Comparison of Performance of Brushless DC Drives under Direct Torque Control and PWM Current Control

Z. Q. Zhu†, Yong Liu* and David Howe*

Abstract - Direct torque control (DTC) was originally developed for induction machine drives, and, more recently has been applied to permanent magnet brushless AC (BLAC) drives. In this paper, the performance of DTC controlled brushless DC (BLDC) drives is compared with that of PWM current controlled BLDC drives, both with and without current shaping. Both simulation and experimental results are presented, as well as the analysis of the resulting torque waveforms. It is shown that, in addition to exhibiting a fast torque response, a DTC controlled BLDC drive has a significantly lower low-frequency torque ripple than the PWM current controlled BLDC drive without current shaping, and that it is easier to implement than PWM current control with current shaping.

Keywords: Brushless DC drive, current shaping, direct torque control, permanent magnet, torque ripple

1. Introduction

Various current control approaches have been adopted to minimize torque pulsations in permanent magnet brushless machines by generating optimal reference current waveforms to compensate for inherent torque ripple. For example, a method for obtaining a smooth torque from a BLDC motor over a wide operating speed range was proposed in [1], in which compensation and prediction terms were added to the controller output. A current control algorithm using Fourier series coefficients was presented and compared with conventional PWM methods in [2]. It reduced the current ripple as well as acoustic noise and vibration. State feedback input-output linearization techniques were used to select the outputs so that the torque-voltage relationship was not only linearized but also optimized in [3], in which simulations were employed to demonstrate the performance capabilities of the proposed scheme. The concept of direct torque control (DTC) of a BLAC drive was extended in [4] to a BLDC drive to achieve instantaneous torque control, and the major differences between the DTC of BLDC and BLAC drives were highlighted.

In this paper, the performance of a BLDC drive under direct torque control and PWM current control is compared. It will be shown that the low-frequency torque ripple which results with PWM current control can be eliminated completely by optimizing the phase current waveform in accordance with the back-emf waveform. Simulated results are presented and validated by experi-ments.

2. PWM Current Control of BLDC Drives

Arguably the most common control method for permanent magnet BLDC motors is PWM current control, which is based on the assumption that a linear relationship exists between the phase current and the torque, similar to that for a brushed DC motor. Thus, by varying the phase current, the electromagnetic torque can be controlled to meet the load requirement. It is relatively simple and widely used in many low-cost applications [5]. However, the relationship between the current and the resultant torque is actually non-linear, whilst in a BLDC drive system, the non-ideal back-EMF waveform and phase current commutation events are cause electromagnetic torque pulsations.

2.1 Conventional PWM Current Control

The general structure of a current controller for a BLDC motor is shown in Fig. 1. The instantaneous current in each phase is regulated by a hysteresis controller, which maintains the current within specified limits. The rotor position is sensed to enable commutation of the phase currents as the rotor rotates, the commutation logic controlling the inverter upper and lower phase leg power switches. The reference current is determined by a PI regulator, which maintains the average rotor speed constant.

2.2 PWM Current Control with Current Shaping

In order to reduce the electromagnetic torque ripple, an

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appropriate reference current waveform is required. Fig.2 shows a schematic of PWM current control with current shaping. In contrast to conventional PWM current control, the reference current is generated according to a pre-determined back-emf waveform so as to maintain the electromagnetic torque constant. The hysteresis current controller adjusts the actual phase current according to the reference current. The electromagnetic torque in a BLDC drive is given by:

$$T = \frac{1}{\omega}(e_a i_a + e_b i_b + e_c i_c) \qquad (1)$$

where ω is the rotor mechanical speed, e_a, e_b and e_c are phase back-emfs, and i_a, i_b and i_c are the phase currents.

Since the mechanical time constant is much longer than the electrical time constant, it can be assumed that the rotor speed will remain constant if the phase current waveforms are controlled as the inverse of the back-emf waveforms to maintain constant electromagnetic torque.

