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Stator flux and load torque observers for PMSM ⋆

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Abstract: In this paper, a stator flux observer and constant load torque estimation method are developed for non-salient permanent magnet synchronous motors. The methods described here are based on implementation of LTI filters and linear regression. The motor resistance and inductance are assumed to be known.

Keywords: Permanent magnet synchronous motor, sensorless control, stator flux observer, load torque observer.

1. INTRODUCTION

In the past decades, permanent magnet synchronous motors (PMSM) have been widely used in industrial servo drives (cranes, elevators, vacuum pumps), transportation (airplanes) and daily life (vacuum cleaners, refrigerators, washing machines, air conditioners). Among the advantages of PMSM there are high efficiency and maintaining a constant speed at impact loads and voltage fluctuations. Field-oriented control of PMSM requires information on motor mechanical variables such as rotor speed and position. But analog and digital detectors are often difficult to install, they also add extra cost to the price of the system and may make it less reliable. So sensorless control which uses only electrical variables measurement instead of mechanical ones has become very popular in order to minimize the cost and increase the reliability of PMSM driven systems.

A review of methods which were first used for sensorless control can be found in Acarnley and Watson (2006). As sensorless controllers are cost effective and flexible, they have become widely used in PMSM control systems, see Nam (2018). In practice the real electrical parameters are not equal to values specified in technical documentation as the parameters usually vary during the system performance. The reason of parameters' variation can be temperature, mechanical wear or external influence, so the quality of sensorless control may become inappropriate. In order to improve it and estimate real values of motor parameters adaptive identification algorithms were developed, see Verrelli et al. (2013), Ichikawa et al. (2006), Piippo et al. (2009). It allows to get values of motor parameters similar to real ones. Verrelli et al. (2013), Kisck et al. (2010), Hinkkanen et al. (2011), Bazylev et al. (2016), Bobtsov et al. (2018) present the algorithms evaluating the stator winding resistance and stator inductance. However in these algorithms position of rotor and rotor speed estimation are not considered.

Position and speed estimation algorithms for high-performance AC motors were introduced in Ortega et al. (2010), Tomei and Verrelli (2011), Bobtsov et al. (2015), Bobtsov et al. (2017a) . The dynamics of such motors is nonlinear and includes uncertain parameters. Angular position of the rotor can be found from trigonometric functions using stator flux. This is a reason of paying special attention to stator flux observers. In particular, lots of papers have been devoted to determining initial conditions of the flux

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and compensation of the shift Dib et al. (2011), Ortega et al. (2010), Shah et al. (2011). A gradient observer for this purpose was proposed in Bobtsov et al. (2015). Its implementation is difficult because of the need to ensure persistent excitation (PE) condition. However it was shown that flux error exponentially approaches to zero. In Bobtsov et al. (2017a) the dynamic regression extension and mixing (DREM) estimation replaced the gradient adaptation algorithm. These observers require the knowledge of the resistance, magnet flux and inductance. But in real PMSM driven systems the load torque is usually unknown and depends on the load shape and dimensions. Magnetic flux varies with the temperature of the rotor. It is necessary to mention that flux and load torque are hard to obtain online. So there are two ways to solve this problem. The first one is development of observers which do not rely on the knowledge of those parameters. The case where the magnet flux is unknown but resistance and inductance are known and described in Bernard and Praly (2018). In Bernard and Praly (2017) an extention of the gradient observer obtained in Lee et al. (2009) was developed. Also a number of papers is devoted to flux and load torque estimation. In Lian et al. (2018) a load torque observer based on sliding mode and two moment of inertia identification methods is proposed. In Ouvang and Dou (2018) authors introduce online identification of stator resistance and permanent magnetic flux linkage on the base of model reference adaptive system. In this paper, we consider a new algorithm for estimation of stator flux and constant load torque of the PMSM with known constant parameters (winding resistance and inductance).

The remaining of the paper is organized as follows. Section 2 presents the model of the PMSM and the assumptions needed for the observer design. Section 3 contains main result. Some representative simulations results can be found in Section 4.

