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Research Article

Fuzzy Control Technique of Auxiliary Ventilation in Heading Laneway

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Abstract: Aimed at air quantity requirement and energy conservation at normal ventilation as well as safety and quickly at methane discharging, this study discussed the design process of self learning fuzzy controller based on basic fuzzy model. Firstly, the control system block is described. Then basic fuzzy model is introduced. Auxiliary ventilation is time-varying parameters, nonlinear and large hysteresis system. Therefore, the design includes the normalization, reference model, time-delay, sample cycle, calculation method and control rule modification. The partial fan speed adjustment adopts Direct Torque Control (DTC). Based on theoretical analysis and simulation, combing DSP chip with Intelligent Power Module (IPM), auxiliary ventilation fuzzy control adjusting speed experiment system is established. Experimental results have shown that the system can safely and efficiently fulfill the function of normal ventilation and methane discharging.

Keywords: Auxiliary ventilation, DTC, heading laneway, self learning fuzzy controller

INTRODUCTION

Coal is one of the most important energy resources in China. However, methane explosion in heading ways results in a lot of life losses during coal production brings disaster to many families. Methane concentration control in heading ways has become more and more critical in the national coal production safety agency. According to statistics, most of the coal mine methane explosions occur in the heading laneway. Methane drainage drilling before excavation can effectively reduce the overall concentration of coal seam methane and coal and methane outburst phenomenon.

Many researchers paid more attention to explore the corresponding control strategy. Li Zhonghua designed methane discharging equipment for Pingmei Coal Group which includes an electrical control box, three methane concentration sensors and an air flow regulator (Li and Liang, 1999).

The device regulates air flow based on the feedback from the methane concentration sensors. Chen Hao and Xie Guilin develops KJK1-60/660 type auxiliary fan which automatically discharges accumulated natural methane (Zhu and Wang, 2003). It can achieve various states from full closed to full open using a Silicon Controlled Rectifier (SCR). Li Jianfeng designed a partial ventilation device using inverter. Therefore, some agreements have been reached that Variable Voltage Variable Frequency (VVVF) control is the accepted way to deal with this problem. In view of complex, uncertain and coupling characteristics, it is difficult to build a perfect mathematical model to describe real situation of the heading laneways. With the development of control theory, intelligent control has been introduced into the auxiliary ventilation system. Fuzzy control theory has obtains great concern since it can simulate the characteristics of the human mind. Zhu and Wang (2003) applied fuzzy control theory to deal with auxiliary ventilation system 3. It described a two-input single-output fuzzy control model for auxiliary fan. Moreover, fuzzy control theory has also been used in ventilation for a long-distance tunnel (Ercument, 2003).

According to the character of air flow and methane concentration distribution in heading laneway, (Shufang *et al*., 2010) design four-inputs one-output dual-model fuzzy controller to meet the ventilation requirement both at normal ventilation state and methane exceeding limited state.

Based on previous studies, this study pays more attention to self learning fuzzy control model design in order to improve the adaptability. DTC is adopted to fulfill the control strategy. The control strategy and speed adjustment of auxiliary fan are simulated in MATLAB. Based on theoretical analysis and simulation results, an auxiliary ventilation experiment platform including DSP and IPM is built. Finally, a prototype is developed using Program Logic Controller (PLC) and inverter.

