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The Intelligent Control System of the Freezing Station in Coal Mine Freezing Shaft Sinking

Xiaoliang Zheng[1,2], Yelin Hu[2] , Zhaoquan Chen[2]
[1]School of Mining and Safety Engineering Anhui University of Science and Technology, Huainan, Anhui 232001, China
[2]School of Electric and Information Engineering Anhui University of Science and Technology, Huainan, Anhui 232001, China
Tel: 0554-6668584
Corresponidng author, e-mail: zhengxl@aust.edu.cn, yelhu@aust.edu.cn, zqchen@aust.edu.cn

Abstract

In order to address the issue of low degree of automation and huge waste of electric energy of the equipment in drilling engineering freezing station which adopts the freezing method of coal mine, we need to design an intelligent control system to control both the brine pump and double stage ammonia screw compressor. According to the actual cooling need in freezing project, this new system is able to adjust the working condition of the equipment so as to optimize the supply as needed. Also, the temperature and flow of the brine are controlled by fuzzy decoupling controller, and variable frequency controller is adopted in the brine pump to change the motor drive speed and finally adjust the flow of the brine appropriately, besides, the reasonable start-stop unit is used in the compressor to control the temperature of the brine. It has turned out that this intelligent control system features a better control performance, and thus has increased the automation level and prolonged the using life of the whole system as well as saved a large amount of electric energy and decreased the electricity cost of construction enterprises.

Keywords: *freezing shaft sinking, freezing station, control system, fuzzy control, energy saving*

1. Introduction

The coal resource accounts for over 70% of the total primary energy in China and will still play a dominant role in our energy consumption structure for quite a long time in the future. Considering the trends of deep mine exploration in our coal mine construction and shaft or other underground projects in deep alluvium or incompetent bed, the freezing method is an efficient way to cross the unstable stratum [1]. There are many difficulties and risks in deep mine freezing engineering, such as broken tube, leaking brine, insufficient strength of the frozen wall and large frozen-heave force, so the engineering technicians have done a lot of successful research in order to better control the freezing construction and accomplish the shaft project safely with a high quality, which includes two aspects: one is the real-time supervision of all the parameters during freezing, for example, the temperature and flow of the brine, the temperature field of the frozen wall and the frozen-heave force of the tjaele etc. [2-7], therefore, they can help the them to know the condition of the frozen wall promptly; the other is the control of freezing station, including the monitoring and control of the equipment working condition at freezing station, however, it’s still limited to the automation control design of the brine pump [8-10], at present, the equipment control in freezing station is still realized manually by the technicians.

Given the low automation level and huge waste of electric energy of the artificial controlled freezing station, setting up an automatic control system for the usage of double stage ammonia screw compressor and brine pump to control both the compressor and brine pump promptly according to the actual cooling need, which can increase the automation level of freezing station, prolong its using life and save lots of electricity, as well as decrease the construction cost, therefore, it has perfectly answered the call of energy conservation and emission reduction policy in our country.

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2. The Structure of the System

The freezing project applies ammonia cycle refrigeration system to cool the brine, in which process the low-temperature brine takes the heat of the formation away through the freezer in the pump so that it can form a frozen wall. The large scale equipment in the freezing station mainly includes the screw compressor and brine pump, both with large power. Take the Fengjing freezing station in Yang village of SDIC XINJI ENERGY Co., Ltd for an example, which is equipped with 24 double stage ammonia screw compressors and 3 brine pumps (with another 6 for standby use), and the power of the motor drive includes 280W, 250kW and 200Kw and so on. The earlier compressor and pump were manually adjusted, and the former controlled capacity-adjusting valve; the later controlled the import and export valve opening. In order to realize the closed-loop control of the refrigerating capacity in the freezing station based on the real cooling needs of the frozen wall, we have designed the intelligent control system to automatically control the double stage ammonia screw compressor and the brine pump, the structure of which is shown in Figure 1.

