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Research on PMSM Active Disturbance Rejection Controller Based on Model Compensation

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Abstract — In the permanent magnetic synchronous motor (PMSM) system with active disturbance rejection controller (ADRC), the estimation accuracy of extended state observer (ESO) will decrease when the ADRC does not depend on the system model completely. In order to improve the estimation accuracy, this paper proposes an improved ADRC approach by adding a model compensation term. Furthermore, the rotor inertia and viscous friction coefficient in the model compensation term is identified by the model reference adaptive identification (MRAI) algorithm. The load torque is estimated according to the mechanical equation of PMSM system. Then the identification values of rotor inertia, viscous friction coefficient, and load torque make up the compensation term of the ESO. Simulation results indicate that this improved ADRC approach has the better parameter robustness and anti-load-disturbance performance.

I. Introduction

With the development of science and technology, servo control technology of alternating current (AC) motor has made remarkable progress. PMSM, as a special AC motor, has been widely used in the industrial fields due to its outstanding advantage of rugged construction, easy maintenance, high efficiency, and high torque to current ratio.

However, PMSM is a typical nonlinear, strong coupling, time-varying parameter system, while its system performance is sensitive to the unknown load torque and friction. To solve the above-mentioned problems, many literatures have been reported about the control approach to improve the system performance, such as fuzzy control, sliding mode control, robust control, and adaptive control.

In recent years, ADRC has been more and more applied to PMSM system due to its advantages of simple algorithm, good parameter adaptability, and well robustness to the system disturbance [1-3]. However, it will decrease the ESO estimation accuracy that the ADRC does not depend on the system model completely. Also, this will decrease the anti-load-disturbance performance of the ADRC. The literature [2] puts forward the thought of introducing the known model into ESO, which improves the ESO estimation accuracy. The literature [3] presents an improved ADRC with the uncertainty compensation in the mechanical equation, which has an excellent robustness to viscous friction torque disturbance. But this method doesn't take the unknown load torque into account.

Also, the ADRC control performance can be improved by compensating the ESO estimation error via the use of online identification to the system mechanical parameters, such as torque, rotor inertia and viscous friction coefficient. The literatures [4-5] adopt the parameter estimation method based on Kalman filter to compensate the ESO estimation error, which is able to realize the online identification to rotor inertia. This approach has fast convergence speed, but it does not have global asymptotic stability. The literatures [6-8] use the identification method based on disturbance observer to improve the ESO estimation accuracy. This approach can estimate rotor inertia through the estimated external load torque and viscous friction. But this approach is difficult to be achieved in the practical engineering, due to its complexity. The literature [9] uses Landau discrete time recursive parameter identification mechanism to identify rotor inertia to improve the ESO estimation accuracy. The literature [10] adopts MRAI method to estimate the rotor inertia to improve the ESO estimation accuracy. However, the above-mentioned two approaches both ignore the effect of viscous friction. The literature [11] proposes identification method based on MIT adaptive law to compensate the ESO estimation error, which is simple, easy to implement. But the stability of the closed-loop system cannot be guaranteed.

This paper proposes a novel ADRC based on model compensation (ADRCMC) for PMSM system to improve the ESO compensation accuracy. The compensation term of the ESO is composed of the identification values of rotor inertia, viscous friction coefficient, and load torque. The rotor inertia and viscous friction coefficient are identified via the use of the MRAI method, while the load torque is estimated according to the mechanical equation of PMSM system. Furthermore, the simulation and the experiment are conducted to verify the validity of the proposed ADRCMC. The simulation and experimental results show that this algorithm has the better parameter robustness and anti-load-disturbance performance.