3. Direct Torque Control of BLDC Drives

Similar to the concept of DTC for BLAC drives [6], the

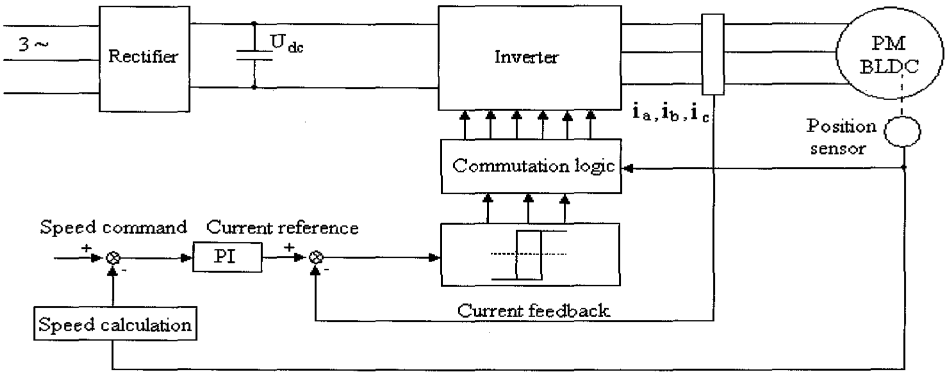


Fig. 1 Schematic of conventional PWM current control

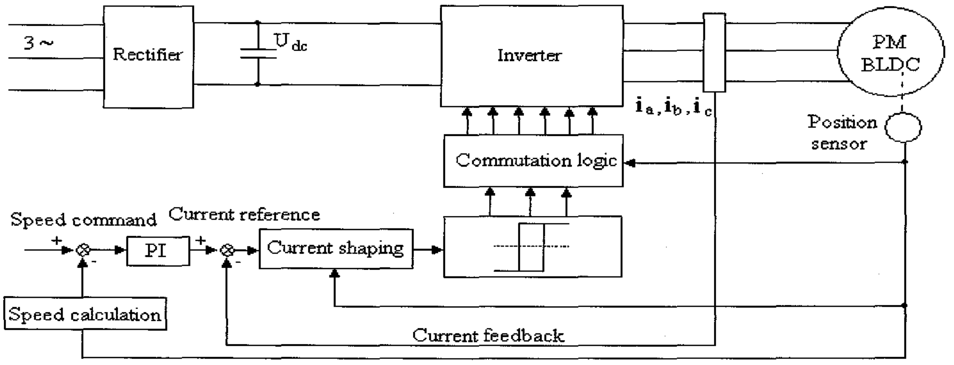


Fig. 2 Schematic of PWM current control with current shaping

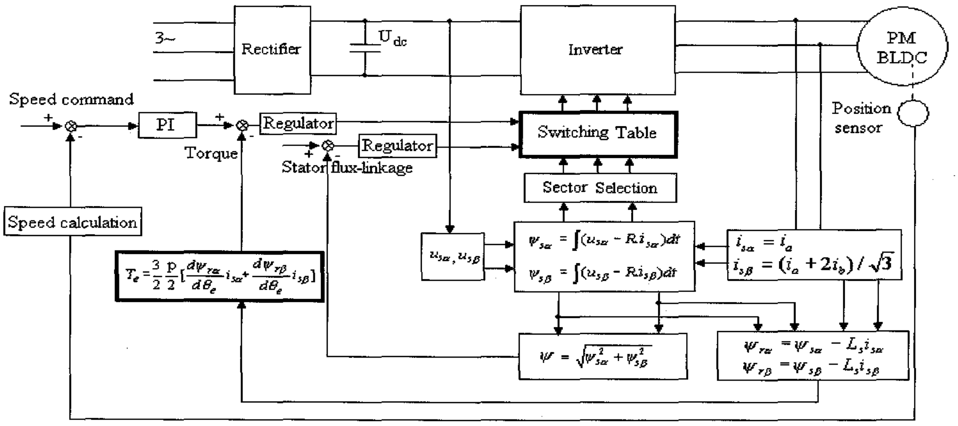


Fig. 3 Schematic of DTC BLDC drive

application of DTC to BLDC drives is based on flux-linkage observer [4]. The magnitude and position of the stator flux-linkage vector can be determined from the measured stator voltages, $\bar{u}_s$, and currents, $\bar{i}_s$. The electromagnetic torque equation for a BLAC motor can be expressed in the stationary reference frame as:

$$T = \frac{3}{2}\frac{p}{2}(\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}) \tag{2}$$

where p is the number of poles, and Ψ_α and Ψ_β are the stator flux-linkages in the α- and β-axes, respectively.

