Research of Intelligent Control of Air Compressor at Constant Pressure

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***Abstract*—The air separation plays an extremely important role in the development of metallurgical industry. And the air compressor which provides not only the required pressure air for the cooling equipment and refrigeration plant but also the raw material required for the separation plant is a key device in the air separation plant. Utilization of the air compressor is extremely extensive in many significant departments such as the metallurgy, oil and chemical industry. The air compressor system is a time-varying, delay and nonlinear complex system. Defects in the traditional control method and controller lead to the pressure instability of the compressed air outputted from the air compressor in volatile gas-consumption situations, sometimes a wide range of fluctuation arising, for gas consumption in the industrial field is irregular. Therefore, the working state of the air compressor becomes unstable. In general, electric energy consumption of the air compressor system working in the stable state counts up to about twenty percentages of the total energy consumption in the enterprise. Moreover, energy consumption in the unstable state is more. It results in both a waste of resources and greater energy consumption. Therefore, guaranteeing the output pressure of the air compressor system steady is extraordinarily significant for improving efficiency and saving energy for the overall air separation system. The turbine compressor system was taken as the research object to analyze its characteristics and control requirements. DCS control technology applied to the system, the ECS-700 system of SUPCON was utilized into configuring the air compressor system and monitoring real-time values of important parameters in the various components. According to the working characteristics of the air compressor system, the fuzzy control theory, as one of the modern control theories, was applied to the constant pressure control system to design a fuzzy pressure controller. The simulation results showed that the controller not only was more convenient and effective but also provided a certain directive significance and reference for control of other parameters of the air compressor system.**

***Index Terms*—Time-varying, Fuzzy control, Simulation, Intelligent control, Air compressor**

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I. INTRODUCTION

The air compressor is a mechanism which compresses and conveys air. In the air-separate equipment it is a vital apparatus, which not only provides compressed air at the necessarily regulated pressure for the cooling equipment(such as the throttle) and refrigerating machinery(such as the expander), but also transports the necessarily raw air to the separation equipment[1]. In the domestic, air compressors in some enterprises choose the loading/unloading working means, whose characteristics are simple control methods and low cost. Nevertheless, negative effects arise at the same time. For example, much energy was waste during no-load operation; the electric current is rather high when the main motor starts up. Moreover, its frequent startup exerts acute impact on the equipment and the motor bearing wear is also serious. Maintenance quantity for the equipment is much and decompression energy in the relief valve is squandered. In addition, the continuous supply-demand adjustment of air supply can not be implemented by regulating the inlet valve in mechanical means. When air consumption varies ceaselessly, air-supply pressure would fluctuate fiercely and becomes unstable. Therefore, it has a bad effect on operation process of the pneumatic components and product quality, even giving rise to waste products.

Chunmiao Hong from Xiamen University applied the variable velocity variable frequency technology to control of air compressors. The frequency converter is the core of the entire control system, whose technology regulates the motor's rotational speed to make it operate under the most efficient state according to load. The output signal of the frequency converter controls the AC motor's rotational speed and turning to regulate rotational speed continuously so that the valve opening was controlled to guarantee parameters of gas-supply pressure and discharge steady[2]. Whereas, the approach defects were that cost of the frequency converter was rather high and the speed regulation was also in the operation state as the air compressor operated normally, and then the frequency converter consumed a part of energy itself. So it was not economic. Bomei Yang from Dalian Maritime University designed a new air-compressor controller based on the

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single chip microcomputer and intelligent control technology. The controller possessed small volume, high reliability, stable control, and easy manipulation. Moreover, parameters could be set, the human-computer interaction was achieved and control accuracy was rather high, which was less than 0.01MPa. Fluctuation during the device operation is less and energy consumption was lower. Consequently, the production cost decreased. The intelligent controller in the system structure implemented real-time monitoring on working conditions of all components and important parameters. Attained data compared with nominal parameters of the system, the corresponding startup and shutdown control was enforced on the system in accordance with control requirements[3]. The intelligent controller module of the controller selected an improved PID control approach. The optimal parameters were chosen to make the control effect best through setting various parameters of P, I and D to test and operate repeatedly. However, control efficiency of the method was not high in the variable working condition. Xueyan Zhang from Guizhou University had researched the PLC-based variable velocity variable frequency system of the air compressor for guaranteeing air-compressor operation steady and outlet pressure stable. He conducted transformation of the variable frequency system on the control system of the original air compressor to make it combined with the PID demodulator. Stable gas pressure was obtained and important parameters as well as the operation condition of the frequency converter during the air-compressor operation could be monitored[4].