II. Mathematical model of PMSM

The mathematical model of the surface-mounted PMSM can be described in the synchronously rotating reference frame (d-q) as follows:

$$\begin{bmatrix} \frac{di_{\mathrm{d}}}{dt} \\ \frac{di_{\mathrm{q}}}{dt} \\ \frac{d\omega}{dt} \end{bmatrix} = \begin{bmatrix} -RL^{-1} & p\omega & 0 \\ -p\omega & -RL^{-1} & -p\psi_{\mathrm{f}}L^{-1} \\ 0 & p\psi_{\mathrm{f}}J^{-1} & -BJ^{-1} \end{bmatrix} \begin{bmatrix} i_{\mathrm{d}} \\ i_{\mathrm{q}} \\ \omega \end{bmatrix} + \begin{bmatrix} u_{\mathrm{d}}L^{-1} \\ u_{\mathrm{q}}L^{-1} \\ -T_{\mathrm{L}}J^{-1} \end{bmatrix} \tag{1}$$

where i_{d}, i_{q}, u_{d}, u_{q}, R, L denote stator voltages, stator currents, stator resistance, stator inductance in the frame of d-q, respectively. Here ω is rotor angular velocity, p is the number of the pole pairs, ψ_{f} is the magnitude of the permanent

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magnet flux linkage, B is friction coefficient, J is Rotor inertia, and T_L is load torque.

III. THE DESIGN OF ADRCMC

In this paper, we adopt the dual closed-loop structure for the PMSM system, including speed loop and current loop. The speed loop adopts the improved ADRC algorithm based on the model compensation, and the current loop adopts proportional integral (PI) control algorithm. Figure 1 shows the vector control system of PMSM based on the ADRCMC proposed in this paper.

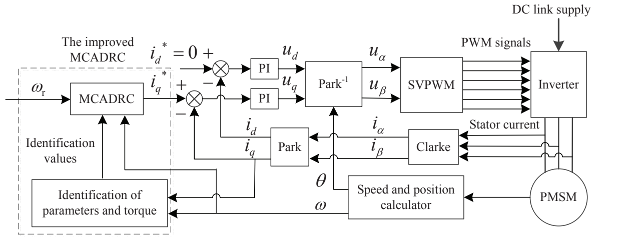

Figure 1 The ADRCMC control system structure diagram of PMSM

Next, we will present the improved ADRC in detail, which consists of three components, a tracking differentiator (TD), an extended state observer (ESO) and a nonlinear state error feedback (NLSEF).

A. Tracking differentiator (TD)

In motor control systems, the differential signal is usually obtained by backward difference of the given signal. Unavoidably, it will contain a certain amount of stochastic noise. TD can solve the problem of differential signal extraction via integration. Generally a second-order TD takes the following form:

$$\begin{cases} \dot{\omega}_1 = \omega_2 \\ \dot{\omega}_2 = -1.76 r \omega_2 - r^2 \left(\omega_1 - \omega_r \right) \end{cases} \tag{2}$$

where ω_r is the input signal, ω_1 is the tracking signal of ω_r, ω_2 is the differential signal of ω_1, and r is the speed factor.

B. Extended state observer (ESO)

The ESO can be constructed as

$$\begin{cases} \dot{z}_1 = z_2 - \beta_{01}\left(z_1 - \omega\right) - \hat{B}\hat{J}^{-1}\omega - \hat{T}_L \hat{J}^{-1} + p\psi_f \hat{J}^{-1} u \\ \dot{z}_2 = -\beta_{02}\left(z_1 - \omega\right) \end{cases} \tag{3}$$

where ω is the system output. Here z_1 is the track signal of ω, z_2 is disturbance of the tracking signal of the system, β_{01} and β_{02} are output error correction gains, and u is the reference q-axis current. Here $\hat{B}$, $\hat{J}$, $\hat{T}_L$ are the estimated values of viscous friction coefficient, rotor inertia, load torque, respectively, which will be estimated in next section. Furthermore, the term $-\hat{B}\hat{J}^{-1}\omega - \hat{T}_L\hat{J}^{-1}$ is the model compensation part for the ESO. When z_1 tracks ω accurately, disturbance that ESO needs to estimate is as follows:

$$z_2 = \left(\hat{B}\hat{J}^{-1} - BJ^{-1}\right)\omega + \hat{T}_L \hat{J}^{-1} - T_L J^{-1} + \left(p\psi_f J^{-1} - p\psi_f \hat{J}^{-1}\right)u + f_1(\omega, t) \tag{4}$$

where $f_1(\omega, t)$ is the unknown disturbance. From (4), when $\hat{B}$, $\hat{J}$, $\hat{T}_L$ separately converges to their true values, the disturbance needing z_2 to estimate is only the unknown disturbance $f_1(\omega, t)$. Compared with the traditional ESO which must estimate all the disturbances, the estimation error amplitude is reduced in the ESO based on the model compensation. Thus the estimation accuracy of ESO is improved.