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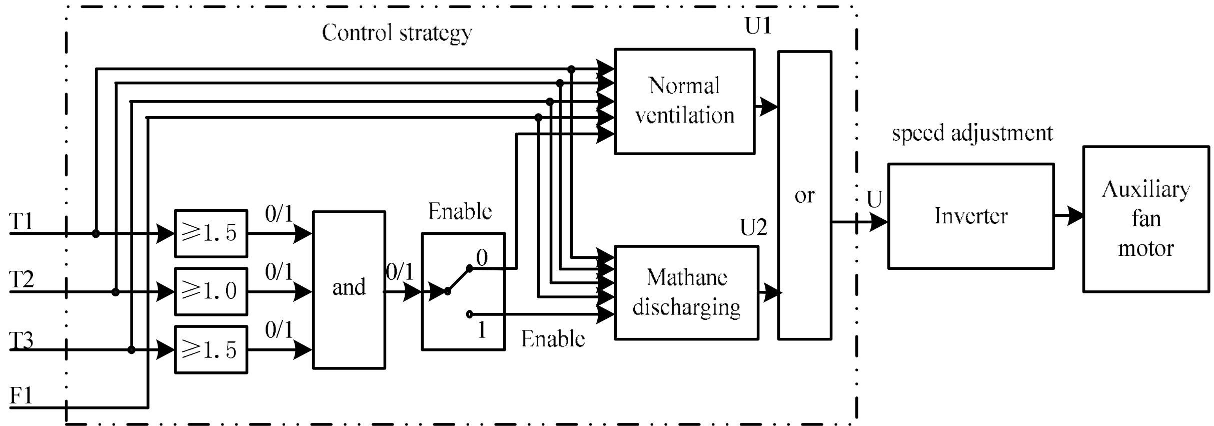


Fig. 1: Control system block of auxiliary ventilation

This study introduces the design process of auxiliary ventilation self learning fuzzy control system in heading laneway. Taking T1 SISO self learning fuzzy controller as example, the design process includes the normalization, reference model, time-delay, sample cycle, calculation method and results. DTC speed adjustment is taken to fulfill the control strategy. Experimental results show that the system can achieve real-time performance and saving energy efficiency.

METHODOLOGY

Control system block of auxiliary ventilation: Based on the analysis, a control system block of auxiliary ventilation system is built, as shown in Fig. 1. It includes three parts, auxiliary fan, controller (including sensors) and duct. To complete this research, two parts work are needed. One is the control strategy establishment; the other is auxiliary fan speed adjustment.

According to analysis, it is difficult to build an accurate mathematical model among T1, T2, T3, F1 and motor speed. Modern control theory brings forward several intelligent control methods, such as neural network, fuzzy logic, adaptation control and so on. Among them, fuzzy control can imitate the decision-making process of the human, thus, fuzzy logic is employed to solve this problem.

In this part, self learning fuzzy controller is designed. In fact, Shufang *et al*. (2010) has designed basic fuzzy model. In this study, what cannot be explained is described in detail. And new design thoughts are put forward.

Fuzzy control model of auxiliary ventilation: As we known, normal ventilation state and methane discharging state are needed in heading laneway. Moreover, three methane concentration sensors and one wind speed sensor are utilized in order to offer information for control strategy. On the basis of analysis above, a four-inputs and one-output dual-mode fuzzy control model which can meet two different working principles is designed.

Each sub model includes four inputs and one output, respectively. Input values are three methane concentration sensor signals T1, T2, T3 and a wind speed sensor signal F1, while the output is frequency of auxiliary fan motor. Sub models switch through Switch 1 and Switch 2. If the value of T1 is under power off point, i.e., 1.5%, the result of Switch1 is 0. If T1 is greater than or equal to power off point, the output of Switch1 is 1. As the input signal Switch 2, the output of Switch1 decides working states. If Switch1 is 0, normal ventilation model is selected; otherwise, methane discharging model is selected.

The definition indicates that a MISO can be decomposed to many SISO fuzzy controllers 6. Control function can be satisfied if proper computation rule is chosen. In heading laneway, four input variables affect on motor speed with different degree. Moreover, coupling exits among four input variables. Used weight calculation, output value of MISO fuzzy controller (U) can be obtained as shown in Eq. (1):

$$U = f(w_1T1 + w_2T2 + w_3T3 + w_4F1) \tag{1}$$

where,

U : Frequency of converter, mean fuzzy relation

wi (i = 1, 2, 3, 4) : The weight of inputs, 0<wi<1, w1+w2+w3+w4 = 1

Self learning fuzzy controller design process: Auxiliary ventilation is time-varying parameters, nonlinear and large hysteresis system. Control rule is not enough to meet the control objectives. Through the system of online learning capabilities to produce more appropriate control rules will be a better choice. Many on line learning methods are put forward. Aim to time-varying parameters, nonlinear and large hysteresis character, the self learning fuzzy control system is chosen since it is simple and easy to fulfill. Taking T1

SISO self learning controller design as an example, the design process is described.

