Fuzzy-PI Control for SRM Speed Regulation System

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Abstract. Switched reluctance motors have complex problems such as strong nonlinear characteristics, variable given speed, and large load disturbances. Aiming at the problem that the switched reluctance motor cannot adapt to the changing speed and large disturbance under the traditional PI control, this paper combines the fuzzy control and the PI control to form the fuzzy-PI controller, which constitutes the fuzzy adaptive speed regulation system of the SRM. Using fuzzy control to correct system parameters in real time can improve the situation that the traditional PI direct torque control system cannot effectively control the strong nonlinearity of SRM. By accurately establishing the nonlinear model of the SRM, and using the finite element simulation software to calculate the static characteristics of the motor's flux linkage, inductance and torque, the mathematical model of the SRM speed control system is established. Then it is shown by MATLAB/Simulink simulation, compared with the traditional PI control algorithm, the fuzzy-PI control algorithm can make the SRM system achieve better control effect in the case of variable speed and large load disturbance, improve the dynamic response of the system, reduce the overshoot, and enhance the robustness.

Keywords: Switched reluctance motor (SRM) · Fuzzy control · Fuzzy-PI controller · Self-adaption

1 Introduction

Switched reluctance motor (SRM) has the characteristics of simple structure, firmness, reliable operation, high efficiency, low cost and good speed regulation performance, etc. [1, 2]. In order to cope with the complex and changeable environment, researchers have optimized the motor speed control system.

The fuzzy sliding mode control method of the switched reluctance motor is studied [3, 4], and the nonlinear mathematical model of the switched reluctance motor is established, and the intelligent sliding mode controller is designed by combining the sliding mode controller and the intelligence of the fuzzy inference system. This reduces system overshoot and improves response speed. Cunhe et al. [5] proposed an adaptive neural network control algorithm with minimum learning parameters, which reduced the number of ideal weights of the neural network, further verified the stability of the

Q. Yang et al. (Eds.): ACCES 2022, LNEE 1012, pp. 1104–1113, 2023.
https://doi.org/10.1007/978-981-99-0357-3_114

control system by using the Lyapunov function, and improved the control accuracy of the motor speed. Xu, J et al. [6] uses fuzzy control to regulate the output gain of the single neuron PID controller, so that the SRM can automatically adjust the parameters in different states, and achieve a better control effect. E. S. Prasad [7] proposes an optimization method based on the current and torque control method, and analyzes the speed and torque of SRM using the Fractional Order PID controller based on the anharmonic optimization algorithm. Oshaba uses the ant colony optimization algorithm to find the optimal parameters and is used to estimate the behavior of the ant colony algorithm to prove that the proposed ant colony algorithm is superior to the genetic algorithm in optimizing PI controller [8]. [9] proposed a variable structure PI controller, which solved the problem of speed overshoot and improved the accuracy of the system at the same time. An overmodulation strategy for DBFC is presented [10], so that the flux linkage can be quantitatively adjusted, thereby improving the system speed regulation performance. [11] uses genetic algorithm combined with fuzzy controller to control the switched reluctance motor, which effectively enhances the robustness and reduces the overshoot.

For the strong nonlinear characteristics of the switched reluctance motor, this paper is designed so that the conventional PI control is added to fuzzy control, the system is adjusted on-line, the system overshoot and the response time are shortened, and the system stability is improved.

2 The Mathematical Model of SRM

The basic equation of SRM consists of the following three parts, The basic equation of SRM includes the following three parts, which are described separately next.

