Precise position control using a PMSM with a disturbance observer containing a system parameter compensator

S.-H. Choi, J.-S. Ko, I.-D. Kim, J.-S. Park and S.-C. Hong

Abstract: A deadbeat load torque observer with a system parameter compensator that can be used to improve the performance of a permanent-magnet synchronous motor in a precision position control system is presented. The compensator makes real systems work as it in a nominal parameter system. Therefore, the observer has a performance level equivalent to that obtained if there is no parameter variation. Noise effects are reduced by the use of past-filter implimented using a moving-average process. A comparison study on the system response for a convertional deadbeat gain observer and the proposed parameter-compensated deadbeat observer is performed. The proposed system can be used to cancel out any steady-state or transient position errors created by external disturbances such as friction, load torque or chattering effects.

1 Introduction

Precise position control is becoming increasingly important in applications such as chip mount machines, semiconductor production machines, precision milling machines, high-resolution CNC machines, precision assembly robots and high-speed hard disk drives. In many applications a permanent-magnet synchronous motor (PMSM) has replaced the conventional DC motor since the trend is for industrial applications to require more powerful actuators with smaller sizes. A PMSM has a low inertia, a large power-to-volume ratio, and a low noise level as compared to a permanent-magnet DC servomotor with the same output rating [1, 2]. However, the disadvantages of this machine are a high cost and the requirement for a more complex controller because of its nonlinear characteristics.

The proportional-integral controller usually used in PMSM control is simple to realise but finds it difficult to produce a sufficiently good performance in tracking applications. In [3] a systematic approach was proposed that uses digital position information in the PMSM system. However, the machine flux linkage is not exactly known for the load torque observer and this creates uncertainty problems. Also, a cogging effect, which can result in damage the permanent magnet and over-current effects which can affect the value of k_t were observed. This resulted in small position or speed errors and increased the chattering effect, which should be reduced as much as possible. It can also lead to the misestimation of the load torque in a deadbeat observer system. We will now propose the use of a parameter compensator that uses a recursive least-square method (RLSM) parameter estimator is to increase the performance of the load torque observer and main controller.

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2 Modelling of the PMSM

The system equations of a PMSM can be written as:

$$\dot{\omega} = \frac{3}{2}\frac{1}{J}\left(\frac{p}{2}\right)^2 \lambda_{\mathrm{m}}\ i_{qs} - \frac{B}{J}\omega - \frac{p}{2J}T_{\mathrm{L}}, \quad \dot{\theta} = \omega_{\mathrm{r}} \tag{1}$$

$$T_{\mathrm{e}} = \frac{3}{2}\frac{p}{2}\lambda_{\mathrm{m}} i_{qs} \tag{2}$$

where p is the number of poles, λ_{m} is the flux linkage of the permanent magnet, ω is the angular velocity of the rotor, ω_{r} is the rotor speed reference, J is the inertial moment of the rotor and B is the viscous friction coefficient.

3 Control algorithm

3.1 Position controller

A state can be defined for the tracking controller using (3). The control input can then be written as:

$$\dot{z} = \theta - \theta_{\mathrm{r}} \tag{3}$$

$$i_{qc1} = -k_1\omega - k_2\theta - k_3 z \tag{4}$$

where k_1, k_2, k_3 are state feedback gains and z is a new augmented state.

The augmented system for the speed control of a PMSM can be expressed as:

$$\begin{bmatrix} \dot{\omega} \\ \dot{\theta} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} -\frac{B}{J} & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \omega\theta \\ z \end{bmatrix} + \begin{bmatrix} k_t \frac{p}{2J} \\ 0 \\ 0 \end{bmatrix} i_{qs} - \begin{bmatrix} \frac{p}{2J} \\ 0 \\ 0 \end{bmatrix} T_L - \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \theta_r \quad (5)$$

$$y = [0 \quad 1 \quad 0] \begin{bmatrix} \omega \\ \theta \\ z \end{bmatrix} \quad (6)$$

If the load torque T_L is known, an equivalent current command i_{qc2} can be expressed as:

$$i_{qc2} = \frac{1}{k_t} T_L \quad (7)$$

Then, the feeding forward of an equivalent q-axis current command to the output controller can compensate for the load torque effect. However, disturbances will either be unknown or inaccessible in a real system.