C. Nonlinear state error feedback (NLSEF)

The NLSEF law can be expressed as

$$\begin{cases} e_0 = \int e_1 dt \\ e_1 = \omega_1 - z_1 \\ u_0 = \beta_0 fal\left(e_0, \ \alpha_0, \ \sigma_0\right) + \beta_1 fal\left(e_1, \ \alpha_1, \ \sigma_1\right) \\ u = u_0 - \left(z_2 - \hat{B}\hat{J}^{-1}\omega - \hat{T}_L \hat{J}^{-1}\right) / \left(p\psi_f \hat{J}^{-1}\right) \end{cases} \tag{5}$$

where e_0 is error signal, and e_1 is error integer. Here β_0 and β_1 are gains of output error, and $fal(i)$ is the optimal integrated control function, which is expressed as

$$fal\left(e, \ a, \ \sigma\right) = \begin{cases} |e|^{\alpha} \operatorname{sgn}(e), |e| > \sigma \\ e / \sigma^{1-\alpha}, |e| < \sigma \end{cases}, \quad \sigma > 0. \tag{6}$$

Above all, the structure of speed ADRCMC can be shown in Figure 2.

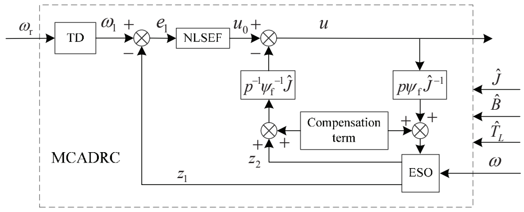

Figure 2 The structure of the ADRCMC

IV. THE IDENTIFICATION OF FRICTION COEFFICIENT, ROTOR INERTIA AND LOAD TORQUE

In order to increase estimation accuracy of ESO, the model compensation part of ADRC need to be calculated accurately, which needs include accurate identification values of friction coefficient, rotor inertia and load torque. In the following, we will firstly identify the values of friction coefficient and rotor inertia.

From (1), we define

$$\begin{cases} \theta_1 = \psi_f J^{-1} \\ \theta_2 = -BJ^{-1} \\ \theta_3 = -J^{-1} \end{cases}. \tag{7}$$

Differentiating to (1), we have

$$\ddot{\omega} = \theta_1 p \dot{i}_q + \theta_2 \dot{\omega} + \theta_3 \dot{T}_L. \tag{8}$$

According to (8), the observation model of PMSM can be designed as

$$\ddot{\hat{\omega}} = \hat{\theta}_1 p \dot{i}_q + \hat{\theta}_2 \dot{\omega} + \hat{\theta}_3 \dot{T}_L + k_1\left(\dot{\omega} - \dot{\hat{\omega}}\right) \tag{9}$$

where the positive constant k_1 is coefficient of negative feedback, which determines the speed of the state error convergence. Here $\hat{\theta}_1$, $\hat{\theta}_2$, $\hat{\theta}_3$ are identification values of parameter respectively, and θ_1, θ_2, θ_3 are real value of parameters respectively. The positive definite matrix of state variables in the Lyapunov function would be difficult to be confirmed if θ_1 is unknown in the motor model. Thus the error feedback is introduced in the state observation model, which can ensure the convergence of system state error.

