Fuzzy Active Disturbance Rejection Control of Three-Motor Synchronous System

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Abstract: A control method based on fuzzy active disturbance rejection controller is proposed and applied to the three-motor synchronous control system, which can adjust the parameters automatically by using the inferential capability of fuzzy control. Double channels compensation of extended state observer is used to estimate and compensate the total disturbance of the system and the coupling between speed and tensions, thus an approximate linear and determinable system is obtained. Experiments about decoupling property, tracking performance and anti-disturbance performance are conducted on the platform constructed by combining with SIMATIC S7-300 PLC. The results prove that the control system has better performances in dynamic and static character, stronger anti-interference ability and better robustness than traditional PID control system.

Keywords: Three-motor, synchronous control, active disturbance rejection controller, fuzzy controller, speed, tension.

1. INTRODUCTION

Multi-motor synchronous system is widely used in the field of modern industrial applications (S.Seung-H et al., 2000).The synchronous performances of the system directly affect the productivity and the quality of products. The performances will become bad with the effect of unsuitable drive characteristic of gearing, disturbance of load, etc. Therefore, how to control the multi-motor synchronous system with high synchronous performances to realize coordinate movements and decoupling control of speed and tensions is a hotspot in the research, which is difficult to achieve (Ye et al., 2004), (Perez-Pinal F et al., 2003) Recently, many strategies dealing with multi-motor speed tension decoupling control have been published, such as forward feed control (G. Hearns et al., 2004), cross couple control (He et al.,2007),(Perez-Pinal, C et al., 2004), relative couple control (Liu et al., 2006),optimal control(Zhu et al., 2009), H∞ control (Huang et al., 2002) etc. But these control methods mostly rely on the accurate mathematic model of the system, and aim at the synchronous control of DC motor system. The accurate mathematic model is difficult to acquire in AC motor system especially in multi-motor system (n>2).

To solve the problem, through model analysis of the three-motor synchronous control system, fuzzy active disturbance rejection controller is involved into three-motor synchronous control system in this paper. This system overcomes the defects of traditional PID control system, and could adjust the parameters automatically by using the inferential capability of fuzzy control. Extended state observer (ESO) is used to estimate and compensate the total disturbance of the system, including internal disturbance, external disturbance and the coupling disturbance between speed and tensions. Then an approximate linear and determinable system is obtained. By experiment show that the control system has better control performances compared with traditional PID control system.

2. THREE-MOTOR SYNCHRONOUS SYSTEM INSTRUCTIONS

The mathematic model of the three-motor synchronous system is shown in Fig.1. Three motors are respectively driven by three Micro-master Vector (MMV) inverters. Motor 1 is the master motor, motor 2 and motor 3 are slave motors. Three motors jointly drive one conveyer belt after they are decelerated in 15:1 ratios by reduction boxes, and floating rollers strain the conveyer belt to increase the friction between the conveyer belt and the driving rollers.

According to the Hooker law, the basic dynamic equations of the system can be described by (1) and (2) (Dai et al., 2006), (Zhao et al., 2008).

The tension F_{12} between motor 1 and motor 2 is shown in (1):

$$\dot{F}_{12} = \frac{AE}{L_1}\left(\frac{1}{n_{p1}} r_1 k_1 \omega_{r1} - \frac{1}{n_{p2}} r_2 k_2 \omega_{r2}\right) - \frac{AV_1}{L_1} F_{12} = \frac{K_1}{T_1}\left(\frac{1}{n_{p1}} r_1 k_1 \omega_{r1} - \frac{1}{n_{p2}} r_2 k_2 \omega_{r2}\right) - \frac{F_{12}}{T_1} \quad (1)$$

The tension F_{23} between motor 2 and motor 3 is shown in (2):

$$\dot{F}_{23} = \frac{AE}{L_2}\left(\frac{1}{n_{p2}} r_2 k_2 \omega_{r2} - \frac{1}{n_{p3}} r_3 k_3 \omega_{r3}\right) - \frac{AV_2}{L_2} F_{23} = \frac{K_2}{T_2}\left(\frac{1}{n_{p2}} r_2 k_2 \omega_{r2} - \frac{1}{n_{p3}} r_3 k_3 \omega_{r3}\right) - \frac{F_{23}}{T_2} \quad (2)$$

here: $K_1 = E/V_1$ and $K_2 = E/V_2$ are delivery coefficients; $T_1 = L_1/(AV_1)$ and $T_2 = L_2/(AV_2)$ are change rates of the tension; r_1, r_2, r_3 and k_1, k_2, k_3 are respectively the radius and the ratio of the speed of three driving rollers; ω_{r1}, ω_{r2}, ω_{r3} and n_{p1}, n_{p2}, n_{p3} are respectively the angular speed and the number of pole-pairs of the three motors; A is the cross-sectional area of the conveyer belt; E is the Young' modulus of elasticity of the conveyer belt; L_1 is the distance between the rack of motor 1 and the rack of motor 2; L_2 is the distance between the rack of motor 2 and the rack of motor 3; V_1 and V_2 are the anticipant speed.

