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Analysis and Design of Variable Structure Type Fuzzy Speed Controller for Field-Oriented Induction Motor Drive System

TAN Jingtao, FAN Zhun and QIN Yi
(Department of Control Science and Engineering, Huazhong University of Science and Technology · Wuhan, P. R. China)

Abstract: The paper uses variable structure control theory to analyze and design fuzzy speed controller for field-oriented induction motor drive system. Based on the above analysis, the method of adding a switching line feedforward term to the output of fuzzy controller to form a fuzzy-linear compound controller is put forward. Experiment results demonstrate that the compound controller obtains the robustness of fuzzy control but also reduces the torque ripple and steady state error as well as acquires fast transition of speed response. It is a highly advisable control alternative when both high-precision and fast response are demanded.

Key words: fuzzy control; variable structure control; PI control; induction motor
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感应电机磁场定向变结构型模糊变频调速系统的分析与设计

谭惊涛　范 □　秦 忆
(华中科技大学控制科学与工程系·武汉,430074)

摘要:运用变结构控制理论分析和设计感应电机磁场定向变频调速系统的模糊速度控制器,并在此基础上提出了在模糊控制器的输出增加开关线的前馈项构成模糊线性复合控制的方法.理论分析和实验结果均表明,这种复合控制方法,不仅保持了模糊控制器原有的鲁棒性,而且既减少了转矩抖振,提高了转速响应的稳态精度,又改善了转速响应的快速性.在高精度,快速响应的场合,这种速度调节器的模糊线性复合控制方法具有较大的实用价值.

关键词:模糊控制;变结构控制;PI 控制;感应电机

1 Introduction

Fuzzy logic controller (FLC) possesses strong robustness, which makes it a better choice than conventional PI controller for induction motor control in most cases. But it has several disadvantages. 1) It is usually a complex and difficult process to design a fuzzy logic controller. 2) There usually exists a static error. 3) It may cause the system chatter[1]. To deal with the above problems, this paper analyzes and designs a fuzzy controller using variable structure control theory (VSC), and puts forward a novel method of adding a switching line feedforward term to improve the performance of the fuzzy controller. Experimental results show that implementing this method can not only repress high frequency chatter of the system effectively, but also reduce the steady-state error and speed the response of the system.

2 Variable structure type FLC

When an FLC is designed using the VSC theory, a switching function $S(e,r)$ should first be generated and then the control rule base of FLC can be established accordingly. In Fig. 1, assume $K_e = \lambda K_d$, the switching function could be expressed as follows:

$$S(e,r) = \lambda e + r = \frac{1}{K_d}(E + R). \qquad (1)$$

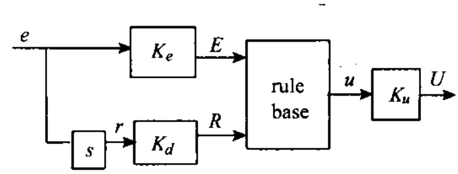

Fig. 1 A typical FLC

Literature [2] analyzes the kind of variable structure type fuzzy controller. Suppose the membership function of E, R and u is chosen as triangular function, the distance between peaks of the triangle is respectively A',

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A', B. The layers of the system could be illustrated as in Fig. 2.

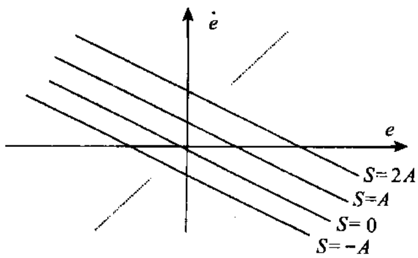


Fig. 2 Layers ofFLC

Suppose $A = \frac{A'}{K_d}$, then the kth layer covers the area with the switching function line $S = kA$ as its centerline and $2A$ as its width. Take the zero layer as an example, the centerline is $S = 0$ and the area covered could be expressed as $|S| \leqslant A$. It is obvious that each layer borders on neighboring layers. It is concluded in [2] that if we use the Mamdani's max-min method to infer and the center of gravity method to obtain a crisp output, then when the state of the system is located in the kth layer, the control law could be expressed as the following equation:

$$u = kB + B\gamma \frac{S^*(k)}{A}, \tag{2}$$

where

$$S^*(k) = S - kA, \tag{3}$$

which represents the distance between the state of the system and the centerline $S = kA$ in the phase plane. γ is a variable, ranging from $\frac{2}{3}$ to 1 according to the position the state of the system is located in the kth layer.

