A New Vector Control Scheme of Brushless DC Motor

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Abstract - In this paper, the new vector control scheme of BLDCM producing loss-minimized ripple-free torque based on the *d-q-0* reference frame is presented including 3 phase unbalanced condition. The optimized phase current wave-forms that are obtained by the proposed method can be a reference values and the motor winding currents are forced to track it by delta modulation technique. As a results, it can be shown that the proposed work provides a simple and clear way to obtain an optimal motor excitation current.

1. Introduction

Permanent magnet brushless DC motors (BLDCM) with trapezoidal back emf are increasingly being used in high performance applications due to the simplicity in their control. In many of these applications, the production of ripple-free torque characteristics of the motor are of primary concern. The two main sources of torque ripple are consisted of cogging torque and mutual torque ripple. It has been well-known that since the cogging torque is created by stator slots interacting with the rotor magnetic field, it can be greatly reduced by skewing the stator slots or rotor magnets by one slot pitch. On the other hand, the mutual torque ripple is created by an improper current excitation. Therefore, when the motors being skewed and having trapezoidal back emf are driven by ideal rectangular pulse current, ripple-free torque can be produced.

However, it is practically impossible to produce the ripple-free torque, because the desired back emf and current waveforms can not be obtained due to the mechanical design trade-off and limitation of current change ratio respectively. Moreover, the skewing makes the back emf waveform more non-trapezoidal. As a result, a great deal of study has been devoted to identifying the sources, characteristics and minimization of torque ripple[1-6]. In particular, interaction between the back emf and current excitation has been described and analyzed by a number of authors[4-6]. LeHuy, Perret and Feuillit[4] investigated that torque ripple can be minimized by appropriately selecting current harmonics to eliminate both excitation and cogging torque ripple components. Hung and Ding[5] used the complex exponential decom-position to find a closed form solution for the current harmonics that simultaneously eliminate torque ripple and maximize efficiency when the motor drive electronics have unrestricted capability. Hanselman[6] extended these prior works to the case of a finite supply voltage and resulting finite *di/dt* capability. However, all these works have been much complicated and made several improper assumptions such that all three phases have an identical back emf waveforms offset $2\pi/3$[rad] electrical angle with respect to one another and the back emf and motor excitation current exhibit half-wave symmetry and are balanced, etc. In practice, due to the several reasons like manufacturing imper-fection or deterioration of permanent magnet or stator windings etc, these assumptions can not be justified and make an considerable problem to eliminate the torque ripple.

This paper deals with the new vector control scheme of BLDCM with maximum efficiency based on the *d-q-0* reference frame considering the cases under unbalanced back emf waveforms. In general, the stator windings of BLDCM are generally concentrated. Consequently, it is well known that the stator to rotor mutual inductances do not vary sinusoidally, and the *d-q-0* reference frame or the space phasor analysis is no longer valid for modeling and simulation of the motor. However, since *d-q-0* reference frame adopted in this paper will be only used to obtain the optimum current waveform for ripple-free torque based on the minimum input power, not to perform the modeling and simulation of the motor itself, the proposed method can be a proper choice. The motor winding currents are forced to track the optimal current waveforms by delta modulation technique, which are obtained by transforming the *d-q-0* variables into *a-b-c* phases inversely. This work provides the new insight into optimal motor excitation simply and clearly, even under the case of three phase unbalanced condition.

2. Torque ripple analysis based on *d-q-0* reference frame

To analyze the torque ripple, the following assumptions are made.

1) Three phase motors are considered.
2) The stator windings are *Y*-connected.
3) The mutual torque produced by the motor is linearly proportional to the phase current.
4) The cogging torque does not exist.
5) The motor windings have a constant and identical resistance and self inductance. The mutual inductance between phases is negligible.
6) DC source voltage is infinite and therefore is capable of delivering infinite *di*/*dt*.

