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Tunnel Ventilation Control Based on PID Parameters' Fuzzy Self-tuning

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Abstract: The energy consumption of highway tunnel operation is big. And tunnel ventilation accounts for a large proportion in the electrical load of tunnel. There will be great energy-saving effects if the frequency conversion technology was applied to the tunnel ventilation system. But parameter setting is a difficult problem while controlling the system of frequency conversion ventilation by using PID control mode. To realize the on-line self-tuning of PID parameters by combining fuzzy control and PID control mode. The control performance of the system will be better under different working conditions. Achieve the goal of energy saving in operation.

Keywords: PID; Fuzzy control; Ventilation of tunnel; Frequency conversion

1. Introduction

There are numerous mountains and a large amount of highway tunnels in our country. The long tunnel accounts for about 62% of the total mileage of highway tunnel. The energy consumption of highway tunnel operation is really big. Especially the ventilation and lighting account for more than 90% of the energy consumption [1]. The electricity consumed by ventilation system of long tunnel and extra-long tunnel power takes up about 70% of the electricity load. It is quite clear that ventilation system of tunnel accounts for a large proportion in the electrical load and the consumption of electricity is amazing.

Jet fan is widely used in ventilation system of tunnel and long tunnels will also include axial flow fan. Motor rated power is always more than the largest possible peak load power of about 30%. And the duration of the peak load is often far less than the total running time. The light load running time of motor often accounts for most of its operating life. But the tunnel fan adopts the sequencing control method now. It can only control the fan one after one open or close separately. Even in the case of light load, motor works according to the high power too and cause unnecessary power consumption.

owing to the formula:

$$n = \frac{60f(1-s)}{p}.$$

f—frequency(Hz); s-- slip ratio; p-- number of pole-pairs; n-- motor speed(r/min). It can be seen that the motor speed is proportional to the frequency.

And according to the principle of fluid mechanics and Electrical Machinery,

$$\frac{Q_1}{Q_2}=\frac{f_1}{f_2};\frac{H_1}{H_2}=(\frac{f_1}{f_2})^2;\frac{P_1}{P_2}=(\frac{f_1}{f_2})^3;$$

Q-- Blower Air Volume; H-- Blower air pressure; P-- Power of fan; f-- power frequency(r/min).

It is observed that air volume is directly proportional to motor speed, air pressure is directly proportional to square of motor speed, power of fan is directly proportional to cube of motor speed. So the air volume is proportional to the power frequency, air pressure is directly proportional to square of the power frequency, power of fan is directly proportional to cube of the power frequency. The motor power will drop more as the air volume reduced and fan speed dropt. When change air volume by the way of frequency control of motor speed, the motor power will drop 49% as air volume drop 20%; the motor power will drop 87.5% as air volume drop 50%.

So the frequency conversion technology is applicable to tunnel ventilation system. Regulate load and control AC motor by changing the power supply frequency. It could reduce the power consumption, reduce the loss and prolong the service life of equipment (Starting current is small: improve frequency and voltage with the acceleration of the motor, the starting current is limited under 150% rated current. Motor can start smoothly; Starting current is 6~7 times of rated current if the motor start directly without the frequency conversion technology.), and so on.

Tunnel ventilation system should adopt PID control method. At present, the PID control has been widely used in engineering. But it is difficult for traditional PID control method to modulate parameters [2]. Modulation of parameters is very important to the performance of the system, therefore, to realize the on-line self-tuning of PID parameters by combining fuzzy control and PID control mode. The control performance of the system will be better than the performance of traditional PID control method under any operation condition.

2. Use the Design Index of CO Concentration to Design Fuzzy PID Control Method for Ventilation

CO concentration is an important index of the tunnel ventilation. There are parameter settings of CO for highway tunnel ventilation in "Guidelines for Design of Ventilation of Highway Tunnel". In normal traffic, the design concentration of CO inside the tunnel can take the value according to Table 1.

Table 1. Design concentration of CO: d

The length of the highway tunnel(m)	≤1000	≥3000
d co(ppm)	150	100

Remark: Take the value by inserting value method when the highway tunnel is 1000~3000m long [3].