The air compressor system is a time-varying, delay and nonlinear complex system. That the original control system technology is obsolete makes output pressure of compressed air instable, especially in some situations where gas consumption is more volatile, the current conventional controller is difficult to meet specified requirements[5]. Therefore, it is extraordinarily essential that technical transformation of the obsolete control system makes pressure of compressed air stable within the requirements for satisfying the demands of devices in the industrial environment. Based on the fuzzy set theory, fuzzy linguistic variable and fuzzy inferential logic, the fuzzy control synthesizes expert experience to simulate the human reasoning and decision process approximately.

Fuzzy control characteristics is that it is not required to attain the precise mathematic model of the controlled object during designing the control system, just needing to synthesize expert experience knowledge and operating data of manipulators in the field. Furthermore, the fuzzy controller is suitable for the system similar to the air compressor which is nonlinear, time-varying and delay. In this paper, a monitoring system for operating state of air compressors was designed to monitor and control its operation for guaranteeing the steady operation of air compressors and shutdown in time on faults arising. The effective control method was designed by combining the fuzzy PID control. And the simulation model of the control system was ascertained. The simulation was fulfilled to test and confirm its effectiveness of the designed control method by utilizing the Matlab software. And then the constant pressure control of the air compressor system was achieved.

The production process flow and control requirements of air compressor system have been introduced in Section II. In Section III, the configuration of monitoring system of the air compressor is analyzed in detail. In Section IV, we describe the design of pressure fuzzy controller. Analysis of simulation results of pressure fuzzy controller is presented in Section V. Finally, conclusions are summarized in Section VI.

II. Production Process Flow and Control Requirements of Air Compressor System

The air compressor is a mechanism which compresses and conveys air. In the air-separate equipment it is a vital apparatus, which not only provides compressed air at the necessarily regulated pressure for the cooling equipment(such as the throttle) and refrigerating machinery(such as the expander), but also transports the necessarily raw air to the separation equipment[1].

The air compressor system components primarily involve air filters, air compressor units, coolers, and fuel tanks and so on. The functional block diagram of process flow for the air compressor system is shown as Fig. 1. Currently, the centrifugal compressor is commonly selected for air compressors. The air compressor system operating, clear air is introduced from the intake pipe into impellers and is rotated to improve its speed and pressure by high-speed rotating blades. The air absolute velocity from impellers is extraordinarily large. The speed is slowed down but the pressure is further enhanced after air enters into the diffuser. The centrifugal compressor used in air-separation plant is generally multistage, which is composed of a number of impellers. Therefore, air is progressively compressed.

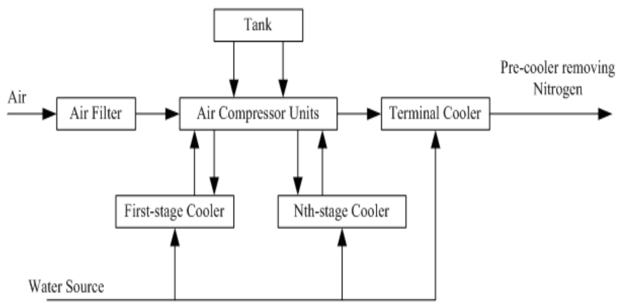

Figure 1. Process flow for air compressor system

The air filter removes the solid impurities from the entered air. If solid impurities in the air are not eliminated, it will cause negative consequences for air compressors: raising wear of blades and diffusers; such as the surface is contaminated so that the thermal conductivity lowered if solid impurities are brought into the water device. There are ordinarily of two kinds: the dry and wet type for filters used in the air-separation plant. In practice, both will be utilized in series, the wet in the front and the dry at the back. After air was compressed, both its pressure and temperature were boosted. Hot air exchanging heat with the surrounding medium leads to energy loss. In order to improve the compressor efficiency, air whose temperature is raised needs to be cooled. After high-temperature air is subjected to multi-stage compression, the compressed air is cooled by the water cooler and then it enters into the next stage. The tank is used to store and supply oil for cooling and lubricating air compressors.

