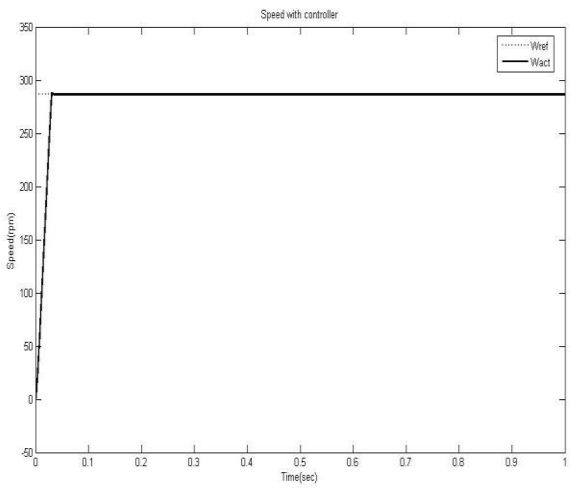

Figure 10. Mechanical speed BLDCM (RPM)

The simulation result of stator phase current of BLDC motor is as shown in the fig 11.

The simulation result of Torque curve of BLDC motor without controller is as shown in the fig12.

The torque curve of BLDC motor without controller simulation result is as shown in the fig 13. Under steady state torque curve which exist six ripples per cycle. The percentage torque ripples calculated is 44.518%.

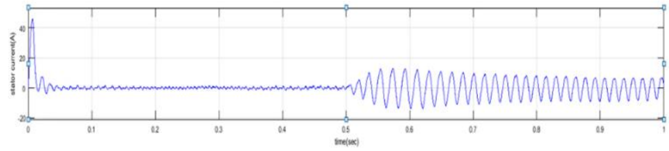

Figure 11. Stator phase current of BLDC Motor

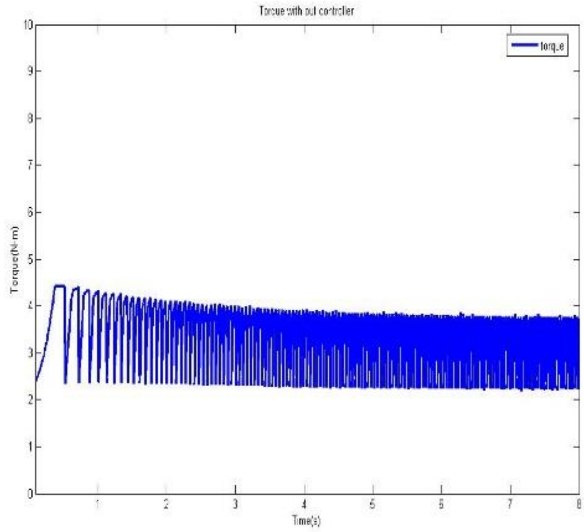

Figure 12. Torque curve of BLDC motor without controller

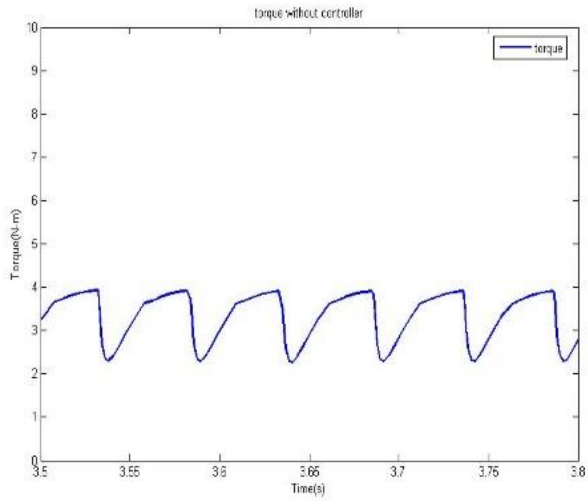

Figure 13. Torque curve of BLDC motor without controller under steady state

From the above curve:
(1) Peak to peak and average torque is T_{P-P}=1.6, T_{AV}=3.594.
(2) Peak-peak ripple torque = (3.8-2.2) =1.6 N-m
(3) Average torque = 3.594 N-m
(4) %Torque ripple= 1.6*100/3.59
= 44.518 %(approx)

The torque curve of BLDC motor without controller simulation result is as shown in the fig 14. Under steady state torque curve which exist six ripples per cycle. The percentage torque ripples is calculated is 30.085%.

