Research on speed regulation system for matrix converter fed induction motor

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Received 1 June 2014, www.tsi.lv

Abstract

This study presents the application of a Matrix Converter (MC) and an active disturbance rejection controller (ADRC) to Direct Torque Control (DTC) system based on an induction motor. Matrix Converter (MC) is applied to Direct Torque Control (DTC) system based on an induction motor in order to reduce power grid harmonic pollution which is caused by AC-DC-AC converter in conventional DTC system. Then a PID controller and an ADR controller are both designed to regulate the speed of the system. Design procedures for ADRC are given in detail. Finally, corresponding results are compared. The simulation results show that the novel DTC system has combined the advantages of both MC and DTC--stable running, strong anti-jamming, good dynamic and static performance.

Keywords: DTC, MC, ADR controller, space vector, PI controller

1 Introduction

Direct Torque Control (DTC) has obtained widespread concern of scholars and has developed rapidly because of the simple control method and the fast system response. Generally, DTC method is used to AC-DC-AC converter, in which DC link not only increases system burden and reduces power factor, but also brings power grid harmonic pollution problem. For these problems, many improved methods have been proposed. An alternative method to reduce torque ripples based on space vector modulation (SVM) technique was proposed [1]. An adaptive DTC control for induction motor drive with a fixed switching frequency and a low torque ripple was reported [2]. A fuzzy logic controller was used to select voltage vector in a conventional DTC system [3]. A fuzzy adaptive controller was used to reduce torque ripple [4]. The principle of variable structure was used in DTC system for IPM Synchronous Motor [6]. A novel control method for DTC based on SVPWM was applied by using all voltage vectors of inverter to give a constant torque switching frequency and reduce torque ripple [7]. A high-performance direct torque control of an induction motor was proposed [8].

The use of matrix converter (MC) to DTC system for induction motor was introduced [5]. It has obtained rapid development; some improved methods were put forward. The induction motor's performance was improved because of these advanced methods, but speed regulator used PI controller in these systems. If the environment changes seriously when the system is activated, PI controller will not be able to adjust the system in real time, which leads to poor system performance. In this paper, ADRC is used to take place of PI controller, in order to obtain better system performance.

In this paper, we will use MC instead of AC-DC-AC converter. It is superior to conventional inverter because it does not have bulky dc-link capacitors and offers bidirectional power flow capacitors, sinusoidal input or output current, and an adjustable input power factor. Furthermore, because of high integration, MC topology is recommended for extreme temperatures and critical volume or weight applications [9]. The modulation for MC includes four methods: double space-vector pulse width modulation, switching function modulation, double line voltage modulation and output circuit hysteretic current. In this paper, double space-vector pulse width modulation is presented, because it has the capability to achieve full control of both output voltage vector and input current vector [10].

In this paper, the combination of DTC and MC has important theoretical significance and provides some engineering reference for frequency converter. Furthermore, Active Disturbance Rejection Control (ADRC) was used to the system, which was invented by Professor Jingqing Han who serves in Chinese Academy of Science. It is a new control method which doesn't depend on the system precision model. It can estimate and compensate the influences of all internal and external disturbances in real time when the system is activated. Combining with the special nonlinear feedback structure, it can realize good control quality, such as small overshoot, fast response and strong robustness.

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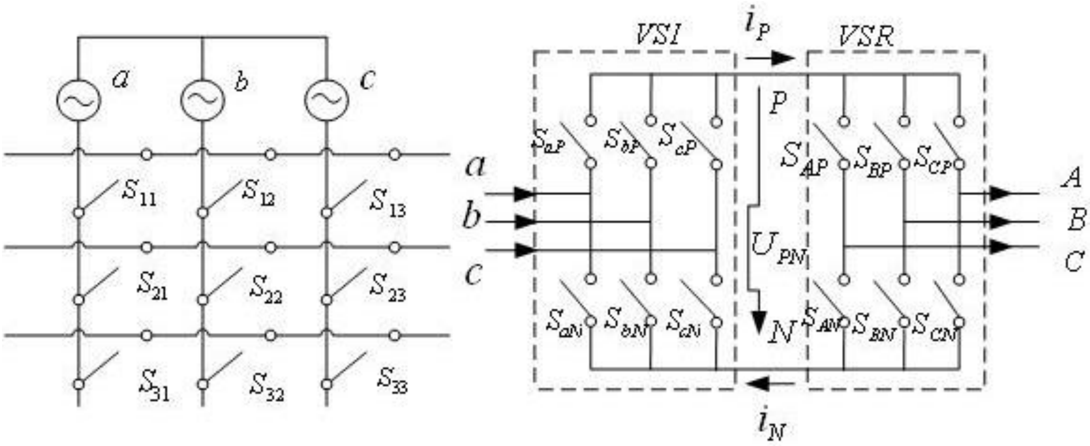