2. PMSM MODEL AND PROBLEM STATEMENT

The classical fixed-frame ($\alpha\beta$) model of the unsaturated non-salient PMSM is given by Chiasson (2005), Shah et al. (2011).

$$\begin{aligned}\dot{\lambda} &= \upsilon - Ri,\\ J\dot{\omega} &= \tau_e - \tau_L,\\ \dot{\theta} &= \omega.\end{aligned} \tag{1}$$

where $\lambda \in R^2$ is the stator flux, $i \in R^2$ are the currents, $\upsilon \in R^2$ the voltages, $R > 0$ is the stator winding resistance, $J > 0$ is the rotor inertia, $\theta \in S := [0, 2\pi)$ is the rotor phase, $\omega \in R$ is the mechanical angular velocity, $\tau_L \in R$ is load torque, τ_e is the torque of electrical origin, given by

$$\tau_e = n_p i^T J_a \lambda,$$

where n_p is the number of pole pairs and J_a is the skew-symmetric matrix

$$J_a := \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}.$$

For surface-mounted PMSMs, the total flux verifies

$$\lambda = Li + \lambda_m C(\theta), \tag{2}$$

where $L > 0$ is the stator inductance, λ_m is the constant flux generated by permanent magnets. To simplify the notation, we define

$$C(\theta) := \begin{bmatrix} cos(n_p\theta) \\ sin(n_p\theta) \end{bmatrix}. \tag{3}$$

The main contribution of the paper is design and investigation of the stator flux observer and load torque estimation for PMSM, assuming that the motor resistance and inductance are known, load torque is unknown and constant.

3. MAIN RESULT

3.1 Stator flux observer

Let us denote derivatives of stator flux $\dot{\lambda}_i, i = 1, 2$ as f_i and rewrite (1) and (2) in the following form

$$\dot{\lambda}_1 = -Ri_1 + u_1 =: f_1, \tag{4}$$

$$\dot{\lambda}_2 = -Ri_2 + u_2 =: f_2, \tag{5}$$

$$\lambda_1 = Li_1 + \lambda_m \cos(n_p\theta), \tag{6}$$

$$\lambda_2 = Li_2 + \lambda_m \sin(n_p\theta), \tag{7}$$

where R and L are known, i_1, i_2, u_1, and u_2 are measured. The goal is to estimate stator flux λ_1, λ_2. Equations (6) and (7) can be rewritten as

$$\begin{aligned}\dot{\lambda}_1 &= L\frac{d}{dt}i_1 - n_p\dot{\theta}\lambda_m \sin(n_p\theta) = \\ &= L\frac{d}{dt}i_1 - n_p\dot{\theta}\left(\lambda_2 - Li_2\right)\end{aligned} \tag{8}$$

and

$$\begin{aligned}\dot{\lambda}_2 &= L\frac{d}{dt}i_2 + n_p\dot{\theta}\lambda_m \cos(n_p\theta) = \\ &= L\frac{d}{dt}i_2 + n_p\dot{\theta}\left(\lambda_1 - Li_1\right).\end{aligned} \tag{9}$$

After multiplication of (8) by $(\lambda_1 - Li_1)$ and (9) by $(\lambda_2 - Li_2)$ we can consider the sum of these products:

$$\begin{aligned}&\dot{\lambda}_1\left(\lambda_1 - Li_1\right) + \dot{\lambda}_2\left(\lambda_2 - Li_2\right) = \\ &= L\frac{d}{dt}i_1\left(\lambda_1 - Li_1\right) + L\frac{d}{dt}i_2\left(\lambda_2 - Li_2\right).\end{aligned}$$

Substituting (4) and (5) into previous expression we obtain

$$\begin{aligned}&f_1\left(\lambda_1 - Li_1\right) + f_2\left(\lambda_2 - Li_2\right) = \\ &= L\frac{d}{dt}i_1\left(\lambda_1 - Li_1\right) + L\frac{d}{dt}i_2\left(\lambda_2 - Li_2\right).\end{aligned} \tag{10}$$

Let us now apply the parameter estimation based observers (PEBO) approach discussed in Bazylev et al. (2017) and rewrite flux as

$$\lambda_i(t) = z_i(t) + \eta_i, i = 1, 2, \tag{11}$$

where η_1, η_2 are unknown constants and z_1, z_2 are the solutions of the following equations

$$\dot{z}_i = Ri_i + u_i \tag{12}$$

with some initial conditions $z_i(0)$. Obviously, the problem of estimation of the signals λ becomes equivalent to the problem of identification of the parameters η.