3 Fuzzy speed controller for induction motor

3.1 Basic scheme

In order to achieve smooth torque control and reduced steady-state error, an integral block is often added after the fuzzy control block to form Fuzzy-PI controller when fuzzy controller is utilized for the motor. Fig. 3 is a simplified block figure of this kind of speed control system of AC

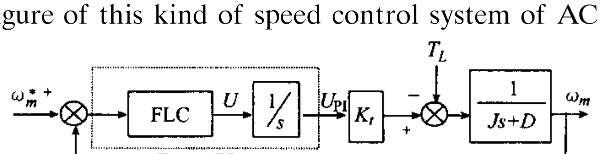


Fig. 3 Speed dirive system with FLC

motor. That is, a constant K_t is used to represent the inner loop, a vector controller. Fuzzy controller is used to control the outer loop. The system could be illustrated with state space method as follows:

$$\begin{pmatrix} \dot{e} \\ \dot{r} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & a \end{pmatrix} \begin{pmatrix} e \\ r \end{pmatrix} + \begin{pmatrix} 0 \\ -b \end{pmatrix} u, \tag{4}$$

where

$$e = \omega_m^* - \omega_m,$$

$$r = \dot{e} = -\frac{\mathrm{d}\omega_m}{\mathrm{d}t}, \ a = \frac{-D}{J}, \ b = \frac{K_t K_u}{J}.$$

From Equations (1), (3) and (4), the following equation could be derived

$$\dot{S}^*(k) = (\lambda + a) r - \frac{K_t K_u}{J} B \left(k + \gamma \frac{S^*(k)}{A}\right), \tag{5}$$

with the above results, we could examine the dynamics of the state of the system in the kth layer.

In the case of $k > 0$:

a) From Equation (5), when $0 < S^*(k) \leqslant A$, if

$$\frac{K_t K_u B}{J}\left(k + \gamma \frac{S^*(k)}{A}\right) > (\lambda + a) r, \tag{6}$$

then $\dot{S}^*(k) < 0$, the state of the system will move toward switching line definitely until the destination is reached and then continues to enter the next layer. Note the state of the system will have no chance to enter the next layer unless the above condition is fulfilled.

As non-linearity always exists in AC motor, Equation (4) could only be an approximate expression. To show this nonlinearity in the model, an additional term should be added in expression (6) and the condition is redefined as:

$$\frac{K_t K_u B}{J}\left(k + \gamma \frac{S^*(k)}{A}\right) > (\lambda + a)(r + f), \tag{7}$$

where, f stands for the influence on the transition process of the unmodeled dynamics.

b) When $-A \leqslant S^*(k) \leqslant 0$, the state of the system has already been at the $(k-1)$th layer. The procedure to analyze whether the state of the system could reach the switching line and enter the next layer is the same as in case a).

The case of $k < 0$ could be analyzed similarly. When $k = 0$, the state of the system is located within the area $|S| \leqslant A$. From Equation (2),

$$u = B\gamma \frac{S}{A} = \frac{B\gamma}{A'}(K_e e + K_d \dot{e}). \tag{8}$$

Obviously, it shows that the system runs under the control of nonlinear PI and will finally reach the equilibrium point.

