A New Instantaneous Torque Control of PM Synchronous Motor for High Performance Direct Drive Systems

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Abstract **- A new instantaneous torque control technique is presented for a high performance control of a permanent magnet synchronous motor. Using the model reference adaptive system technique, the linkage flux of the motor is estimated and the torque is instantaneously controlled by the proposed torque controller combining with a variable structure control and space vector PWM. The proposed torque control provides the advantage of reducing the torque pulsation caused by the flux harmonics. This control strategy is applied to the high torque PM synchronous motor drives for direct drive systems and is implemented by using a software of the DSP TMS320C30. The experiments are carried out for this system and the results well demonstrate the effectiveness of the proposed control.**

I. INTRODUCTION

Permanent magnet(PM) synchronous motors are generally used in a wide range of high performance servo applications such as industrial robots and machine tools because of their high power density, high torque to inertia ratio, and free maintenance. Especially, the recent researches for high coercive magnet materials, such as the samarium-cobalt and neodymium-iron-boron, marvelously increase the magnetic and thermal capabilities of the PM and thus the PM synchronous motor is often employed as an effective actuator in the special purpose applications. The direct drive system without a speed reducing mechanism is a typical example of these applications. Unlike the traditional servo system with a speed reducing mechanism, this system requires the high torque and low speed characteristics, and high stall torque to endure the gravity force of the external load coupled directly. Since the PM synchronous motor has the suitable configuration of satisfying these requirements, it is generally utilized in most direct drive systems.

In the direct drive system, although the elimination of the speed reducing mechanism can provide many useful advantages of eliminating the mechanical problems such as the backlash, friction, and wear, it is also a source of other problems. One of the important problems is the torque pulsation caused by the non-sinusoidal distribution of the magnetic flux. In the traditional servo system operated in high speed region, it is not necessary to consider this problem because the torque pulsation is naturally filtered out by the inertia moment of the motor and load. However, in the direct drive system, this problem degrades the control performance because the motor is generally operated in low speed region.

In order to deal with this problem, a new instantaneous torque control is proposed in this paper. In the proposed control scheme, the linkage flux of the PM synchronous motor is estimated by the model reference adaptive system(MRAS) technique and the torque is calculated by using this estimated flux. Then, the torque of the motor is instantaneously controlled by the proposed torque controller using the VSC with an integral action, so called IVSC, and the space vector PWM technique. Since the proposed estimation method does not require the differentiation of the current, the estimating performance is less sensitive to the measurement noise than that of the conventional approach employing the least square method. The experiments are carried out for the DSP based PM synchronous motor drives, and the results well demonstrate the effectiveness of the proposed control scheme.

II. MODELING OF PM SYNCHRONOUS MOTOR

The motor considered in this paper is a surface mounted type three phase PM synchronous motor which consists of a three phase stator winding and permanent magnet rotor. The voltage equation in the synchronous reference frame can be represented as follows[1, 2]:

$$v_{ds} = r_s i_{ds} + p\lambda_{ds} - \omega_r \lambda_{qs} \tag{1}$$

$$v_{qs} = r_s i_{qs} + p\lambda_{qs} + \omega_r \lambda_{ds} \tag{2}$$

where

$$\begin{aligned} \lambda_{ds} &= l_d i_{ds} + m_{dq} i_{qs} + m_{df} i_f \\ \lambda_{qs} &= l_q i_{qs} + m_{qd} i_{ds} + m_{qf} i_f \end{aligned}$$

and the inductances considering the flux harmonics are represented as

$$\begin{aligned} l_d &= L_{q0} + L_{d6}\cos 6\theta_r + L_{d12}\cos 12\theta_r + \dots \\ m_{dq} &= M_{dq6}\sin 6\theta_r + M_{dq12}\sin 12\theta_r + \dots \\ m_{df} &= M_{df0} + M_{df6}\cos 6\theta_r + M_{df12}\cos 12\theta_r + \dots \\ l_q &= L_{q0} + L_{q6}\cos 6\theta_r + L_{q12}\cos 12\theta_r + \dots \\ m_{qd} &= M_{qd6}\sin 6\theta_r + M_{qd12}\sin 12\theta_r + \dots \\ m_{qf} &= M_{qf6}\sin 6\theta_r + M_{qf12}\sin 12\theta_r + \dots\ . \end{aligned}$$