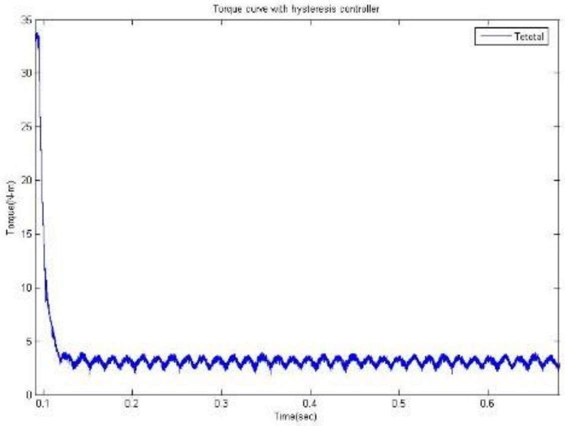

Figure 14. Torque curve of BLDCM with Hysteresis controller

In the below curve:
(1) Peak to peak and average torque is T_{P-P}=0.9, T_{AV}=2.992.
(2) Peak-peak ripple torque = (3.4-2.5) =0.9 N-m
(3) Average torque = 2.992N-m
(4) %Torque ripple = 0.9*100/2.992
= 30.0815 %(approx)

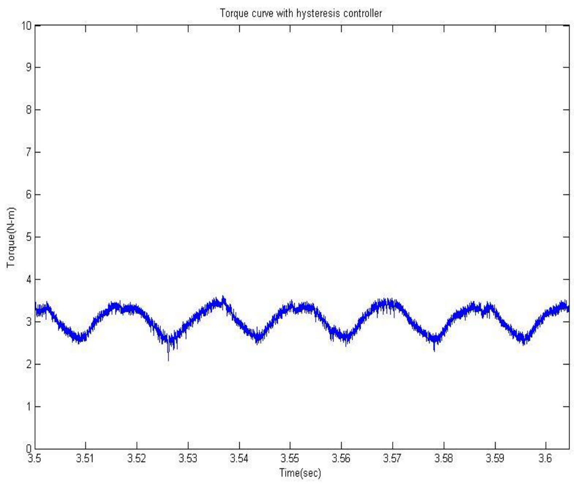

Figure 15. Torque curve of BLDCM with Hysteresis controller under steady state

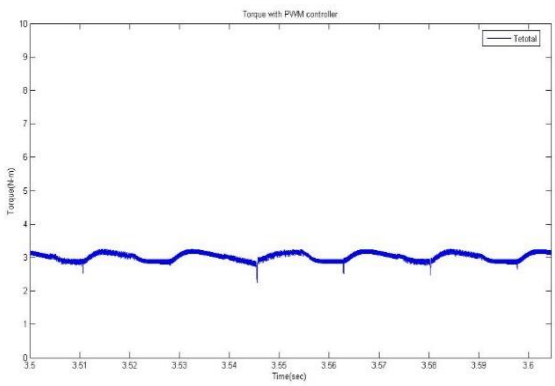

Figure 16. Torque curve of BLDCM with PWM controller under steady state

From the fig16:
(1) Peak to peak and average torque is = (3.2-2.8)
= 0.4 N-m
(2) Average torque = 3.033 N-m
(3) % Torque ripple=0.4*100/3.033 = 13.188% (approx)

4. CONCLUSIONS

In this paper, the Hysteresis current and PWM controllers of BLDC motor are presented with Simulink/Matlab model. The output of hysteresis controller, which reduces the motor torque ripples to 30% when compared to without controller. The BLDCM with PWM controller the torque ripples still reduced to 13.18% . The PWM controller improves the torque performance over hysteresis current controller. So the PWM controller reduces the motor torque ripples as required in the industries. So this controller is applicable for most industrial applications.

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