For example, build the CO concentration fuzzy controller of two inputs and three outputs for 1 km long tunnel. Input variables are the deviation of CO concentration and the change rate of deviation. Output variables are KP, Ki and Kd of the PID parameters. Then change the power output frequency of inverter to control the fan speed through the PID adaptive adjustment of the size of the output data. And ensure that the CO concentration of highway tunnel is in the permitted range.

Digital PID formula after a discretization process:

$$u(k)=K_p e(k)+K_i T\sum_{j=0}^{k}e(j)+\frac{K_d}{T}[e(k)-e(k-1)]\}\ ,$$

$u(k)$ --output controlled quantity of the controller of the first k sampling time; $e(k)$ -- deviation of the first k sampling time; K_p -- proportional gain; K_i -- integral gain; K_d -- differential gain.

Find out fuzzy relationship between the three controller parameters (K_p , K_i , and K_d) and deviation e, change rate of deviation ec. Constantly test the values of e and ec in operation and input the data to controller. Then the controller online adjust the three parameters based on fuzzy control rules to meet the different requirements of different e and ec to the controller parameters. So that the controlled object has a good dynamic and static performance.

3. Fuzzy-PID Controller

3.1. Set the domain of input and output variables and membership function of fuzzy subset

The design concentration of CO is 150ppm for 1km long highway tunnel according to the specification. In order to prevent the lag of the adjustment, confirm the value as 140 parts per million.

Deviation of the CO concentration is defined as e.

$$e = s - C_{co}\ .$$

s -- design concentration of CO (ppm); C_{co} --measured concentration of CO(ppm).

The actual concentration range of CO is 120~160ppm in the process of fan operating. So the variation region of CO concentration is -20~20ppm.

Transform the variable X of the real domain of CO concentration to the discrete domain (-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6) by using the formula of y=3(140-x)/10. e=140-x. y=3e/10. The fuzzy subset is set to {NB, NM, NS, Z, PS, PM, PB}. Elements of subset respectively represent large negative, middle negative, small negative, zero, small positive, middle positive, large positive. NB indicates that pollutant concentration is much higher than set value. NM indicates that pollutant concentration is higher than set value. NS indicates that pollutant concentration is a bit higher than set value. Z indicates that pollutant concentration is the same as set value. PS indicates that pollutant concentration is a bit lower than set value. PM indicates that pollutant concentration is lower than set value. PB indicates that pollutant concentration is much lower than set value.

The change rate of deviation of CO concentration is defined as ec.

$$e_c = e_t - e_{t-1}\ .$$

The actual domain of ec is -10~10. Transform the variable of the real domain to the discrete domain (-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6) by using the formula of y=12x/20=3x/5. The fuzzy subset is set to { NB, NM, NS, Z, PS, PM, PB }. Elements of subset respectively represent large negative, middle negative, small negative, zero, small positive, middle positive, large positive. NB indicates that the increasing speed of pollutant concentration is fast. NM indicates that the increasing speed of pollutant concentration is ordinary. NS indicates that the increasing speed of pollutant concentration is slow. Z indicates that change rate of pollutant concentration is zero. PS indicates that decreasing speed of pollutant concentration is slow. PM indicates that decreasing speed of pollutant concentration is ordinary. PB indicates that decreasing speed of pollutant concentration is fast.

Kp's stable setting range is 0.1~999.9%; Ki's stable setting range is 1~21; Kd's stable setting range is 0~30. The initial PID parameters of PLC have initial value: Kp0 is set to 280%, Ki0 is set to 14.0, Kd0 is set to 3.8.

The fuzzy subset of output variables are all set to { NB, NM, NS, Z, PS, PM, PB }. Quantify the three parameters to discrete area (-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6).
The choice of membership function: Select the triangle membership function. This kind of pointed shape fuzzy subset has high resolution and control sensitivity.