3.2 Load torque observer with a moving-average process

It is known that an observer is required when the input is unknown and inaccessible. For simplicity, a zeroth-order observer is selected [3]. The system equation can be expressed as:

$$\begin{bmatrix} \dot{\hat{\omega}} \\ \dot{\hat{y}} \\ \dot{\hat{T}}_L \end{bmatrix} = \begin{bmatrix} -\frac{B}{J} & 0 & -\frac{p}{2J} \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{\omega} \\ \hat{y} \\ \hat{T}_L \end{bmatrix} + \begin{bmatrix} k_t \frac{p}{2J} \\ 0 \\ 0 \end{bmatrix} i_{qs} + L \left(y - [0 \quad 1 \quad 0] \begin{bmatrix} \hat{\omega} \\ \hat{y} \\ \hat{T}_L \end{bmatrix} \right) \quad (8)$$

where a hat denotes an estimated value. A deadbeat controller has been realised using a discrete model and the Matlab program [4]. To reduce the disadvantage of a deadbeat observer that it is too sensitive to noise, a moving-average (MA) filter is used [5]:

$$\tilde{T}_L(k) = \frac{1}{2}\left(\hat{T}_L(k) + \hat{T}_L(k-1)\right) \quad (9)$$

It should be noted that this is a low-order filter.

3.3 Parameter estimator and compensator

The discrete dynamic equation of the PMSM can be written as:

$$y(k+1) = \alpha\omega(k) + \beta y(k) + \gamma i_{qs}(k) + \delta T_L(k) \quad (10)$$

where

$$\alpha = \frac{J}{B}\left(1 - \exp\left(\frac{Bh}{J}\right)\right), \quad \beta = 1,$$

$$\gamma = k_t \frac{P}{2J}\frac{J}{B}\left(h - \frac{J}{B} + \frac{J}{B}\exp\left(\frac{Bh}{J}\right)\right)$$

$$\text{and} \quad \delta = \frac{P}{2J}\frac{J}{B}\left(\frac{J}{B} - h - \frac{J}{B}\exp\left(\frac{Bh}{J}\right)\right) \quad [4]$$

If we assume that there is no load torque effect then two feed-back gains and a feed-forward gain can be defined as in terms of C_1, C_2 and C_3 respectively [6]. Then a control input able to compensate parameter variation and make the system equivalent to a nominal system can be written as:

$$i^*_{qc}(k) = C_1(k)\omega(k) + C_2(k)y(k) + C_3(k)i_{qc}(k) \quad (11)$$

This discrete-time system can be implemented using a digital signal processor (DSP) to create a continuous real system. Therefore, the resultant compensated system is equal to the nominal equivalent system:

$$\begin{aligned} y(k+1) &= \alpha\omega(k) + \beta y(k) + \gamma(C_1(k)\omega(k) + C_2(k)y(k) + C_3(k)i_{qc}(k)) \\ &= \alpha_n\omega(k) + \beta_n y(k) + \gamma_n i_{qs}(k) \end{aligned} \quad (12)$$

where α, β, γ and α_n, β_n, γ_n are actual parameters and nominal parameters, respectively. These values can be obtained easily using (12) and $C_1 = (\alpha_n - \alpha)/\gamma$, $C_2 = (\beta_n - \beta)/\gamma$, $C_3 = \gamma_n/\gamma$ respectively.