FIGURE 1 Matrix converter topology structure and equivalent AC-DC-AC structure

2 Modulation strategy of matrix converter

2.1 PRINCIPLE

Three phase MC topology is shown in Figure 1. Input phase voltage of MC is *Va*, *Vb*, *Vc* respectively, output line voltage is V_{AB}, V_{BC}, V_{CA} respectively, there is:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = V_{im} \begin{bmatrix} \cos(\omega_i t) \\ \cos(\omega_i t - 2\pi/3) \\ \cos(\omega_i t - 4\pi/3) \end{bmatrix}, \tag{1}$$

$$\begin{bmatrix} V_{AB} \\ V_{BC} \\ V_{CA} \end{bmatrix} = \sqrt{3} V_{om} \begin{bmatrix} \cos(\omega_o t - \phi_o + \pi/6) \\ \cos(\omega_o t - \phi_o + \pi/6 - 2\pi/3) \\ \cos(\omega_o t - \phi_o + \pi/6 - 4\pi/3) \end{bmatrix}. \tag{2}$$

There is a transfer matrix T of duty ratio, which makes:

$$\begin{vmatrix} V_{AB} \\ V_{BC} \\ V_{CA} \end{vmatrix} = T \begin{vmatrix} V_a \\ V_b \\ V_c \end{vmatrix}. \tag{3}$$

The matrix T can be written as follow:

$$T = m \begin{bmatrix} \cos(\omega_o t - \phi_o + \pi/6) \\ \cos(\omega_o t - \phi_o + \pi/6 - 2\pi/3) \\ \cos(\omega_o t - \phi_o + \pi/6 - 4\pi/3) \end{bmatrix} \begin{bmatrix} \cos(\omega_i t) \\ \cos(\omega_i t - 2\pi/3) \\ \cos(\omega_i t - 4\pi/3) \end{bmatrix}^T, \tag{4}$$

where *m* is modulation factor, $0 \le m \le 1$, ω_i is input power frequency, ω_o is output power frequency , ϕ_i is arbitrary power factor angle, and there is

$$U_{om} = \frac{\sqrt{3}}{2} U_{im} m \cos\phi_i. \tag{5}$$

So the MC input power factor can be any value, it can be positive, negative and even one. In actual operation, duty ratio transfer matrix T can be calculated according to modulation strategy in real time.

2.2 MODULATION STRATEGY OF MATRIX CONVERTER

Space vector modulation of matrix converter was put forward by L. Hubera and D. Borojevic in 1989. It is a kind of indirect modulation algorithm. The space vector modulation technology is being used to pre-virtual rectifier and rear virtual inverter. The sinusoidal wave with adjustable angular displacement can be obtained on the input side of MC, and fundamental voltage with adjustable amplitude, phase and frequency can be obtained on the output side of MC. Finally overall control is realized through combining the two parts, which is known as dual space vector method.

For inverter part, output voltage vector distribution and output voltage reference vector synthesis are shown in Figure 2. Output voltage vector is synthesized by two non-zero voltage vectors and one zero voltage vector, its expression is $V_{oL} = \frac{T_\alpha}{T_s} V_\alpha + \frac{T_\beta}{T_s} V_\beta + \frac{T_0}{T_s} V_0$, so duty ratio of effective vector V_α , V_β and zero vector V_0 can be calculated according to sine theorem and space vector modulation principle as follows [11]:

$$\begin{cases} d_\alpha = \frac{T_\alpha}{T_s} = m_u \sin(60^\circ - \theta_j) \\ d_\beta = \frac{T_\beta}{T_s} = m_u \sin\theta_j \\ d_0 = 1 - d_\alpha - d_\beta \end{cases}. \tag{6}$$

and $\theta_j = \theta_0 + k\omega_0 T_s$, $m_u = U_{im} / U_{dc}$, m_u is voltage modulation coefficient, T_s is switch cycle.

