Electrical line-shafting control for permanent magnet synchronous motors using active disturbance rejection control

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Abstract. This study presents an electronic line-shafting (ELS) control strategy based on Active Disturbance Rejection Controller (ADRC) for permanent magnet synchronous motor systems. In order to improve the speed synchronization accuracy of the system when startup and a disturbance occurs, the TD of ADRC is used to arrange the same transition process for each drive unit. In addition, the ESO (Extended State Observer) in ADRC is used to observe the load disturbance of each drive unit and give feedback to the virtual line-shafting, thus the system obtained high speed synchronization. Effectiveness of the proposed ELS control scheme is verified by experiment results.

1. Introduction

In paper making, printer, steel rolling, robots and other industrial fields[1], multi-motor synchronous control technology is essential. Synchronization in traditional multi-motor system is mainly realized by mechanical shaft and gear transmission. With the development of science and technology, the traditional mechanical synchronous method was replaced by the electronic synchronous method rapidly.

The electronic synchronous method can be divided into non-coupling control structures and coupling control structures according to its control structure. The non-coupling control structures includes parallel control and master-slave control. The coupling control structures includes cross-coupling control, adjacent cross-coupling control and ELS control. ELS control was first proposed by Lorenz and Schmidt[2], and then Kevin summarized it and formally proposed ELS control[3]. Studies show that the system using conventional ELS control can obtain better synchronization accuracy in steady state, but the synchronization accuracy of the system will deteriorate due to the parameter differences between the motors and controllers of each drive unit during the start and stop of multi-motor system[4]. In addition, due to the existence of calculation delay, the load feedback by each drive unit to the virtual line-shaft is not accurate when load disturbance occurs, which is also detrimental to the synchronization of the multi-motor system. Therefore, this paper adopts the ADRC control method, Using the TD part of ADRC to arrange the same start and stop process for each drive unit in the multi-motor system, thus to improve the synchronization accuracy of the system in the start and stop process. In addition, the real-time load
torque observed by ESO in ADRC is fed back to the virtual line-shaft to improve the synchronization accuracy of the system when load disturbance occurs.

The remainder of this paper is organized as follows. In Section 2, the traditional virtual line-shaft control is described, the mathematical model of PMSM is obtained, and the virtual line-shaft control based on ADRC is designed. Experimental results are presented in Section 3. Finally, conclusions are drawn in Section 4.

2. ELS control based on ADRC

The ELS control structure is shown in Fig 1. In the conventional ELS control, virtual line-shaft and the current and speed of PMSM are controlled by PI controller. The ELS control combines parallel control and cross-coupling control. What’s the difference from parallel control is that the sum of the load torque of each drive unit is fed back to virtual line-shaft in the ELS control. It is the feedback of load torque that forms the coupling between each drive unit, thus eliminating the speed synchronization error between each drive unit. When load disturbance of a drive unit occurs, the speed of the drive unit will decrease, and the load torque feedback back to virtual line-shaft will increase, which make the speed of the virtual line-shaft reduce gradually. Then the speed of other drive units will decreases gradually. Thus, the speed of all the drive units in the multi-motor system will be synchronized. Fig 2 shows the ELS control based on ADRC.

![Figure 1. Block diagram of conventional ELS control.](image.png)

The ADRC-based ELS multi-motor control system proposed in this paper is shown in the figure. As can be seen from the figure, ADRC controller is used for both virtual spindle and PMSM, and PI controller is used for current loop of PMSM.

2.1. PMSM Mathematical Model

Owing to high power density and efficiency, PMSMs have been employed as servo motors in many high-dynamic and high-precision applications. Each drive unit in Fig 2 involves the same structure and algorithm. In this section, the ith drive unit will be modeled.