The basic process of the air compressor system is: firstly air in the atmosphere enters into the air filter, secondly after impurities are eliminated, the air is transferred into the air compressor where the air is subjected to compression in several stages and its pressure is heightened step by step. Moreover, water cooling need be implemented on the compressed air at each level. At the same time, the tank conveys engine oil to the air compressor. Lubricating the equipment, the oil circulation system also takes some heat. At last the air is transmitted from the final stage to the Nitrogen pre-cooler for further cooling so that it will service subsequent devices.

The most basic control in air compressors embodies start/stop control of the air compressor motor as well as the constant pressure or constant flow control of the outlet pressure. The constant pressure control or constant flow control is namely that the air compressor outlet pressure or flow is kept stable by certain adjusting means when the compressor flow or pressure fluctuates. There are approaches, such as inlet-outlet flow regulation and variable speed regulation and so on.

Variable speed regulation is an utmost adjustment range and most economical regulation approach, but it is not easy to master its regulation accuracy; the inlet-flow regulation method is simple and possesses a wide adjustment range. It is an economic regulation method and mainly was applied to centrifugal compressors at the constant speed. The alternative between the constant pressure and constant flow control actually depends on the practical process. The first controlled object in either the constant pressure or the constant flow control is consistently the inlet guide vane opening (the rotational speed is invariable when the motor drives). The inlet guide vane opening is regulated by the outlet pressure signal of the air compressor in the constant pressure control, but the inlet guide vane opening is controlled by the outlet pressure difference(the outlet flow) of the air compressor in the constant flow control. The constant pressure control is selected commonly for large-scale air-separation systems. The rest of control such as automatic loading/unloading of air compressors, anti-surge control, motor-overload-protection control, control of startup and interlock protection of air compressors are installed for unit-safe operation.

III. Configuration of Monitoring System of Air Compressor

The monitoring software designed possessed function as follows:

1) According to requirements of the system monitoring, the Windows XP Professional Edition in Chinese version was selected for system software environment as a platform to develop a graphical interface where it was convenient for users to operate effectively.

2) The main control interface showed the real-time data and history records of each primary parameter of air compressors to provide the basis for designing the effective control program.

3) In the monitoring interface, the operation-log window, history-alarm-log window, report window of air compressors could be displayed by switching.

4) The start-up modes were divided into soft start-up and manual start-up for air compressor control. Through compiling the relevant program, air compressors were started or stopped by manually clicking a button on the control interface.

The ECS-700 system in the DCS configuration tool was utilized to develop its monitoring software during designing the monitoring system of air compressors. The system which possessed characteristics of flexible configuration, perfect control function, convenient data processing, focused display operation, friendly HMI, simple installation, easy debugging, powerful versatility and reliable operation integrated the latest field-bus technology, embedded software technology, advanced control technology and network technology. The DCS system generally selected the dual-redundant control unit. When a control unit failed, a relevantly redundant real unit was switched into the working unit without disturbance.

For design of the air-compressor control system, work below was completed in the mass:

1) The engineering operation, structural configuration and setting tasks of engineer authority management were completed in structural design environment. Structural configuration included the control domain, control station, operation domain and addition of operation nodes.

2) Control configuration and monitoring configuration were achieved in the configuration environment.