In general, the arbitrary back emf waveform can be described as follows,

$$e_p(t)=\sum_{n=1}^{\infty}E_n\sin[n\{\omega_e t+\frac{2\pi}{3}(p-1)\}+\theta_n] \quad (1)$$

where n is the harmonic order, E_n is the Fourier series coefficient, ω_e is the oprating angular frequency and p=1,2,3. In most previous works, this back emf waveform is assumed half-wave symmetrical and identical for three phase windings except phase offset by 2π/3[rad]. However, this is not the case of the general motors under use. In this situations, the optimum currents for different back emf waveform to produce ripple-free torque are also different and it is much complicated and tedious to obtain the desired current waveforms for each phase. Therefore, it is very simple and clear to obtain the desired current waveforms from the synchronously rotating *d-q-0* reference frame. For this purpose, each back emf waveform in natural *a-b-c* reference frame is first transformed to the *d-q-0* reference frame as follows.

$$\begin{bmatrix} e_d \\ e_q \\ e_0 \end{bmatrix} = C\bullet\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (2)$$

$$C=\begin{bmatrix} \sin(\theta_e-\theta_0) & \sin(\theta_e-\theta_0-\frac{2\pi}{3}) & \sin(\theta_e-\theta_0+\frac{2\pi}{3}) \\ \cos(\theta_e-\theta_0) & \cos(\theta_e-\theta_0-\frac{2\pi}{3}) & \cos(\theta_e-\theta_0+\frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

where $\theta_e=\omega_e t$, ω_e is an electrical angular frequency and θ_0 is an angular displacement and C is the transformation matrix of 3 phase to synchronously rotating *d-q-0* reference frame. In *d-q-0* reference frame, the mutual torque is derived by equating the electrical power absorbed by the motor to the mechanical power produced

$$T\frac{\omega_e}{P}=\frac{3}{2}(e_d i_d+e_q i_q+e_0 i_0) \quad (3)$$

where T is an ripple-free torque required by load, P is the number of pole pairs and ω_e/P is the motor mechanical speed. Considering that the magnetic field of the BLDCM is provided by the permanent magnet in the rotor and also that the sum of phase current must be zero at any instant, the current components i_q and i_0 must be zero. Therefore the Eq.(3) can be rewritten by

$$T\frac{\omega_e}{P}=\frac{3}{2}e_d i_d \quad (4)$$

From the above equation, i_d component can be obtained as follows.

$$i_d=\frac{2}{3}T\frac{\omega_e}{P}\frac{1}{e_d} \quad (5)$$

The each optimum phase current waveform can be derived by transforming the *d-q-0* variables to *a-b-c* ones inversely

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = C^{-1}\bullet\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} \quad (6)$$

It should be emphasized that in order to minimize losses and the change ratio of current, each phase current must be excited in phase with the corresponding phase back emf. Therefore, it is obvious that the instantaneously optimized current waveforms can be easily obtained by proposed approach when the back emf waveforms are known even though the back emf waveforms of each phase do not exhibit half-wave symmetry and have different amplitude.

3. Numerical Results

A speed control scheme that is implementable is shown in Fig. 1. The optimized reference current waveforms are obtained from the look-up table using position and speed information from the shaft encoder. The motor currents are forced to track the reference currents within the predetermined bandwidth by the delta modulation technique. The controller can be implemented by TMS320C40 DSP as shown in the figure.

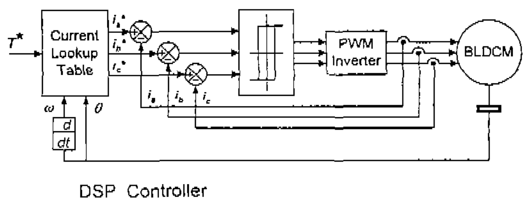

Fig. 1. Speed control scheme

The back emf amplitude is directly proportional to the motor speed. Therefore The back emf is measured and normalized by constant speed test for 4 pole, Y-connected, 60[Hz] BLDCM. Fig. 2 shows the simulation results when the motor is assumed to be half-wave symmetrical and have same amplitude. Fig. 2(a) and (b) shows the back emf waveforms of *a-b-c* phases and their *d-q-0* components. It is clear that though the motor is half-wave symmetrical and has same amplitude, e_d has pulsating components and e_q and e_0 are not zero. Therefore, to produce ripple-free torque, torque current i_d should have its value obtained from e_d by Eq. (5) and i_q and i_0 must be zero to minimize the losses as shown in Fig. 2(c). The instantaneously optimized phase current and torque waveforms by proposed approach are shown in Fig. 2(d) and (e). By exciting these currents, ripple-free loss-minimized resultant torque can be obtained and is also shown in Fig. 2(e) by straight line (value of 1 p.u.).