2.1 Circuit Equation

According to the KVL column, write the voltage balance equation of each phase as follow:

$$U_x = r_x \cdot i_x + \frac{d\psi_x(i_x, \theta)}{dt} \tag{1}$$

where U_x,r_x,i_x,Ψ_x is the voltage, resistance, current and flux linkage for x-phase. The flux linkage Ψ_x of the phase winding is a function of i_x and θ, in the case of ignoring the mutual inductance of the windings, the flux linkage is equal to the product of the inductance $L_x(\theta, i_x)$ and the current i_x,

$$\psi_x(\theta, i_x) = L_x(\theta, i_x) i_x \tag{2}$$

It can be obtained (3) by (1) and (2),

$$\begin{aligned} U_x &= r_x i_x + \frac{\partial \psi_x}{\partial i_x}\frac{di_x}{dt} + \frac{\partial \psi_x}{\partial \theta}\frac{d\theta}{dt} \\ &= r_x i_x + (L_x + i_x \frac{\partial L_x}{\partial i_x})\frac{di_x}{dt} + i_x \frac{\partial L_k}{\partial \theta}\frac{d\theta}{dt} \end{aligned} \tag{3}$$

2.2 Mechanical Equation

From the laws of mechanics, the SR mechanical equation can be deduced as shown in the formula:

$$T_e = \sum_{x=1}^{m} T_x = J\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} + T_L \quad (4)$$

where T_e, T_L, J, D are the electromagnetic torque of the motor, load torque, moment of inertia and the damping factor, respectively.

2.3 Electromechanical Contact Equation

The conversion of electromechanical energy of the motor can start from the one phase winding, it can calculate and describe according to the plane running trajectories of flux linkage and current. Since the mutual inductance between the windings is negligible, calculating electromagnetic torque can start from one phase of the motor, because of the principle of virtual work, the instantaneous torque at any point can be expressed as follow:

$$T_x(i_x, \theta) = \left.\frac{\partial W_x'(i_x, \theta)}{\partial \theta}\right|_{i_x = const} = \frac{1}{2} i_x^2 \frac{\partial L}{\partial \theta} = \frac{1}{2} i_x^2 \frac{dL}{d\theta} \quad (5)$$

where T_x,$W_x{}'(i_x,\theta)$ are the electromagnetic torque and magnetic common energy.

3 Traditional PI Direct Instantaneous Torque Control System

This article takes the 6/20 motor as an example, the core of torque control is direct instantaneous torque control, the core of the speed control system is traditional PI control. Use torque control as the inner loop and speed control as the outer loop, constitute the structure of direct instantaneous torque control double closed-loop system. The system includes control object SRM, drive circuit, torque hysteresis controller, torque estimation unit and PI speed regulator. The SRM double closed loop system is shown in Fig. 1.

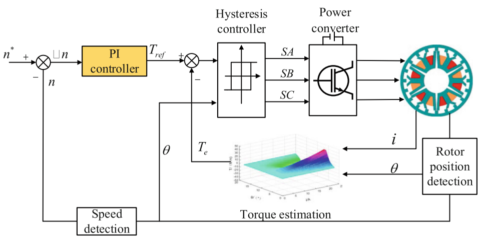


Fig. 1. Traditional PI SRM double closed-loop control system

3.1 Direct Instantaneous Torque Control Strategy

The direct instantaneous torque control of SRM takes the actual instantaneous torque as the controlled object, during motor operation, the difference between the expected torque value and the actual torque value is input to the torque controller, the resulting signal acts on the power converter, thereby, the torque control is realized by the control of the switching device.

Figure 2 is a three-phase SRM asymmetric half-bridge power converter. The three-phase A, B, C three-phase structure is independent, do not affect each other, IGBT is the main switching device, a freewheeling diode is connected at the same time, the control signal output by the torque controller acts on the IGBT, so as to realize the power on and off.

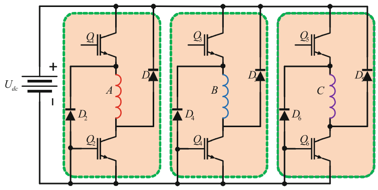


Fig. 2. Three-phase SRM asymmetric half-bridge power converter

In one phase, When the upper and lower IGBTs are turned on at the same time, forward voltage applied to the winding, in a state of excitation, that is to generate a "1" signal; when the lower IGBT turns on, zero voltage applied to the winding, in freewheeling state, that is to generate a "0" signal;

when the upper and lower IGBTs are turned off at the same time, reverse voltage applied to winding, that is to generate a "-1" signal. The three working states of asymmetric half-bridge power converters are shown in Fig. a-c in Fig. 3.