Thus, we obtain

$$\begin{aligned}&f_1z_1 + f_1\eta_1 - Li_1f_1 + f_2z_2 + f_2\eta_2 - Li_2f_2 = \\ &= Lz_1\frac{d}{dt}i_1 + L\eta_1\frac{d}{dt}i_1 - L^2i_1\frac{d}{dt}i_1 + \\ &+ Lz_2\frac{d}{dt}i_2 + L\eta_2\frac{d}{dt}i_2 - L^2i_2\frac{d}{dt}i_2.\end{aligned} \tag{13}$$

Let us apply LTI filter $\frac{k}{k+p}$, where $p = d/dt$ and k is gain.

Then recalling the Swapping Lemma, see Morse (1980), Sastry and Bodson (1989) we have

$$\frac{k}{p+k}\left[\frac{d}{dt}i_i\right] = \frac{pk}{p+k}[i_i], \tag{14}$$

$$\frac{k}{p+k}\left[z_i\frac{d}{dt}i_i\right] = \\ = z_i\frac{kp}{p+k}[i_i] - \frac{1}{p+k}\left[\left(\frac{pk}{p+k}[i_i]\right)(Ri_i+u_i)\right], \tag{15}$$

$$\frac{k}{p+k}\left[i_i\frac{d}{dt}i_i\right] = \frac{1}{2}\frac{pk}{p+k}\left[i_i^2\right]. \tag{16}$$

Let us denote

$$z_i\frac{kp}{p+k}[i_i] - \frac{1}{p+k}\left[\left(\frac{pk}{p+k}[i_i]\right)(Ri_i+u_i)\right] =: \psi_i. \tag{17}$$

After applying the LTI filter $\frac{k}{p+k}$ to the both sides of (13) and using (17) we obtain

$$\frac{k}{p+k}[f_1z_1 - Li_1f_1 + f_2z_2 - Li_2f_2] - L\psi_1 + \\ +\frac{L^2}{2}\frac{pk}{p+k}\left[i_1^2\right] - L\psi_2 + \frac{L^2}{2}\frac{pk}{p+k}\left[i_2^2\right] = \\ \left(L\frac{pk}{p+k}[i_1] - f_1\right)\eta_1 + \left(L\frac{pk}{p+k}[i_2] - f_2\right)\eta_2. \tag{18}$$

Previous expression can be considered as a linear regression of the form

$$y = \phi^\top\eta, \tag{19}$$

where

$$y := \frac{k}{p+k}[f_1z_1 - Li_1f_1 + f_2z_2 - Li_2f_2] - \\ -L\psi_1 + \frac{L^2}{2}\frac{pk}{p+k}\left[i_1^2\right] - L\psi_2 + \frac{L^2}{2}\frac{pk}{p+k}\left[i_2^2\right], \tag{20}$$

$$\phi := \left[L\frac{pk}{p+k}[i_1] - f_1 \qquad L\frac{pk}{p+k}[i_2] - f_2\right]^\top. \tag{21}$$

Now, the parameters η_i can be estimated using any proper technique, for instance

$$\dot{\hat{\eta}} = \gamma\phi\left(y - \phi^\top\hat{\eta}\right), \tag{22}$$

where $\gamma > 0$ is adaptation coefficient.

From (22) we have $\hat{\eta}$ and then from (11) we can find stator flux estimate $\hat{\lambda}$.

For convergence of errors $\tilde{\eta} = \eta - \hat{\eta}$ to zero PE condition on the regressor must hold (see for instance Aranovskiy et al. (2016)).