Here, the state observation error is defined as

$$e = \dot{\omega} - \dot{\hat{\omega}}. \tag{10}$$

The parameter observation error is defined as

$$e_\theta = \begin{bmatrix} e_{\theta_1} \\ e_{\theta_2} \\ e_{\theta_3} \end{bmatrix} = \begin{bmatrix} \theta_1 - \hat{\theta}_1 \\ \theta_2 - \hat{\theta}_2 \\ \theta_3 - \hat{\theta}_3 \end{bmatrix}. \tag{11}$$

Subtracting (8) from (9), we get the equation of state observation error as

$$\dot{e} = -k_1 e + e_{\theta_1} p \dot{i}_{\mathrm{q}} + e_{\theta_2} \dot{\omega} + e_{\theta_3} \dot{T}_{\mathrm{L}}. \tag{12}$$

When identification values can accurately estimate real values, estimation value of acceleration converges to the true value. According to the state observation error equation and adaptive theory, Lyapunov function is designed as

$$V = \frac{e^2}{2} + \frac{\left(\theta_1 - \hat{\theta}_1\right)^2}{2g_1} + \frac{\left(\theta_2 - \hat{\theta}_2\right)^2}{2g_2} + \frac{\left(\theta_3 - \hat{\theta}_3\right)^2}{2g_3} \tag{13}$$

where g_1, g_2, g_3 are positive constant. Differentiating both sides of (13) derives

$$\dot{V} = -k_1 e^2 - \frac{e_{\theta_1}\left(\dot{\hat{\theta}}_1 - g_1 p \dot{i}_{\mathrm{q}} e_{\dot{\omega}}\right)}{g_1} - \frac{e_{\theta_2}\left(\dot{\hat{\theta}}_2 - g_2 \dot{\omega} e_{\dot{\omega}}\right)}{g_2} - \frac{e_{\theta_3}\left(\dot{\hat{\theta}}_3 - g_3 \dot{T}_{\mathrm{L}} e_{\dot{\omega}}\right)}{g_3}. \tag{14}$$

According to (14), we take the parameter adjustment rules as

$$\begin{cases} \dot{\hat{\theta}}_1 = g_1 p \dot{i}_{\mathrm{q}} e \\ \dot{\hat{\theta}}_2 = g_2 \dot{\omega} e \\ \dot{\hat{\theta}}_3 = g_3 \dot{T}_{\mathrm{L}} e \end{cases}, \tag{15}$$

then $\dot{\mathrm{V}} \leq 0$. According to the theory of Lyapunov, e, e_{θ_1}, e_{θ_2}, e_{θ_3} are bounded. Differentiating both sides of (14) derives

$$\ddot{V} = 2k_1^2 e^2 - 2k_1 e e_{\theta_1} p \dot{i}_{\mathrm{q}} - 2k_1 e e_{\theta_2} \dot{\omega} - 2k_1 e e_{\theta_3} \dot{T}_{\mathrm{L}}. \tag{16}$$

Because input and output of actual motor system are bounded, $\ddot{V}$ is bounded. Thus $\dot{V}$ is uniformly continuous. According to Barbalat lemma, the balance point $e = 0$ has asymptotic stability, which means state observation error converges to zero over time. Because the control signal contains rich harmonics in servo motor system, sufficient motivate condition would be satisfied. Thus the balance point $e_\theta = 0$ has asymptotic stability, which means parameter observation error converges to zero over time.

Next, we will identify the value of load torque of the PMSM system. The discrete form of (12) can be described as:

$$\begin{aligned} \hat{\omega}(k) = {} & (2 - k_2 T)\hat{\omega}(k-1) + (k_2 T - 1)\hat{\omega}(k-2) + Tp\hat{\theta}_1(k-1)\left[i_{\mathrm{q}}(k-1) - i_{\mathrm{q}}(k-2)\right] \\ & + T\left[\hat{\theta}_2(k-1) + k_2\right]\left[\omega(k-1) - \omega(k-2)\right] + T\hat{\theta}_3(k-1)\left[T_{\mathrm{L}}(k-1) - T_{\mathrm{L}}(k-2)\right] \end{aligned} \tag{17}$$

where T is the sampling period. The load torque in (12) is assumed to change slowly, i.e. $T_{\mathrm{L}}(k-1) = T_{\mathrm{L}}(k-2)$. As a result, the (15) and (17) can be rewritten as

$$\begin{cases} \dot{\hat{\theta}}_1 = g_1 p \dot{i}_{\mathrm{q}} e \\ \dot{\hat{\theta}}_2 = g_2 \dot{\omega} e \end{cases} \tag{18}$$

and

$$\begin{aligned} \hat{\omega}(k) = {} & (2 - k_2 T)\hat{\omega}(k-1) + (k_2 T - 1)\hat{\omega}(k-2) + Tp\hat{\theta}_1(k-1)\left[i_{\mathrm{q}}(k-1) - i_{\mathrm{q}}(k-2)\right] \\ & + T\left[\hat{\theta}_2(k-1) + k_2\right]\left[\omega(k-1) - \omega(k-2)\right]. \end{aligned} \tag{19}$$