Parameter compensation requires the estimation of the real parameters. Using a discrete system equation without disturbance we can separate the system into a parameter and a measured parameter:

$$y(k+1) = \alpha\omega(k) + \beta y(k) + \gamma i_{qs}(k) = \boldsymbol{\theta}^T\boldsymbol{\phi}(k) \quad (13)$$

where $\boldsymbol{\theta}^T = [\alpha \;\; \beta \;\; \gamma]$ and $\boldsymbol{\phi}^T(k) = [\omega(k) \;\; y(k) \;\; i_{qs}(k)]$.

A RLSM can estimate the real parameter. The equations for this are as follows [7–9].

$$\hat{\boldsymbol{\theta}}(k+1) = \hat{\boldsymbol{\theta}}(k) + F(k+1)\tilde{\boldsymbol{\phi}}(k)E(k+1) \quad (14)$$

$$F(k+1) = F(k) - \frac{F(k)\tilde{\boldsymbol{\phi}}(k)\tilde{\boldsymbol{\phi}}^T(k)F(k)}{1 + \tilde{\boldsymbol{\phi}}^T(k)F(k)\tilde{\boldsymbol{\phi}}(k)} \quad (15)$$

$$E(k+1) = y(k+1) - \hat{\boldsymbol{\theta}}(k)^T\tilde{\boldsymbol{\phi}}(k) \quad (16)$$

where $\hat{\boldsymbol{\theta}}^T(k) = [\alpha \;\; \beta \;\; \gamma]$, $\boldsymbol{E}$ is the parameter estimation error, and F is the projection function of the adaptive rule.

$$\tilde{\boldsymbol{\phi}}^T(k) = \left[\omega(k) \quad y(k) \quad i_{qs}(k) - \frac{\hat{T}_L}{k_t}\right]$$

$$F(0) = \frac{1}{\delta}\boldsymbol{I} \quad (0 < \delta \ll 1)$$

A block diagram for the proposed controller is shown in Fig. 1.

4 Configuration of the overall system

A block diagram of the proposed controller is shown in Fig. 2. A C-language program and a TMS320C31 DSP implement the digital control part [10, 11]. The MT method, which uses pulse duration to increase speed, is realised using a FPGA, and used to reduce the quantisation error.

Experimental load systems directly coupled to a motor axis are depicted in Fig. 3. This system creates a time-varying load torque which will be used to demonstrate the effectiveness of the proposed algorithm using the experimental system depicted in Fig. 4.