It can be depart into four steps to design: output modification; increment model; advance modification Control rule modification. Combing with auxiliary ventilation system, the design process includes the normalization, reference model, time-delay, sample cycle, calculation method and results. The maximum inscribed circle of the palm.

Normalization and reference model: The error and error change rate of inputs have been defined in dual-model fuzzy control model. In order to facilitate the calculation, the domain of its normalized to [-1, 1] here. In this study, taking T1 self-learning fuzzy control subsystem at normal ventilation as an example, parameter calculation is introduces in detail.

As to T1 SISO model, error $e^* = e_{max} = 0.7$, error change rate $e_c^* = e_{cmax} = 0.35$, the basic domain and is set to [-5, 5], the domain after normalized is [-1, 1]. After normalized, fuzzy control model is expressed in Eq. (2). Because T1 desire value is 0.8, then the reference model output expected response selection $Y^*(k) = 0.8$:

$$
\underset{\sim}{R}_D = \begin{array}{cccccc}
\underset{\sim}{A}_i \underset{\sim}{B}_j : & NB & NS & NO & PS & PB \\
PB & -1 & -0.75 & -0.5 & -0.25 & 0 \\
PZ & -0.75 & -0.5 & -0.25 & 0 & 0.25 \\
PS & -0.5 & -0.25 & 0 & 0.25 & 0.5 \\
ZO & -0.25 & 0 & 0.25 & 0.5 & 0.75 \\
NS & 0 & 0.25 & 0.5 & 0.75 & 1 \\
NZ & 0.25 & 0.5 & 0.75 & 1 & 1 \\
NB & 1 & 1 & 1 & 1 & 1
\end{array} \quad (2)
$$

Time-delay: When determining the time-delay, effect of delay duct is ignored. T1 is placed at mixed field, to eliminate the error, take average methane concentration in 2 min as the actual methane concentration. Then the time-delay was determined as follows: When the system is in steady state, choose a methane concentration values at T1, such as 1.0, observe how many times is needed when it drops from 1.0 to 0.9, record. Then record the time drops from 0.9 to 0.8. Each time 0.1 methane concentration is considered. Measurement length of heading laneway is 1000 m, the cross section area is 14.5 m^2. Average 20 sets of data to ensure the accuracy of time-delay, we obtain time-delay of T1 is 35 sec. However, T2, T3 time-delay is much greater than T1, because it will take a longer time for air flow approaching the position of T2, T3. By measurement, time-delay of T2, T3 and F1 is 8, 11 and 2 min, respectively.

Sample cycle: According to Shannon Sampling Theorem, $v \geq 2B$ should be met to ensure no information lost and no additional information gained. For hysteresis auxiliary ventilation system, sampling cycle should longer to acquire effective data. Synthesize real condition, 2 min is chosen as sampling cycle.

Calculation method: Set the desired output response of T1 SISO controller is Y^*, the actual output response of Y, deviation $E = Y^* - Y$ after domain normalized, error change rate $E_c = [E(k) - E(k-1)]/T$, the ideal response can be expressed as $Y^* = Y + \Delta Y$, $\Delta Y = (E + EC)/2$. Set MY, ME, ME_c are Y, E, E_c after modification. Since $E = Y^* - Y$, $MY = Y + \Delta Y$, $ME = E - \Delta Y$, $ME_c \approx E_c - \Delta Y$, then:

$$ME + ME_c \approx E + E_c - 2\Delta Y \approx 0 \quad (3)$$

Equation (3) shows that system can acquire desire response by *f*. Then the increment function of T1 is Eq. (4):

$$J(E, EC) = (E + EC)/2 \quad (4)$$

$\Delta Y(k) = M \Delta U(K - \tau - 1)$, M is normalized value of ΔU, $M = 1/5$. The self-learning fuzzy control algorithm for each step of the calculation as follows: For the sampling time *k*, the desired output response is $Y^*(k)$, the actual output response is $Y(k)$, then the error is $E(k) = Y^*(k) - Y(k)$, the error change rate is $EC(k) = [E(k) - E(k-1)]/T$. The desire response is shown in Eq. (5) from reference model $\Delta Y(k)$, we can get Eq. (5):