Since the 3rd harmonics and its multiples are internally canceled out in the Y-connected three phase circuit, the remaining harmonics are of the 5th, 7th, 11th, 13th, ... Therefore, the inductances in the synchronous frame can be represented to the fundamental term and multiples of six. The developed torque can be given as

$$\begin{aligned} \tau_e = \frac{3}{2}\frac{P}{2}\Bigg[& \left(\frac{dl_d}{d\theta_r} i_{ds} + \frac{dm_{dq}}{d\theta_r} i_{qs} + \frac{dm_{df}}{d\theta_r} i_f - \lambda_{qs} \right) i_{ds} \\ & + \left(\frac{dl_q}{d\theta_r} i_{qs} + \frac{dm_{qd}}{d\theta_r} i_{ds} + \frac{dm_{df}}{d\theta_r} i_f - \lambda_{ds} \right) i_{qs} \Bigg]. \end{aligned} \tag{3}$$

In the motor employing the high coercive PM material, the contributions to the torque by the self and mutual inductances of the stator windings are much smaller than that by the PM[5]. Thus, the self and mutual inductances of the stator winding can be assumed as $l_d = L_{d0}$, $l_q = L_{q0}$, and $m_{dq} = m_{qd} = 0$. Therefore, the torque and current relation of interest can be considered as

$$\tau_e = \frac{3}{2}\frac{P}{2}[\psi_{dm} i_{qs} + \psi_{qm} i_{ds} + (L_{d0} - L_{q0}) i_{qs} i_{ds}] \qquad (4)$$

where

$$\begin{aligned} \psi_{dm} &= \Psi_{d0} + \Psi_{d6}\cos 6\theta_r + \Psi_{d12}\cos 12\theta_r + \dots \\ \psi_{qm} &= \Psi_{q0} + \Psi_{q6}\sin 6\theta_r + \Psi_{q12}\sin 12\theta_r + \dots \end{aligned}$$

and

$$\begin{aligned} &\Psi_{d0} = M_{df0} i_f, \quad \Psi_{d6} = (6M_{qf6} + M_{df6}) i_f, \dots \\ &\Psi_{q0} = 0, \qquad\quad \Psi_{q6} = (6M_{df6} + M_{qf6}) i_f, \dots . \end{aligned}$$

From the above relation, the voltage equation given in (1) and (2) can also be rewritten as

$$v_{ds} = r_s i_{ds} + L_{d0} p i_{ds} - L_{q0} i_{qs} \omega_r + \psi_{qm} \omega_r \qquad (5)$$

$$v_{qs} = r_s i_{qs} + L_{q0} p i_{qs} + L_{q0} i_{ds} \omega_r + \psi_{dm} \omega_r. \qquad (6)$$

By using the concept of the field orientation, it can be assumed that the d axis current i_d is controlled to be zero, in which the developed torque is maximized for given stator current. Under this assumption, the torque and current relation can simply be described as

$$\tau_e = k_t \cdot i_{qs}$$

where

$$k_t = \frac{3}{2}\frac{P}{2}\psi_{dm}.$$

III. TORQUE CONTROL OF PM SYNCHRONOUS MOTOR

A. Overview of previous approaches

Fig. 1 shows the traditional torque control scheme of the PM synchronous motor using a sinusoidal current control, where the d axis current control loop is omitted for a simplicity. Under the assumption that the flux distribution is purely sinusoid, the torque can be controlled by the sinusoidally injected stator current. However, if the flux distribution is not purely sinusoid, the flux harmonics may produce the undesirable torque pulsation because the torque is developed by the combination of the flux and current.

In order to overcome the problem mentioned above, the concept of the instantaneous torque control is introduced[6]. This technique employs the torque control loop instead of the current control loop as shown in Fig. 2. It is known that this technique is an effective method of reducing the torque pulsation because the instantaneous torque can be directly controlled by the torque control strategy. However, in practice, this technique has the significant problem how the information on the instantaneous torque is obtained. Since the torque measuring mechanism using the strain gauge is very expensive and bulky, the direct measuring method is not available for most industrial servo applications. Therefore, the torque estimation method using the mathematical model and measurable variables is proposed in the previous approach[6]. The least square method is generally used to estimate the instantaneous torque of the motor. It is, however, known that the least square method is very complex to implement. Moreover, since this estimation method requires the differentiation of the motor current which is very noisy, it is very difficult to obtain the high estimating performance.