3.2. The set of fuzzy rules

The PID controller parameters adjustment are as follows:
(1)Kp is in proportion to reflect the deviation of the system, it is used to speed up the system response speed and improve accuracy of adjustment. The bigger the Kp, the faster the response speed, the higher the accuracy. But it is easy to cause overshoot even lead to instability. If Kp is too small, it will reduce the accuracy and make slow response and extend the time of adjustment. Static and dynamic characteristics of the system will be poor.
(2) The effect of Ki is to eliminate the steady-state error, the bigger the Ki, the faster the elimination. But if Ki is too large, there will be integral saturation phenomenon in early response process and lead to overshoot. If Ki is too small, it will be hard to eliminate static error and also affect accuracy of adjustment.
(3) The effect of Kd is to improve the dynamic performance of the system. It can forecast the change of deviation and inhibit the change of deviation in any direction in the response process. If Kd is too large, it will extend the time of adjustment and reduce the anti-interference ability [4]. There will ahead of the brake in response process.
In the system design, two fuzzy controller input variables are all 7 levels fuzzy partition. The system contains 49 fuzzy rules. Write out the fuzzy reasoning according to the characteristics of ventilation control and the function of Kp, Ki, Kd for the system control.
Rule1 : if (e is NB) and (ec is NB) then (kp is PB) and (ki is NB) and (kd is PS);
Rule2 : if (e is NB) and (ec is NM) then (kp is PB) and (ki is NB) and (kd is NS);
……
Rule49 : if (e is PB) and (ec is PB) then (kp is NB) and (ki is PB) and (kd is PB).
Adjustment rules of Kp, Ki, Kd are shown in Table 2-4.

Table 2. Adjustment rules of Kp

e	ec						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PM	PS	Z	Z
NM	PB	PB	PM	PS	PS	Z	NS
NS	PM	PM	PS	PS	Z	NS	NS
Z	PM	PM	PS	Z	NS	NM	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	PS	Z	NS	NM	NM	NM	NB
PB	Z	Z	NM	NM	NM	NB	NB

Table 3. Adjustment rules of Ki

e	ec						
	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NM	NM	NS	Z	Z
NM	NB	NB	NM	NS	NS	Z	Z
NS	NB	NM	NS	NS	Z	PS	PS
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PS	PM	PB
PM	Z	Z	PS	PS	PM	PB	PB
PB	Z	Z	PS	PM	PM	PB	PB

Table 4. Adjustment rules of Kd

e	ec						
	NB	NM	NS	Z	PS	PM	PB
NB	PS	NS	NB	NB	NB	NM	NS
NM	PS	NS	NB	NM	NM	NS	Z
NS	Z	NS	NM	NM	NS	NS	Z
Z	Z	NS	NS	NS	NS	NS	Z
PS	Z	Z	Z	Z	Z	Z	Z
PM	PB	PS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

3.3. Fuzzy inference

The fuzzy relations between the input and output of each fuzzy conditional statement adopt Mamdani inference method. For example, for Kp: R1＝NBe×NBec×PBKp; R2＝NBe×NMec×PBKp; …… R49＝PBe×PMec×NBKp. The formula of fuzzy relation matrix R is:

$$R = \bigcup_{i=1}^{49} R_i \ .$$

The fuzzy relationship matrix R of Ki and Kd can be obtained in a similar way. Three output of fuzzy reasoning can be obtained by U＝(e×ec)$^{\circ}$R.

3.4. Defuzzification

It is referred defuzzification to convert the fuzzy quantity to a precise amount. This controller uses gravity method in defuzzification process. Gravity method is a special case of weighted average method. Computation formula is as follows:

$$C(k) = \frac{\sum_i m_c(c_i)\ c_i}{\sum_i m_c(c_i)}$$

Every calculated fuzzy element X can obtain a corresponding precise value in real field. Conversion formula is as follows:

$$K_p = 0.1 + X / \frac{12}{9.99 - 0.1};$$

$$K_i = 1 + X / \frac{12}{21 - 1};$$

$$K_d = 0 + X / \frac{12}{30 - 0}$$

Plug into the formula: $K_P = K_p + K_{p0}$; $K_I = K_i + K_{i0}$; $K_D = K_d + K_{d0}$.