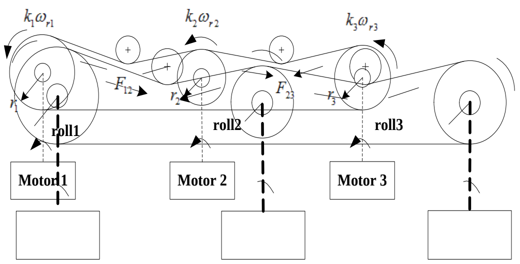

Fig.1. Three-motor synchronous system

3. PID CONTROL SYSTEM

The classic digital increment PID arithmetic can be described as following:

$$u(k) = u(k-1) + K_P(e(k) - e(k-1)) + K_I e(k) + K_D(e(k) - 2e(k-1) + e(k-2)) \quad (3)$$

Here: K_p, K_I and K_D are respectively proportion integral differential coefficient; $e(k)$, $e(k-1)$ and $e(k-2)$ are respectively k, $(k-1)$ and $(k-2)$ error signals; $u(k)$, $u(k-1)$ are respectively k and $(k-1)$ outputs of the controller.

The structure of three-motor synchronous control system based on traditional PID controller is shown in Fig.2. Three traditional PID controllers respectively and directly control the speed of master motor and two tensions of the system.

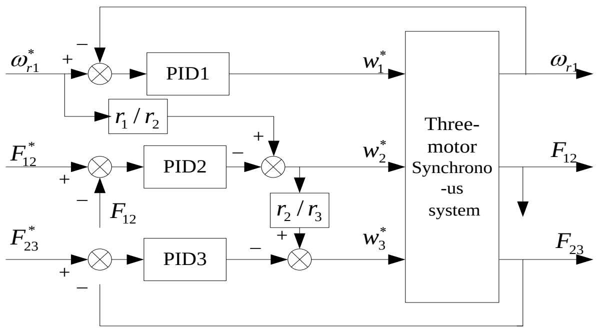

Fig.2 .Structure of PID control system

Here: ω_{r1}^* is master motor reference speed; ω_{r1} is master motor actual speed; F_{12}^* is reference tension between motor1 and motor2; F_{23}^* is reference tension between motor2 and motor3; w_1^*, w_2^*, w_3^* are respectively reference frequency of the three inverters; r_1, r_2, r_3 are the three fixed value of roller radiuses in controlled system.

PID control tuning parameters method includes theoretical calculation and engineering. In this study, 4:1 attenuated oscillation method of the engineering is used to tune the parameters of PID controller. The traditional PID parameters depend on the system model, and it's difficult to select optimal parameters. These parameters of controller are unable to adjust automatically when some parameters of the system changes. So it's difficult and nonlinear to describe the mathematic model of the three-motor synchronous control system. In addition, the traditional PID control fails to fulfill high synchronous performances for strong coupling system between speed and tensions.

4. FUZZY ACTIVE DISTURBANCE REJECTION CONTROLLER

4.1 ADRC Principle

Fig. 3 shows the structure of active disturbance rejection controller (ADRC) (Han, 2009), (Shao et al., 2008). In order to achieve high dynamic performance and robustness, this controller includes the tracking-differentiator (TD) which gets continuous signal and differential signal from the input reference signal, the extended state observer (ESO) estimating the state variables, and the nonlinear state error feedback (NLSEF) control law. The equation of the controlled object is as follow (4).

$$x^{(n)} = f_0\left(x^{(0)}, x^{(1)}, \cdots, x^{(n-1)}, t\right) + b_0 u + f_1\left(x^{(0)}, x^{(1)}, \cdots, x^{(n-1)}, w(t)\right) + b_1 u \quad (4)$$

Here: $f_1(\bullet)$, b_1 are primarily unknown, $w(t)$ is the external disturbance, u is input, $f_0(\bullet)$ is known and b_0 is constant.

