Torque Ripple Minimization of BLDC Motor by Using Vector Control

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ABATRACT*:* This paper provides an alternative approach to reduce torque ripple in Square-wave PM Motors (BLDC motor). Instead of conventional square-wave form, the method uses the principle of vector control to optimally design the wave-form of reference current in such a way that the torque ripple is minimal. The proposed Vector Control has advantage of the torque ripple is greatly reduced, and the flux weakening for constant-power high-speed mode can be achieved by injecting a negative d-axis current into the control system, just like for the case of PM Synchronous Motors (sine type machines)

Keywords-- Brushless DC motor, Trapezoidal type machine, PM synchronous motor, Sine type machine, Vector control, Torque ripple minimization

I. INTRODUCTION

a. *Sine-wave PM Motor vs. Square-wave Motor: Vector Control vs. Phase Current Control*

With the recent development of permanent magnet (PM) materials, PM (brushless) motors have become more and more popular and find their applications in a wide range of fields: industry, office use machines, house appliances, space equipments. The use of permanent magnets has great advantage in that the created magnetic field is high-density and without loss, providing a high-efficiency operation of the whole drive. PM motors can be divided into 2 categories depending on its current wave-form.

- Sine-wave PM motor, which is also called PM synchronous motor (PMSM), is fed by sine-wave current supply;
- Square-wave PM motor that is fed by square-wave current and it is often called Brushless DC Motor(BLDCM).

The main difference between two kinds of motors from the control viewpoint resides on current control techniques and on the torque quality. The torque produced in a sine-wave PM motor is smooth as a result of the interaction between the sinusoidal stator current and the sinusoidal rotor flux. High performance PM synchronous motor drives are regulated by the well-known vector control method, in which motor currents are controlled in synchronously rotating d-q frame. Rotor position at any instant (measured by a high resolution position sensor, or estimated by an observer) is the mandatory requirement in the high-performance vector control method. Vector control method cannot however be utilized for BLDCMs, due to the fact that terminal variables (currents, voltages) and back-EMFs wave-form are not sinusoidal. Therefore, the phase current control technique is normally employed for this kind of motor. The control technique is relatively simple because the square-wave reference currents can be generated in a step manner, every 360/(m*p) electrical degrees, where m is the number of phases, p is the pole-pair number. Hence, low cost Hall-effect sensors served as position sensor are enough for the control purpose. Simplicity in control, BLDCMs suffer however from a big drawback: because of phase commutation, the torque is not as smooth as that produced by their counterpart, sine wave PM motors. A BLDCM is, moreover, recognized as having the highest torque and power capability for a given size and weight due to its (quasi) square-wave current and trapezoidal form of back-EMF. In addition to that, a BLDCM also presents the cost advantage over the sine-wave PM motor, due to its construction and winding. Therefore, it seems to be evident that if the torque ripple in BLDCM can be overcome, this kind of motor would become a very attractive solution for many industrial and house-appliances applications.

b. *Torque ripple in BLDCM and its reduction techniques*

Torque ripple is the main concern of the BLDCM because it limits this kind of motor from many applications. There are three main sources of torque production (and therefore of the torque ripple) in BLDCMs: cogging torque, reluctance torque, and mutual torque. The torque ripple can be reduced by (a) motor design; (b) control means; (c) or both of them. If in a BLDCM, either stator slots or rotor magnets are skewed by one slot pitch, the effect of the first two torque components is greatly reduced. Therefore, if the waveforms of phase back-EMFs and the phase currents are perfectly matched, torque ripple is minimized. However, perfect matching phase back-EMF and phase current is very difficult considering unbalanced magnetization and imperfect windings [1]. Moreover, due to the finite cut-off frequency of the current control loop, the transient error of the controlled currents always occurs, especially in commutation instants, when the current profile changes drastically and also, the turn-on and turn-off characteristics of the power devices are not identical. This is one of the most critical problems in control of BLDCM drives. We can find in literature a lot of efforts to reduce the torque ripple. [2-6] are only some to name. Le-Huy, Perret and Feuillit [2] analyzed the torque by using Fourier series and shown that the torque ripple can be reduced by appropriately injecting selected current harmonics to eliminate the torque ripple components. Yong Liu, Z. Q. Zhu and David Howe [5] utilized DTC to reduce torque ripple in addition to increasing torque dynamics. Haifeng Lu, Lei Zhang and Wenlong Qu [6] calculated duty cycles in the torque controller considering un-ideal back EMFs.