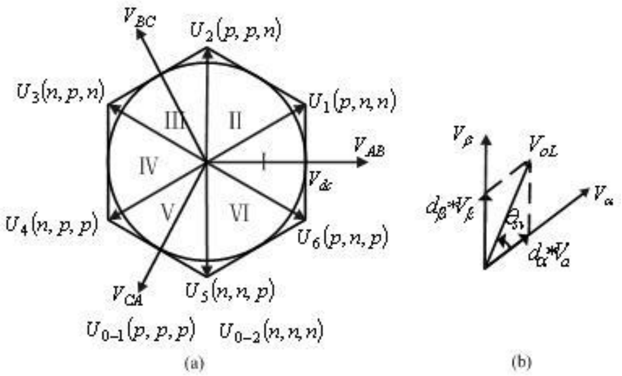

FIGURE2 Output voltage vector distribution and the reference vector synthesis

For rectifier part, its space vector modulation is similar to inverter part, input current vector is synthesized by two non-zero current vectors and one zero current vector, its expression is $I_i = \frac{T_\mu}{T_s} I_\mu + \frac{T_\nu}{T_s} I_\nu + \frac{T_0}{T_s} I_0$, so duty ratio of effective vector I_μ, I_ν and zero vector I_0 can be calculated according to sine theorem and space vector modulation principle as follows:

$$\begin{cases} d_\mu = \frac{T_\mu}{T_s} = m_c \sin\left(60^\circ - \theta_k\right) \\ d_\nu = \frac{T_\nu}{T_s} = m_c \sin\theta_k \\ d_0 = 1 - d_\mu - d_\nu \end{cases} \tag{7}$$

and $\theta_k = \theta_0 + k\omega_i T_s$, $m_c = I_{im} / I_{dc}$, m_c is current modulation coefficient, T_s is switch cycle.

AC-AC converter control law is gotten by synthesizing input current vector and output voltage vector. Four basic voltage and current vectors V_α, V_β, I_μ, I_ν, zero voltage vector and their action time are shown in Equations (8)-(12) then sent to the gate terminal of MC in the form of pulse signal, and modulate required amplitude and frequency.

In T_α time, duty ratio of switch state of two adjacent output voltage vectors are:

$$d_{\alpha\mu} = d_\mu d_\alpha = m \sin\left(60^\circ - \theta_k\right) \sin\left(60^\circ - \theta_j\right), \tag{8}$$

$$d_{\beta\mu} = d_\mu d_\beta = m \sin\left(60^\circ - \theta_k\right) \sin\theta_j \,. \tag{9}$$

In T_β time, duty ratios of switch state of two adjacent output voltage vectors are:

$$d_{\alpha\nu} = d_\nu d_\alpha = m \sin\theta_k \sin\left(60^\circ - \theta_j\right), \tag{10}$$

$$d_{\beta\nu} = d_\nu d_\beta = m \sin\theta_k \sin\theta_j \,. \tag{11}$$

The duty ratio of zero switch vectors is

$$d_0 = 1 - d_{\alpha\mu} - d_{\beta\mu} - d_{\alpha\nu} - d_{\beta\nu} \,. \tag{12}$$

The final switch state is obtained through synthesizing Equations (4)-(7) and input modulating switch of input current vectors.

3 The fusion of matrix converter and direct torque control structure

In order to improve performance of speed response and ensure higher input power factor, space vector modulation strategy and DTC constitute a new control strategy. The control principle diagram is shown in Figure 3 [12].

In Figure 3, switch time calculating unit determines working time of switch combination of output voltage vector of MC. PWM unit gives signal to control switch state. Switch converter unit provides safe conversion. Direct torque control link is composed of torque controller, flux controller, torque and flux observers, which control and observe torque and flux of induction motor. PI regulator realizes speed response of induction motor. But it cannot adjust quickly when loads and parameters of induction motor change. So in this paper, ADRC is used instead of PI regulator.

