Fuzzy-PID Based Induction Motor Control and Its Application to TBM Cutter Head Systems

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Abstract. Induction motor is used to drive cutter head system of tunnel boring machine (TBM). Due to the complex working environment, the conventional PID based vector control method cannot meet the varying motor parameters and load disturbances. In this paper, the fuzzy theory and PID control are investigated and applied to the speed control and electromagnetic torque control of induction motor for TBM cutter head systems. Based on the fuzzy-PID control strategy of each induction motor, a multi-motor synchronization control using master-slave control strategy is studied and analyzed. Simulation results show the effectiveness and robustness of the proposed method.

Keywords: Induction motor · Fuzzy-PID · TBM · Synchronization control

1 Introduction

Nowadays, the world is witnessing an increasing need for tunnels because of their unique characteristics and potential applications. Tunnels are artificial underground space in order to provide a capacity for particular goals such as water transfer, road tunnels, and mine. TBM is commonly used for tunneling due to its high safety, rapid excavation, and low manual labor [1] . The cutter-head undertakes the task of excavating rocks and soil. The cutter-head driving system plays an important role in TBM. Traditionally, the cutter is driven by hydraulic system, but in recent years, three-phase AC asynchronous motor controlled by transducer is applied in cutter head driving system, as shown in Fig. 1. Compared with hydraulic drive system, motor drive system is simple in mechanical design, installation and maintenance.

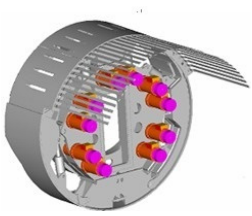

Fig. 1. TBM cutter-head driving motor

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TBM cutter system is driven by multi-motor, if one of the motor speed is lower or higher than the other motor speed, the motor will heat and probably get damaged if this lasts for a long time. To achieve stability of cutter-head driving, speed control is of crucial importance. However, induction motors are much more difficult to control and not suitable for high dynamic performance applications because of their complex nonlinear dynamics. Vector control provides decoupled control of the flux magnitude and the torque producing current, which is commonly used in asynchronous motor. Classical PI controller is a simple method used in the control of induction motor drive. However, the drawbacks of PI controller are the sensitivity of performance to the system-parameter variations and inadequate rejection of external disturbances and load changes [2]. Considering the complex underground tunneling environment and the changes of motor parameters, we proposed a self-tuning fuzzy-PID controller is proposed for a vector control based induction motor drive.

The rest of this paper are organized as follows. In Section 2, mathematical model of induction motor is built. Section 3 presents the vector control theory. In Section 4, we investigate the fuzzy PID based vector control of induction motor. Section 5 gives the simulation results and Section 6 concludes this paper.

2 Mathematical Model of Induction Motor

A three-phase induction motor is used in TBM cutter-head drive system. The fundamentals of assuming that the three-phase AC voltages are balanced and the stator windings are uniformly distributed. The mathematical model [3] of induction motor can be expressed as follows:

$$\begin{cases} \dfrac{d\omega}{dt} = \dfrac{n_p^2 L_m}{JL_r}\left(i_{s\beta}\psi_{r\alpha} - i_{s\alpha}\psi_{r\beta}\right) - \dfrac{n_p}{J}T_L \\ \dfrac{d\psi_{r\alpha}}{dt} = -\dfrac{1}{T_r}\psi_{r\alpha} - \omega\psi_{r\beta} + \dfrac{L_m}{T_r}i_{s\alpha} \\ \dfrac{d\psi_{r\beta}}{dt} = -\dfrac{1}{T_r}\psi_{r\beta} + \omega\psi_{r\alpha} + \dfrac{L_m}{T_r}i_{s\beta} \\ \dfrac{di_{s\alpha}}{dt} = \dfrac{L_m}{\sigma L_s L_r T_r}\psi_{r\alpha} + \dfrac{L_m}{\sigma L_s L_r}\omega\psi_{r\beta} - \dfrac{R_s L_r^2 + R_r L_m^2}{\sigma L_s L_r^2}i_{s\alpha} + \dfrac{u_{s\alpha}}{\sigma L_s} \\ \dfrac{di_{s\beta}}{dt} = \dfrac{L_m}{\sigma L_s L_r T_r}\psi_{r\beta} - \dfrac{L_m}{\sigma L_s L_r}\omega\psi_{r\beta} - \dfrac{R_s L_r^2 + R_r L_m^2}{\sigma L_s L_r^2}i_{s\beta} + \dfrac{u_{s\beta}}{\sigma L_s} \end{cases} \tag{1}$$