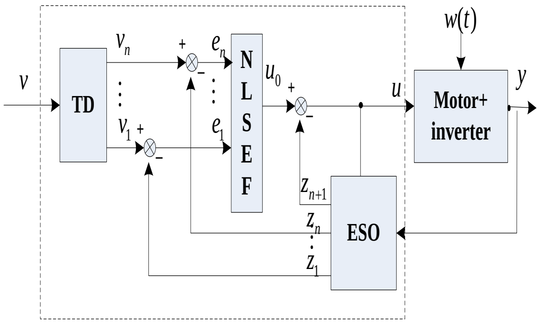

Fig.3. The structure of ADRC

4.2 Design of first-order ADRC

Active disturbance rejection controller is a newly nonlinear controller which can overcome the defects of traditional PID. Vector control model of the induction machine drive system is the first-order model, and correspondingly, the second-order structure of ESO is used. The rotor flux linkage generally maintains constant in the vector control system. The effects of rotor flux error $\Delta\psi_r$, rotational inertia error ΔJ , external disturbance T_{L1} , tension change F , the coupling between speed and tensions, etc. are totally estimated and compensated by Z_2 of the ESO. With the help of double channels compensation of the ESO, an approximate linear and determinable system is obtained. The block diagram of first-order ADRC is shown in Fig.4.

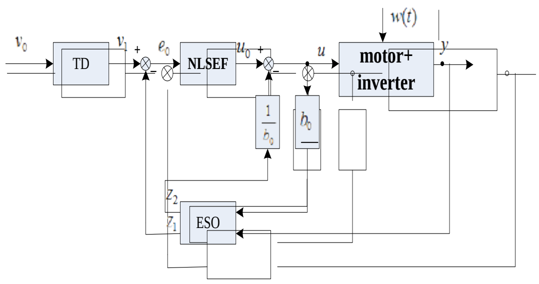

Fig.4 .The block diagram of first-order ADRC

4.2.1Tracking-differentiator

The TD tracks input signal v_0, obtains the smooth input signal v_1 and estimates the differential signal v_2 of v_0. The discrete form of TD is:

$$\begin{cases} fh = fhan(v_1 - v_0, v_2, r_0, h) \\ \dot{v}_1 = v_1 + hv_2 \\ \dot{v}_2 = v_2 + hfh \end{cases} \tag{5}$$

Here: h is sample period of speed, and $fhan(v_1 - v_0, v_2, r_0, h)$ is a new integrated optimal control function, r is tracking speed factor. The function fh is shown in (6).

$$fh = fhan(x_1, x_2, r, h) = \begin{cases} d = rh \\ d_0 = hd \\ y = x_1 + hx_2 \\ a_0 = \sqrt{d^2 + 8r|y|} \\ a = \begin{cases} x_2 + \dfrac{(a_0 - d)}{2} sign(y), & |y| > d_0 \\ x_2 + \dfrac{y}{h}, & |y| \le d_0 \end{cases} \\ fhan = -\begin{cases} rsign(a), & |a| > d \\ r\dfrac{a}{d}, & |a| \le d \end{cases} \end{cases} \tag{6}$$

4.2.2 Extended state observer

The ESO takes the system's output y and input u as its input, estimates plant's state variable and unknown part. The discrete form of ESO is:

$$\begin{cases} e = z_1 - y \\ \dot{z}_1 = z_1 + h(z_2 - \beta_{01}e + b_0 u) \\ \dot{z}_2 = h\beta_{02}\, fal(e, \alpha, \delta) \end{cases} \tag{7}$$

Here: β_{01}, β_{02} are observer gains, z_1 is the tracking signal of the output, z_2 is the observed value of $w(t)$, an example of $fal(e, \alpha, \delta)$ is:

$$fal(e, \alpha, \delta) = \begin{cases} |e|^{\alpha} sign(e) & , |e| > \delta \\ \dfrac{e}{\delta^{1-\alpha}} & , |e| \le \delta \end{cases} \tag{8}$$

Here: α is nonlinear coefficient, δ is turning point of fal function.

4.2.3 Nonlinear state error feedback control law

$$\begin{cases} e_1 = v_1 - z_1, e_2 = v_2 - z_2 \\ u_0 = k(e_1, e_2, p) \\ u = u_0 - z_2(t) / b_0 \end{cases} \tag{9}$$

Here: p is a set of parameters, b_0 is the compensation factor.