B. Proposed control scheme

In order to improve the above disadvantages, a new instantaneous torque control technique is proposed in this paper. As shown in Fig. 3, the proposed control scheme consists of two parts: the torque estimation and control parts. In the estimation part, the MRAS technique is employed, where the reference model is the real PM synchronous motor and the adjustable system is the mathematical model including the estimated linkage flux. The linkage flux is estimated by using the error between the outputs of the reference and adjustable models and then the instantaneous torque is estimated by using this estimated linkage flux and feedback current. As compared with the least square method used previously, the proposed torque technique is simpler and has higher noise immunity because it does not requires the differentiation of the motor current. The control part of the proposed scheme is composed of the IVSC and space vector PWM. The estimated instantaneous torque is fed to the proposed IVSC and then the control voltage is applied to the terminals of the motor by using the space vector PWM technique. The integral action in the proposed IVSC provides the useful

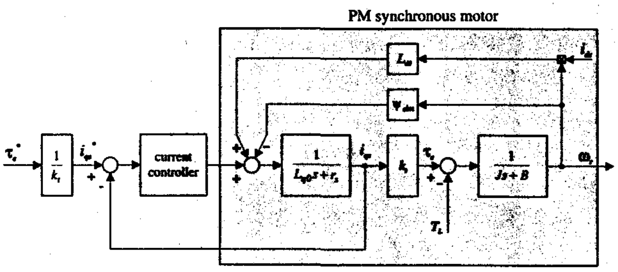

Fig. 1 Traditional torque control scheme of PM synchronous motor employing sinusoidal current control

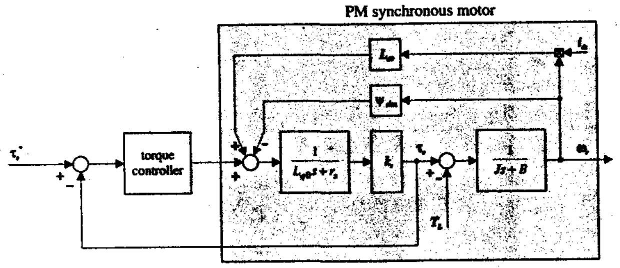

Fig. 2 Instantaneous torque control scheme of PM synchronous motor

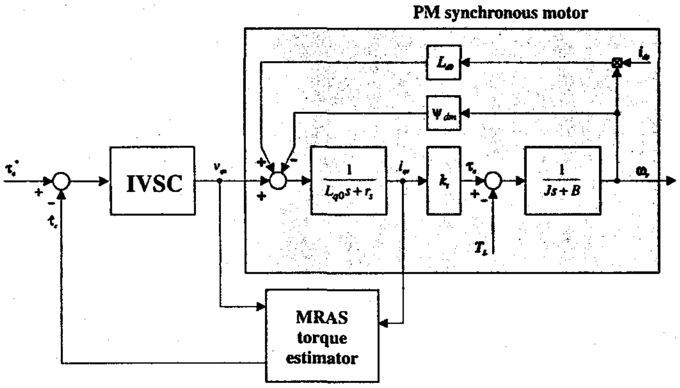

Fig. 3 Proposed torque control scheme of PM synchronous motor using MRAS torque estimator

advantage of improving the steady state performance and robustness[8]. Furthermore, the switching characteristics of the PWM inverter can also be improved by employing the space vector PWM technique.

IV. DESIGN OF PROPOSED CONTROLLER

A. Design of torque estimator using MRAS technique

The model of the PM synchronous motor given in (5) and (6) can be represented to the state space form as:

$$\dot{x} = Ax + Bu + D\psi \tag{8}$$

where

$$x = [i_{ds}\ i_{qs}]^T,\ u = [v_{ds}\ v_{qs}]^T,\ \psi = [\psi_{qm}\ \psi_{dm}]^T$$

$$A = \begin{bmatrix} -\frac{r_s}{L_{d0}} & \frac{L_{q0}}{L_{d0}}\omega_r \\ -\frac{L_{d0}}{L_{q0}}\omega_r & -\frac{r_s}{L_{d0}} \end{bmatrix}, B = \begin{bmatrix} \frac{1}{L_{d0}} & 0 \\ 0 & \frac{1}{L_{q0}} \end{bmatrix}, D = \begin{bmatrix} -\frac{\omega_r}{L_{d0}} & 0 \\ 0 & -\frac{\omega_r}{L_{q0}} \end{bmatrix}.$$