The mathematical Model of ith PMSM under rotational d-q reference frame can be expressed as:

$$
\begin{align*}
\frac{du_d}{dt} &= R_d i_d - \omega_L L_{dq} i_q + L_{dq} \frac{di_d}{dt} \\
\frac{du_q}{dt} &= R_q i_q + \omega_L L_{dq} i_d + L_{dq} \frac{di_q}{dt}
\end{align*}
$$

(1)

Where $d/dt$ is the derivative operator; $u_d, u_q$ are the voltage for d-axis and q-axis, respectively; $i_d, i_q$ are the current for d-axis and q-axis, respectively; $L_{dq}, L_{dq}$ are the inductances of d-axis and q-axis,
respectively; $R_s$ is the stator-winding resistance; $\psi_b$ is the flux linkage of permanent magnets; $\omega_{ei}$ is the electrical rotor speed.

The electromagnetic torque generated by PMSM can be expressed as:

$$T_{ei} = \frac{3}{2} p_n \psi_b i_{qi}$$  \hspace{1cm} (2)

Where $p_n$ is the number of poles of PMSM; $T_{ei}$ is the electromagnetic torque of the PMSM.

The electromechanical dynamic equation can be expressed as:

$$J_i \frac{d\omega_{ri}}{dt} = T_{ei} - T_{Li} - \beta_i \omega_{ri}$$  \hspace{1cm} (3)

Where, $J_i$ is the rotor moment of inertia; $\omega_{ri}$ is the mechanical rotor speed; $\beta_i$ is the friction coefficient; $T_{Li}$ is the load torque.

2.2. ADRC Controller Design

For the convenience of controller design, Equation (3) is transformed into the following form:

$$\dot{\omega}_i = \frac{1}{J_i} (1.5 p_n \psi_b i_{qi} - T_{Li} - \beta_i \omega_{ri}) = K_i i_{qi} + a(t)$$

$$K = \frac{1.5 p_n \psi_b}{J_i}$$

$$a(t) = -\frac{1}{J_i} (T_{Li} + \beta_i \omega_{ri})$$  \hspace{1cm} (4)

Make $a(t)$ as the disturbance of system. The design of ADRC controller includes four steps: arranging the transition process, expanding state observer, state error feedback control law and disturbance compensation.

Substituting $\omega_{ri}^*$ to standard TD equation[5] can obtain the TD of PMSM speed ADRC controller as:
\[
\begin{align*}
  fh &= fhan(v_1(t) - \omega^*_n, v_2(t), r_0, h) \\
  v_1(t+h) &= v_1(t) + h \cdot v_2(t) \\
  v_2(t+h) &= v_2(t) + h \cdot fh
\end{align*}
\]

\[
\begin{align*}
  d &= rh^2, a_0 = hx^*_n, y = x_1 + a_0 \\
  a_1 &= \sqrt{d(d + 8|y|)} \\
  a_2 &= a_0 + \text{sign}(y)(a_1 - d)/2 \\
  s_y &= (\text{sign}(y + d) - \text{sign}(y - d))/2 \\
  a &= (a_0 + y - a_2)s_y + a_2 \\
  s_a &= (\text{sign}(a + d) - \text{sign}(a - d))/2 \\
  fhan &= -r(a/d - \text{sign}(a))s_a - r\text{sign}(a)
\end{align*}
\]

Where \(v_1(t)\) is the observed value of \(\omega^*_n\); \(v_2(t)\) is the derivative of \(\omega^*_n\).

The ESO of PMSM speed ADRC controller can be defined as:

\[
\begin{align*}
  e(t) &= z_1(t) - \omega^*_n \\
  z_1(t+h) &= z_1(t) + h \cdot (z_1(t) - \beta e(t) + Ki_e) \\
  z_2(t+h) &= z_2(t) - h \cdot \beta_2 \cdot \text{fal}(e(t))
\end{align*}
\]

\[
\text{fal}(e, \alpha, \delta) = \begin{cases} 
  \frac{e}{\delta^{1-\alpha}} & |e| \leq \delta \\
  \text{sign}(e)|e|^{\alpha} & |e| > \delta
\end{cases}
\]

Where \(e(t)\) is the error between the real speed and observe speed; \(z_1\) is the observe speed; \(z_2\) is the observe value of \(a(t)\).

The error feedback control law can be defined as:

\[
u_0(t) = K_p(v_1(t) - z_1(t))
\]

Where \(K_p\) is the gain of gain.