$$\Delta U(k - \tau - 1) = 5\Delta Y = 2.5[E(k) + E_c(k)] \quad (5)$$

From reference model $\Delta Y(k)$, we can get Eq. (6):

$$\Delta U(k - \tau - 1) = 5\Delta Y = 2.5[E(k) + E_c(k)] \quad (6)$$

Since each step control value is saved in memory and then $\Delta U(k - \tau - 1)$ can be acquired. Control value after modification $U^*(k - \tau - 1)$ can be expressed in Eq. (7):

$$U^*(k - \tau - 1) = U(k - \tau - 1) + \Delta U(k - \tau - 1) \quad (7)$$

Change $U^*(k - \tau - 1)$ into fuzzy value $\underset{\sim}{A}_u^*$, take each step control value *f* before and fuzzy to $\underset{\sim}{A}_1, \underset{\sim}{A}_2, \ldots \underset{\sim}{A}_k$.

A new control rule will be formed as shown in Eq. (8):

$$E_u^* = [E_1 \wedge (\underset{\sim}{A}_1 \times \underset{\sim}{A}_u^*) \times [E_2 \wedge (\underset{\sim}{A}_2 \times \underset{\sim}{A}_u^*)] \times \cdots \times [E_k \wedge (\underset{\sim}{A}_k \times \underset{\sim}{A}_u^*)] \tag{8}$$

Self-learning fuzzy control is based on the deviation between the output response and the ideal response to modify or create new rules by online. For simple, set air flow cross section is always A_0 and the speed is v_0. It can reach at excavation heading face at speed v_0. Then fresh air mixed with the methane emission from excavation heading face. The methane emission amount is $Q_{me}t$. l_0 is the distance between duct to excavation heading face . l_1 is the distance between excavation heading face to T1. v_1 is the speed of mixed methane. After $t = l_0 / v_0 + l_1 / v_1$, the methane mixed with fresh air at T1 then return along the laneway. Δl is the Unit length. According to section two, the methane average concentration in the whole laneway $\overline{c}$ can be rewritten as Eq. (9):

$$c_2 = c_1 t + \frac{Q_B t}{A \Delta l} = c_1 t + \frac{v_0 A_0}{A \Delta l} t = c_1 t + \frac{v_0 A_0}{A} t \tag{9}$$

Taking $y(k)$ and $y(k-1)$ as the methane concentration at k and $k-1$, 30 sec as time delay, 1s as simulation step, then self learning fuzzy control can be expressed in Eq. (10):

$$y(k) = (\frac{l_0}{v_0} + \frac{l_1}{v_1}) y(k-1) + \frac{A_0}{A} u(k-30) \tag{10}$$

New control rule can be acquired in Eq. (11):

$$\underset{\sim}{R}_{D1} = \begin{array}{c|ccccc} \underset{\sim}{A}_i \underset{\sim}{B}_j: & NB & NS & ZO & PS & PB \\ PB & -1 & -0.7 & -0.5 & -0.2 & 0 \\ PZ & -0.8 & -0.6 & -0.4 & -0.1 & 0.1 \\ PS & -0.5 & -0.3 & -0.1 & 0.2 & 0.4 \\ ZO & -0.2 & 0 & 0.2 & 0.4 & 0.7 \\ NS & 0 & 0.2 & 0.5 & 0.7 & 0.9 \\ NZ & 0.4 & 0.6 & 0.8 & 1 & 1 \\ NB & 1 & 1 & 1 & 1 & 1 \end{array} \tag{11}$$

SIMULATION RESULTS

Simulation curve is shown in Fig. 2. The curve is relationship between the sampling time and output value.

In the Fig. 8, the first shock occurred when the system runs. The system is not easy to stabilize at the first run because the system features is a big lag and time-varying characteristics. The third time running result is slow to stabilize, starting from the eighth the system gradually stable, indicating the end of the learning process. In order to facilitate visual comparison before and after learning the rules change, Fig. 3 shows T1 control surfaces.