3.2 Analysis of robustness about the system

To analyze the robustness of the control system, we examine what the response of the system is when the motor is initially started and/or when an arbitrary load is added suddenly.

a) When the motor is started, $e>0, r=0$, suppose currently $(k+1)A>S>kA$, then the state of the system is located in the kth layer. From Equation (2), the output of the FLC is: $(k-1)B>u>kB$, thus the torque of the motor increases, and $r<0$. At this time only when K_u is set big enough, the f can be suppressed and clauses for Equation (7) can be fulfilled, and thus render the system to arrive at the switching line $S=kA$ instantly and enter $(k-1)$ layer. Repeat the same process until the state of the system is settled in the 0th layer.

b) When an arbitrary load is added suddenly. $e=0$, $r>0$, suppose currently $(k+1)A>S>kA$, which means the state of the system is located within the kth layer, we get that the output of the fuzzy controller is $(k-1)B>u>kB$. Although the torque of the motor increases, the condition of Equation (7) could not be fulfilled if the load added is too big, thus the state of the system will move toward the $(k+1)$th layer. But as the torque accelerates, after a certain time, the condition of Equation (7) could be fulfilled, then the state of the system begins to move toward the lower layer until the zero layer is reached.

Based upon the above analysis the following conclusions could be reached:

1) The bigger K_u, the more robust the system, the faster the response. However, when K_u is too big, there is a risk for the system to induce a big chatter.

2) The bigger λ, the faster the response. But when λ is too big, not only the robustness of the system is decreased, but there is a risk for the system to be unstable.

3) From Equation (7) it could be seen that K_d does not play any role in the system. Instead it influences the width of the layer. As K_d is increased, the input of the fuzzy controller is easily saturated, and thus the system will be more likely to be unstable. On the other hand, as K_d is decreased, K_e decreased accordingly, the precision of the system will be decreased too.

4 Fuzzy-linear compound control

4.1 Influence of quantification and saturation to the system performance

In a drive system, fuzzy controller is usually implemented through retrieval of a fuzzy decision table to meet the demand of real-time control. Suppose $A'=B=2$, the fuzzy control table could be illustrated as Table 1. Generally, the fuzzy controller that is based on the decision table of Table 1, cannot lead to excellent performance both in the transient and static periods.

Table 1 The lookup decision table

R	E												
	−6	−6	−5	−4	−3	−2	−1	0	1	2	3	4	5
6	0	1	2	3	4	5	6	6	6	6	6	6	6
5	−1	0	1	2	3	4	5	5	6	6	6	6	6
4	−2	−1	0	1	2	3	4	5	6	6	6	6	6
3	−3	−2	−1	0	1	2	3	4	5	5	6	6	6
2	−4	−3	−2	−1	0	1	2	3	4	5	6	6	6
1	−5	−4	−3	−2	−1	0	1	2	3	4	5	5	6
0	−6	−5	−4	−3	−2	−1	0	1	2	3	4	5	6
−1	−6	−5	−5	−4	−3	−2	−1	0	1	2	3	4	5
−2	−6	−6	−6	−5	−4	−3	−2	−1	0	1	2	3	4
−3	−6	−6	−6	−5	−5	−4	−3	−2	−1	0	1	2	3
−4	−6	−6	−6	−6	−6	−5	−4	−3	−2	−1	0	1	2
−5	−6	−6	−6	−6	−6	−5	−5	−4	−3	−2	−1	0	1
−6	−6	−6	−6	−6	−6	−6	−6	−5	−4	−3	−2	−1	0

The two inputs of the fuzzy controller E, R are quantified which means when $i-0.5 \geqslant R > i+0.5$ and $j-0.5 \geqslant E > j+0.5$ we assume $R=i, E=j$. At this time, the output of the fuzzy controller corresponds to the ith row and jth column of the lookup decision table, which is noted as $u(i,j)$. As could be seen from the table $u(i,i)=0$, which means the output of the controller is zero in the vicinity of the switching line $S=0$, regardless of the absolute value of the input e and r. This is the main factor that gives rise to chatter and steady state error. To reduce steady state error the integral of e has to be inserted to the controller[3].

As could also be seen from the table that the maximum increase of the output is $6K_u$ during each sample time. Consequently, when speed error is relatively big, K_u largely determines the time interval taken for the electromagnetic torque to reach an appropriately big value. Input saturation could also slow down the response of the system. For example, in the cases when $e=200$ r/min and $e=1500$ r/min in this paper, E should both be set as 6, which is the maximum value of the input the system could provide. Moreover, the input will not increase once the condition R

$= -6$ is fulfilled in both the cases. It is necessary to constrain the abrupt change of the error near the equilibrium point/target value to avoid the occurrence of overshot. But it makes no good to constrain the change of the error and will slow down the response of the system when the state of the system still has a long way to go to reach the equilibrium point.