For a BLDC motor with a non-sinusoidal back-emf waveform, the electromagnetic torque equation can be expressed as:

$$T = \frac{3}{2}\frac{p}{2}\left[\frac{d\psi_{r\alpha}}{d\theta_e} i_{s\alpha} + \frac{d\psi_{r\beta}}{d\theta_e} i_{s\beta}\right] \tag{3}$$

where θ_e is the rotor electrical angle, and $\psi_{r\alpha}$ and $\psi_{r\beta}$ are the rotor flux-linkages in the α- and β-axes of the stationary reference frame, respectively, which can be calculated as:

$$\psi_{r\alpha} = \psi_{s\alpha} - L_s i_{s\alpha} \tag{4}$$

$$\psi_{r\beta} = \psi_{s\beta} - L_s i_{s\beta} \tag{5}$$

where L_s is the stator winding inductance. Equation (2) can be regarded as a particular case of equation (3), when the back-emf waveform is sinusoidal, and represents the fundamental component of the electromagnetic torque. However, when the back-emf waveform is non-sinusoidal, equation (3) should be used for the calculation of the electromagnetic torque.

In a BLAC drive, the voltage space vectors can be represented by 3 digits, which fully represent all the states of the inverter switches. In a BLDC drive, however, since the upper and lower switches in a phase leg may both be simultaneously off, irrespective of the state of the associated freewheel diodes, 6 digits are required to represent the voltage space vectors, one digit for each switch. The voltage space vectors in the α-β reference frame for a BLDC drive have a 30° phase difference relative to those for a BLAC drive. Two non-zero voltage space vectors now bound each sector of the vector circle, while in a BLAC drive each sector is centered on a non-zero voltage space vector. Fig. 3 shows a schematic of a DTC BLDC drive, which is essentially the same as that for a DTC BLAC drive, except for the switching table and torque estimation.

In summary, the main differences between the DTC of BLDC and BLAC drives are in the torque estimation and the representation of the inverter voltage space vectors. The control algorithms for the torque demand, the stator flux-linkage and the output voltage vectors can be established in a similar manner as for BLAC drives.

4. Simulated and Experimental Results

The current and torque control methods, with single switch chopping mode, for a BLDC drive have been demonstrated by simulation and validated experimentally for a surface-mounted permanent magnet BLDC motor, whose parameters are given in the appendix. The simulation model is developed using Matlab/Simulink, whilst the main elements of the experimental drive system are shown in Fig. 4. The control system is composed of DAC and ADC boards, a transducer board, a TMS320C31 DSP, on which the control algorithms are implemented, and a rotor position board, which is simply an interface between the DSP and the rotor position sensor, which is an incremental encoder. Each DAC board has four 12-bit digital-to-analogue converter (AD767) channels, which are used to output parameters such as the rotor speed and stator phase current. Its output port provides gate drive signals for the power switching devices. Each ADC board has four 12-bit analogue-to-digital converter (AD678) channels and a 12-bit digital input parallel port. In addition, there are current transducers (LEM LA25-NP) and voltage transducers (LEM LV25-P). The phase currents and voltages are measured and sampled by the transducer board and ADC board, respectively.

Fig. 5 shows the measured phase and line back-emf waveforms of the BLDC motor. Simulated and measured phase current and electromagnetic torque waveforms which result with conventional PWM current control are given in Figs. 6 and 7, respectively. It can be seen that the phase current is essentially flat topped during the 120° elec. conduction period and that the electromagnetic torque exhibits a significant low-frequency torque pulsation. Figs. 8 and 9, respectively, compare simulated and measured phase current and electromagnetic torque waveforms