4.3 Simplification of ADRC

ESO only outputs observed values of the controlled object and unknown disturbance in the first-order ADRC, and not the differential output of the controlled object. So the simplified model of ADRC can omit TD. In the simplified structure, the nonlinear feedback is substituted by the linear feedback partially for ESO and NLSEF. As a result, nonlinear operation in the typical ADRC model is reduced effectively, the calculation of the simplification model algorithm is decreased and the real-time performance is greatly improved, finally a nice control performance is obtained. The simplified model structure of first-order ADRC is in Fig.5.

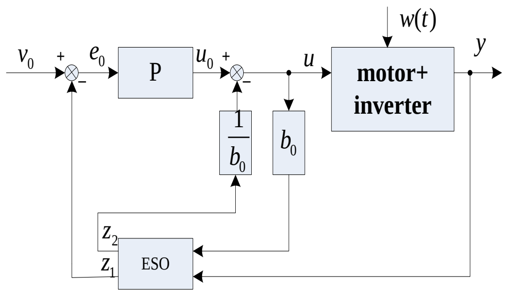

Fig.5 The simplification block diagram of one-order ADRC

Complete algorithm of the simplified controller is described in (10).

$$\begin{cases} ESO\begin{cases} e = z_1 - y \\ \dot{z}_1 = z_1 + h\left(z_2 - \beta_{01}e + b_0 u\right) \\ \dot{z}_2 = h\beta_{02}\, fal\left(e,\alpha,\delta\right) \end{cases} \\ NLSEF\begin{cases} e_0 = v_0 - z_1 \\ u_0 = k_p e_0 \end{cases} \\ u = \dfrac{u_0 - z_2}{b_0} \end{cases} \tag{10}$$

Here: v_0 is the set value, k_p is the proportional coefficient of the feedback control law. The paper reduces parameters of the controller via the simplified structure, in (10) uncertain parameters are β_{01}, β_{02}, k_p and b_0. The research indicates that β_{01} and β_{02} are mainly decided by the speed sampling period of the controller, generally taking $\beta_{01} = \frac{1}{\mathrm{h}}$ and $\beta_{02} = \frac{1}{5\mathrm{h}^2}$. In the paper, the sampling period of the speed is set to h =100ms, taking β_{01} =10 and β_{02} =20, so uncertain parameters of the controller are only k_p and b_0.

Fuzzy logic control strategy is applied to the system, which could adjust the parameter k_p automatically by using the inferential capability of fuzzy control. A large number of experiments prove that parameter b_0 has better practicability and can get the expected control effect within a large range, which is tuned easily.

4.4 Fuzzy ADRC

In view of three-motor synchronous control system is a complex, multi-variable, nonlinear and strong-coupling system, this paper proposes a kind of decoupling control method based on fuzzy ADRC controller. The controller's inputs are E_0 and E_C (Chen et al.,2005).The parameter Δk_p is adjusted by using the inferential capability of fuzzy control, the structure of speed controller is shown in Fig.6, which also can be used for tension control system similarly.

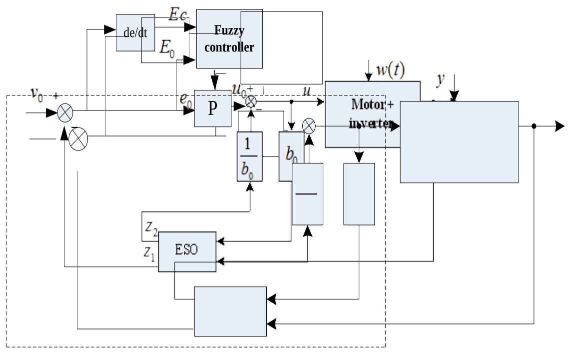

Fig.6 The block diagram of one-order fuzzy ADRC

In this paper, membership function is set as triangle function and defuzzification adopts the center of gravity method. Both inputs E_0 and E_C range from -6 to +6 ,meanwhile, the output Δk_p ranges from -1 to +1.They are divided into 7 categories, NB(negative big), NM(negative medium), NS (negative small), ZO (zero),PS (positive small), PM (positive medium) and PB(positive big).

According to the operation experience, control rules of Δk_p are shown in Table 1.

Table 1. Fuzzy control rules of Δk_p

Δk_p (E_C \ E_0)	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

The modified parameter Δk_p searched from Table 1 is used into the formula to obtain the adjustable k_p, which is show in (11).

$$k_p = k_{p0} + \Delta k_p \qquad (11)$$

Here: k_{p0} is the initial value of k_p.

4.5 Fuzzy ADRC control system

Three-motor synchronous control system is a three-input-three-output system. The first-order simplified fuzzy ADRC is applied to design a new control system. The structure of system is shown in Fig.7.