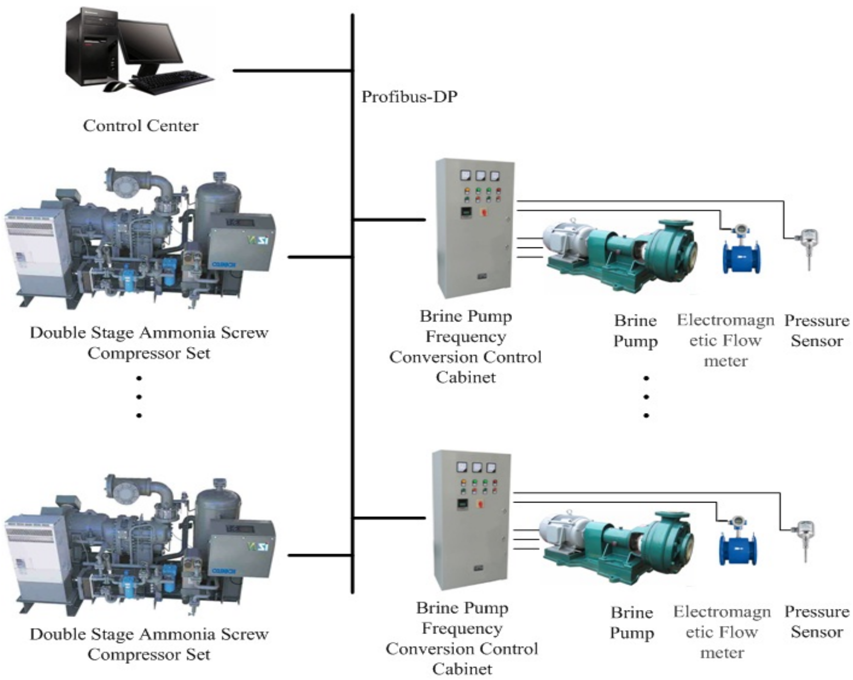

Figure 1. The Structure of the System

The Profibus-DP bus network is for transferring the information, and the control center consists of an IPC (Industrial Personal Computer) and a Profibus-DP interface card, by which the technicians are able to observe the working status of all the compressors and pumps and manipulate them, as for the configuration software, it is used for storing and managing all the data.

The brine pump uses the variable frequency control for changing the flow of brine through adjusting the speed of motor drive in time instead of the former import and export valve, as a result, the energy has been saved obviously. PLC (Programmable Logic Controller) and the frequency converter as well as some relative accessories form the frequency conversion control cabinet to start, adjust and stop the control of the motor drive by the water pump. The electromagnetic flow meter and the pressure sensor are responsible for observing the real time pressure and flow of the brine inside the pump, and then the two signals are both connected into PLC controller. Using the flow value as the feedback to adjust the close-loop PID with the pressure value as the reference to avoid the too low or too high pressure inside the pump, it is quite different from the normal variable-frequency constant-pressure water supply system without the pressure as a controlled parameter. The freezing brine circulation system realizes the brine circulation between the freezer and the brine tank through the freezer, and the heights of outlet pipe and return pipe are the same, that is, the static lift of the water pump is zero, so the speed of it just changes the water flow, nothing to do with the lift itself, also, because of its kinetic energy and potential energy and the continuity of the brine in the closed pump, the brine can still flow under a low speed of the water pump. As a consequence, the pressure value will not affect the whole brine circulation too much, instead, the flow plays an important role in the cooling supply, and therefore, it is used to realize the closed-loop control.

The double stage ammonia screw compressor is equipped with an PLC controller, which will cause two problems if we change it to frequency converting control: one is the high transformation cost owing to many compressors; the other is the large difficulty because of the double stage compressor, so it's hard to achieve the goal, so we just transformed the network of the compressor set to start or open it according to the real cooling need. Although we didn't adjust the working status of every compressor set, though the reasonable start and stop, we still decreased the energy consumption and increased the efficiency.

3. The Design of Control Algorithm

3.1. Control Logic

In the freezing operation, the cooling capacity quantity from the freezing brine to the formation heat exchange can be calculated through the brine flow and the brine temperature difference of the outlet and return circuit, besides, we must first know the scale of cooling capacity needed during the formation of the frozen wall so as to complete the automatically control of both the compressor set and the water pump, and then we need to confirm the flow and temperature of the brine in the freezing circulation to further control the double stage ammonia screw compressor and brine pump and finally to reach the real need of the cooling capacity in the heat exchange. The whole control logic is shown as Figure 2, obviously, the given cooling capacity needed in the heat exchange is calculated by some related observed data and the development condition of the frozen wall, moreover, the cooling capacity supply is realized through controlling the compressor and brine pump, and then we can get the real cooling capacity need in the formation heat exchange, finally, compared with the given data, the closed-loop control will be achieved.