ADRC equations of induction motor are described as follows:

Differentiation-tracker

$$\begin{aligned} &\varepsilon_0 = z_{11} - v \\ &\dot{z}_{11} = -r f_{al}\left(\varepsilon_0, \alpha_0, \delta_0\right) \end{aligned}. \tag{13}$$

Extended state observer

$$\begin{aligned} &\varepsilon = z_{21} - y \\ &\dot{z}_{21} = z_{22} - \beta_{01} f_{al}\left(\varepsilon, \alpha, \delta\right) + bu\left(t\right). \\ &\dot{z}_{22} = -\beta_{02} f_{al}\left(\varepsilon, \alpha . \delta\right) \end{aligned} \tag{14}$$

Nonlinear state error feedback

$$\begin{aligned} &\varepsilon_1 = z_{11} - z_{21} \\ &u_0 = \beta_1 f_{al}\left(\varepsilon_1, \alpha_1, \delta_1\right). \\ &u\left(t\right) = u_0\left(t\right) - \frac{z_{22}}{b} \end{aligned} \tag{15}$$

The expression of optimal control function f_{al} is

$$f_{al}\left(\varepsilon, \alpha, \delta\right) = \begin{cases} \left|\varepsilon\right|^\alpha \operatorname{sgn}\left(\varepsilon\right) & \left|\varepsilon\right| > \delta \\ \frac{\varepsilon}{\delta^{1-\alpha}} & \left|\varepsilon\right| \le \delta \end{cases}, \tag{16}$$

where *v* is a given signal for ADRC; z_{11} is tracking signal to *v*; *r* is tracking speed factor; *y* is system output; z_{21} is tracking signal to *y*; z_{22} is tracking signal to disturbance signal *ω(t)*; *ε* is error signal; *α* is nonlinear factor; *δ* is ESO filter factor; β_{01}, β_{02} are correction gain for output error; *β* is gain error.

The structure of ADRC controller is shown in Figure 4:

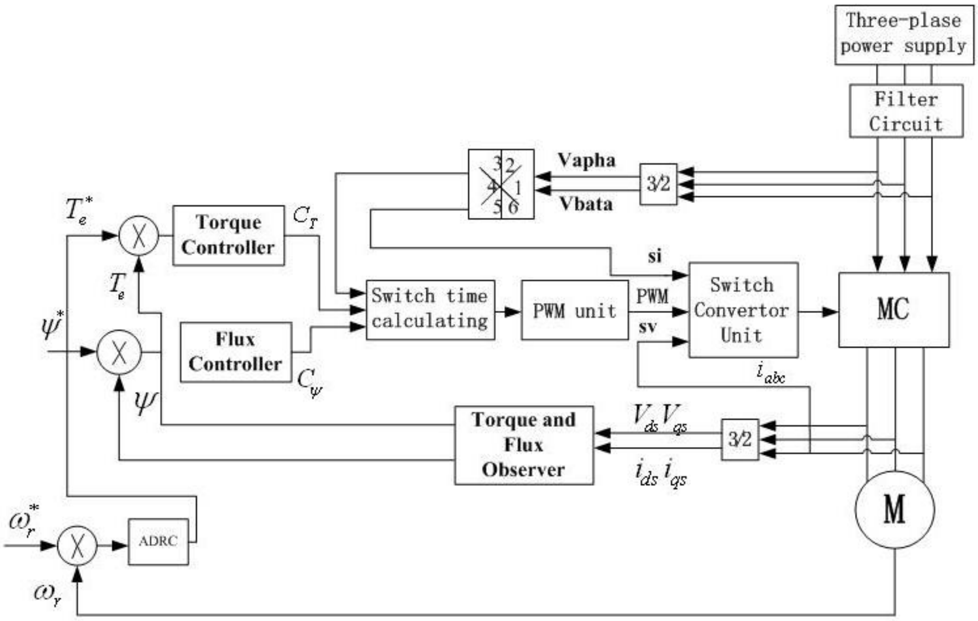

FIGURE 3 Direct torque control system structure based on matrix

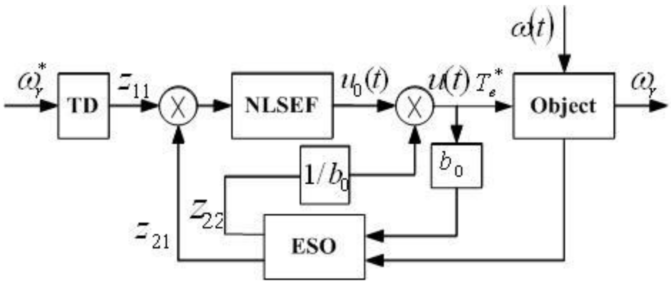

FIGURE 4 Structure of ADRC controller

In Figure 4, ω_r^* and T_e^* are given speed and given torque; ω_r is system speed feedback signal; z_{11} is tracking signal to ω_r^*; z_{21} is tracking signal to ω_r; TD arranges transition process for ω_r^*, obtaining smoothing input signal, causing system quick response without overshoot. ESO link estimates all state variables in real time, and observes internal and external disturbances and uncertain model accurately, feedback linearization of dynamic system can be come true to compensate uncertainty of controlled object in the feedback so that we can achieve the goal of refactoring object; NLSEF can realize integrated disturbance compensation and nonlinear control of "small error and great gain" in order to improve system steady-state accuracy.

4 The simulation experiments and analysis

According to the previous analysis, direct torque system model for induction motor can be built based on PI control and ADRC control respectively.

Motor parameters are:

Rs=0.435Ω, Rr=0.816Ω, Ls=0.02H, Lr=0.02H, Lm=0.69H, motor pole p=2, load torque Tg=25N·m, flux reference Ψ=0.56Wb.

ADRC parameters are: b=1385, $\beta_{01}=\beta_{02}=4300$, $\beta_1=3$, α=0.8, δδ=0.05, $\alpha_1=0.8$, $\delta_1=0.04$; PI control parameters are: Kp=3, KI=0.45.

Figure 5 is ADRC system steady-state waveform when speed and torque are given; Figure 6 is PI control system and ADRC control system dynamic waveform when load mutates; Figure 7 is PI control and ADRC control steady-state waveform under the disturbance.

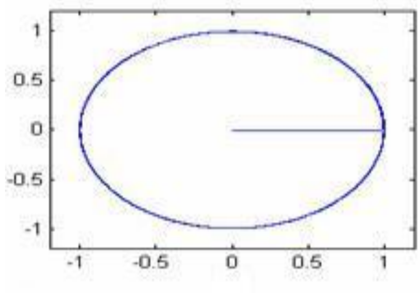

FIGURE 5a Stator flux linkage

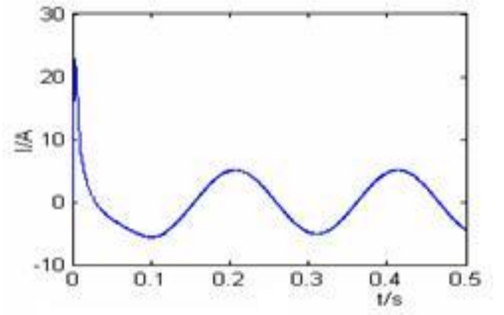

FIGURE 5b Stator current

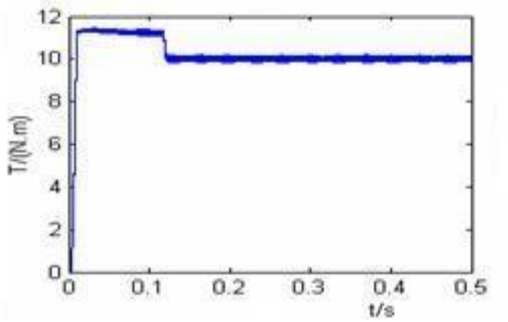

FIGURE 5c Electromagnetic torque

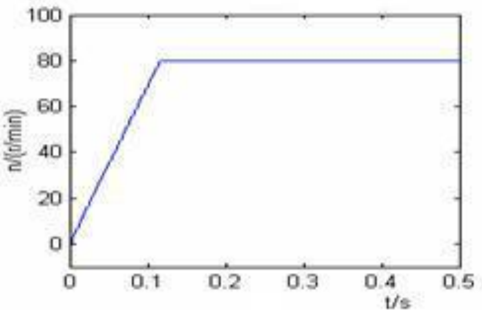

FIGURE 5d Speed

*Figure 5 shows that low performance changes obviously, torque ripple is well improved