3.2 Estimation of load torque ($\tau_L = const$)

Consider model of the unsaturated nonsalient PMSM

$$\begin{cases} \lambda_1 - Li_1 = \lambda_m\cos(n_p\theta), \\ \lambda_2 - Li_2 = \lambda_m\sin(n_p\theta), \end{cases} \tag{23}$$

$$\ddot{\theta} = \frac{1}{J}(-\tau_L + n_p i_{\alpha\beta}^T J_a\lambda) = -\frac{1}{J}\tau_L + \frac{1}{J}\tau_e. \tag{24}$$

The goal is to estimate load torque τ_L under assumption that $\tau_e = n_p i_{\alpha\beta}^T J_a\lambda$ and λ are known.

Let us denote

$$\begin{cases} r_1 = \lambda_1 - Li_1 = \lambda_m\cos(n_p\theta), \\ r_2 = \lambda_2 - Li_2 = \lambda_m\sin(n_p\theta). \end{cases} \tag{25}$$

Then after applying the LTI filter $\frac{1}{p+1}$ to (25) we have the following chain of expressions

$$\bar{r}_1 = \frac{1}{p+1}r_1 = \frac{1}{p+1}\lambda_m\cos(n_p\theta) = \\ = \lambda_m\cos(n_p\theta) + \frac{n_p}{p+1}(\dot{\theta}\lambda_m\sin(n_p\theta)) = \\ = r_1 + \frac{n_p}{p+1}(\dot{\theta}r_2) = \\ = r_1 + \dot{\theta}\frac{n_p}{p+1}r_2 - \frac{n_p}{p+1}(\ddot{\theta}\frac{1}{p+1}r_2) = \\ = r_1 + n_p\dot{\theta}\bar{r}_2 - \frac{n_p}{p+1}(-\frac{1}{J}\tau_L\bar{r}_2 + \frac{1}{J}\tau_e\bar{r}_2). \tag{26}$$

$$\bar{r}_2 = \frac{1}{p+1}r_2 = \frac{1}{p+1}\lambda_m\sin(n_p\theta) = \\ = \lambda_m\sin(n_p\theta) - \frac{n_p}{p+1}(\dot{\theta}\lambda_m\cos n_p\theta) = \\ = r_2 - \frac{n_p}{p+1}(\dot{\theta}r_1) = \\ = r_2 - \dot{\theta}\frac{n_p}{p+1}r_1 + \frac{n_p}{p+1}(\ddot{\theta}\frac{1}{p+1}r_1) = \\ = r_2 - n_p\dot{\theta}\bar{r}_1 + \frac{n_p}{p+1}(-\frac{1}{J}\tau_L\bar{r}_1 + \frac{1}{J}\tau_e\bar{r}_1). \tag{27}$$

Let us rewrite (26) and (27). Then we obtain

$$\begin{cases} \bar{r}_1 = r_1 + n_p\dot{\theta}\bar{r}_2 + n_p\frac{1}{J}\tau_L\frac{1}{p+1}\bar{r}_2 - n_p\frac{1}{J}\frac{1}{p+1}(\tau_e\bar{r}_2), \\ \bar{r}_2 = r_2 - n_p\dot{\theta}\bar{r}_1 - n_p\frac{1}{J}\tau_L\frac{1}{p+1}\bar{r}_1 + n_p\frac{1}{J}\frac{1}{p+1}(\tau_e\bar{r}_1), \end{cases} \tag{28}$$

$$\begin{cases} \xi_1 = n_p\dot{\theta}\bar{r}_2 + \tau_L\omega_1 = n_p\omega\bar{r}_2 + \tau_L\omega_1, \\ \xi_2 = -n_p\dot{\theta}\bar{r}_1 - \tau_L\omega_2 = -n_p\omega\bar{r}_1 - \tau_L\omega_2, \end{cases} \tag{29}$$

where $\omega_1 = \frac{n_p}{J}\frac{1}{p+1}\bar{r}_2$ and $\omega_2 = \frac{n_p}{J}\frac{1}{p+1}\bar{r}_1$.

From previous equations we can find

$$\xi_1\bar{r}_1 + \xi_2\bar{r}_2 = \tau_L(\omega_1\bar{r}_1 - \omega_2\bar{r}_2). \tag{30}$$

Now we have linear regression model

$$y_\tau = \phi_\tau^\top\tau_L, \tag{31}$$

where $y_\tau = \xi_1\bar{r}_1 + \xi_2\bar{r}_2$ and $\phi_\tau^\top = \omega_1\bar{r}_1 - \omega_2\bar{r}_2$.