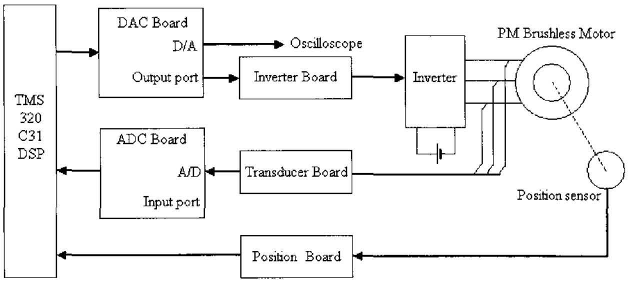


Fig. 4 Schematic of BLDC drive system

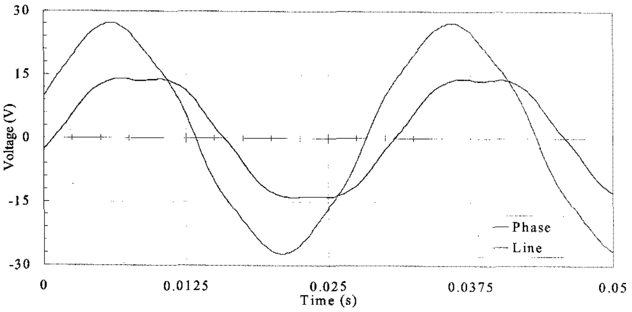
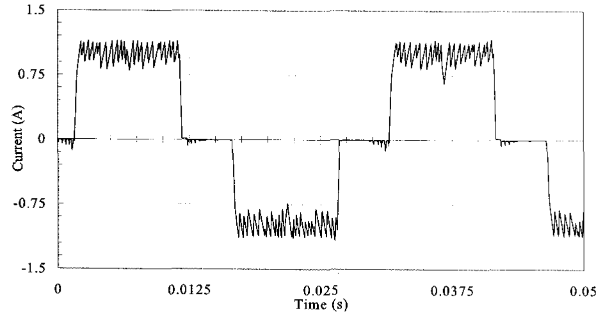
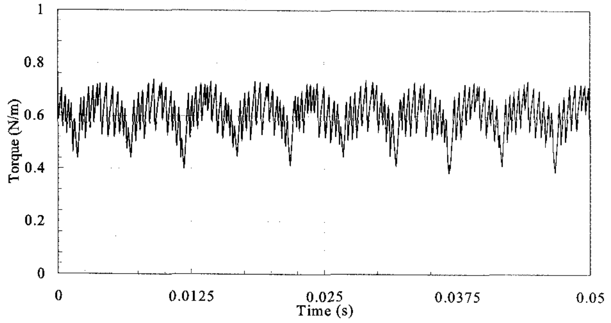


Fig. 5 Back-emf waveforms of BLDC motor



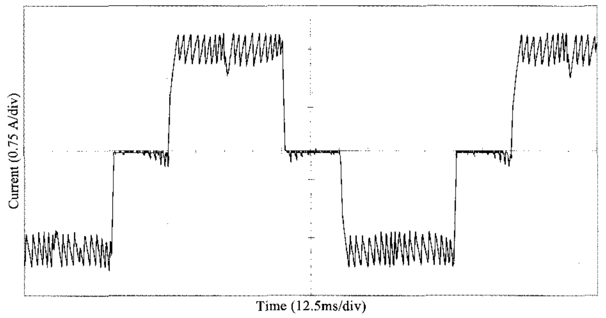
(a) Phase current



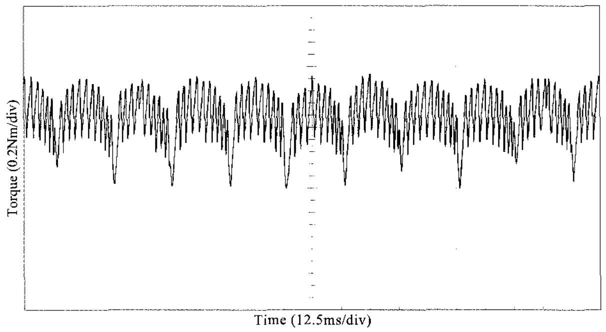
(b) Electromagnetic torque

Fig. 6 PWM current control without current shaping (simulated)

which result when PWM current control with current shaping is employed. As will be seen, the reference phase current is a mirror image of the pre-determined back-emf waveform, and the actual phase current eliminates the low-frequency torque ripple. Fig. 10 shows simulated phase winding terminal to ground voltage, phase voltage, phase current and electromagnetic torque waveforms which result when direct torque control is employed. The corresponding experimental results are shown in Fig.11. In general, good agreement is achieved between simulated and measured results. It will be seen that the phase current waveform inherently mirrors the inverse of the back-emf waveform within the 120° elec. conduction period so as to maintain constant electromagnetic torque. However, a high-frequency torque ripple still exists in both the simulated and measured waveforms due to the low winding inductances and PWM events. However, the low-frequency torque ripple which would have resulted with a conven-tional PWM current control has been eliminated since DIC inherently optimises the phase current waveform in accordance with the back-emf waveform. In addition, direct torque control is potentially more attractive since it is easier to implement than current control with current shaping and results in a faster torque response.