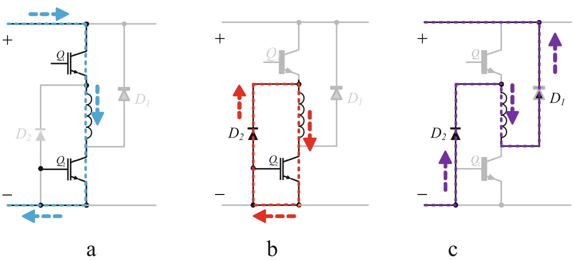


Fig. 3. Three working states of asymmetric half-bridge power converters

3.2 Traditional PI Control

According to the research status of motor speed, the traditional PI control method is most applied in the current research process, its advantage lies in its simple structure and convenient adjustment. It mainly consists of two parts: proportional link function and integral link function. The proportional link will immediately start regulation to reduce the error when the system generates errors, and the integral link is mainly used to eliminate static errors. Its control principle diagram is shown in the Fig. 4.

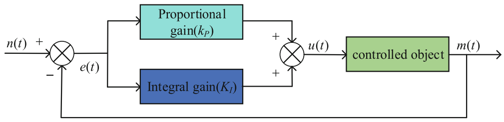


Fig. 4. PI control schematic

4 Algorithm Design

Conventional PI control can use fixed parameters to control control objects, and it is not easy to satisfy the control accuracy requirements under the influence of disturbances and other factors. For the above problems, the fuzzy PI controller of the instantaneous torque control system was designed using the fuzzy control algorithm combined with the PI control algorithm, and the motor speed was adjusted. A control block diagram is shown in Fig. 5. To achieve optimal control effects according to its difference between the given rotational speed and the rate of change between the real time rotational speed and the difference.

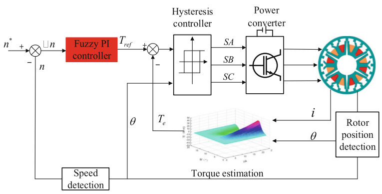


Fig. 5. Fuzzy PI control double closed loop system

4.1 Fuzzy-PI Controller Design

Figure 6 is the fuzzy PI controller, the controller selects the speed error E and the speed error rate of change EC as the input quantities, after fuzzification, fuzzy regularization, and defuzzification, the output quantities are the correction value Δk_p of the proportional coefficient k_p and the correction value Δk_i of the integral coefficient k_i, respectively. Thus online tuning of PI parameters, finally make the system achieve good control requirements and improve system stability.

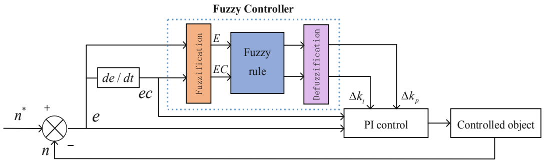


Fig. 6. Fuzzy PI controller

Among them, the online tuning formula of the fuzzy-PI controller to the traditional PI control algorithm is expressed as follow:

$$\begin{aligned} k_p &= k_p^{'} + \triangle\, k_p \\ k_I &= k_I^{'} + \triangle\, k_I \end{aligned} \tag{6}$$

where k'_p, k'_I are the original PI controller parameters respectively.

4.2 The Choice of the Basic Domain

Take 6/20 motor speed as the control amount, The basic domain of its error E is [−500, 500], the basic domain of error change rate EC is [-2000, 2000]; the basic domain of output corrections Δk_p and Δk_i are both [–100, 100]. The basic domain is a continuous numerical value, it needs to be discrete fuzzified, after discrete fuzzification, it is the fuzzy domain. In this article, the fuzzy universe of input and output are both set to [-6, 6], which is {−6, −5, −4, −3, −2, −1, 0, 1, 2, 3, 4, 5, 6}, the quantization level is level 13.