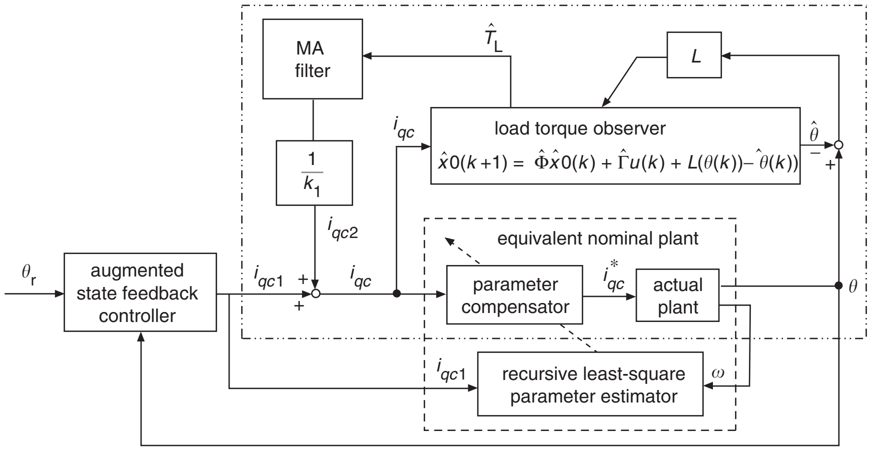

Fig. 1 *Block diagram of the proposed controller*

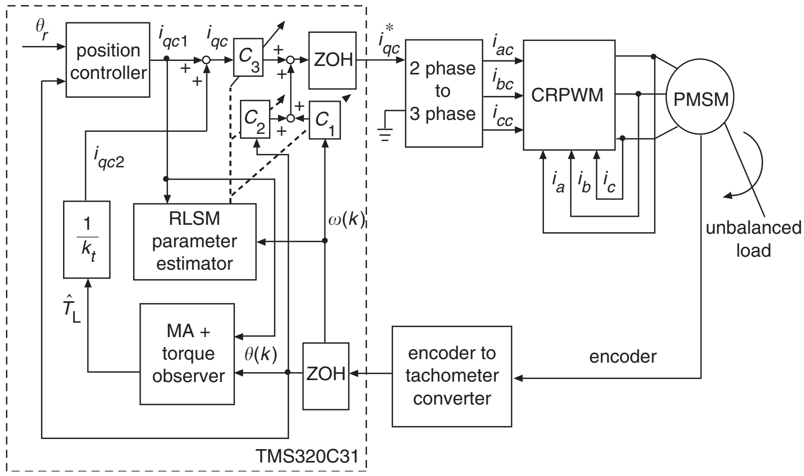

Fig. 2 *Block diagram of the proposed control system*

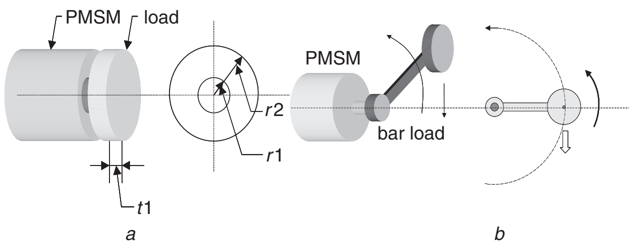

Fig. 3 *The experimental load system used for parameter and load variation*
a Inertial load
b Bar load

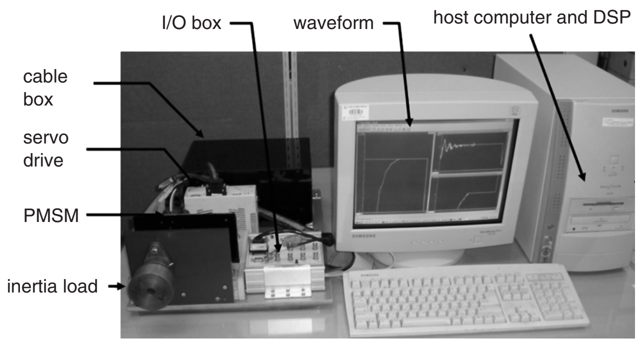

Fig. 4 *The experimental system*

5 Simulation and experimental results

The parameters of the PMSM motor used in the simulation and expanded studies are listed in Table 1.

The hysteresis bandgap of the current control was taken to be 0.01 A and the sampling time h was determined to be 0.2 ms. The weighting matrix of the optimal control theory was selected to be $\boldsymbol{Q} = \mathrm{diag}[0.1 \;\; 60 \;\; 1000]$, $R = 1$ and the optimal gain matrix then becomes $\boldsymbol{k} = [0.0771 \;\; 3.2321 \;\; 11.4195]$. The deadbeat observer and the gain matrices were calculated from nominal values [10, 12]. The gain is obtained using the pole placement method at the origin of the z-domain and $\boldsymbol{L} = [9623.9 \;\; 2.7000 \;\; -275.00]^T$ [4]. The simulation results are shown in Figs. 5 and 6. Figure 5 shows the speed response of the conventional controller, there is a small speed ripple and a small overshoot which is caused by a

Table 1: PMSM parameters

Power: 400 W	Inertia: 0.363×10^{-4} kgm^2
Rated torque: 1.3 Nm	Stator resistance: 1.07 Ω
Rated current: 2.7 A	Phase inductance: 4.2 mH