The values of $\hat{\theta}_1$ and $\hat{\theta}_2$ can be achieved by solving (18) and (19). According to (7), the identification values of rotor inertia and friction coefficient can be written as

$$\begin{cases} \hat{J} = \hat{\theta}_1^{-1} \psi_{\mathrm{f}} \\ \hat{B} = -\hat{\theta}_1^{-1} \hat{\theta}_2 \psi_{\mathrm{f}} \end{cases}. \tag{20}$$

According to (1), the load torque is estimated as

$$\hat{T}_{\mathrm{L}} = p\psi_{\mathrm{f}} i_{\mathrm{q}} - \hat{B}\omega - \hat{J}\frac{d\omega}{dt}. \tag{21}$$

V. Simulation Analysis

To validate the effectiveness of ADRCMC in this paper, the simulation of the PMSM system has been conducted based on the software MATLAB.

The parameters of the PMSM used in the simulation as follows: $R = 0.19\,\Omega$, $L = 0.25\,\mathrm{mH}$, $p = 2$, $\psi_{\mathrm{f}} = 0.8\,\mathrm{Wb}$, $B = 0.002\,\mathrm{N \cdot m \cdot s}$, $J = 0.01\,\mathrm{kg \cdot m^2}$.

Figure 3 shows the speed response of the PMSM system with a load torque steps from $T_{\mathrm{L}} = 0\,\mathrm{N \cdot m}$ to $T_{\mathrm{L}} = 0.1\,\mathrm{N \cdot m}$. Note that in the figures, method 1 is the traditional ADRC algorithm, and method 2 is the ADRCMC. The max speed fluctuation of the system with method 1 is 3 rpm, while that of method 2 is 0.5 rpm. Compared with the method 1, the system with the method 2 has a smaller speed fluctuation when the load torque changes suddenly. Therefore, the system with the method 2 has better anti-load-disturbance performance.

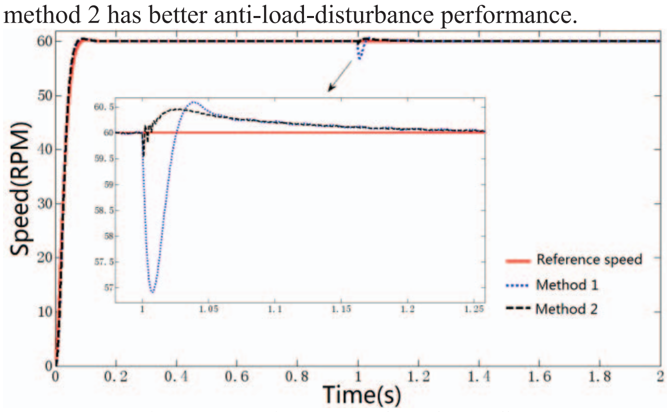

Figure 3 Dynamic response of speed controller

Figures 4-6 show the simulation waveforms of parameter identification for the system with the method 2. The red lines are the true values of each parameter in the graphs. Note that the identification values of the system parameters will deviate from the true values when the load torque changes suddenly. However, they can still converge to their true values over time with the method 2. Furthermore, as shown in Figure 6, compared with the method 1, the system with the method 2 has better rapidity to estimate the external load disturbances.