4.3 Scale Factors and Quantization Factors

To quantify the actual interval to the discrete interval required by the system, it is also necessary to design the scale factor and quantization factor. First, in the basic domain, set the error E and error rate EC as $[e_L, e_H]$ and $[ec_L, ec_H]$, fuzzy universe is {-n, -n + 1, …, −1, 0, 1, …, n-1, n}, the basic domains of output are $[u_{PL}, u_{PH}]$ and $[u_{IL}, u_{IH}]$, then the quantization factor of the input variable can be defined as:

$$k_e = \frac{2n}{e_H - e_L} \tag{7}$$

$$k_{ec} = \frac{2n}{ec_H - ec_L} \tag{8}$$

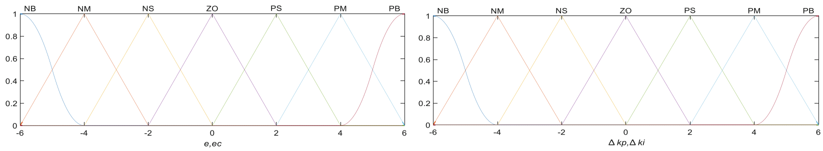
Similarly, the scale factor of the output variable can be defined, it needs to convert the discrete interval into the actual interval, which is the ratio of the basic universe of the output to the fuzzy universe, it can be defined as:

$$k_{up} = \frac{u_{PH} - u_{PL}}{2n} \tag{9}$$

$$k_{ui} = \frac{u_{IH} - u_{IL}}{2n} \tag{10}$$

4.4 Fuzzy Control Rules

In order to make the fuzzification process clearer, simpler and more intuitive, the input and output membership functions all use triangular membership functions. The language variables in this paper are selected as: negative large (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), positive large (PB). The fuzzy domains of input and output set as [-6, 6], then the fuzzy subset is { negative large, negative medium, negative small, zero, positive small, positive medium, positive large},it marked as {NB, NM, NS, ZE, PS, PM, PB}. And the membership functions of input and output are shown in Fig. a,b in Fig. 7.



(a) (b)

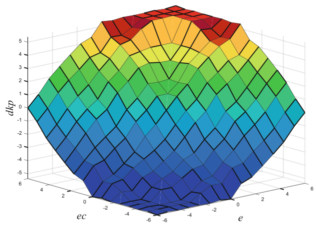
Fig. 7. Membership functions of the input and output varibles

Fuzzy rules are the core of fuzzy controllers, it is the key to determine the correction amount of the PI coefficient so that the system can achieve the expected optimization effect, on the basis of expert experience and practical experience of operators, and at the same time after a lot of simulation debugging, the fuzzy rule table of corrections Δk_p and Δk_i is obtained as shown in the Table 1.

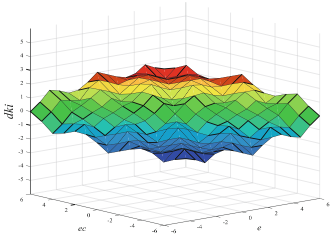
Table 1. Table of fuzzy rule for Δk_p and Δk_i

Δk_p|Δk_i		*ec*						
		NB	NM	NS	ZO	PS	PM	PB
e	NB	NB|PB	NB|PB	NB|PM	NB|PM	NM|PS	NS|PS	ZE|ZE
	NM	NB|PB	NB|PM	NB|PM	NM|PS	NS|PS	ZE|ZE	PS|NS
	NS	NB|PM	NB|PM	NM|PS	NS|PS	ZE|ZE	PS|NS	PM|NS
	ZO	NB|PM	NM|PS	NS|PS	ZE|ZE	PS|NS	PM|NS	PB|NM
	PS	NM|PS	NS|PS	ZE|ZE	PS|NS	PM|NS	PB|NM	PB|NM
	PM	NS|PS	ZE|ZE	PS|NS	PM|NS	PB|NM	PB|NM	PB|NB
	PB	ZE|ZE	PS|NS	PM|NS	PB|NM	PB|NM	PB|NB	PB|NB

According to the above fuzzy rules, make the surface graph of Δk_p and Δk_i in Matlab, the distribution map of the changing surface is shown in Fig. a,b in Fig. 8, By observing the changes of parameters Δk_p and Δk_i with the input, the characteristics of fuzzy PI control can be clearly displayed.