where $T_r = \dfrac{L_r}{R_r}$, $\sigma = 1 - \dfrac{L_m^2}{L_s L_r}$.

Moreover, electromagnetic torque equation can be represented as:

$$T_e = \frac{n_p L_m}{L_r}(i_{s\beta}\psi_{r\alpha} - i_{s\alpha}\psi_{r\beta}) \tag{2}$$

In (1), the subscripts s and r refer to the stator and rotor, and subscript α and β denote the mathematical model in a synchronous rotating reference frame for a three phase induction motor. The features of parameters in dynamic model of induction motor are shown in Table 1.

Table 1. Parameter of dynamic model of induction motor

Parameters	Feature
ω	Rotor speed
n_{p}	The number of pole pairs
L_m	Mutual inductance
L_r , L_s	Stator and rotor inductances
R_s , R_r	Stator and rotor resistence
J	Moment of inertia
$i_{s\beta}$, $i_{s\alpha}$	Stator current components
$\psi_{r\alpha}$, $\psi_{r\beta}$	Rotor flux components
T_L	Load torque

3 Vector Control Theory

In the induction motor dynamic model, there is a direct coupling between the parameters of rotor and stator. The speed of induction motor is difficult to control. Vector control is a control method where the stator currents of a three-phase induction motor are identified as two orthogonal components that can be visualized with a vector. The vector control leads to control torque and the flux independently likes in the case of DC motors using d-q rotating reference frame [4]. If synchronously rotating d-q-0 frame was selected, which d-axes is precisely adjusted with the rotor field, the q component of the rotor flux would be zero, that is:

$$\psi_{rm} = \psi_{rd} = \psi_r \tag{3}$$

$$\psi_{rt} = \psi_{rq} = 0 \tag{4}$$

Hence the equations (1) can be written as

$$\begin{cases} \dfrac{d\omega}{dt} = \dfrac{n_p^2 L_m}{J L_r}\left(i_{s\beta}\psi_r\right) - \dfrac{n_p}{J} T_L \\ \dfrac{d\psi_r}{dt} = -\dfrac{1}{T_r}\psi_r + \dfrac{L_m}{T_r} i_{sm} \\ \dfrac{di_{sm}}{dt} = \dfrac{L_m}{\sigma L_s L_r T_r}\psi_r - \dfrac{R_s L_r^2 + R_r L_m^2}{\sigma L_s L_r^2} i_{sm} + \dfrac{u_{sm}}{\sigma L_s} \\ \dfrac{di_{st}}{dt} = \dfrac{L_m}{\sigma L_s L_r T_r}\psi_r - \dfrac{R_s L_r^2 + R_r L_m^2}{\sigma L_s L_r^2} i_{s\beta} + \dfrac{u_{st}}{\sigma L_s} \end{cases} \tag{5}$$

The motor phase currents i_a, i_b, i_c are converted to i_d and i_q in the stationary reference frame. These are then converted to the synchronously rotating reference frame d-q currents, i_{ds} and i_{qs}. Using these conditions, the induction motor can be controlled as a DC motor.

A block diagram of a vector control method using SVPWM voltage-fed inverter is shown as Fig. 2. The rotor speed ω is compared with the reference speed ω^* and adjusted by PI controller. The output is the quadratic current i_q^*. There are three control loops including the speed control, torque control and flux control. Rotor speed and flux is controlled in a closed-loop form.