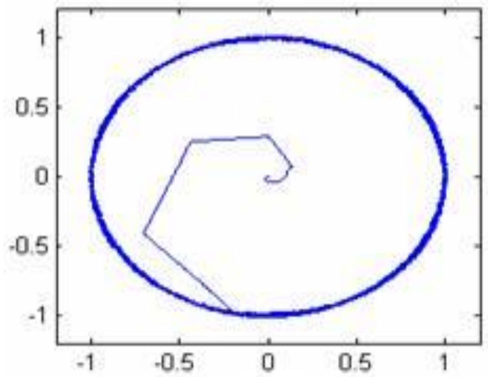

FIGURE 6a Stator flux based on PI controller

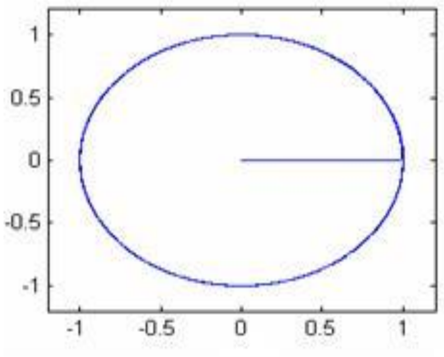

FIGURE 6b Stator flux based on ADRC controller

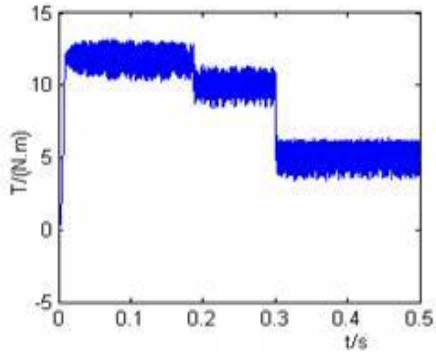

FIGURE 6c Electromagnetic torque based on PI controller

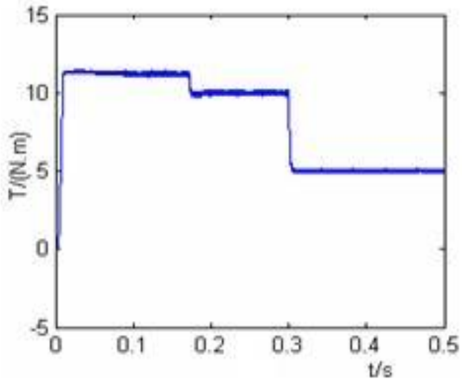

FIGURE 6d Electromagnetic torque based on ADRC controller

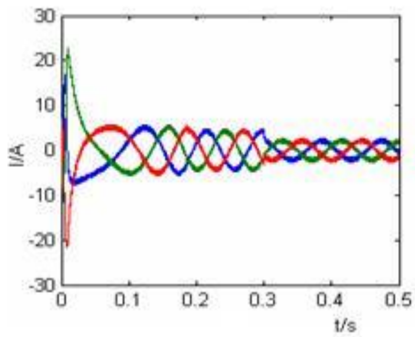

FIGURE 6e Three phase stator currents based on PI controller

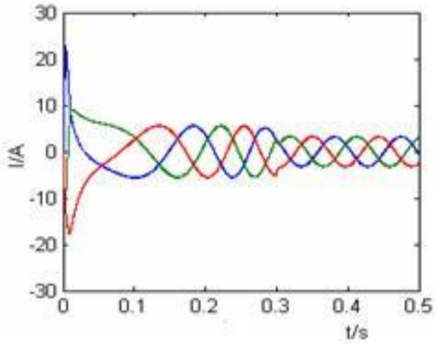

FIGURE 6f Three phase stator currents based on ADRC controller

Figure 6 shows that stator flux is more close to circular, stator flux and stator current disturbance is small, torque ripple is effectively suppressed when the load torque mutates in direct torque control system based on ADRC.