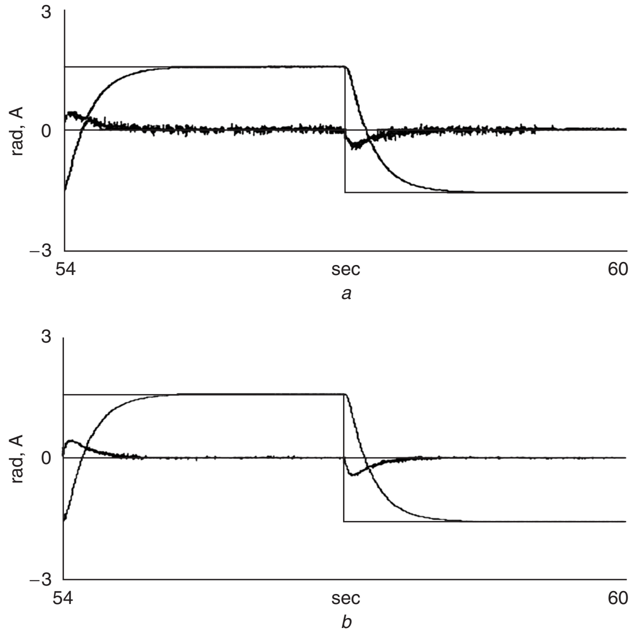

Fig. 5 *Simulation results on the rotor position, q-phase current command for no load*
a Deadbeat observer
b Deadbeat observer and parameter compensator algorithm

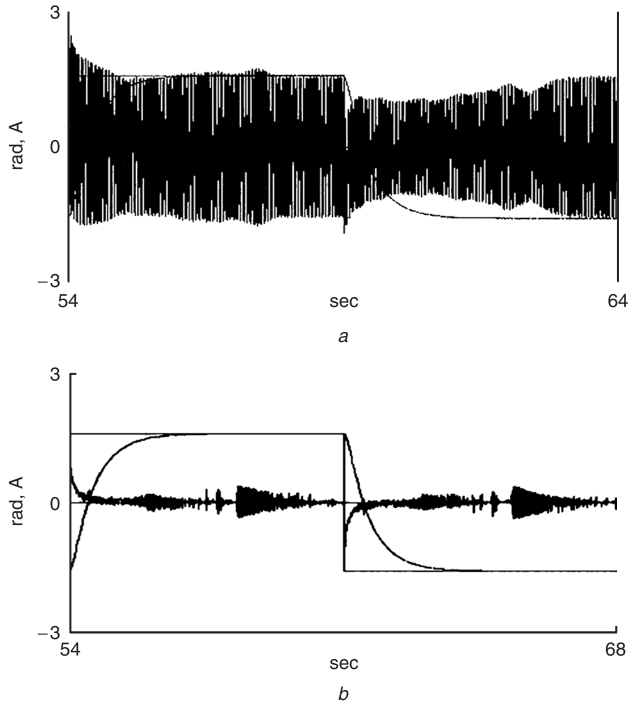

Fig. 6 *Simulation results for the rotor position, q-phase current command for the inertia load for an inertia parameter of 30-times that of the permanent-magnet value and variation of R and L*
a Using the disturbance observer
b Disturbance observer and parameter compensator

current ripple in the hysteresis bandgap and parameter variation. The inertial parameter has a value 100-times that of the permanent-magnet value and is two-times that of the R and L value. This conventional algorithm responds to parameter variation by creating a current ripple. Figure 6 shows the result obtained using the proposed algorithm under the same position command and the same disturbance condition as in Fig. 5.