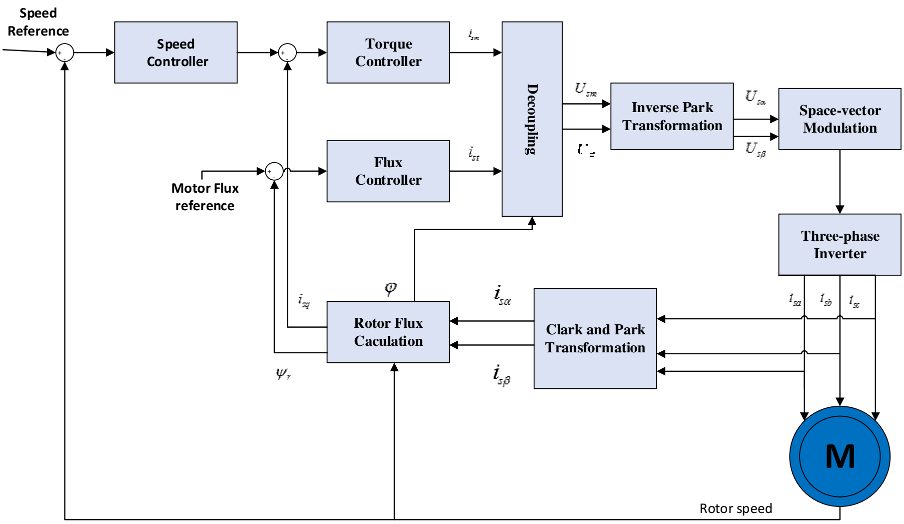


Fig. 2. Vector control block diagram with rotor flux orientation

4 Fuzzy Vector Control of Induction Motor

The conventional PID controller has advantages of simple structure and simply implemented [5]. However, it cannot adjust its coefficient adaptively to the change of motor parameters and system disturbance. Fuzzy PID control, combining the advantage of PID control and fuzzy logic, demonstrates the significant performance improvement over the conventional PID control [6]. The fuzzy PID control structure is shown in Fig. 3.

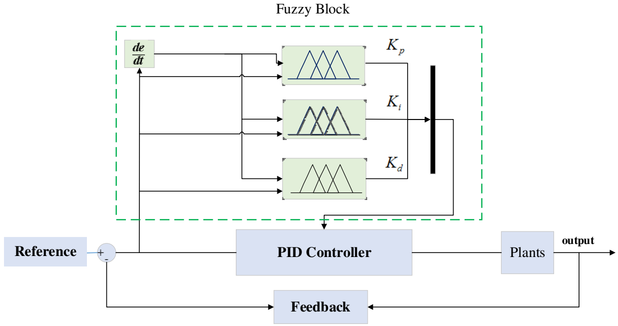


Fig. 3. Self-tuning fuzzy PID control structure

According to Fig. 3, the three coefficients K_p, K_i and K_d is tuned by fuzzy tuners using the following equation:

$$K_a = K_{a0} + U_a \Delta K_a, U_a \in [0,1] \quad a \text{ is } p, i \text{ or } d \tag{6}$$

where U_a is the parameter obtained from the output of the fuzzy controllers, ΔK_a are the correction coefficients. Three coefficients K_p, K_i and K_d are tuned by using the three independent fuzzy tuners. Consequently, the three separate fuzzy controllers are combined to form the fuzzy PID controller.

The fuzzy inference is based on fuzzy set theory [7]. Fig. 4 shows the membership functions for the controller inputs on the common interval [-1, 1] (i.e., normalized error E and normalized change of error EC), and output of fuzzy controller is on common interval [0, 1] [8]. Table 2 shows the proposed two dimensional rule base.