SPEED ADJUST AND EXPERIMENT

As stated above, auxiliary ventilation system is divided into two parts, the control strategy established and auxiliary fan speed adjustment. Through Fuzzy control model, fan motor speed is decides according to four input signals, while through speed adjuster, given speed is achieved. Nowadays, Auxiliary fan motor

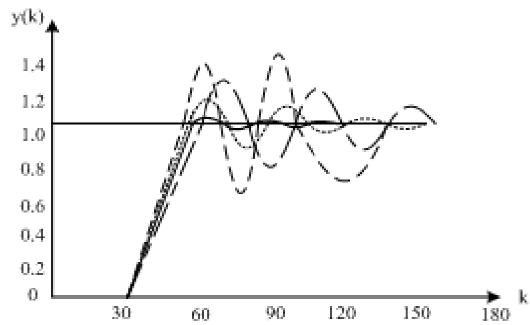


Fig. 2: The response of T1 simulation output
_ _ _ _ : The running result at the first time; _ . _ . _: The third result; ------ : The fifth result; —— : Seventh result

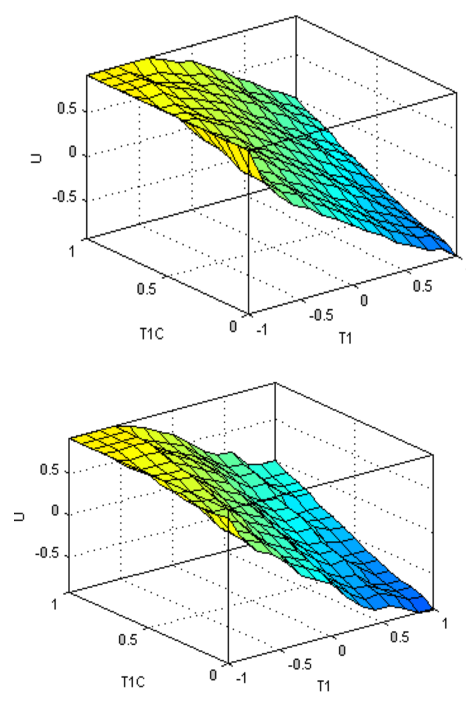


Fig. 3: Control surface before and after self learning of T1

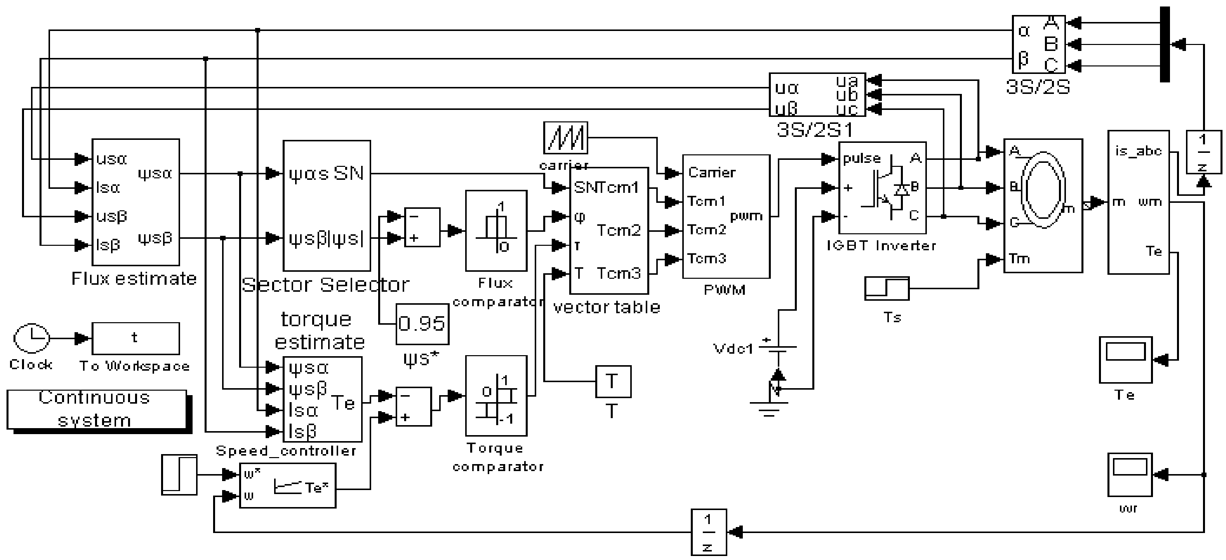