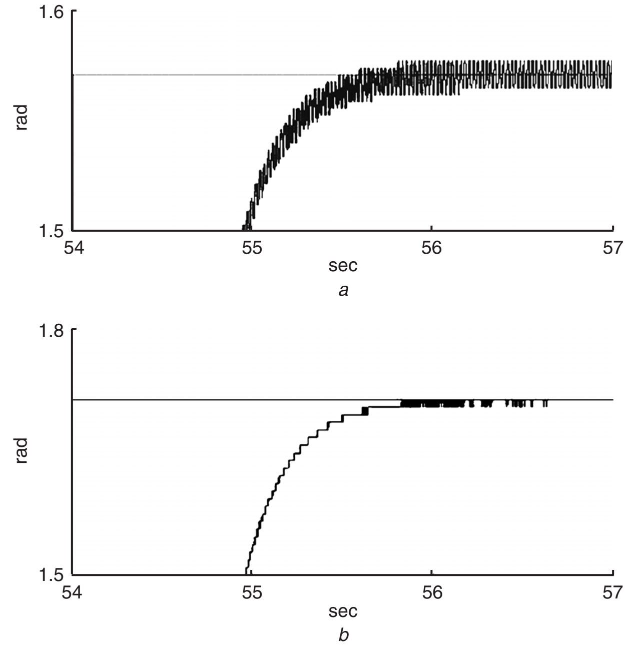

Fig. 7 *Performance comparison of the two controllers*
a Disturbance observer
b Disturbance observer with *a* parameter compensator

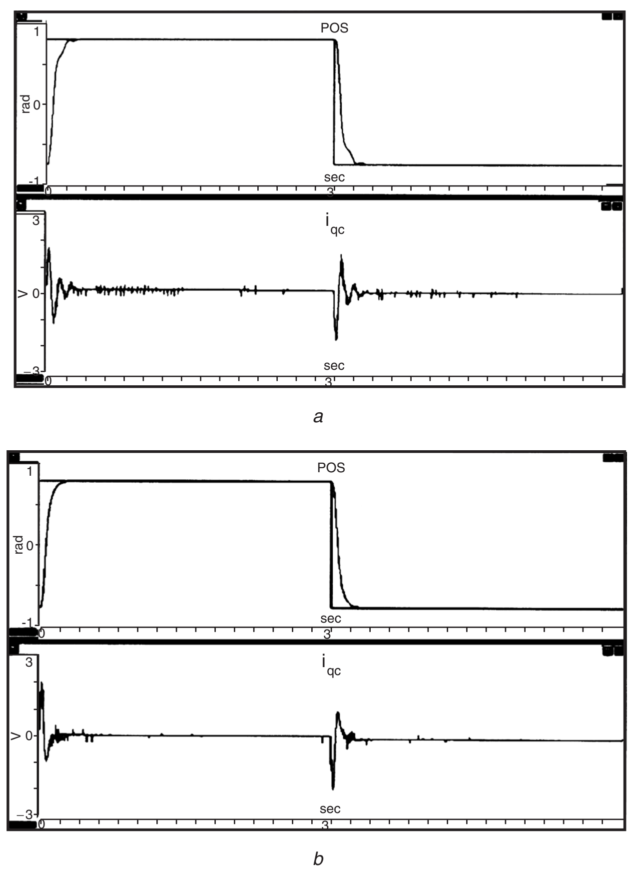

Fig. 8 *Experiment results for the rotor position, q-phase current command for an inertial load*
a Disturbance observer
b Disturbance observer and parameter compensator (after 20 min)

We can see that the load effects are reduced using the proposed algorithm for parameter compensation. In case of bar load, inertia variation affects are reduced in comparison to a directly coupled inertia load. Therefore, the parameter algorithm does not have too much work to perform.