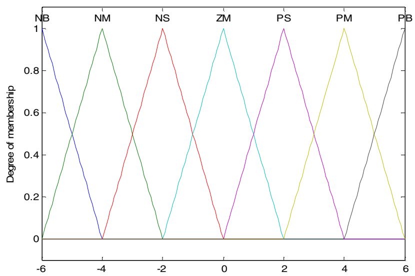


Fig. 4. Member function of fuzzy inference

Table 2. Fuzzy rule

		E						
		NB	NM	NS	ZM	PS	PM	PB
EC	NB	NB	NB	NB	NB	NM	NS	ZM
	NM	NB	NB	NB	NM	NS	ZM	PS
	NS	NB	NB	NM	NS	ZM	PS	PM
	ZM	NB	NM	NS	ZM	PS	PM	PB
	PS	NM	NS	ZM	PS	PM	PB	PB
	PM	NS	ZM	PS	PM	PB	PB	PB
	PB	ZM	PS	PM	PB	PB	PB	PB

5 Simulation Results

5.1 Fuzzy-PID Based Induction Motor Control

The simulation of the proposed controller of induction motor are carried out in MATLB/SIMULINK. The block diagram of implementation of fuzzy PID vector control model of induction motor is shown in Fig. 5. Table 3 shows the motor parameters which is used in TBM cutter head driving system [9]. Sampling time in this simulation is 3s.

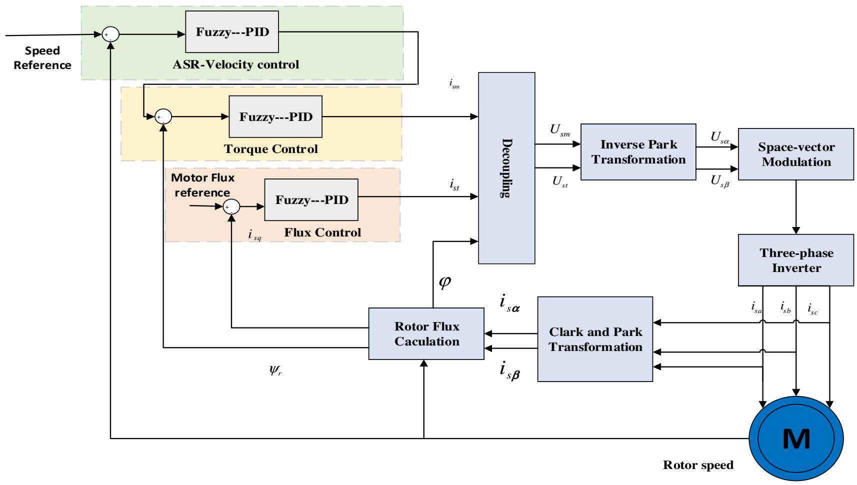


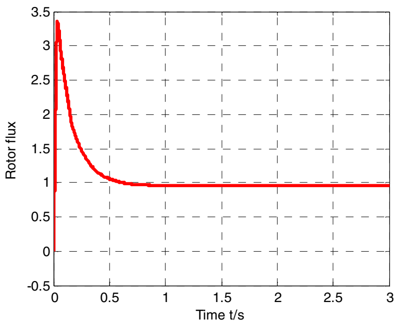
Fig. 5. Structure of fuzzy-PID control system

Table 3. Parameters value of induction motor

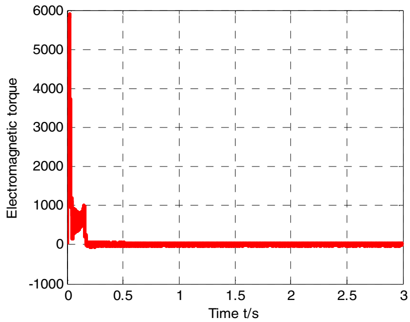
Mutual inductance	Rotor inductance	Stator inductance	Stator resistance	Rotor resistance
34.7mH	0.8mH	0.8mH	0.087 Ω	0.087 Ω