Fig. 4: Simulation model of DTC adjustable speed system

Table 1: Partial simulation data at normal ventilation

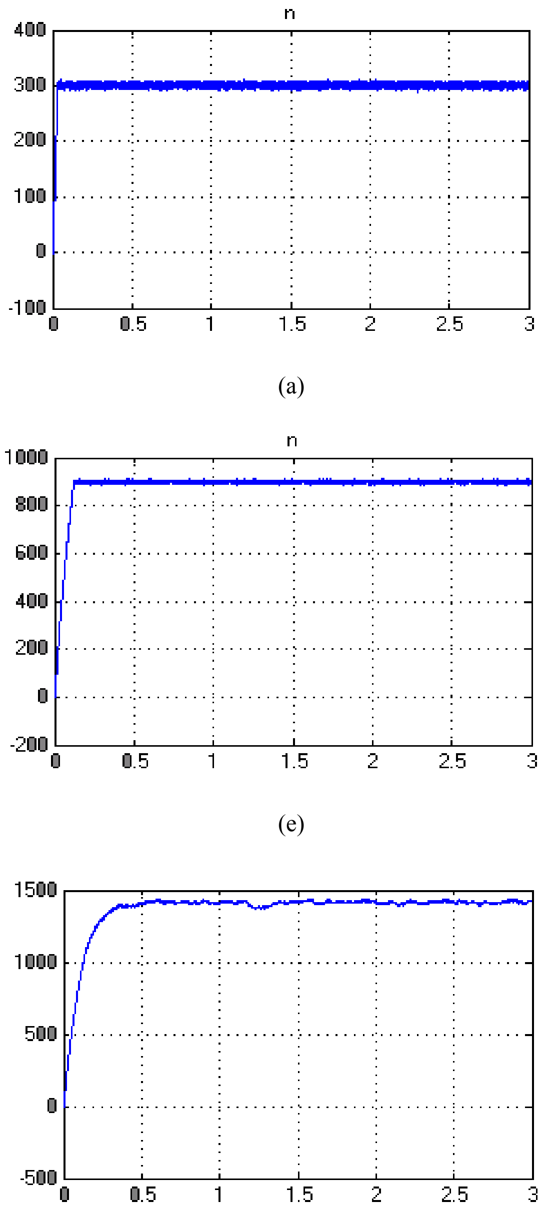
T1	T1C	T2	T2C	T3	T3C	F1	F1C	Speed
0.3 (error)	-0.4	-0.2	-0.2	-0.3	-0.4	0.75	-0.50	570
0.5 (real)	-0.2	0.8	-0.1	1.1	-0.2	1.75	- 0.25	750
	0.0		0.0		0.0		0.00	900 (e)
	0.2		0.1		0.2		0.25	1050
	0.4		0.2		0.4		0.50	1170 (f)
0 (error)	-0.4	0.0	-0.2	0.0	-0.4	0.0	-0.50	750 (d)
0.8 (real)	-0.2	0.6	-0.1	0.8	-0.2	2.5	- 0.25	930
	0.0		0.0		0.0		0.00	1080
	0.2		0.1		0.2		0.25	1230
	0.4		0.2		0.4		0.50	1350 (h)
-0.6 (error)	-0.4	0.4	-0.2	0.6	-0.4	-1.5	-0.50	1260
1.4 (real)	-0.2	0.2	-0.1	0.2	-0.2	4.0	-0.25	1350 (h)
	0.0		0.0		0.0		0.00	1400
	0.2		0.1		0.2		0.25	1450 (i)
	0.4		0.2		0.4		0.50	1450 (i)