C. *Purpose of the present work.*

The objective of the present work is to provide an alternative approach to reduce torque ripple in BLDCM drive. Instead of conventional square-wave form, the method uses the principle of vector control to optimally design the waveform of reference current in such a way that the torque ripple is minimal. The currents are however still controlled in the phase current control manner.

II. SYSTEM CONFIGURATION

The configuration of the control system proposed in this paper is described in Fig. 2 where the part generating current references is marked by the break-line frame It can be noted that except for the current reference generation part, the system is nearly the same as of the conventional control system for BLDC motor . The motor is fed by a SVPWM-controlled inverter. As we can see in Figs. 2 , the currents are controlled by 2 current controllers in stationary frame. By convention, the superscript * refers to the reference variables and quantities. The reference currents generating part of the proposed vector Control is consisted of 2 blocks, as shown in Fig.2, corresponding to their function that will be described later. In order to perform the direct transformation and the invert one, the rotor position will be calculated by θe.

III. MATHEMATICAL MODEL OF BLDC MODEL

Typically, the mathematical model of a brushless DC motor is not totally different from the conventional DC motor. The major difference is the phases involved in the operation of BLDC motor drive will peculiarly affect the resistive and the inductive nature of the BLDC model arrangement. The mathematical model of the BLDC motor is modeled based on the equations illustrated below

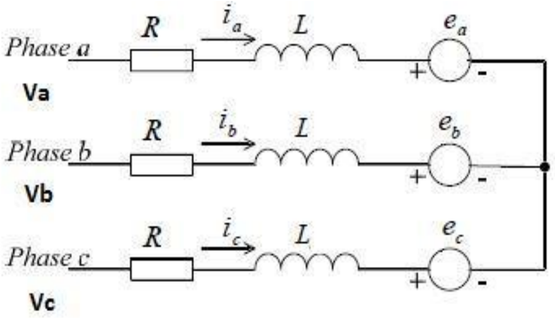

Fig 1:Electrical equalent circuit of BLDC Motor

The coupled equations of stator windings in terms of motor electrical constraints are

$$\mathrm{Van} = i_a R + e_a + L(di_a/dt) \quad (1)$$

$$\mathrm{Van} = i_b R + e_b + L(di_b/dt) \quad (2)$$

$$\mathrm{Van} = i_c R + e_c + L(di_c/dt) \quad (3)$$

Where L - armature self-inductance $[H]$

Va,Vb, Vc - Terminal phase Voltages $[V]$

R - Armature resistance $[\Omega]$

i_a ,i_b ,i_c - Motor input currents

e_a,e_b,e_c - Motor Back emf"s $[V]$

The electromagnetic torque is given by

$$T_e = [e_a i_a + e_b i_b + e_c i_c]\frac{1}{\omega m} \quad (4)$$

where T_e is the electromagnetic torque and ω_m is the motor mechanical angular speed.
The instantaneous induced emf 's can be written as

$$e_a = f_a(\theta_r)\,\lambda_p\,\omega_m \quad (5)$$

$$e_b = f_b(\theta_r)\,\lambda_p\,\omega_m \quad (6)$$

$$e_c = fc(\theta_r)\,\lambda_p\,\omega_m \quad (7)$$

Where the functions $f_a(\theta_r)$, $f_b(\theta_r)$, $f_c(\theta_r)$ have same shape as induce emf s and λ_p is rotor magnetic flux linkage(wb).The equation of motion for a simple system with inertia J , friction coefficient B, and load torque T_1 is $J\frac{d\omega m}{d\theta}+B\,\omega_m = T_e - T_l$ (8)