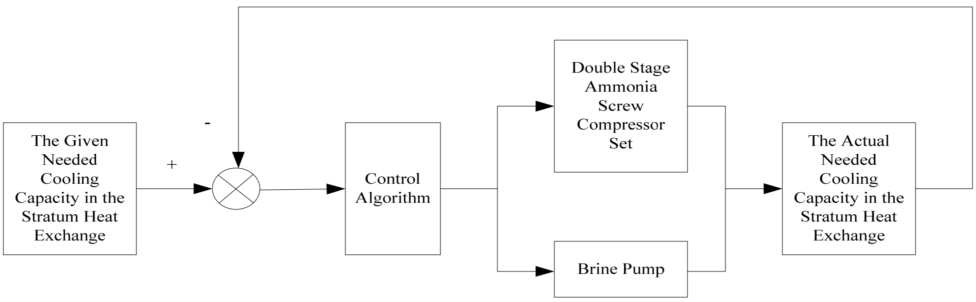

Figure 2. Logic Control

3.2. The Relation between the Flow and Temperature

Based on the following related formulas in the *Concise Coalmine Construction Engineering Manual* [11]:

$$\begin{cases} Q_0 = K\pi \mathrm{d}nH\mathrm{q} \\ \mathrm{q}=\dfrac{t_0 - t_c}{\dfrac{1}{\alpha}+\dfrac{r_0}{\lambda_2}\ln\dfrac{\xi}{r_0}+\dfrac{r_0}{\lambda_1}\ln\dfrac{R}{\xi}} \\ Q = \dfrac{Q_0}{\rho \mathrm{c} \Delta \mathrm{t}} \end{cases} \quad (1)$$

The mathematical relationship between the flow and temperature of the brine is thus to be:

$$Q = \frac{K \pi \mathrm{d} \mathrm{n} H (t_0 - t_c)}{\rho \mathrm{c} \Delta \mathrm{t} (\frac{1}{\alpha} + \frac{r_0}{\lambda_2} \ln \frac{\xi}{r_0} + \frac{r_0}{\lambda_1} \ln \frac{R}{\xi})} \quad (2)$$

Q_0 is the real cooling capability to freeze a shaft, and its unit is kW; k means the loss coefficient in the pipe cooling of the freezing pipe (1.1~1.25); d is the diameter of the freezing pipe with the unit of meter; n represents for the number of the freezing pipe; H is the depth of the freezing and the unit also is meter; q equals to the absorptivity (0.26~0.29) of the freezing pipe, the unit of which is w/m^2; t_0 is the initial temperature of the stratum; t_c means the outlet temperature of the brine ; α is the coefficient of the heat exchange in the freezing pipe (70~128w/m^{2}k); r_0 is the radius of the freezing pipe with meter as the unit; R is the effected freezing radius, meter as its unit; λ_1, λ_2 are the extensive radiuses of the freezing columns, and the unit is still meter; ξ means the heat conductivity coefficient of the melted soil and frozen soil. Q is the brine flow and ρ is the density of the circular brine (1250~1270kg/m^3); C is the specific heat of the circular brine with a value of 2.73; Δt is the temperature difference of the outlet and loop of the circular brine.

3.3. The Fuzzy Decoupling Controller

The brine flow and temperature together determine the scale of the heat exchange between all the freezers and the stratum, and there is tight coupling between the two, so it's hysteretic in controlling and difficult to get the real time change of the freezing process by building dynamic mathematical model. The fuzzy decoupling controller features a better adaptivity and robustness to satisfy the control of brine flow and temperature, suitable for the control with the uncertain model and parameter, because it doesn't depend on the accurate mathematical model of the controlled object, thus to avoid the difficulty in distinguishing the system. The structure is shown in Figure 3, mainly including the fuzzy controller and the decoupling controller; as for the fuzzy controller, it is comprised by a brine flow fuzzy controller and a brine temperature fuzzy controller, and the output quantity C_Q and C_T of the fuzzy controller respectively represent for the input quantity of the brine flow and temperature of the decoupling controller. Finally, add the more accurate controlled value U_Q and U_T to the actuator brine pump and compressor [12-14].