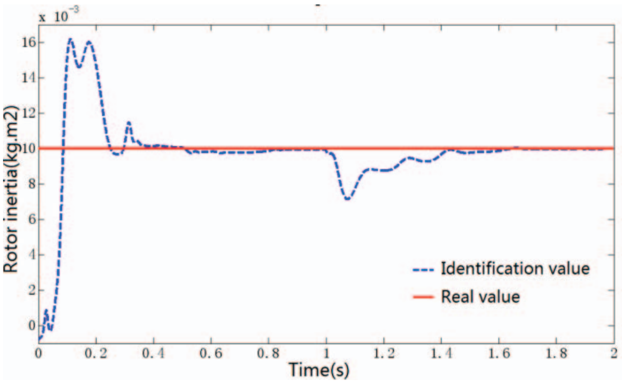

Figure 4 Dynamic identification of rotor inertia

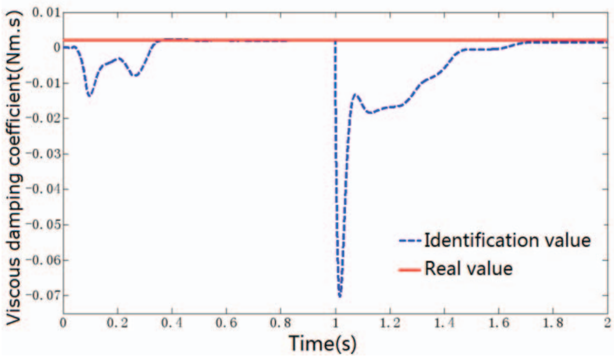

Figure 5 Dynamic identification of friction coefficient

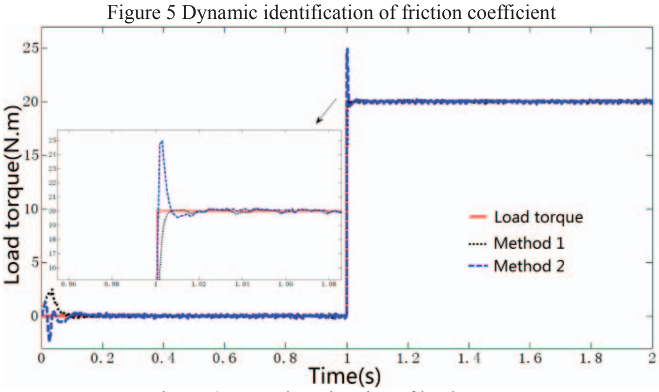

Figure 6 Dynamic estimation of load torque

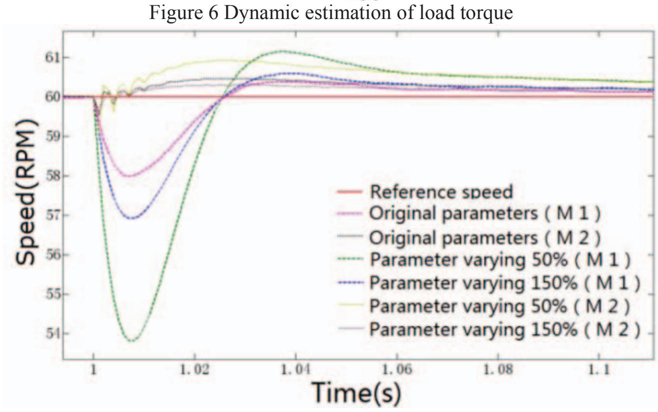

Figure 7 Dynamic response of speed controller

Figure 7 shows the speed response with load torque steps for the PMSM system with the parameter variation. Here we take two parameter variation conditions for examples. One is that both the rotor inertia J and friction coefficient B decrease by 50%, while the other is that both the rotor inertia J and friction coefficient B increase by 50%. As shown in Figure 7, the speed fluctuation of the system with method 2 is 0.9 rpm, while that of the method 1 is 6.3 rpm. As a result, the system with the method 2 has better parameter robustness.

VI. Conclusion

This paper proposes an improved ADRCMC for PMSM system to improve the ESO compensation accuracy. The MRAI method is adopted to identify rotor inertia and viscous friction coefficient, which increases the estimation accuracy of disturbance in PMSM system. The load torque is estimated according to the mechanical equation of PMSM system. The identification values of rotor inertia, viscous friction coefficient, and load torque make up the compensation term of the ESO. Compared with the traditional ADRC, simulation results indicate that this approach has better parameter robustness and anti-load-disturbance performance.

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