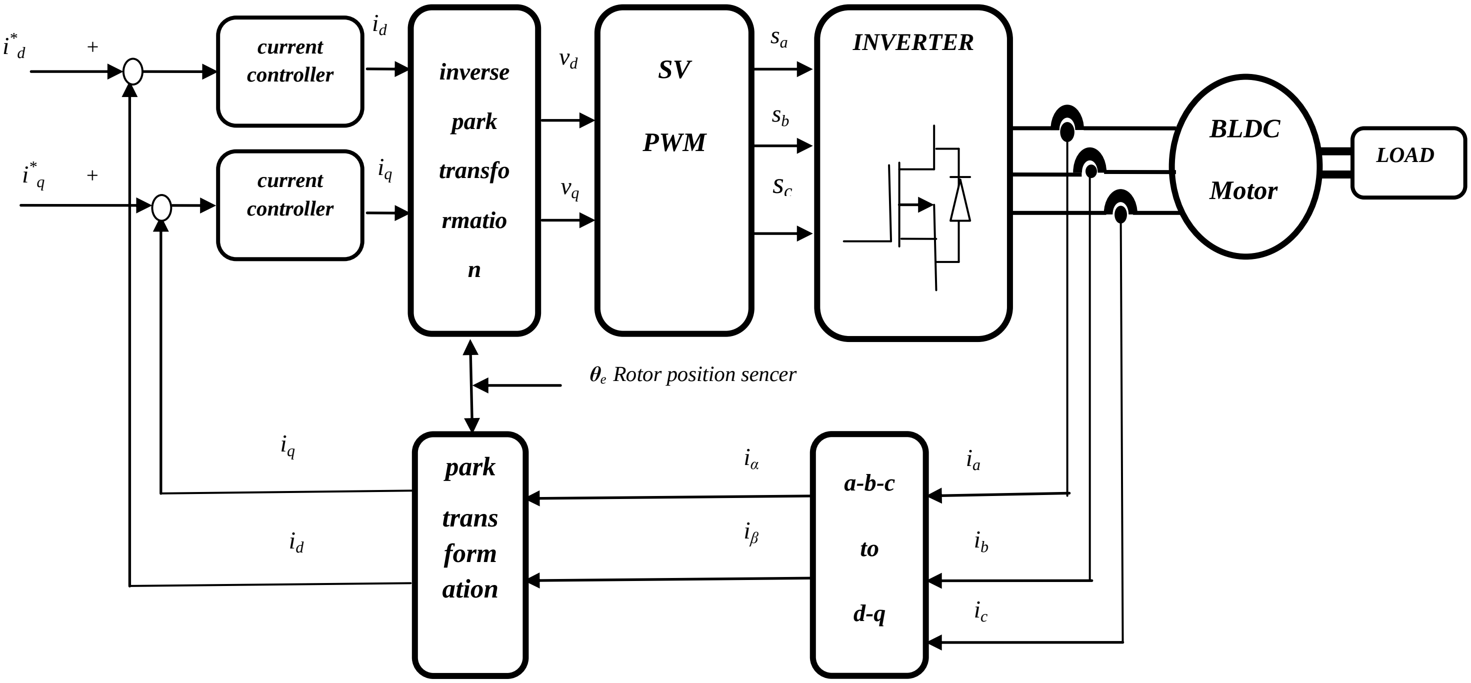

Fig. 2. Typical block-diagram of Vector Control for BLDC drives

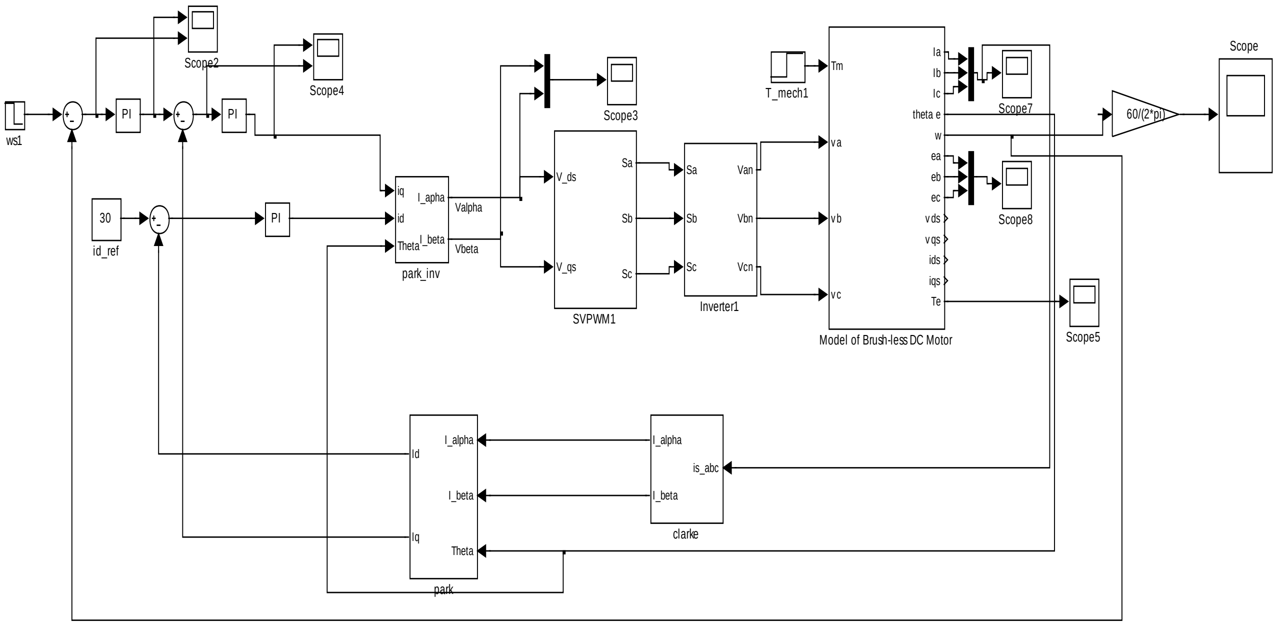

Fig. 3. Typical block-diagram of proposed Vector Control for BLDC drives

The back-EMF in *d-q* frame i_d, i_q, are obtained from phase EMF i_α i_β by Park's transformation. As previously mentioned, the zero-sequence current *i0* is forced to be zero in our system, so only v_d and v*q* need to be calculated using simplified Park's transformation.

$$M=\frac{2}{3}\begin{bmatrix} -\cos(\theta_e) & -\cos(\theta_e-\frac{2\pi}{3}) & -\cos(\theta_e+\frac{2\pi}{3}) \\ \sin(\theta_e) & sin(\theta_e-\frac{2\pi}{3}) & sin(\theta_e+\frac{2\pi}{3}) \end{bmatrix}$$

where θ_e is the rotor position $\theta_e = \omega_e.t$ with ω_e is the electrical angular speed $\omega_e = (\omega_m.p)$ ω_m is the motor (mechanical) angular speed and *p* is the pole-pair number.