Now we can estimate τ_L using any proper technique, for instance

$$\dot{\hat{\tau}}_L = \gamma(\omega_1\bar{r}_1 - \omega_2\bar{r}_2)(\xi_1\bar{r}_1 + \xi_2\bar{r}_2 - \hat{\tau}_L(\omega_1\bar{r}_1 - \omega_2\bar{r}_2)), \tag{32}$$

where $\gamma > 0$ is adaptation coefficient.

For convergence of load torque estimation error $\tilde{\tau}_L = \tau_L - \hat{\tau}_L$ to zero PE condition on the regressor must hold (see for instance Aranovskiy et al. (2016))

4. SIMULATIONS

For simulation we use parameters of the motor BMP0701F as in Bobtsov et al. (2017a), Bobtsov et al. (2017b) listed in Table 1.

Simulation results are shown in Fig. 1-Fig. 11.

Table 1. Parameters of the PMSM BMP07F1

Parameter (units)	Value
Inductance $L(mH)$	40.03
Resistance (Ω)	8.875
Drive inertia $J(kg \cdot m^2)$	60×10^{-6}
Pairs of poles $n_p(-)$	5
Magnetic flux (Wb)	0.2086

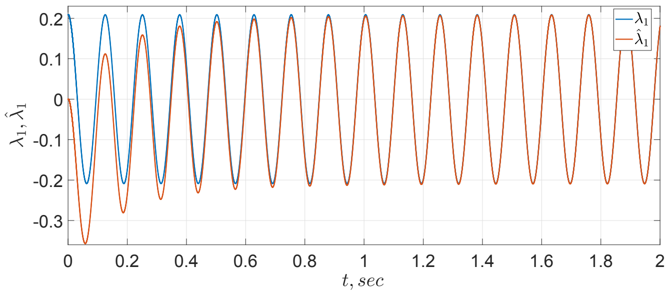

Fig. 1. Stator flux λ_1 and stator flux estimate $\hat{\lambda}_1$

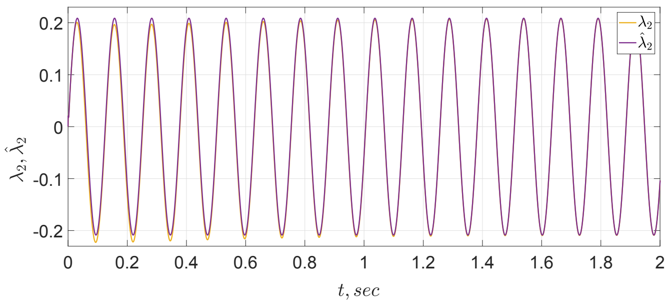

Fig. 2. Stator flux λ_2 and stator flux estimate $\hat{\lambda}_2$

Fig. 1, 2 demonstrate the transients of stator flux and stator flux estimates, Fig. 3...Fig. 6 demonstrate the transients of stator flux errors $e_{\lambda_1} = \lambda_1 - \hat{\lambda}_1$ and $e_{\lambda_2} = \lambda_2 - \hat{\lambda}_2$ of PMSM when load torque $\tau_L \equiv 0$ and rotor speed $\omega = 10$, adaptation gain in (22) $\gamma = 25$ for Fig. 3 and Fig. 4 and adaptation gain in (22) $\gamma = 100$ for Fig.5 and Fig. 6.

Fig. 7 demonstrates comparison of Bernard and Praly (2018) method and method proposed in this paper when load torque $\tau_L \equiv 0$ and rotor speed $\omega = 10$. Adaptation gain from Bernard and Praly (2018) $q = 10$ and adaptation gain in (22) $\gamma = 8$.

Fig. 8 demonstrates the same comparison as Fig. 7 but with gain $q = 100$ and $\gamma = 80$. It is noticeable that for small adaptation gains transients of the stator flux error looks almost the same. However to increase speed of estimation it is necessary to increase adaptation gains in both methods. In Bernard-Praly's method this causes error fluctuations which limit the gain increase. In the method proposed in this paper adaptation gain is limited only by technical capabilities.