Inertia	Pole pairs	Frequency	Power
1.662$\mathbf{kg.}\boldsymbol{m^2}$	2	50Hz	50HP

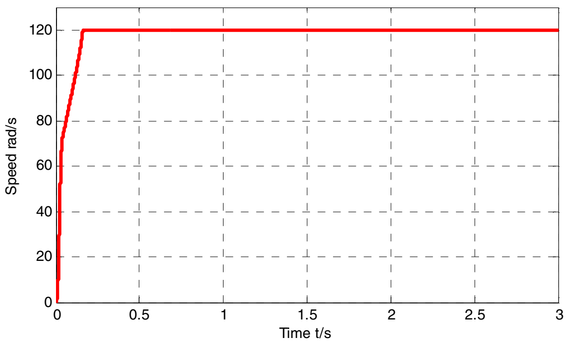
Set the reference speed as 120 rad/s, and the load torque as 0. The results of rotor speed, flux and magnetic torque response of fuzzy PID control are shown in Fig. 6. The results show that the speed can reach the reference value quickly without overshoot. Meanwhile, the rotor flux and the magnetic torque can reach steady state fast.



a) Rotor flux



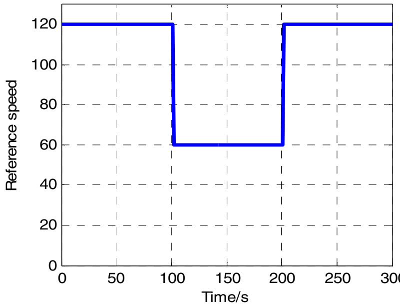
b) Electromagnetic torque

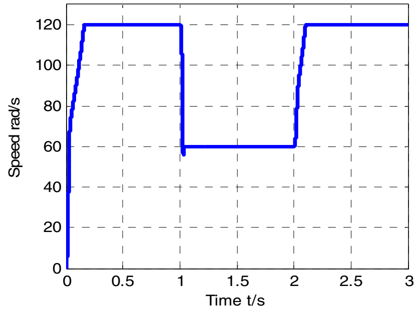


c) Output of rotor speed

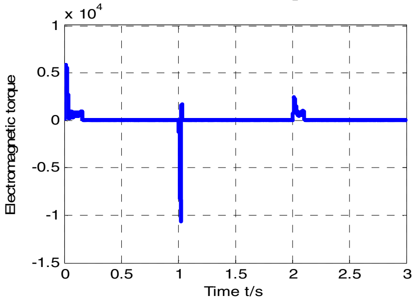
Fig. 6. Response of fuzzy-PID control by applying load torque T=0 Nm and reference speed as 120rad/s between t=0 to 3s

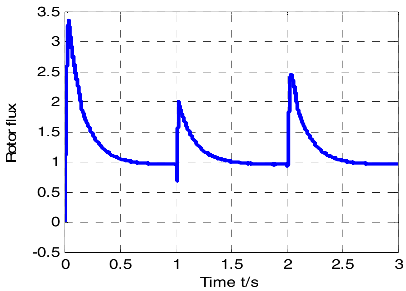
Moreover, the control of time-varying speed references are given in Fig. 7. Fig. 7 (a) gives the reference speed.





a) Reference speed b) Output of rotor speed

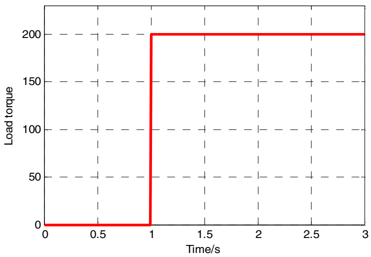


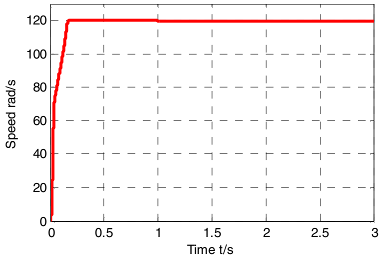


c) Electromagnetic torque d) Rotor flux

Fig. 7. Response of fuzzy-PID control by applying load torque T=0 and a variable reference speed from t=0 to 3s.