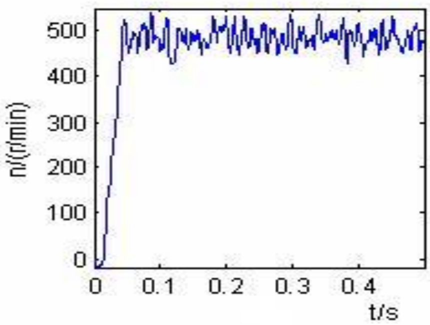

FIGURE 7a Speed based on PI controller in interference environment

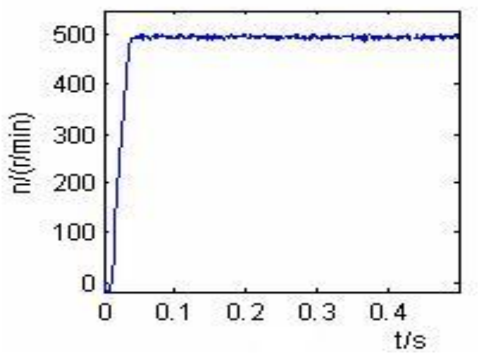

FIGURE 7b Speed based on ADRC controller in interference environment

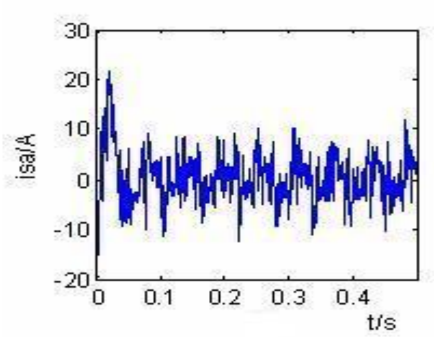

FIGURE 7c Stator current based on PI controller in interference environment

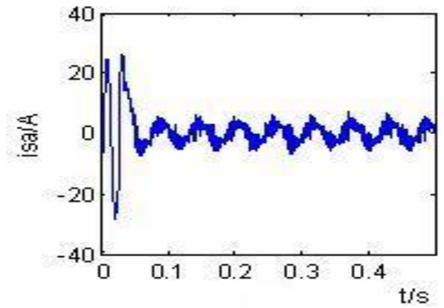

FIGURE 7d Stator current based on ADRC controller in interference environment

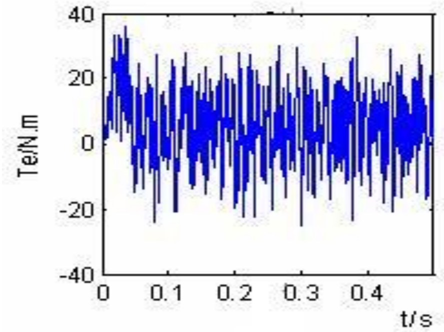

FIGURE 7e Electromagnetic torque based on PI controller in interference environment

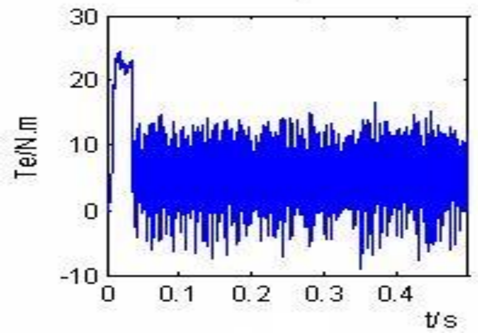

FIGURE 7f Electromagnetic torque based on PI controller in interference environment

5 Conclusion

This paper has adopted ADRC algorithm for induction motor based on MC. It has shown that ADRC control strategy is independent of system model and external disturbance. The performance of ADRC controller and conventional PI controller are compared under the same situation. Simulation results show that the ADRC controller has good dynamic and static characteristics, while the traditional PI controller is hard to guarantee high precision and high disturbance rejection ability with the existence of disturbance.

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