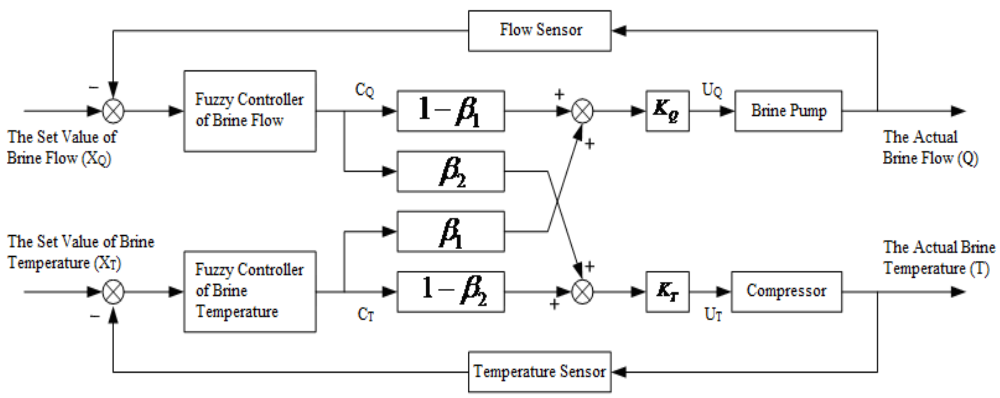

Figure 3. The System Structure of Fuzzy Decoupling Controller

3.4. The Design of Fuzzy Controller

The brine flow and temperature fuzzy controllers are both PD model and they apply the two-input and one-output fuzzy structure; in addition, the degree of membership between deviation E and output control value C is 7, with the corresponding word set as{ NB, NM, NS, ZO, PS, PM, PB} , which mean negative big, negative medium, negative small, zero, positive small, positive medium and positive big; the membership degree of the deviation rate of change EC is 5, and the corresponding word set is {NB, NS, ZO, PS, PB}, known as negative big, negative small, zero, positive small, and positive big;. The domains of discourse are:

{E}= {-10 -8 -6 -4 -2 0 2 4 6 8 10};
{EC}= {-1 -0.5 0 0.5 1};
{C}= {-1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1}.

Table 1. Fuzzy Control Rule Table

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

3.5. The Design of Decoupling Controller

There exists tight decoupling in the brine flow and temperature, so we need to import decoupling to decouple the output quantity of the fuzzy controller. During this process, we use the decoupling coefficient, that is, to add two decoupling coefficients β_1 and β_2 between the brine flow and temperature to make the value of brine flow and temperature as following formulas (3) and (4):

$$U_Q = K_Q[C_Q \times (1-\beta_1) + C_T \times \beta_1], \quad \beta_1 \in [0,1] \tag{3}$$

$$U_T = K_T[C_T \times (1-\beta_2) + C_Q \times \beta_2], \quad \beta_2 \in [0,1] \tag{4}$$

When β_1 and β_2 are zero, $U_Q = K_Q * C_Q$, $U_T = K_T * C_T$, and there is no decoupling control between the brine flow and temperature; when β_1 and β_2 are both 1, $U_Q = C_T$, $U_T = C_Q$, and the brine flow and temperature are in extreme decoupling condition. If β_1 and β_2 are between 0 and 1, we need to test the brine circulation system to ensure the reasonable decoupling coefficient and thus to decoupling control the brine flow and temperature, at last, adding the output quantity U_Q and U_T into the actuator brine pump and compressor.