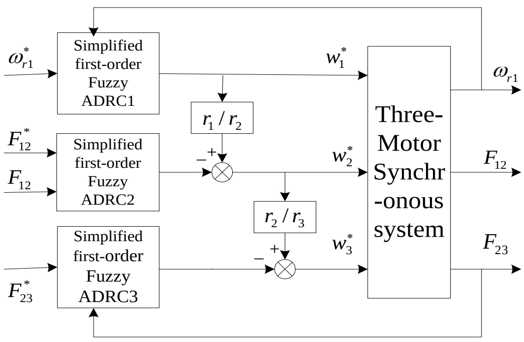

Fig.7 Structure of fuzzy ADRC control system

Here: ADRC1 is speed controller. ADRC2 and ADRC3 are tension controllers.

Belt tension between the motors is essentially decided by the speed difference between the two neighboring motors. So the speed of Motor 2 is adjusted by the given speed of Motor 1 and the output of ADRC2; likewise, the speed of Motor 3 is adjusted by the input speed of Motor 2 and the output of ADRC3. Thus the purpose of belt tension control is realized.

5. EXPERIMENTAL RESEARCH OF THE CONTROL SYSTEM

5.1 Setting up the experimental platform

Fig. 8 Experimental platform of three-motor synchronous system

In this paper, the experimental platform of the three-motor synchronous control system is mainly made up of the common load, three induction motors with rated speed 1420r/min, three Micro-master Vector (MMV) frequency inverters, PG, siemens S7-300 PLC, photoelectric encoder, tension sensor and so on, which is shown in Fig.8.

5.2 Tracking velocity experiment

To examine tracking performance, the initial speed of motor is 400(r/min), then changes as square wave with 80 seconds periodicity from 400(r/min) to 300(r/min). Fig.9.(a) and Fig.9.(b) are the speed track response curves respectively using the traditional PID controller and the fuzzy ADRC controller. From the analysis of the data, the steady state error e_{ss} of square wave tracking velocity is respectively $\pm$ 8.58% and $\pm$ 2.27%. It easily can be seen that the fuzzy ADRC control system is more stable than the traditional PID control system.

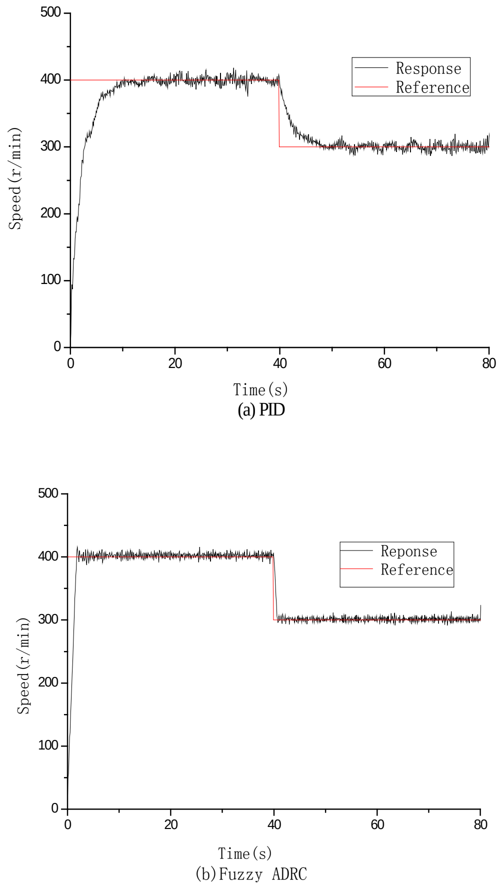

Fig.9 Response of speed tracking square wave

5.3 Decoupling experiment

To examine decoupling performance, tension F_{12} reference keeps in 150(N), tension F_{23} reference remains in 120(N), and the speed ω_{r1} reference is increased suddenly from

300(r/min) to 400(r/min) at the 80th seconds. The output responses adopting the traditional PID are shown in Fig. 10.(a) and the output responses adopting the fuzzy ADRC are shown in Fig.10(b).