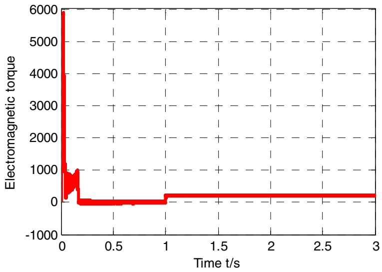
Fig. 8 shows the dynamic responses of fuzzy PID control with disturbance on the torque at $t = 1.5s$. It is noted that self-tuning fuzzy PID controller performs well in terms of speed rise time and disturbance rejection.



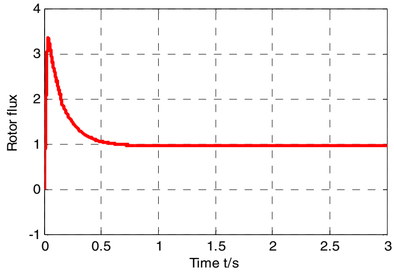


a) Load torque with abrupt change b) Output of rotor speed

Fig. 8. Response of Fuzzy-PID controller by applying reference speed as 120 rad/s and load torque with abrupt change at t=1.5 from 0 to 200Nm



c) Electromagnetic torque



d) Rotor flux

Fig. 8. (*Continued*)

5.2 Application to Synchronization Control of TBM Cutter Head Systems

To verify effectiveness of the proposed fuzzy-PID controller of induction motor used in TBM cutter head driving system, a multiple motor system including three induction motors is established and simulated in MATLAB based on master-slave synchronization techniques [10]. The master-slave control strategy is widely adopted in cutter head rotation electric systems. Master-slave configuration for a three-motor system is shown in Fig. 9. The output speed of the master motor serves as the speed reference of the other two slave motors.

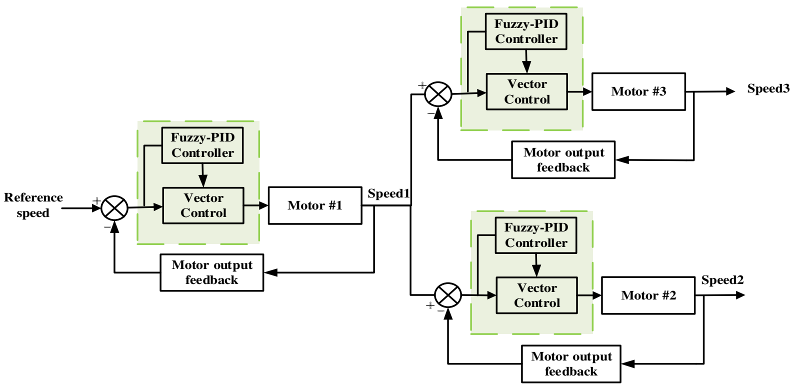
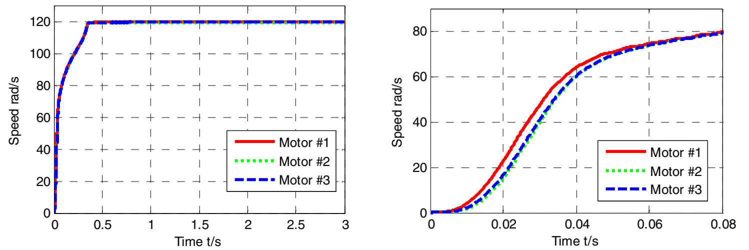
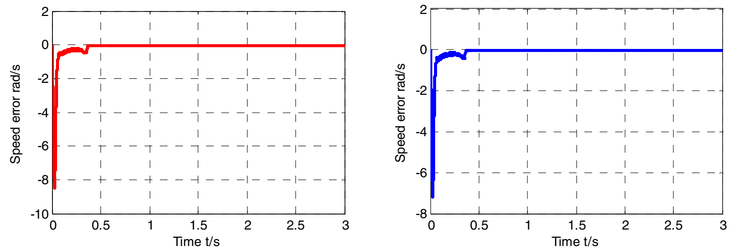