Having calculated v_d, v_q, the 3 phase reference currents i_d, i_q, θ_e are obtained by inverse Park transformation $M^{-1.}$

$$M^{-1}=\begin{bmatrix} -\cos\theta e & \sin\theta e \\ -\cos(\theta_e-\frac{2\pi}{3}) & sin(\theta_e-\frac{2\pi}{3}) \\ -\cos(\theta_e+\frac{2\pi}{3}) & sin(\theta_e+\frac{2\pi}{3}) \end{bmatrix}$$

VI. RESULT AND DISCUSSION

The simulation results of BLDC motor performance can be critically evaluated under various input parameters in the MATLAB/SIMULINK environment.

Fig 4 (a) speed response of the BLDCM drive with the hysteresis control

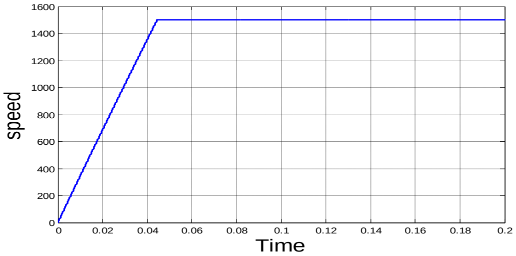

fig 4 (a) shows the plot of time Vs speed where the BLDC motor attains a reference speed of 1500rpm at 0.04 sec.