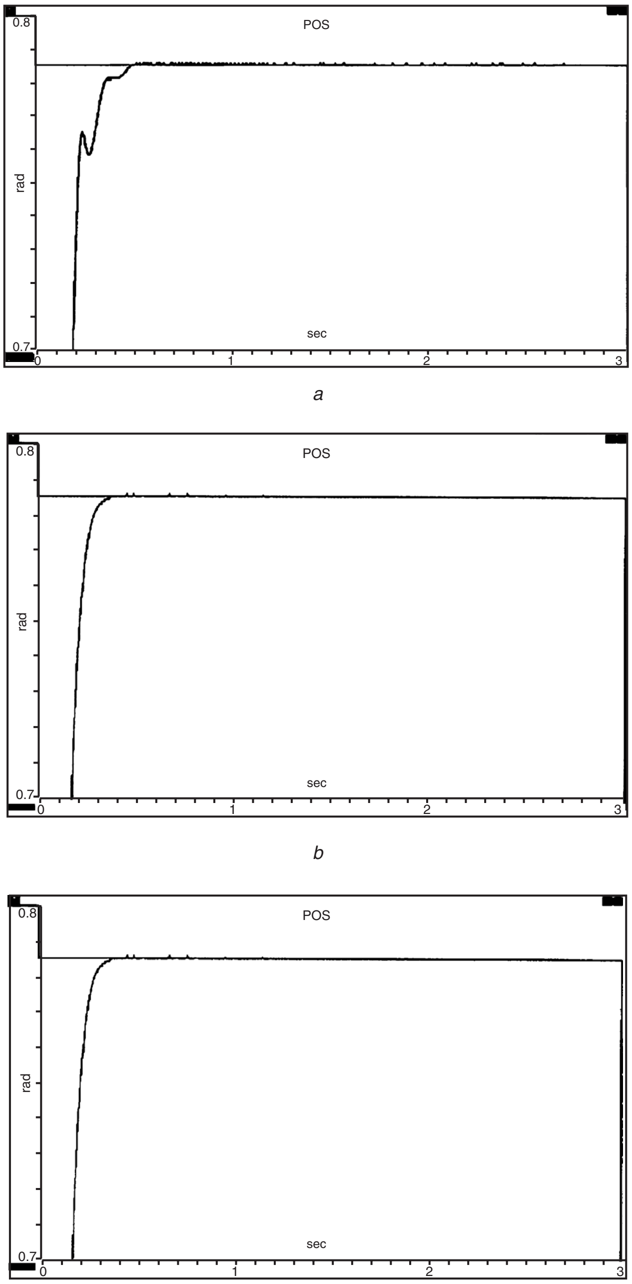

Fig. 9 *Detailed plots of the experiment results for the rotor position under an inertial load*
a Disturbance observer algorithm
b Disturbance observer and parameter compensator (after 1 min)
c Disturbance observer and parameter compensator (after 20 min)

Figure 7 presents 0.1 rad-scaled simulation results to show a comparison between two controllers. The conventional controller of Fig. 6*a* has a large position ripple compared with the proposed system of Fig. 6*b*. This is a result of the parameter compensator.

Experimental results are depicted in Figs. 8 and 9. In these experiments, the real observer gains are reduced by about 30% to obtain the same effectiveness as the parameter compensation. The parameter compensator calculates the real parameter and current to compensate the mistuned gain. Figure 8*a* and 8*b* show experimental position results for a current command with 3 s duration. There is a current ripple udner steady-state conditions and a large position overshoot in transient conditions in Fig. 8*a*. However, after 20 min, there is no current ripple and the position error in the proposed system is as shown in Fig. 8*b*. Since the *R* and *L* values cannot be changed by a factor of 30 in a real system the current ripple is not as big as in Fig. 6. Furthermore, a large viscous friction effect reduces the position ripple, and also the current ripples.

Figure 9 contains expanded views of parts of Fig. 8 and it is clear that the position error gradually decrease as the time increases.

6 Conclusions

A deadbeat load torque observer with a system parameter compensator that can be used to improve the performance of a PMSM in a precision position control system has been presented. This compensator makes real systems work as it in a nominal parameter system. Therefore, the observer has a performance level equivalent to that obtained if there is no parameter variation. Noise effects are reduced by the use of a post-filter implemented using a MA process. A comparison study on the system response for a conventional deadbeat gain observer and our proposed parameter-compensated deadbeat observer has been performed. Since the parameter-compensated system acts as if there is no parameter variation, the conventional deadbeat load torque easily adapts to a real system. It can be used to cancel out any steady-state or transient position error created by external disturbances such as friction, load torque or chattering effects.

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