The optimized phase current waveforms can also be obtained for the cases when the back emf waveforms of each phases are not symmetrical and have different amplitude as shown in Fig. 3(a) and (b). The torque current i_d is obtained by same way from e_d by Eq. (5) and i_q and i_0 must be zero as shown in Fig. 3(c). The instantaneously optimized phase current are shown in Fig. 3(d) and corresponding phase torques and total torque are presented in Fig. 3(e). In this case, each phase torque produced has different magnitude and waveform and do not half-wave symmetry due to the back emf, but total torque excited by current in Fig. 3(d) exhibits ripple-free

4. Conclusion

In this paper, novel vector control scheme of BLDCM producing loss-minimized ripple-free torque based on the *d-q-0* reference frame is presented including 3 phase unbalanced condition. The optimized phase current waveforms that are obtained by the proposed method can be a reference values and the motor winding currents are forced to track it by delta modulation technique. The implementation of the proposed scheme and its experimental results will be given in the next work.

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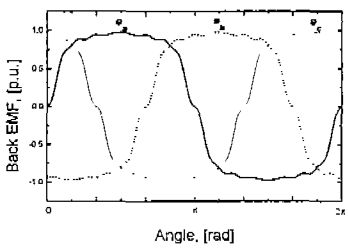
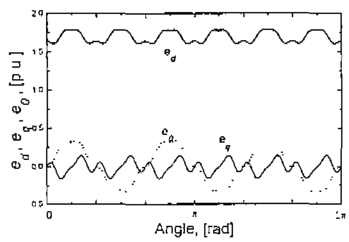
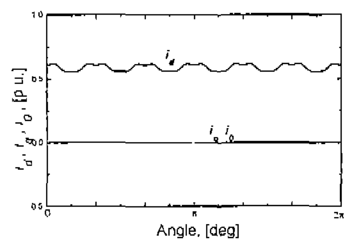


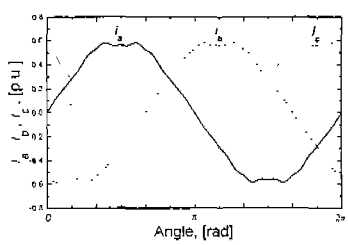
(a) e_a, e_b, e_c waveforms



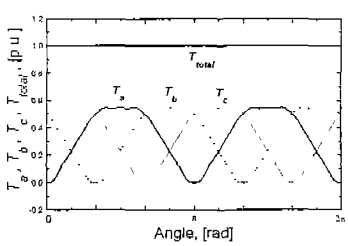
(b) e_d, e_q, e_0 waveforms



(c) desired i_d, i_q, i_0 waveforms

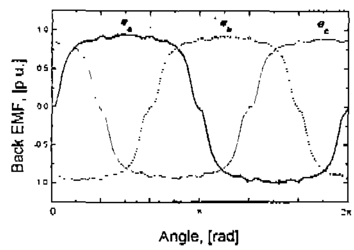


(d) Desired i_a, i_b, i_c waveforms

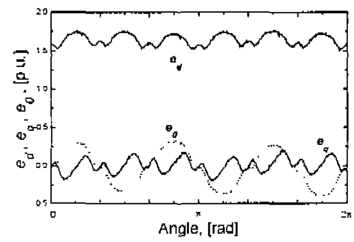


(e) Developed total and phase torque waveforms

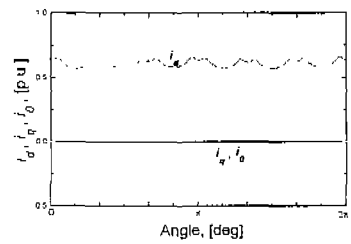
Fig. 2. Three phase balanced condition



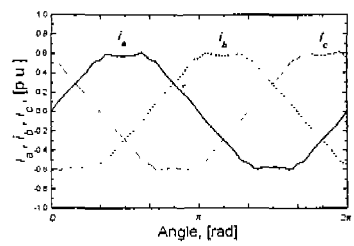
(a) e_a, e_b, e_c waveforms



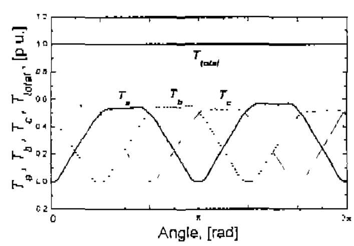
(b) e_d, e_q, e_0 waveforms



(c) Desired i_d, i_q, i_0 waveforms



(d) Desired i_a, i_b, i_c waveforms



(e) Developed total and phase torque waveforms

Fig. 3. Three phase unbalanced condition