4.2 Analysis and implementation of compound control

In [4], a method of control in which the sliding line is feedfowarded is developed to enhance the robustness of the drive using sliding mode speed controller. Similarly, in this paper a feedforward item with switching line function is inserted into the fuzzy controller to speed up the transient of the system and reduce the steady state error. Here

$$u_{\text{hybrid}} = u + k_\sigma S \tag{9}$$

is implemented to be the ouput of the new fuzzy controller, where K_σ is a parameter to be determined. Substituting (2) into (9), the above equation could be rewritten as

$$u_{\text{hybrid}} = k(B + k_\sigma A) + \left(\frac{B\gamma}{A} + k_\sigma\right)S^*(k). \tag{10}$$

It could be seen that it is the sum of two nonlinear terms, the first term is related to the layer the state of the system is located in, the second term is related to the specific position the state of the system is located within the layer. Obviously, Equation (10) has a similar format as Equation (2), it could be concluded that the system using this controller has strong robustness as the former fuzzy controller.

Implementing integral algorithm on both sides of Equation (10), the following equation can be derived:

$$\int_0^t u_{\text{hybrid}} \mathrm{d}t = \int_0^t u \,\mathrm{d}t + \int_0^t k_\sigma(\lambda e + \dot{e})\mathrm{d}t. \tag{11}$$

As could be seen from Equation (11), the introduction of a feedforward term of swithching line has resulted in a linear proportional-integral unit in parallel with the fuzzy-PI controller. As shown in Fig. 4, FLC is still implemented through retrieval of the fuzzy decision table. Since in the vicinity of $S = 0$, the output of FLC is zero, the system is solely driven by the linear PI controller, so that the torque chattering in the steady state can be avoided, and smooth operation obtained. In addition, when the speed error is relatively large, the linear PI controller has large output, so the system has a fast response.

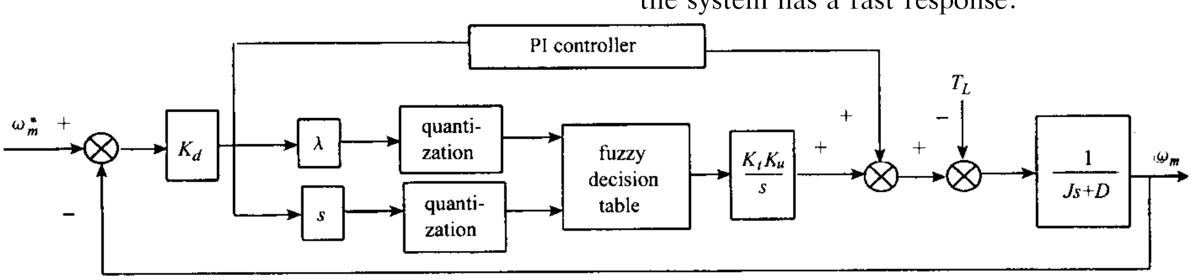


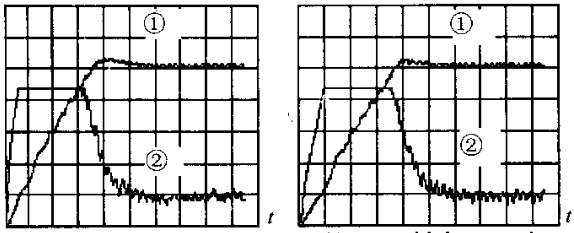
Fig. 4 Speed drive system with fuzzy – linear compound control

5 Experimental results

The control algorithms presented in the previous section were experimentally tested. The experimental system was constituted of a three-phase insulated gate bipolar transistor (IGBT) inverter with the dc-link voltage equal to 320V, a 0.37-kW four-pole three phase IM with a 3600-pulse incremental encoder. Rotor speed was derived from encoder pulses using a first-order digital filter. The system is a digital-analogue system whose core is a microprocessor 80196KC. The current controller is a large linear proportional regulator implemented by analogue circuit. Vector control mode is indirect and sampling interval of the speed loop is 1ms.