Control of air compressors primarily incorporated the motor start/stop and the constant pressure control of outlet pressure, supplemented with an accident interlock protection control during the air compressor operating. The monitoring screen mainly embodied the air compressor start/stop and accident interlock. The air compressor start and stop was divided into the automatic and manual mode. In the constant pressure control process, we should pay attention to preventing compressor surge and outlet flow matching inlet pressure. The low flow or high pressure could lead to the air compressor surge[6, 7]. It could directly damage the air compressor equipment, even causing the air-separation shutdown. Fig. 2 showed the operating characteristic curve of the MAN Turbo compressor. The curve was provided by the compressor manufacturer. The offset value between the control line and the surge line was about 8~10% of the flow measurement range value. For a certain reason, the operating point entering into the control line opened the vent valve quickly and let the operating point leave the control lines. As long as faults existed, the operating point would move around the control line and not enter the surge zone. Faults eliminated, the operating point would leave from the control line and return to the normal position. The less the offset value was, the higher the scan rate required for the system was. Whereas, the larger the offset value was, the greater energy loss was. The offset could be adjusted appropriately to achieve maximum efficiency after the field configuration.

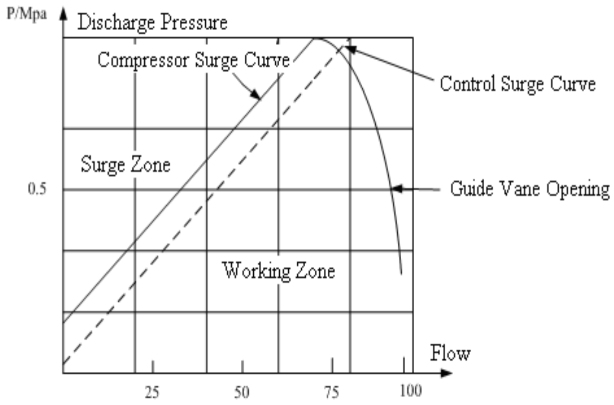

Figure 2. Characteristic curve

1) Hardware configuration. The system selected the controller FCU711-S developed by SUPCON, which could collect real-time process information periodically from the I/O module. Each controller could control 500 circuits and the relevant I/O module was configured in accordance with the measure points required. After the hardware configuration, the structural configuration was implemented, and the control engineering of the air compressor system could be established. Then the control domain, control station, operation domain and operation node were added to set the engineer authority management.

2) After the establishment of the engineering, management configuration was conducted on the system. The connection module, communication module and I/O module were added, and each channel was set, such as the signal type, the upper and lower limit of electrical range. There are different settings for various module channels. After hardware configuration is completed, the scanning of current system modules was accomplished to obtain the hardware configuration information and upload it to the new local configuration. According to the numbers of monitoring and controlling points, the bit-mark configuration was carried out.

3) After the fulfillment of the management configuration, monitoring configuration was also implemented on the system. The operating group was added and installed, and operation pictures and flow chart configuration were added[8,9]. The chain program of the surge-power-failure was shown in Fig. 3.

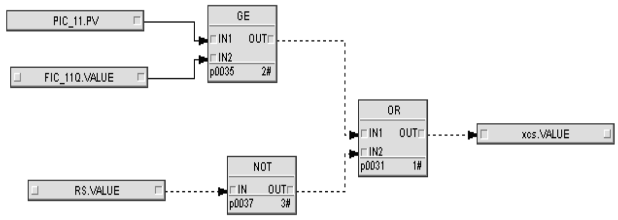

Fig. 3 Anti-surge Interlocking Program

IV. Design of Pressure Fuzzy Controller

A. Fuzzy Controller Structure

The fuzzy controller structure was shown in Fig.4[10,11,12]. In theory, the signal received by the fuzzy control was continuous. However, in engineering, the fuzzy control was implemented by the digital computer. Therefore, a discrete fuzzy controller was adopted in practice. The signal was converted through A/D and then loaded into the controller.

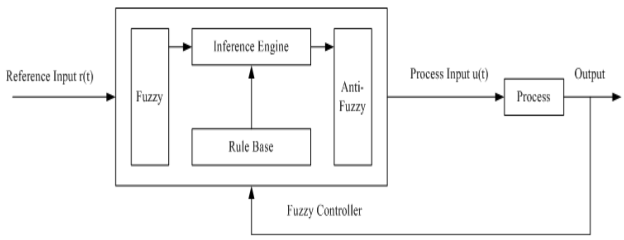

Figure 4. Fuzzy Controller Structure

As shown in Fig.4, the controller structure consisted of four parts:

1) The rule base. It quantized the successful control experience depicted in the expert language to obtain the fuzzy control rule.