Obtain the value of K_P, K_I and K_D, then change the current value of the input parameters of PLC. Then achieve the goal of adaptive adjustment of parameters.

4. The Establishment of the Fuzzy Controller in MATLAB

Run a "fuzzy" in the MATLAB command window to get into the fuzzy editor, and establish a Mamdani type file of "fuzzy PID. FIS". Then establish membership functions and the quantization interval of the input variable e and output variable ec. Fuzzy reasoning method "And" adopts "prod"; "Or" adopts "max"; "Implication" adopts "prod"; "Aggregation" adopts "sum"; "Defuzzification" adopts "centroid". Thus establish the fuzzy PID control system structure model, as shown in Figure 1.

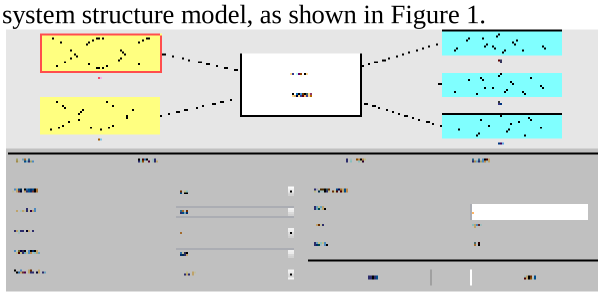

Figure 1. Fuzzy PID control system

Membership function of input and output obtained by the fuzzy logic toolbox of MATLAB is shown respectively in Figure 2 and Figure 3.

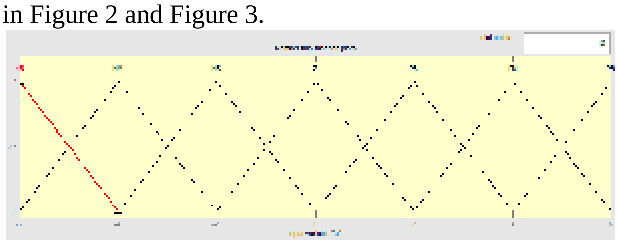

Figure 2. Membership function of e and ec

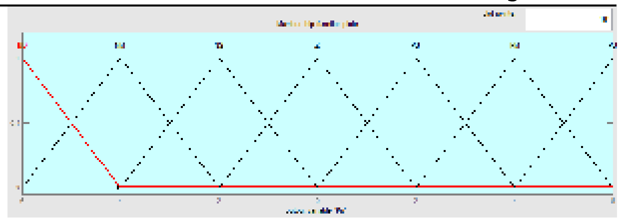

Figure 3. Membership function of Kp, Ki and Kd

Establish the fuzzy rules as shown in Figure 4-6:

1. If (e is NB) and (ec is NB) then (Kp is PB)(Ki is NB)(Kd is PS) (1)
2. If (e is NB) and (ec is NM) then (Kp is PB)(Ki is NB)(Kd is NS) (1)
3. If (e is NB) and (ec is NS) then (Kp is PM)(Ki is NM)(Kd is NB) (1)
4. If (e is NB) and (ec is Z) then (Kp is PM)(Ki is NM)(Kd is NB) (1)
5. If (e is NB) and (ec is PS) then (Kp is PS)(Ki is NS)(Kd is NB) (1)
6. If (e is NB) and (ec is PM) then (Kp is Z)(Ki is Z)(Kd is NM) (1)
7. If (e is NB) and (ec is PB) then (Kp is Z)(Ki is Z)(Kd is NS) (1)
8. If (e is NM) and (ec is NB) then (Kp is PB)(Ki is NB)(Kd is PS) (1)
9. If (e is NM) and (ec is NM) then (Kp is PB)(Ki is NB)(Kd is NS) (1)
10. If (e is NM) and (ec is NS) then (Kp is PM)(Ki is NM)(Kd is NB) (1)
11. If (e is NM) and (ec is Z) then (Kp is PS)(Ki is NS)(Kd is NM) (1)
12. If (e is NM) and (ec is PS) then (Kp is PS)(Ki is NS)(Kd is NM) (1)
13. If (e is NM) and (ec is PM) then (Kp is Z)(Ki is Z)(Kd is NS) (1)
14. If (e is NM) and (ec is PB) then (Kp is NS)(Ki is Z)(Kd is Z) (1)
15. If (e is NS) and (ec is NB) then (Kp is PM)(Ki is NB)(Kd is Z) (1)
16. If (e is NS) and (ec is NM) then (Kp is PM)(Ki is NM)(Kd is NS) (1)
17. If (e is NS) and (ec is NS) then (Kp is PS)(Ki is NS)(Kd is NM) (1)
18. If (e is NS) and (ec is Z) then (Kp is PS)(Ki is NS)(Kd is NM) (1)