Fig. 9, 10 demonstrate the transients of load torque estimate $\hat{\tau}_L$ of PMSM when load torque $\tau_L = 0,1$ (Fig. 9) and $\tau_L = 0,5$ (Fig. 10), rotor speed $\omega = 10$, adaptation gain in (32) $\gamma = 100$.

Fig. 11 demonstrates the transients of load torque estimate $\hat{\tau}_L$ of PMSM for step load torque, rotor speed $\omega = 10$, adaptation gain in (32) $\gamma = 100$.

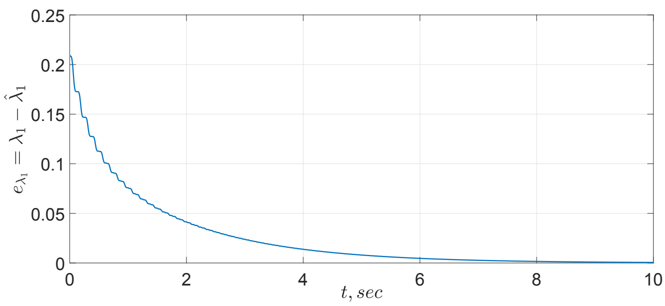

Fig. 3. Convergence of estimation error $e_{\lambda_1} = \lambda_1 - \hat{\lambda}_1$ for $\gamma = 25$

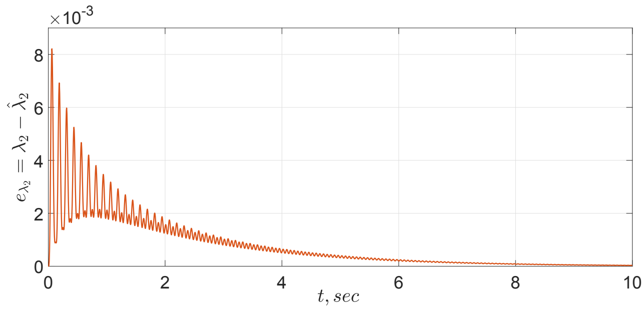

Fig. 4. Convergence of estimation error $e_{\lambda_2} = \lambda_2 - \hat{\lambda}_2$ for $\gamma = 25$

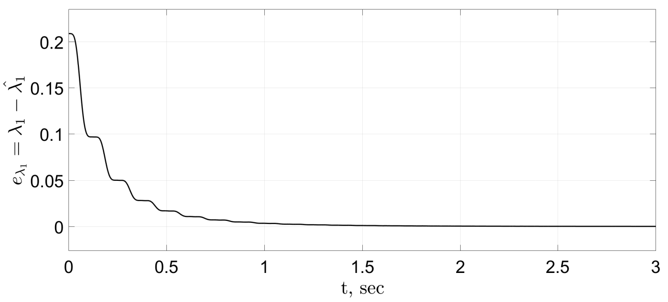

Fig. 5. Convergence of estimation error $e_{\lambda_1} = \lambda_1 - \hat{\lambda}_1$ for $\gamma = 100$

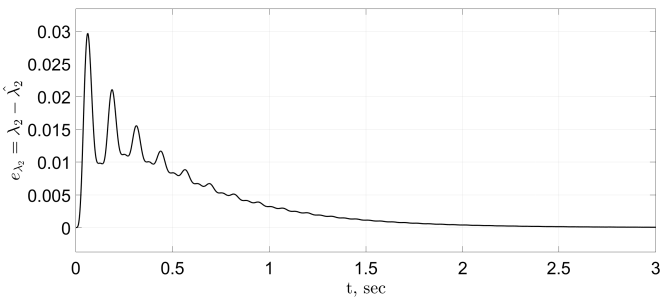

Fig. 6. Convergence of estimation error $e_{\lambda_2} = \lambda_2 - \hat{\lambda}_2$ for $\gamma = 100$

5. CONCLUSION

In this paper we propose a stator flux observer. The problem of flux estimation is transformed into the identification problem via implementation of LTI filters and linear regression. A similar method is used for load torque estimation.