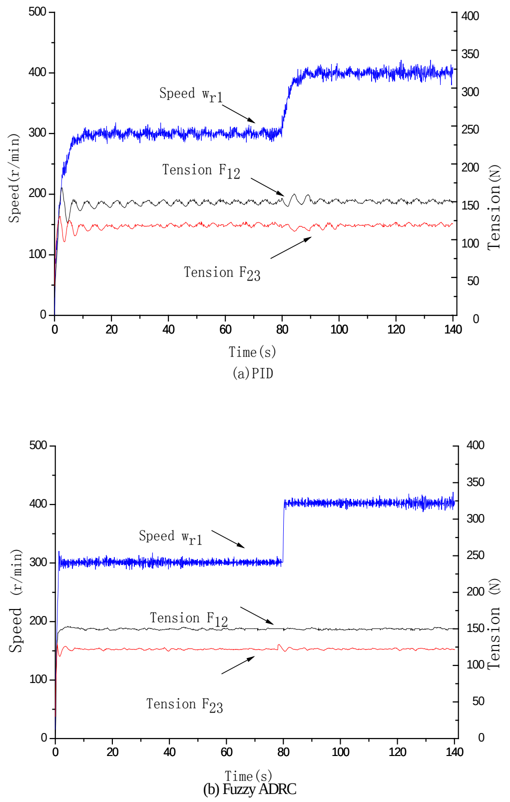

Fig.10 Response of sudden speed change

Fig.10 shown that the adjustment time of speed and tensions based on the fuzzy ADRC control system is shorter than the traditional PID control system. In the initial stage, beginning at 300(r/min), the speed overshoot $\sigma\%$ of PID is 14.1% and the regulation time t_s is 13.4s, while the speed overshoot $\sigma\%$ of the fuzzy ADRC is 4.0% and the regulation time t_s is 1.6s.When the speed change suddenly from 300(r/min) to 400(r/min), PID has a greater influence on tensions than the fuzzy ADRC. The recovery time of tension F_{12} and tension F_{23} are 6.4s and 10.1s respectively in PID, while the recovery time of tension F_{12} and tension F_{23} are 0.6s and 0.7s respectively in the fuzzy ADRC. Obviously, the latter is better than the former.

5.4 Load experiment

After the starting of free-load, load is added at 70th second, which is decreased at 120th second. Speed and tensions experimental waves of the multi-motor system are respectively shown in Fig. 11(a) and Fig. 11(b). As can be seen, the fuzzy ADRC control can make corresponding control adjustment according to the load change to keep speed and tensions constant maximum. And in contrast to the PID control, it can reduce the influence of load disturbance on tension.

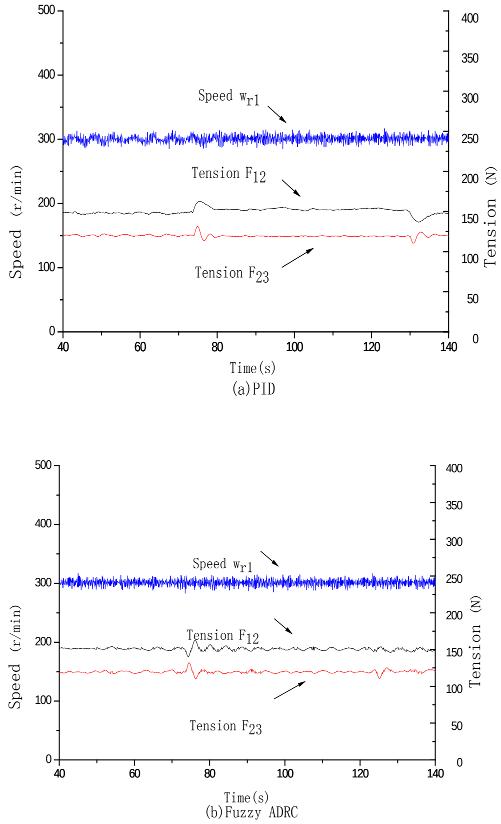

Fig.11 Response of sudden load change

6. CONCLUSIONS

In view of complex characteristics of three-motor synchronous control system, this paper proposes a kind of decoupling control method based on the fuzzy ADRC. By the speed tracking experiment the decoupling experiment and the load experiment, comparing with the traditional PID, obviously, the fuzzy ADRC control method can achieve a better decoupling control of speed and tensions in three-motor synchronous system. This controller can quickly respond a sudden change of the input. Furthermore, it has higher performances of dynamic and static status and a stronger ability of speed tracking. Meanwhile, the stability of the entire system has been enhanced. This method can be used as a new control idea in a complex nonlinear motion system.

ACKNOWLEDGEMENT

The subject is funded by the priority Academic program development of jiangsu higher education institutions (PAPD), and by the National Nature Science Foundation (60874014), The authors would like to thanks the sponsors for giving a chance to publish the paper.

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