Figure 4. Fuzzy rules table

19. If (e is NS) and (ec is PS) then (Kp is Z)(Ki is Z)(Kd is NS) (1)
20. If (e is NS) and (ec is PM) then (Kp is NS)(Ki is PS)(Kd is NS) (1)
21. If (e is NS) and (ec is PB) then (Kp is NS)(Ki is PS)(Kd is Z) (1)
22. If (e is Z) and (ec is NB) then (Kp is PM)(Ki is NM)(Kd is Z) (1)
23. If (e is Z) and (ec is NM) then (Kp is PM)(Ki is NM)(Kd is NS) (1)
24. If (e is Z) and (ec is NS) then (Kp is PS)(Ki is NS)(Kd is NS) (1)
25. If (e is Z) and (ec is Z) then (Kp is Z)(Ki is Z)(Kd is NS) (1)
26. If (e is Z) and (ec is PS) then (Kp is NS)(Ki is PS)(Kd is NS) (1)
27. If (e is Z) and (ec is PM) then (Kp is NM)(Ki is PM)(Kd is NS) (1)
28. If (e is Z) and (ec is PB) then (Kp is NM)(Ki is PM)(Kd is Z) (1)
29. If (e is PS) and (ec is NB) then (Kp is PS)(Ki is NM)(Kd is Z) (1)
30. If (e is PS) and (ec is NM) then (Kp is PS)(Ki is NS)(Kd is Z) (1)
31. If (e is PS) and (ec is NS) then (Kp is Z)(Ki is Z)(Kd is Z) (1)
32. If (e is PS) and (ec is Z) then (Kp is NS)(Ki is PS)(Kd is Z) (1)
33. If (e is PS) and (ec is PS) then (Kp is NS)(Ki is PS)(Kd is Z) (1)
34. If (e is PS) and (ec is PM) then (Kp is NM)(Ki is PM)(Kd is Z) (1)
35. If (e is PS) and (ec is PB) then (Kp is NM)(Ki is PB)(Kd is Z) (1)
36. If (e is PM) and (ec is NB) then (Kp is PS)(Ki is Z)(Kd is PB) (1)

Figure 5. Fuzzy rules table

37. If (e is PM) and (ec is NM) then (Kp is Z)(Ki is Z)(Kd is PS) (1)
38. If (e is PM) and (ec is NS) then (Kp is NS)(Ki is PS)(Kd is PS) (1)
39. If (e is PM) and (ec is Z) then (Kp is NM)(Ki is PS)(Kd is PS) (1)
40. If (e is PM) and (ec is PS) then (Kp is NM)(Ki is PM)(Kd is PS) (1)
41. If (e is PM) and (ec is PM) then (Kp is NM)(Ki is PB)(Kd is PS) (1)
42. If (e is PM) and (ec is PB) then (Kp is NB)(Ki is PB)(Kd is PB) (1)
43. If (e is PB) and (ec is NB) then (Kp is Z)(Ki is Z)(Kd is PB) (1)
44. If (e is PB) and (ec is NM) then (Kp is Z)(Ki is Z)(Kd is PM) (1)
45. If (e is PB) and (ec is NS) then (Kp is NM)(Ki is PS)(Kd is PM) (1)
46. If (e is PB) and (ec is Z) then (Kp is NM)(Ki is PM)(Kd is PM) (1)
47. If (e is PB) and (ec is PS) then (Kp is NM)(Ki is PM)(Kd is PS) (1)
48. If (e is PB) and (ec is PM) then (Kp is NB)(Ki is PB)(Kd is PS) (1)
49. If (e is PB) and (ec is PB) then (Kp is NB)(Ki is PB)(Kd is PB) (1)

Figure 6. Fuzzy rules table

Click “View Rules” can enter interface for fuzzy control rules, as shown in Figure 7 and Figure 8.