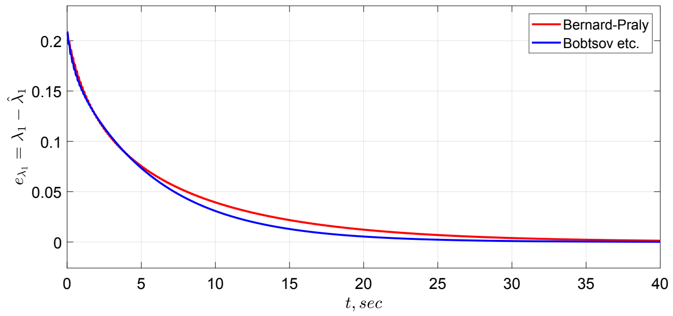

Fig. 7. Convergence of estimation error $e_{\lambda_2} = \lambda_2 - \hat{\lambda}_2$ for $\gamma = 8$ and $q = 10$

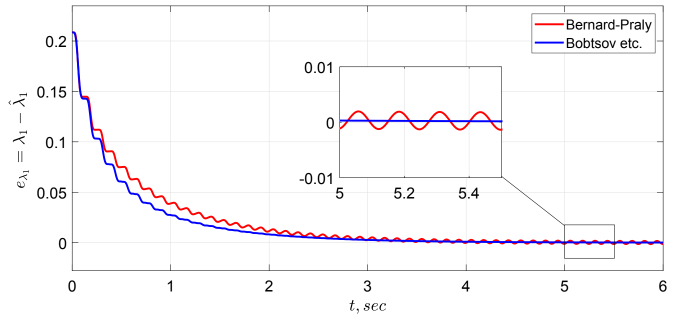

Fig. 8. Convergence of estimation error $e_{\lambda_2} = \lambda_2 - \hat{\lambda}_2$ for $\gamma = 80$ and $q = 100$

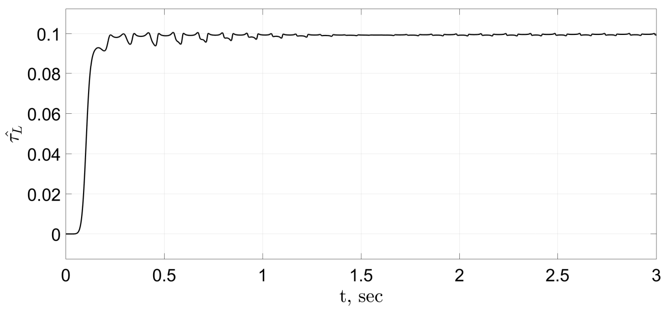

Fig. 9. Load torque estimate $\hat{\tau}_L$ for $\tau_L = 0,1$

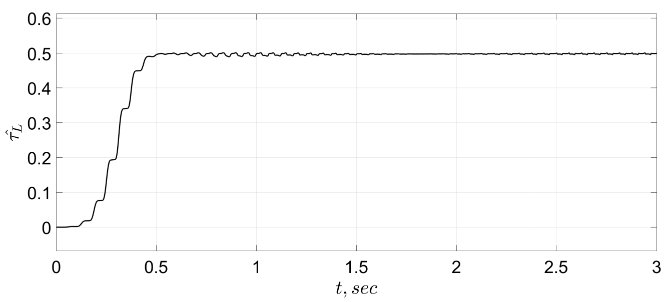

Fig. 10. Load torque estimate $\hat{\tau}_L$ for $\tau_L = 0,5$

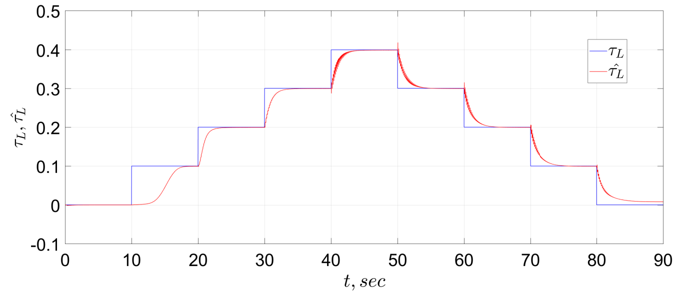

Fig. 11. Load torque estimate $\hat{\tau}_L$ for step load torque

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