Fig. 5(a) and Fig. 5(b) are respectively experiment results when K_u with moderate gain and K_d with different gain. From Fig. 5, we know that as the system performance has no noted variation when K_d varies in a large range, and so K_d is set moderate for the following experiments.

It could be seen from Fig. 6 that when K_u is set larger the system has a faster response. No overshoot but torque ripples seriously on this occasion.

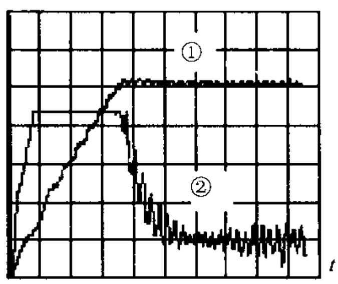


(a) K_d with smaller gain (b) K_d with larger gain

①:speed, 240 r·min⁻¹/div;

②:torque current command, 0.75 A/div; time: 0.1s/div

Fig. 5 FLC when k_d with different gain

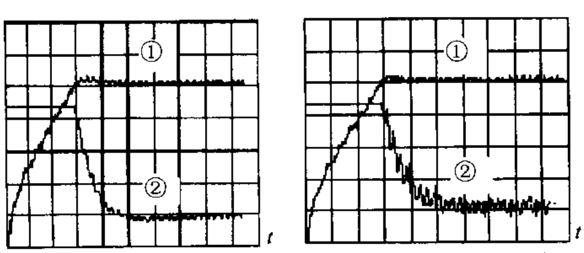


①:speed, 240 r·min⁻¹/div;

②:torque current command, 0.75 A/div; time: 0.1s/div

Fig. 6 FLC when k_u with larger gain

Experimental results of the system implementing the compound control put forward in this paper are shown in Fig. 7 when K_u is reduced appropriately and PI control is added on the basis of the former FLC. As can be seen that reducing K_d appropriately could enhance the operating range of the linear control solely and help to reduce the steady state error. Compared with fuzzy control, the compound control could not only obtain faster response but also repress the vibration of the torque effectively.



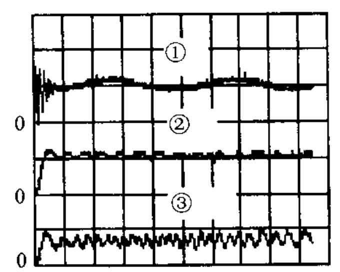
(a) K_d with smaller gain (b) K_d with larger gain

①:speed, 240 r·min⁻¹/div;

②:torque current command, 0.75 A/div; time: 0.1s/div

Fig. 7 Compound control when k_d with different gain

To verify the robustness of the system, a low speed experiment is introduced in this paper. The result shows: as motor runs at low speed, because of the existence of error of rotor position measurement, the system has strong nonlinearity when implementing indirect vector control, when simple PI control is implemented in speed loop control, the response of the output demonstrates some characteristics of low-frequency vibration after entering stable state. Although fuzzy control possesses strong robustness and is insensitive to this kind of nonlinearity, there exist noted steady-state error and high-frequency chatter in the response of the system output. Fig. 8 demonstrates the performance of speed control of the motor driver system with set speed 25.6 r/min when implementing PI control, FLC and fuzzy-linear compound control respectively. As can be seen from Fig. 8 that compound control has strong robustness as fuzzy control and is free from high frequency chatter and steady-state error, thus repress the nonlinear characteristic of the system effectively.



① : PI controller;

② : fuzzy-linear controller;

③ : FLC; time:0.1s/div;speed:24 r·min⁻¹/div

Fig. 8 Comparison of responses with various controllers

6 Conclusion

This paper analyzes fuzzy controller using variable structure control theory, and based upon this puts forward a novel method to improve robustness by feedforwarding a sliding line in a fuzzy controller. It is concluded that this method results in a compound of fuzzy and linear control. This compound control has a faster response and no torque ripples than fuzzy control and more strong robustness than conventional PI control. As it is a good control method combining the favorable qualities of both fuzzy control and conventional PI control, it is a highly advisable control alternative when both high-precision and fast response are demanded.

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