Fig. 9. Structure of the Master-slave for a three motor system

In actual construction, even if we select the same motors, the parameters cannot be exactly the same because of environmental disturbs and some other reasons [11]. In this simulation, we set the three motors with different parameters, where the rotor resistance value of motor #1 is half of the other two motors, and the inductance value of motor #2 is half of motor #1 and motor#3, the mutual inductance value of motor #3 is half of motor #1 and motor #2. The simulation results are shown in Fig. 10.



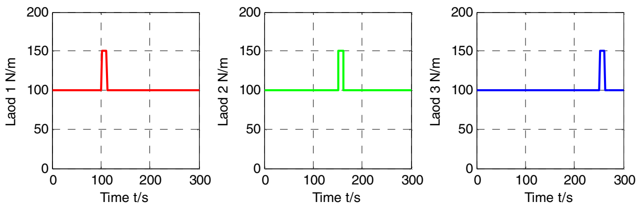
a) Speed response of three motors b) Detailed information of start-up phase



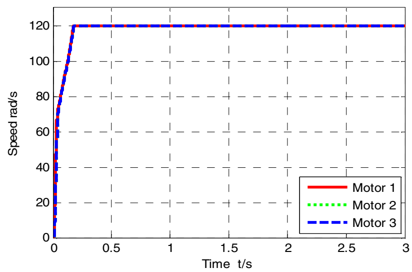
c) Speed error of motor #1 and motor #2 d) Speed error of motor #1 and motor #3

Fig. 10. Response of speed master-slave control of three motors with different parameters

Then we consider the load change case. The load torque of motor #1 change at $t = 1s$, the load torque of motor #2 change at $t = 1.5s$, the load torque of motor #3 change at $t = 2.5s$. The speed response and tracking errors of the master and slave motors are shown in Fig. 11.

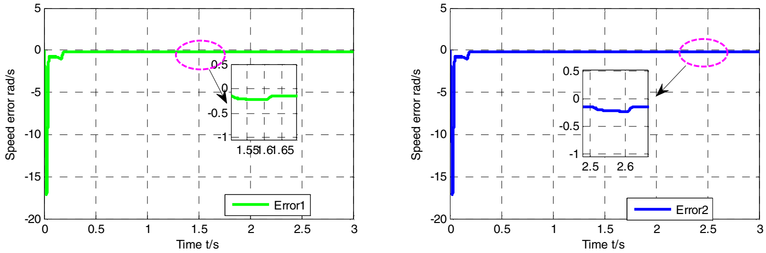


a) Load torque of motor #1, #2 and #3



b) Speed response of three motors

Fig. 11. Response of speed master-salve control of three motors with random load change



c) Speed error of motor #1 and motor #2 d) Speed error of motor #1 and motor #3

Fig.11. (*Continued*)

From the above results we can conclude that multi-motor system with fuzzy-PID based induction motor can achieve fast track performance and high synchronization accuracy. It can effectively eliminate the impact of motor parameter variations and abrupt load change of different motors.

6 Conclusion

In this paper, a Fuzzy-PID controllers of a field-oriented induction motor is proposed and implemented. The design of the controller is achieved using a simple fuzzy logic adaptation mechanism. Through simulation analysis, it can be concluded that the designed adaptive fuzzy-PID controller achieves a good dynamic behavior with various reference speed and a rapid setting time without overshoot. Meanwhile, its application to TBM cutter head driving system using master-slave synchronization techniques is accuracy which verify effectiveness of the proposed fuzzy-PID controller.

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