(a) Δk_p



(b) Δk_i

Fig. 8. Out spatial surface of Δk_p and Δk_i

5 Simulation Verification

This article with the help of MATLAB/SimuLink to build the model of the switched reluctance motor direct instantaneous torque double closed-loop control system, adjust the conventional PI control and fuzzy PI control respectively, meanwhile, the simulation and comparative analysis of motor starting, speed mutation and load mutation are carried out. The motor used for the simulation is a three-phase 6/20 switched reluctance motor with permanent magnet and the parameters are shown in Table 2.

Table 2. The main parameters of 6/20 SRM

Parameter	Value
Phase number	3
Stator and rotor poles	6/20
Rotor outer diameter (mm)	172
Rotor inner diameter (mm)	143.2
Stator outer diameter (mm)	142
Stator inner diameter (mm)	60
Stack length (mm)	100
length of air gap (mm)	0.6

Figure 9 shows the comparison of the simulated speed curves when the motor load is 5N at a set speed of 500 r/min. The traditional PI controller arrive at the steady state in 0.034 s, while the fuzzy PI controller arrive at the steady state in 0.024 s.

Figure 10 shows the comparison of the simulated speed curves when the motor load with a set speed of 500 r/min is abruptly changed. At 0.1s, the load abruptly changed from 0 N·m to 5 N·m, and at 0.2 s, it suddenly returned to 0 N·m. Finally, the traditional PI controller returns to steady state at 0.105 s and 0.218 s, while the fuzzy PI controller returns to steady state at 0.103 s and 0.215 s.

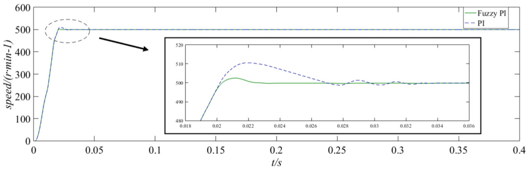


Fig. 9. Comparison of simulated speed curves when the motor load is set to 5N at a set speed of 500 r/min

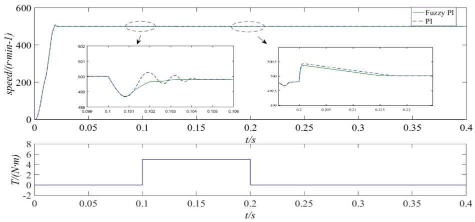


Fig. 10. Comparison of the simulated speed curves when the motor load with a set speed of 500 r/min

Figure 11 shows the comparison of simulation speed curves for sudden changes of motor no-load given speed between 500 and 300 r/min. At 0.1s, the given speed suddenly changes from 500 r/min to 300r/min, and at 0.2 s, it suddenly returns to 500 r/min. Finally, the traditional PI controller returns to steady state at 0.151 s and 0.222 s, while the fuzzy PI controller returns to steady state at 0.139 s and 0.216 s .

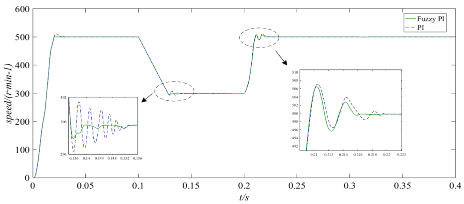


Fig. 11. Comparison of simulation speed curves for sudden changes of motor no-load given speed between 500 r/min and 300 r/min

6 Conclusion

A Fuzzy-PI controller is designed by using the fuzzy control algorithm combined with the PI control algorithm. It can make the PI parameters in the speed control system perform real-time self-adjustment. Using this fuzzy-PI controller can make the SRM speed control system respond faster, reduce overshoot, shorten the time required to return to a steady state, and high steady-state accuracy can be maintained. The stability of the double closed loop system in direct instantaneous torque control is improved.

After simulation comparison, its comprehensive control performance is better than the traditional PI speed controller.

Acknowledgments. This article is funded by the scientific and technological research project of Jiangxi Education Department (GJJ190448).

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