When e=-1.09, ec=0.938, then Kp=0.15; Ki=-0.15; Kd=-2.58.

Click "View Surface" can enter interface to look for the corresponding relations between output and input variables, as shown in Figure 9~11.

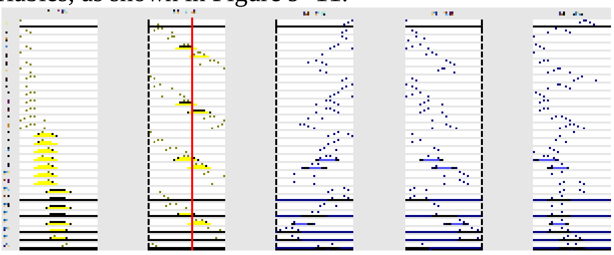

Figure 7. Fuzzy control rules

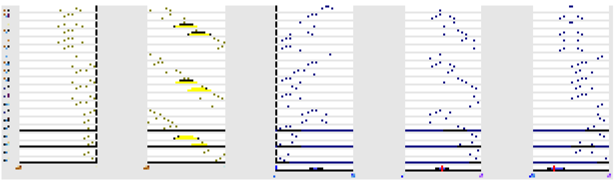

Figure 8. Fuzzy control rules

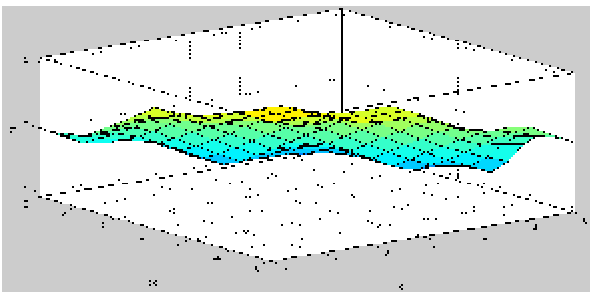

Figure 9. The corresponding relation between Kp and input variables

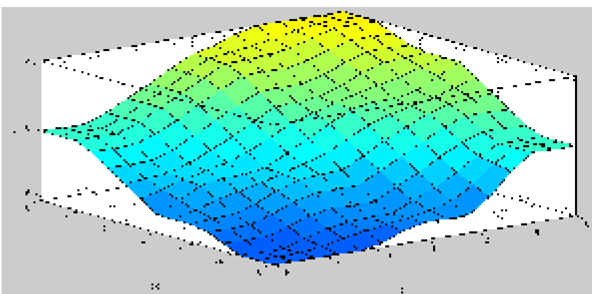

Figure 10. The corresponding relation between Ki and input variables

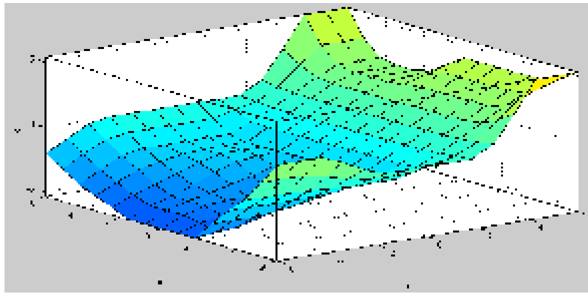

Figure 11. The corresponding relation between Kd and input variables

5. Conclusion and Recommendation

It can realize the on-line self-tuning of PID parameters by combining fuzzy control and PID control mode. This method will help the system fully exerts the performance of variable frequency ventilation control system and provide a feasible scheme for the realization of the variable frequency ventilation control in tunnel.

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