(b) Three phase back EMF response

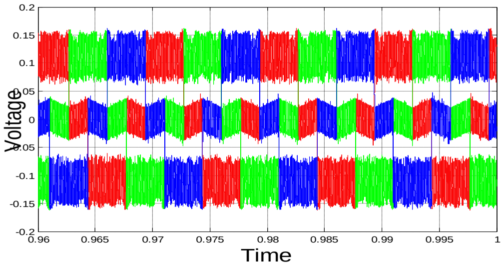

fig 4 (b) shows the three phase back EMF of the hysteresis control for BLDCM

(c) Load Torque response of BLDCM with hysteresis control

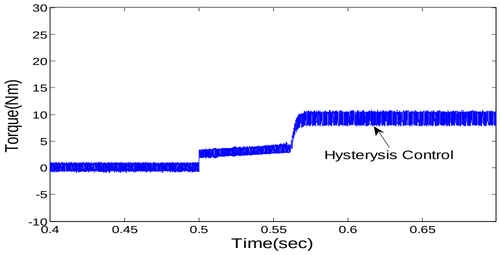

fig 4 (c) shows the torque response of the motor at 0.5 sec with 10N-m load applied and this load torque ripples minimized at 0.6 sec and the 10N-m is applied at 0.6 sec

The simulation results of the hysteresis Control for the BLDCM drives is reported in the above figures and the proposed vector control of BLDCM results is shown in below

Figure 5 (a) speed response of the BLDCM drive with the vector control

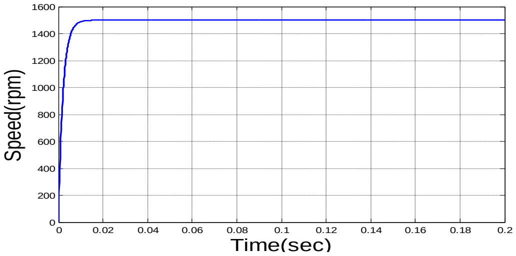

fig 5 (a) shows the plot of time Vs speed where the BLDC motor attains a reference speed of 1500rpm at 0.01 sec.

(b) Three phase back EMF response

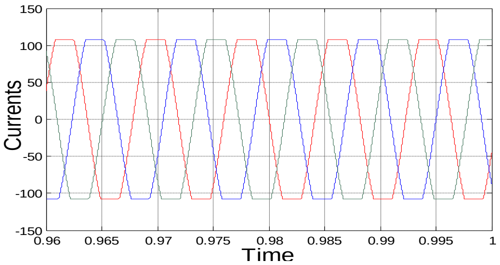

fig 5 (b) shows the trapezoidal three phase back EMF of the of BLDCM which is not obtained in the hysteresis control of BLDCM method.

(c) Load Torque response of BLDCM with hysteresis control

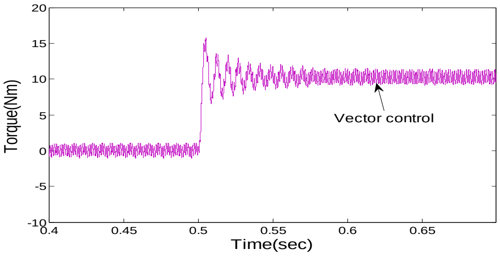

fig 5 (c) shows the torque response of the motor at 0.5 sec with 10N-m load applied and this load torque ripples minimized at 0.55 sec and this is noticeable.

(d) Load Torque response of BLDCM

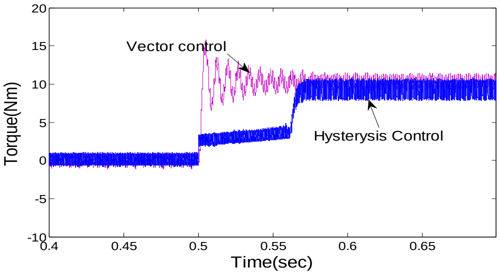

fig 5 (d) shows the torque comparison between the hysteresis control and vector control techniques.

IV. CONCLUSION

The *vector Control* has been presented in this paper in order to improve the performance of the Brushless DC Motor drives. The vector-control principle in *d-q* synchronously rotating frame is utilized for the generation of current references only, and the motor currents are regulated, as usual for PM trapezoidal type machines, by individual phase current control in the stationary *a-b-c* frame.

The performance of the proposed Control has been tested in simulation in the Matlab/Simulink environment and the results have been compared with those of the conventional phase current control method. The improvement in torque ripple reduction has been obtained. The VC can therefore be a very promising method for applications using BLDCM.

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