Table 2: Partial simulation data at methane discharging

T1	T1C	T2	T2C	T3	T3C	F1	F1C	Speed
-1.4 (error)	-0.3	-0.4	-0.2	-0.6	-0.4	-1.5	0.5	300 (a)
2.4 (real)	0.0	1.0	0.0	1.4	0.0	0.1	0.0	450
	0.3		0.2		0.4		-0.5	690
-1.05 (error)	-0.3	-0.2	-0.2	-0.3	-0.4	-0.75	0.5	510
2.05 (real)	0.0	0.8	0.0	1.1	0.0	0.85	0.0	600 (c)
	0.3		0.2		0.4		-0.5	630
-0.7 (error)	-0.3	0.0	-0.2	0.0	-0.4	0.0	0.5	570
1.7 (real)	0.0	0.6	0.0	0.8	0.0	1.6	0.0	630
	0.3		0.2		0.4		-0.5	780

adopts open-loop constant *V/f* ratio adjusting speed mode. While, DTC system is dual close-loop adjustable-speed system, the inside loop adopts flux and torque close-loop. The flux error and the torque error are gained by flux and torque hysteresis comparers and then the space voltage vector is selected reasonably according to the flux error, the torque error and stator flux sector. Applying dual closed-loop control, DTC adjust speed accurately and rapidly (Murat *et al*., 2010). In this study, the construction of DTC and simulation model is described in Fig. 4. Simulation parameters are shown as following:

Three-phase asynchronous motor parameters: Rated Power P_N = 12 kW, Rated frequency f_N = 50 Hz, ψ_N = 0.95 Wb, R_s = 0.16891 Ω, R_r = 0.13973 Ω, L_s = 0.02877



(a)

(e)

(i)

Fig. 5: Partial simulation result

H, L_m = 0.02777 H, L_r = 0.02894 H, Number of pole pairs n_p = 2, moment of inertia J = 0.1349 kg.m^2.

Control system parameters: ψ_s^* = 0.95 Wb, given speed 80 rad/s, Load torque given T_L = 20 N.m, Torque limit amplitude 45 N.m, The ratio of the speed PI regulator coefficients K_p = 80, integral coefficient K_i = 500.

Partial simulation data at two states are shown in Table 1. Table 2 shows the partial simulation data at methane discharging. Moreover, partial simulation results are shown in Fig. 5.

EXPERIMENT AND PROTOTYPE

In terms of dual-mode fuzzy control strategy and DTC speed adjustment mentioned above, a DSP experiment platform with TMS320LF2407 and Intelligent Power Module (IPM) is established to testify validity of design, shown in Fig. 6. The rated voltage is 660 V while the rated input current of converter 82.5 A. The range of frequency variety is between 0~50 Hz while the range of control voltage 0~9 V. The power of internet adapter motor is 75 kW, rated current 82.5 A, rated speed 3000 r/min.

Acceptable simplification is adopted since it is difficult to simulate heading laneway environment in coal mine. Moreover, common three-phase asynchronous motor is used in experiment instead of auxiliary fan. Zero to one hundred mA analog current is employed to replace the values of three methane sensors while 1~5 mA for the value of wind speed sensor. The correlation exits between the value of wind speed sensor and the value of wind speed at duct outlet. Basically, the control strategy is available.

After that, a prototype with Program Logic Controller (PLC) and inverter is designed. The system block is shown in Fig. 7.

In the prototype, a high concentration of methane sensor KG9001B, two low-concentration methane sensor KG9701 and speed sensor KGF3 are adopted as input signal, Siemens S7-200 PLC is taken as controller. The value of the sensor and the current in a normal state of ventilation or methane emission are shown on the screen in TD200. The picture of prototype is shown in Fig. 8.