Then we can compensate the disturbance and obtain the control value as:

\[
u(t) = u_0(t) - \frac{z_2(t)}{K}
\]

3. Experimental results

Fig 3. shows a photograph of the experimental setup. The experimental setup consists of two PMSM drivers, two PMSMs and an EtherCAT master. The EtherCAT master is a desktop computer running Windows7 and TwinCAT3. The Two PMSM drivers is implemented on XMC4800 produced by Infineon, which includes an ESC(EtherCAT Slave Controller). The two PMSMs’ parameters is same, while their specifications are listed in Table 1.

To verified the effectiveness of the proposed ADRC-ELS control strategy. Comparison experiments between conventional ELS control and ADRC-ELS control have been carried out. The two PMSMs used
Table 1. Parameters of PMSMs.

| Parameter                     | Value | Parameter                     | Value |
|-------------------------------|-------|-------------------------------|-------|
| Rate Voltage (V)              | 220   | Rate Current (A)              | 1.9   |
| Rate Speed (rpm/min)          | 3000  | Rate Torque (N-m)             | 0.64  |
| Phase Resistance (Ω)          | 1.99  | Phase Inductance (mH)         | 4.37  |
| Rotor Flux Linkage (Wb)       | 0.0377| Rotor Inertia (kg-m²)         | 0.819e-4 |
| Rate Power (W)                | 200   | Position Sensor               | 17bit bus encoder |

The same control parameters. Reference speed of the system is set as \( \omega_{\text{ref}} = 262 \text{rad/s} \). The two PMSMs start without load under virtual-line shaft control and then stop after a while. Next, Reference speed of the system is set as \( \omega_{\text{ref}} = 262 \text{rad/s} \). The two PMSMs start without load under virtual line-shaft control. After \( \omega_{r1} \) and \( \omega_{r2} \) reached the reference speed, a random load torque was applied to PMSM1. Fig 4 shows the experimental results.

Figure 4. Experimental results of a dual motor system. (a) Speed of two PMSMs when system startup under ELS control. (b) Speed of two PMSMs when system startup under ADRC-ELS control. (c) Zoom in of (a). (d) Zoom in of (b). (e) Speed of two PMSMs when a random load torque is applied to PMSM1 under ELS control. (f) Speed of two PMSMs when a random load torque is applied to PMSM1 under...
ADRC-ELS control.

Fig 4a, Fig 4c and Fig 4e shows the speed tracking performance of the conventional ELS control scheme. Because speed PI controller are adopted in conventional ELS control scheme, it is difficult to obtain same startup process for the two PMSM. So error and overshoot between two PMSMs exists when they startup under the control of virtual line-shaft. When random load torque was applied to PMSM1, PMSM2 tend to catch up with PMSM1. But the tracking performance is poor.

Fig 4b, Fig 4d and Fig 4f shows the speed tracking performance of the ADRC-ELS control scheme. Because speed ADRC controller are adopted in ADRC-ELS control scheme, utilize the TD part of ADRC to plan same startup process for the two PMSM. So error and overshoot between two PMSMs didn’t exists when they startup under the control of virtual line-shaft. When random load torque was applied to PMSM1, PMSM2 can catch up with PMSM1. The tracking performance is better than conventional ELS control scheme.

4. Conclusions
In the multi-motor system based on conventional ELS control, because of the difference between the motors and the controllers, the synchronization accuracy of the multi-motor system becomes worse in the startup process. In addition, the load torque calculation of each drive unit used for feedback is delayed, which also causes the speed synchronization accuracy of the multi-motor system to deteriorate. Therefore, an new ELS control based on ADRC is proposed in this paper. TD in ADRC is used to make each drive unit in the system obtain the same startup process, which improves the speed synchronization accuracy between each drive unit when system startup. In addition, the torque obtained by ESO real-time observation is feedforward to enhance the anti-disturbance performance of each drive unit. On the other hand, it is used as the load torque feedback to virtual line-shaft, which improves the synchronization accuracy of the multi-motor system when the load disturbance occurs. By using ADRC control strategy, the multi-motor control system based on ADRC-ELS can obtain better synchronization accuracy.

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