2) The inference engine, which simulated the expert decision, explained and applied how to control the best knowledge for the control object.

3) The fuzzifierion interface, which was the input interface of the fuzzy controller, converted the controller input into a type of information, which made it easy that the inference engine was activated and the relational rule was utilized.

4) The defuzzifierion interface. It converted the inference results into the actual input of the process or control object.

B. Design of Fuzzy Controller for Air Pressure

(1)Determine the domain and membership function. The control structure of the pressure fuzzy controller designed in this paper was shown in Fig.5[13,14,15]. The pressure control was rather crucial, since surge in the air compressor occurred when the outlet flow mismatched the discharge pressure in the air compressor. That is to say, the flow was low or the pressure was high. The surge arising would lead to severe consequences: significant deterioration in performance of the air compressor, increased noise and damage to air compressor components. The error deprived from comparison between the actual outlet pressure signal measured by pressure sensors in the air compressor and the prescribed value and the error variation ratio were defined as the input quantity. The output was the opening value of controlling the compressor inlet guide blade. The input quantity was required to be discretized and fuzzified. A certain corresponding relationship between the discretely numerical quantity and the fuzzy quantity indicating the fuzzy language was established to convert the accurate quantity into the fuzzy quantity. The input quantity need be multiplied by the relational quantitative factor during constructing the corresponding relationship. The quantitative factors were indicated by the K. K_e and K_c denoted the deviation and the quantitative factor of the deviation variation, respectively. K_u represented the proportion factor which the output quantity through the defuzzifierion treatment multiplied by the output control quantity made. Their formulas were shown as follows[5]:

$$K_e = \frac{n}{x_e},\ K_c = \frac{m}{x_c},\ K_u = \frac{y_0}{l} \tag{1}$$

Where X_e and X_c denotes two input values in the basic domain, respectively; y_0 is the accuracy quantity of output of the basic domain; m, n, and l are the corresponding maximums in the discrete domain, respectively.

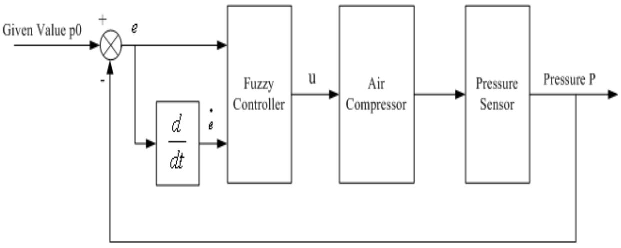

Figure 5. Structure figure of fuzzy control for pressure

According to control experience of operators on the spot, the deviation E in the basic domain was determined as {-0.5,+0.5}, and the domain was X={-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6}. Therefore the calculated quantitative factor was K_e=6/0.5=12. Each fuzzy subset possessed many choices of membership functions in the domain X. In general, simpler membership functions such as the trigonometric membership function were adopted in the engineering design. They not only needed less computational effort, diminished memory space but also met common control requirements. The membership functions were demonstrated in Fig.6.