DATA ANALYSIS AND DISCUSSION

When T1, T2 and T3 is in the normal range, system choose normal ventilation states. As state in fuzzy set, the desire value of T1, T2 and T3 is 0.8, 0.6 and 0.8 in turn. In order to energy conservation, the speed of

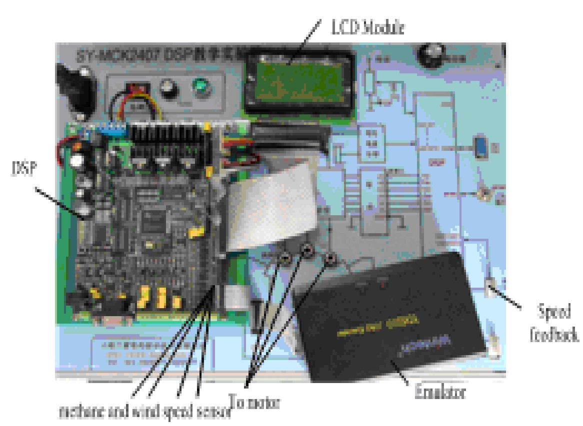


Fig. 6: Experiment platform

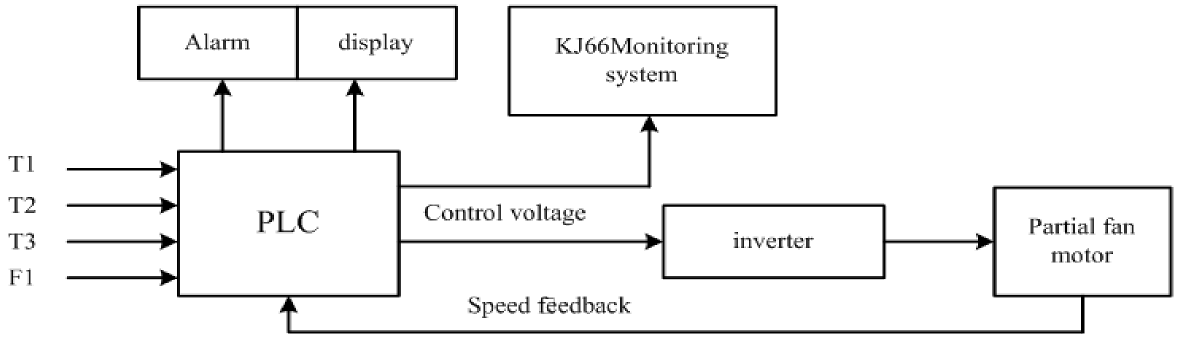


Fig. 7: The prototype system block

Fig. 8: The prototype picture

motor decreases when the T1 is below 0.6%, T2 is below 0.5%, T3 is below 0.6% since the methane concentration is lower than desire value. The speed of motor maintains when the T1 is between 0.6~0.9%, T2 is between 0.5~0.7%, 0.6~0.9%, T3 is between 0.6~0.9% that is close to desired value. The speed of motor increases to dilute methane when the T1 methane concentration is between 0.9~1.4%, T2 is between 0.7~1.0%, T1 is between 0.9~1.4%. That is beyond desired value. Therefore, energy saving and safety is ensured at normal ventilation. When T1 reaches to 1.5% or above, system chooses methane discharging states. Compared with normal ventilation, motor speed is lower. To discharge methane safely and efficiently, methane concentration of T2, T3 must be close to desired value. The speed of motor increases for efficiency when the T2 is 0.5%, T3 is 0.6%. While the speed of motor maintains when the T2 is between 0.5~0.8%, T3 is between 0.6~0.9%. Furthermore, for safety, the speed of motor decreases when the T2 is between 0.8~1.0%, T3 is between 0.9~1.4%.

Known from analysis above, dual-mode fuzzy control strategy and DTC speed adjustment are effective to complete safely and efficiently the task of normal ventilation and methane discharging in heading laneway.

This study tries to synthesis fluid analysis and control technique to deal with the auxiliary ventilation problem. During research, we just find heading laneway is a complicated system; the information about heading laneway is not enough. With the depth of heading laneway, so many field have not sensor to detect, is it offer probability methane exploration? How much methane concentration sensors are needed to know the most information? How they are assignment in reason? For further study, more experiment and simulation about air flow and methane heading laneway should be taken.

CONCLUSION

This study introduces the design process of auxiliary ventilation self learning fuzzy control system in heading laneway. Taking T1 SISO self learning fuzzy controller as example, the design process includes the normalization, reference model, time-delay, sample cycle, calculation method and results. DTC speed adjustment is taken to fulfill the control strategy. Experimental results show that the system can achieve real-time performance and saving energy efficiency.

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