From this model, the adjustable system to estimate the linkage flux can be chosen as[4]

$$\hat{\dot{x}} = A\hat{x} + Bu + D\hat{\psi} + Fe \tag{9}$$

where $e = x - \hat{x}$ and F is a gain matrix. The adaptation rule can be given as

$$\hat{\dot{\psi}} = \gamma D^T Ge \tag{10}$$

where γ is adaptation gain and G is a solution of the Lyapunov equation given as

$$\overline{A^T}G + G\overline{A} = -Q \tag{11}$$

for the positive definite matrix Q, where $\overline{A} = A + F$ and the poles of lie in the open left half plane. The stability of the proposed adaptation mechanism can be proved by using the Lyapunov's direct method. To show the stability, the Lyapunov function candidate can be chosen as

$$V(e, \phi, t) = e^T Ge + \gamma^{-1}\phi^T\phi \tag{12}$$

where $\phi = \psi - \hat{\psi}$. The time derivative is derived as

$$\begin{aligned} \dot{V}(e, \phi, t) &= e^T(\overline{A^T}G + G\overline{A})e + 2\phi^T D^T Ge + 2\gamma^{-1}\phi^T\dot{\phi} \\ &= -e^T Qe + 2\phi^T D^T Ge + 2\gamma^{-1}\phi^T(\dot{\psi} - \hat{\dot{\psi}}). \end{aligned} \tag{13}$$

From the assumption that the time variation of the flux is much slower than the dynamics of the flux estimator, that is $\dot{\psi} = 0$, the following inequality can be made:

$$\dot{V}(e, \phi, t) \le -e^T Qe \le -\lambda_{\min}(Q)\|e\|^2 \le 0. \tag{14}$$

Therefore, the stability of the proposed adaptation mechanism is proved in the Lyapunov sense. Using the estimated linkage flux, the developed torque of the PM synchronous motor can be obtained as follows:

$$\hat{\tau}_e = \hat{k}_t \cdot i_{qs}. \tag{15}$$

B. Design of torque controller using VSC with integral action

In the proposed control, the control variables of interest are the d axis current i_{ds} and the developed torque τ_e. Thus, the error states to be controlled can be defined as

$$X_i = i_{ds} - i_{ds}^*,\quad X_\tau = \tau_e - \tau_e^*. \tag{16}$$

For these states, the sliding surface can be chosen as

$$s_i = X_i + c_i \int_{-\infty}^{t} X_i(\zeta)d\zeta = 0 \tag{17}$$

$$s_\tau = X_\tau + c_\tau \int_{-\infty}^{t} X_\tau(\zeta)d\zeta = 0 \tag{18}$$

where c_i and c_τ are the coefficients of the sliding surface. The structure of the control input can be given as

$$v_{ds} = K_{i1}X_i + K_{i2} \tag{19}$$

$$v_{qs} = K_{\tau 1}X_\tau + K_{\tau 2}. \tag{20}$$

The gains of the control inputs *Ki*1, *K*1, *Ki*2, and *K*2 can be determined by using the well known the sliding mode existence condition given as[3]

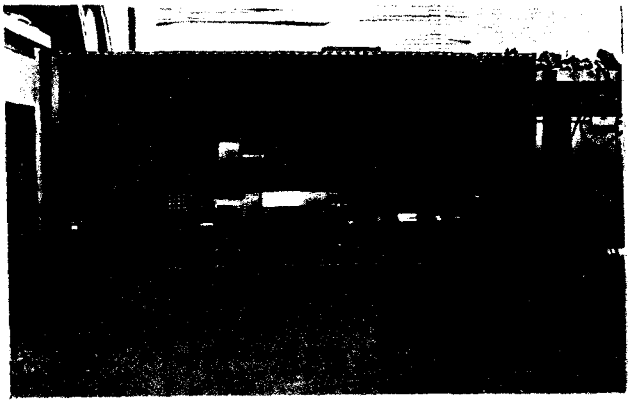

Fig. 4 Setup for experiments

$$s_i\dot{s}_i < 0,\quad s_\tau\dot{s}_\tau < 0. \tag{21}$$

From the above inequalities, the gains of the control inputs are determined as follows:

$$K_{i1} = \begin{cases} \alpha_{i1} > \max(-r_s + L_{d0}c_i) & \text{for } s_iX_i < 0 \\ \alpha_{i1} < \min(-r_s + L_{d0}c_i) & \text{for } s_iX_i > 0 \end{cases} \tag{22}$$

$$K_{i2} = \begin{cases} \alpha_{i2} > \max(L_{q0}\omega_r i_{qs} - \psi_{qm}\omega_r - r_s i_{ds}^* - L_{d0}\dot{i}_{ds}^*) & \text{for } s_i < 0 \\ \alpha_{i2} < \min(L_{q0}\omega_r i_{qs} - \psi_{qm}\omega_r - r_s i_{ds}^* - L_{d0}\dot{i}_{ds}^*) & \text{for } s_i > 0 \end{cases} \tag{23}$$

$$K_{\tau 1} = \begin{cases} \alpha_{\tau 1} > \max\left[\left(-r_s + L_{d0}\frac{\dot{k}_t}{k_t} + L_{q0}c_\tau\right)\right]\frac{1}{k_t} & \text{for } s_\tau X_\tau < 0 \\ \alpha_{\tau 1} < \min\left[\left(-r_s + L_{d0}\frac{\dot{k}_t}{k_t} + L_{q0}c_\tau\right)\right]\frac{1}{k_t} & \text{for } s_\tau X_\tau > 0 \end{cases} \tag{24}$$

$$K_{\tau 2} = \begin{cases} \alpha_{\tau 2} > \max\left[-L_{d0}\omega_r i_{ds} - \psi_{dm}\omega_r - \left(r_s - L_{q0}\frac{\dot{k}_t}{k_t}\right)\frac{\tau_e^*}{k_t} - \frac{L_{q0}}{k_t}\dot{\tau}_e^*\right] & \text{for } s_\tau < 0 \\ \alpha_{\tau 2} < \min\left[-L_{d0}\omega_r i_{ds} - \psi_{dm}\omega_r - \left(r_s - L_{q0}\frac{\dot{k}_t}{k_t}\right)\frac{\tau_e^*}{k_t} - \frac{L_{q0}}{k_t}\dot{\tau}_e^*\right] & \text{for } s_\tau > 0 \end{cases} \tag{25}$$

VI. EXPERIMENTS

A. Experimental system

Fig. 4 shows the experimental setup for the PM synchronous motor drive system, which consists of the high torque PM synchronous motor with a power rating of 120 [W], torque transducer, and DC generator. The proposed control scheme is implemented using the DSP-based control system using the DSP TMS320C30 with a clock frequency of 33 [MHz], which provides the computing performance of 33 [MFLOPS]. All of the proposed control algorithms including the torque estimator and IVSC are implemented using a software of the DSP. The position and speed of the rotor are detected by using the brushless resolver. The resolutions of the position and speed are calibrated as 16 [bit/rev] and 0.06 [rpm], respectively. The phase current of the stator is measured by using the Hall effect devices and the measured analog signal is converted to the digital value by using the A/D converter with a resolution of 12 [bit]. The three phase PWM inverter is constructed by using the intelligent power module(IPM). The gate firing logic to implement the space vector PWM is developed by using the single chip erasable programmable logic device(EPLD). The sampling time of the proposed control scheme is set as 100 [sec].

B. Experimental results

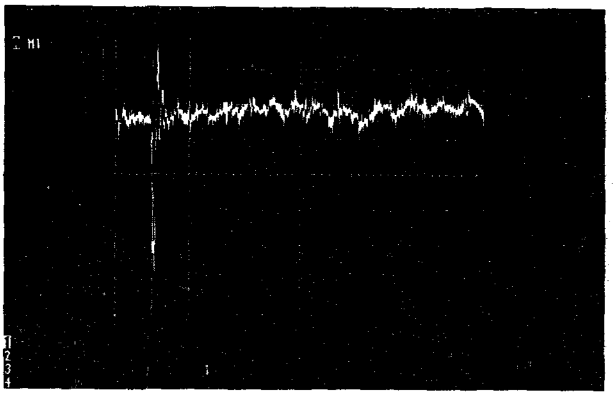

Fig. 5 Estimated flux by MRAC technique (0.2wb/div)