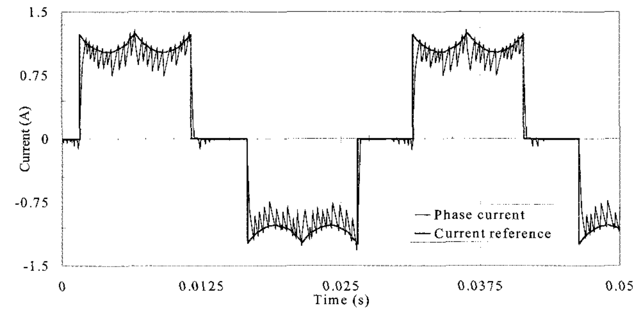


(a) Phase current

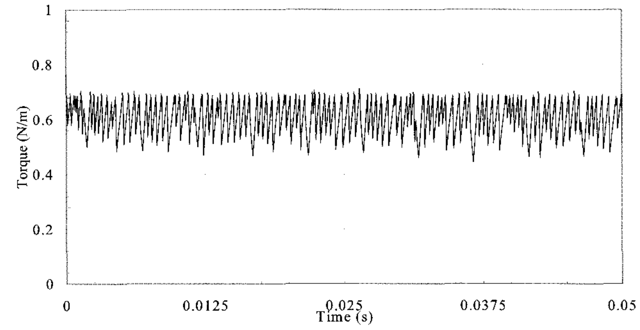


(b) Electromagnetic torque

Fig. 7 PWM current control without current shaping (measured)

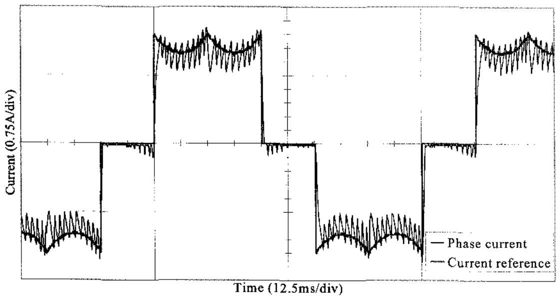


(a) Phase current

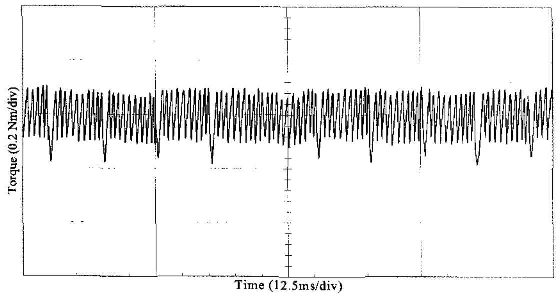


(b) Electromagnetic torque

Fig. 8 PWM current control with current shaping (simulated)

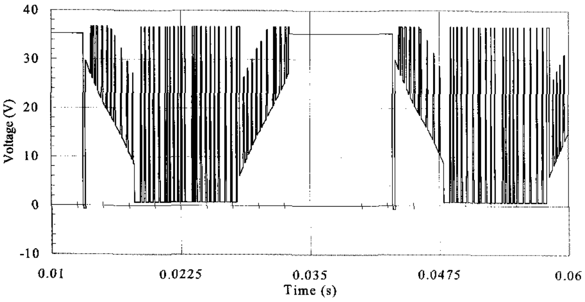


(a) Phase current

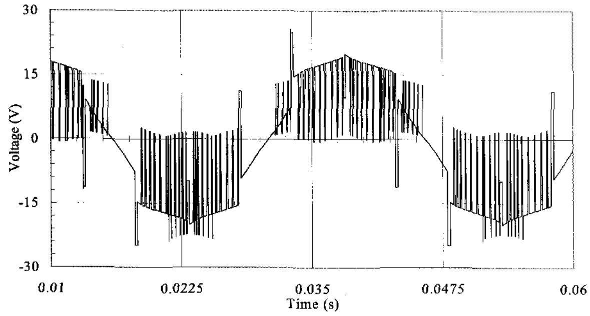


(b) Electromagnetic torque

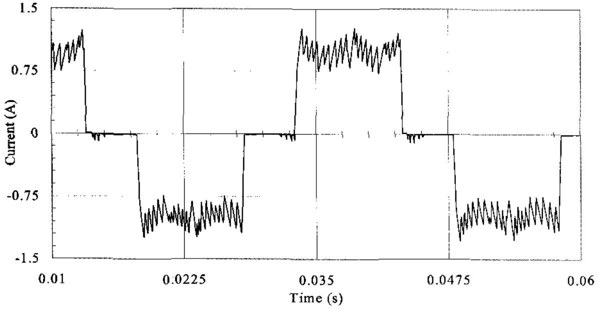
Fig. 9 PWM current control with current shaping (measured)