3.6. Simulation Analysis

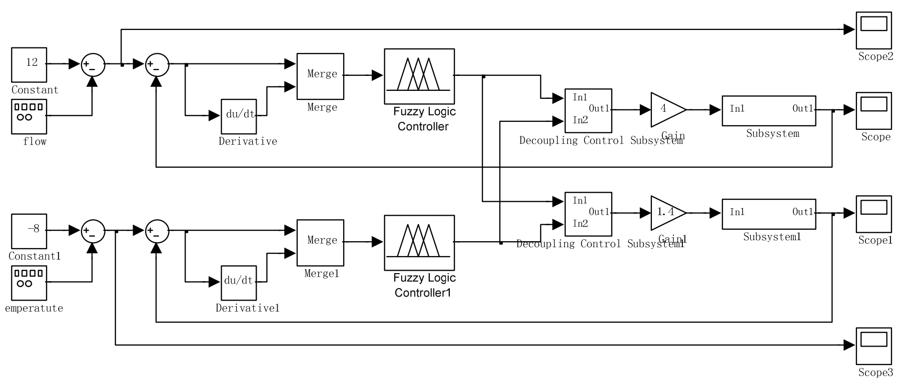

Figure 4. Simulation Model of the System

Figure 4 shows the simulated model of the system after MATLAB simulation. Figure 5 is the change curve of the brine flow before and after the fuzzy decoupling control, in which we can come to a conclusion that there exists a larger fluctuation between the brine flow and the set value when adopting the traditional way to control, however, the fuzzy decoupling control can stabilize the brine flow and thus reach a better control effect.

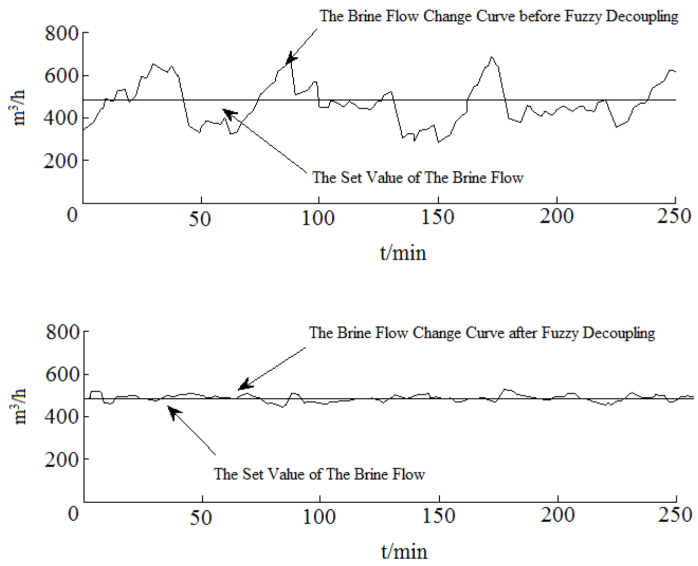

Figure 5. The Change Curve of the Brine Flow Before and After the Fuzzy Decoupling Control

4. Energy Saving Effect

Once the intelligent control system of coalmine shaft freezing station is put into operation and replaces manually adjusted control in the past, all that the technicians need to do is just calculate the flow value and temperature value of the circular brine according to the development condition of the frozen wall, and then the system adjusts the equipment when needed, so the electric energy can be saved to a large scale. The brine circulation is also much more stable because of the frequency control and opening of the in-and-out water valves, which changes the brine flow through the motor speed driven by the water pump, hence, the wasted energy inside the pipe will also be saved. Through the real cooling capacity need and reasonable start and stop of the equipment, the double stage ammonia screw compressor can not only save the electric energy, but also prolong the using life of the equipment.

Table 2. Energy saving table of frequency control brine pump

	The Pressure of Pipeline	The Output Frequency of the Transducer Hz	The Estimated Motor Speed rpm	The Leading-out Terminal of the Transformer		The Brine Flow m^3/h	The rate of power saving
				Voltage V	Current A		
Without the Transducer	0.5		1490	380	460	860	
With the Transducer	0.55	41	1220	380	300	918	34.8%
	0.49	37	1100	380	240	822	47.8%
	0.41	32	950	380	152	794	67%

The brine pump motor model is Y2-355L1-4 in the Fengjing freezing station in Yang village of SDIC XINJI ENERGY Co., Ltd with the rated power of 280kW, rated current of 500A, and nominal voltage of 380V, and the double stage ammonia screw compressor low-voltage motor drive model is Y355M2-2, with the rated power of 250kW, rated current of 433A and nominal voltage of 380V, besides, the high-voltage motor drive model is Y315L2-2, with the rated power of 200kW, rated current of 365A and nominal voltage of 380V. If we stop one double stage ammonia screw compressor during the running, we can save (*250+200*) *kW*24h=10800kW/h*. the detailed energy saving status through frequency converting controlled brine pump is shown as Table 2.