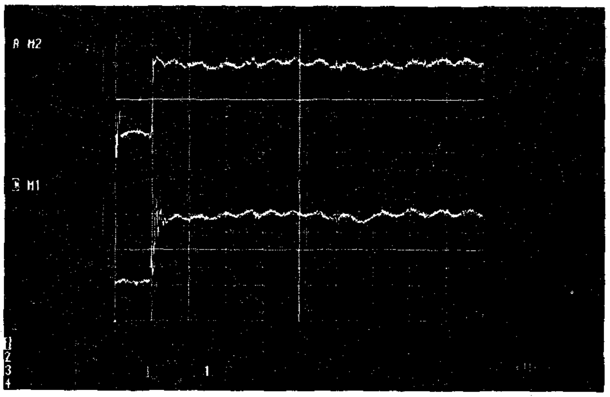

Fig. 6 Real and estimated torque (upper: real, lower: estimated, 0.5Nm/div)

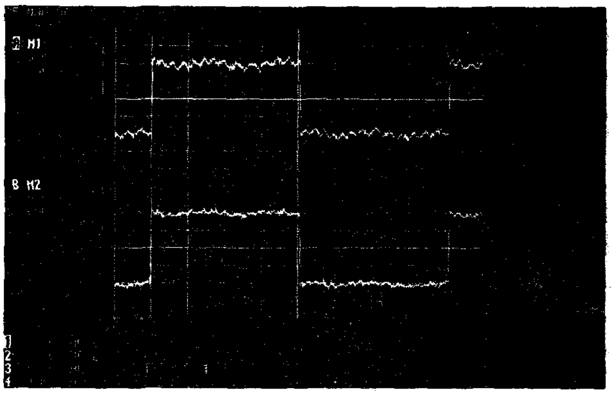

Fig. 7 Torque responses of both control schemes (upper: sinusoidal, lower: proposed, 0.5Nm/div)

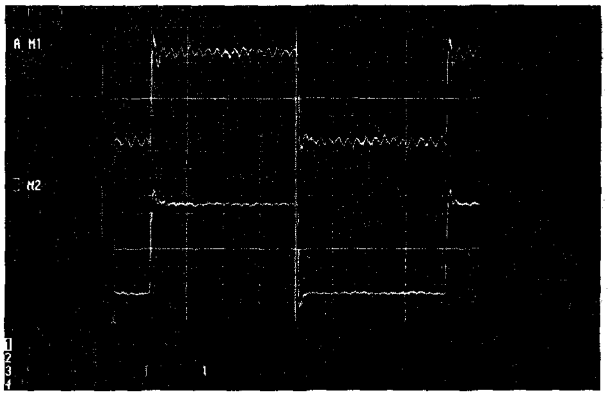

Fig. 8 Speed responces of both schemes (upper: sinusoidal, lower: proposed, 4rpm/div)

In order to verify the effectiveness of the proposed torque control scheme, the experiments are carried out for the DSP-based PM synchronous motor control system. Fig. 5 show the estimated flux of the motor. Fig. 6 shows the real estimated torques. Fig. 7 shows the torque responses of the sinusoidal current control and proposed torque control schemes. It is shown that the torque pulsation is remarkably reduced by employing the proposed torque control scheme. Fig. 8 shows the speed control performances of both scheme, when the reference speed is given as 10 [rpm], respectively, where the PI controller is used as an outer loop controller in both scheme. It is observed that the speed pulsation is also reduced in the proposed scheme.

VII. CONCLUSIONS

A new instantaneous torque control strategy is presented for a high performance control of a PM synchronous motor designed for direct drive systems. To deal with the torque pulsating problem caused by the non-sinusoidal flux distribution, the characteristics of the instantaneous torque control scheme is first considered. In order to improve the disadvantages of the existing approaches, the new torque estimation scheme is then proposed by using the MRAS technique. This estimation scheme is combined with the IVSC and space vector PWM technique, and the developed torque of the motor is instantaneously controlled by the proposed torque control scheme. To show the effectiveness of this scheme, the experiments are carried out for the DSP-based PM synchronous motor control system. It is well demonstrated from these results that the proposed torque control scheme provides a good control performance suppressing the undesirable torque pulsation.

APPENDIX

Motor Parameters

Rated Power	123 W	Rated Speed	123 rpm
Rated torque	9.8 Nm	Stator Resistance	18 Ω
Stator inductance	20 mH	Torque const.	4.7 Nm/A

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