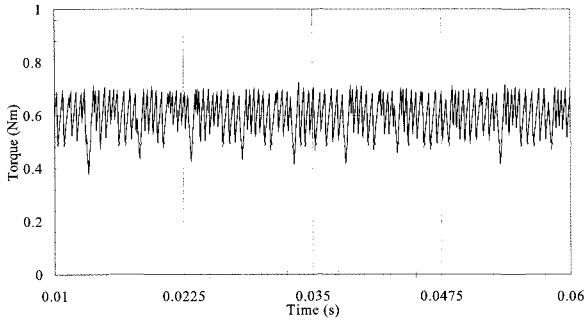
(a) Phase winding terminal to ground voltage



(b) Phase voltage

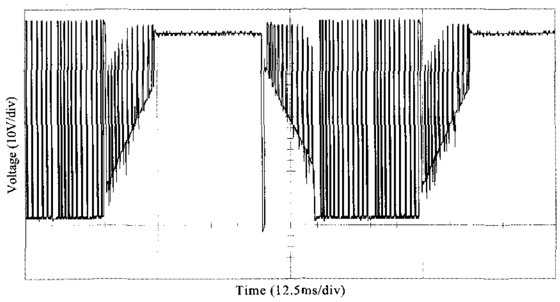


(c) Phase current

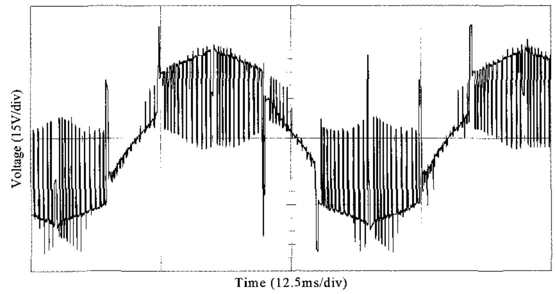


(d) Electromagnetic torque

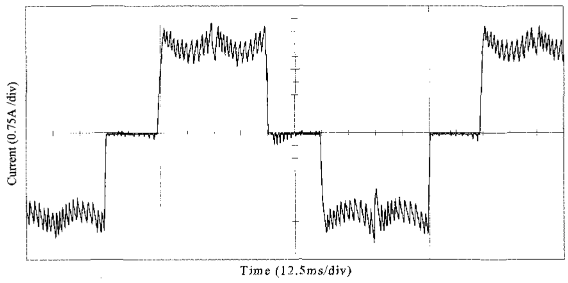
Fig. 10 Direct torque control (simulated)



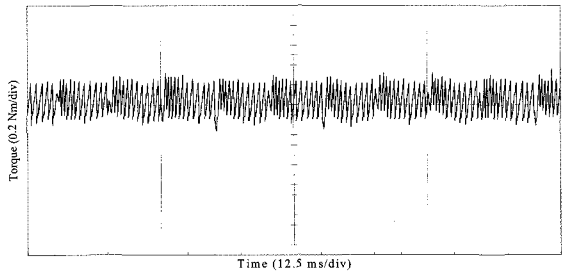
(a) Phase winding terminal to ground voltage



(b) Phase voltage



(c) Phase current



(d) Electromagnetic torque

Fig. 11 Direct torque control (measured)

4. Conclusions

The performance of a direct torque controlled permanent magnet BLDC drive has been compared with that of PWM current controlled drives both with and without current shaping. Since the torque is controlled directly, rather than indirectly by current control, a direct torque controlled BLDC drive exhibits significantly lower low-frequency torque ripple than a PWM current controlled BLDC drive without current shaping, while it is easier to implement and provides better torque control capability than a PWM current controlled BLDC drive with current shaping, as has been validated by both simulations and measurements.

Appendix

Parameters of Surface-Mounted PM Brushless BLDC Motor

Number of poles, p	*10*
DC link voltage (V)	*36*
Phase resistance (Ω)	*0.35*
Self-inductance (mH)	*3.9*
Mutual-inductance (mH)	*-0.0023*
Rated speed (rpm)	*400*
PM excitation flux-linkage (Wb):	*0.0794*

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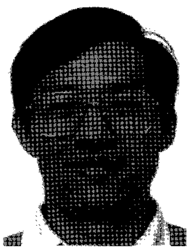

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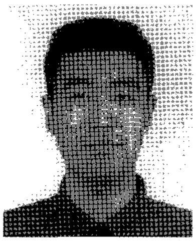

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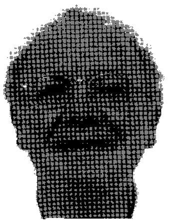

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