Supposing we stop one double stage ammonia screw compressor per day, and the power saving rate of 3 brine pumps is 50%, moreover, the electric charge is 0.7yuan per kilowatt hour, and construction period is 300 days, the electric charge saved will be:

3*280kW*50%*24h*300d*0.7yuan/kilowatt hour=2.1168million RMB
(250+200)kW*24h*300d*0.7yuan/kilowatt hour =2.268million RMB
Total amount: 226.8+211.68=4.3848million RMB

5. Conclusion

The intelligent control system of the freezing station has increased the automation level of the equipment and changed the undeveloped manually controlled method in the past. According to the actual heat exchange scale in freezing project, it calculates both the brine flow and temperature so as to control the whole equipment. In terms of the working of the equipment, the system has optimized the working status and decreased the repair rated, therefore prolong its using life; from the perspective of energy saving, because of the reasonable equipment adjustment and on-demand supply, the electric energy is saved to a large degree, as a result, the operation cost of the enterprises has been saved and the profit rate been increased. The next step should be focused on the real-time detection of the freezing temperature field and estimation of the development status of the frozen wall, and then under the help of the expert system, we can control the working status of the equipment in time so that the automation level of the freezing project can be further improved. Whereas, given there is still no recognized accurate way to analyze the freezing temperature field, it still remains to be deeply studied by the researchers.

Acknowledgments

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References

[1] YANG Geng-She, XI Jia-mi. Review and Prospect of Research on Freezing Design Theory of Coal Mine Shaft. *Chinese Journal of Underground Space and Engineering*. 2010; 6: 627-635.
[2] LI Pan, XIE Xiong-yao. Research on Optimization of Freezing-temperature Monitoring Design and Method of Data Analysis in Shanghai Yangtze River Tunnel. *Chinese Journal of Underground Space and Engineering*. 2012; 8: 122-128.
[3] ZHAI Yan-zhong, XU Shu-rong. *Design and Application of Remote Monitoring and Measuring System for Ground Freezing*. Coal Science and Technology. 2008; 36: 68-71.
[4] ZHENG Xiao-liang, GUO Zhao-kun, XIE Hong-zhi, et al. *Monitoring and Measurement System of Freezing Temperature Field Based on Distributed Optical Fiber Sensor Technology.* Coal Science and Technology. 2009; 37: 18-21.
[5] HU Xiang-dong, LIU Rui-feng. Temperature Monitoring System for Freezing Method Based on “1-wire Bus. *Chinese Journal of Underground Space and Engineering*. 2007; 3: 937-940.
[6] SONG Lei, YANG Wei-hao, LI Hai-peng. Monitoring of Freezing Shaft Sinking in Ultra-Deep Alluvium of Guotun Coal Mine. *Journal of Mining & Safety Engineering.* 2010; 7: 19-23.
[7] ZHENG Xiao-liang, HU Ye-lin, SHEN Hua-jun, et al. *Application of Distributed Fiber Temperature Detection Technology in the Shaft Freezing Restoration Project.* TELKOMNIKA Indonesian Journal of Electrical Engineering. 2014; 12(5): 3936-3942.
[8] ZHENG Xiao-liang, MA Lie, HU Ye-lin. *The Design of Freezing Station Brine Pump Variable Frequency Energy-saving System*. Mine Construction Technology. 2008; 29: 19-22.

[9] SU Jing-ming, GONG Yan, TANG Chao-li, *Study on Intelligent Control System of Brine Water in Mine Ground Freezing Refrigeration Station for the Mine Freezing Shaft Sinking*. Coal Engineering. 2012; 36: 104-106.
[10] HONG Yan, SU Jing-ming, TANG Chao-li, et al. *Research on the Intelligent Flow Control of Freezing Sinking Based on the Expert-Fuzzy PID Algorithm*. Computer Engineering & Science. 2012; 34: 166-171.
[11] CUI Yun-long. Concise Mine Construction Engineering Handbook. Beijing: The China Coal Industry Publishing House, 2003.
[12] Li Fei, MA Xiu, CAO Wei-hua, et al. Fuzzy compensation decoupling control of calorific value and pressure in gas mixing process. *Journal of Central South University (Science and Technology).* 2011; 42: 94-98.
[13] Wen Biao Wang, Yong Sun, Si Yuan Wang, et al. Application of Intelligent Three-state Pang-Pang Control to Heat Exchange Station. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(5): 3529-3536.
[14] Xie Peizhang, Zhou Xingpeng. Time Delay MIMO Decoupling Control based on DOBSVM Inverse System. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2013; 11(12): 7525-7532.