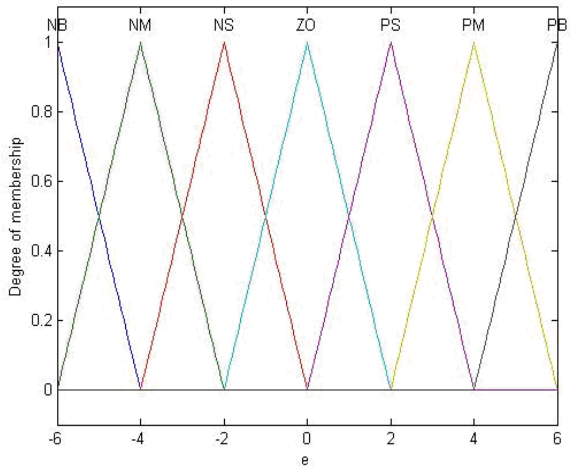

Figure 6. Membership function of pressure error

The basic domain of the deviation variation ratio EC was determined as {-0.3，+0.3}, The domain X={-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6}. Calculate the quantitative factor Kc=6/0.3=20. The membership function of each fuzzy subset in the domain X selected the trigonometric function, as shown in Fig.7. The fuzzy controller adopted the incremental output approach. The basic domain of the output variable U was defined as {0, 1}. The selection of its domain, linguistic variable and membership function was identical to that of E and EC, as shown in Fig.8. Apparently, the maximum incremental value of U was $6K_u$. Moreover, two percent of U was preliminarily chosen as the maximum in general. Consequently, K_u=0.02/6=0.003 was calculated. Both input and output selected seven linguistic variables which were the negative big, negative medium, negative small, zero, positive small, positive medium and positive big, respectively. They were abbreviated to NB, NM, NS, ZO, PS, PM and PB, respectively[16,17,18].

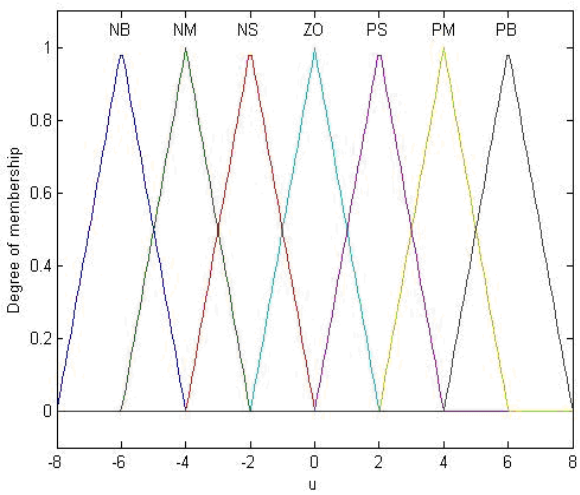

Figure 7. Membership function of variation ratio of pressure error

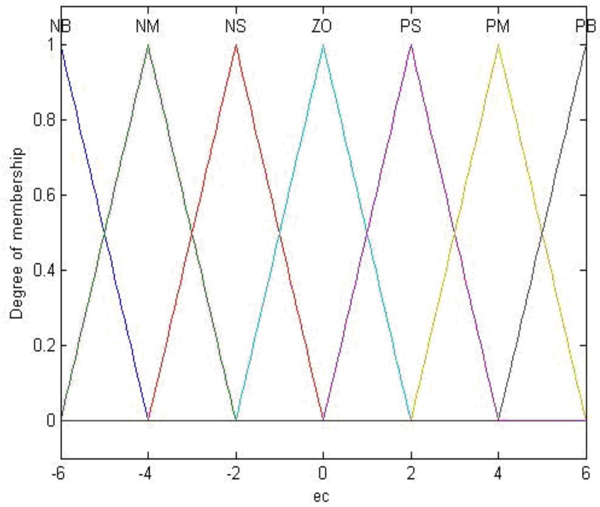

Figure 8. Membership Function of Variable U

(2)Establish control rule. According to operator experience as well as expert experience or the fuzzy control rule generated by process knowledge, the rule table was depicted as the sentence forms as follows:

1）If (*e* is NB) and (*ec* is NB) then (*u* is NB)

2）If (*e* is NB) and (*ec* is NM) then (*u* is NB)

3）If (*e* is NB) and (*ec* is NS) then (*u* is NB)

4）If (*e* is NB) and (*ec* is ZO) then (*u* is NB)

5）If (*e* is NB) and (*ec* is PS) then (*u* is NM)

6）If (*e* is NB) and (*ec* is PM) then (*u* is NS)

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48）If (*e* is PB) and (*ec* is PM) then (*u* is PB)

49）If (*e* is PB) and (*ec* is PB) then (*u* is PB)

(3)Control surface of the fuzzy controller. Utilizing the fuzzy toolbox in Matlab set the reasoning process of the fuzzy controller. The rule antecedent and implication adopted the “minimizing” rule. The area centroid method was applied to the defuzzifierion rule. Therefore, the control surface of output of the two-dimensional controller was shown in Fig.9.

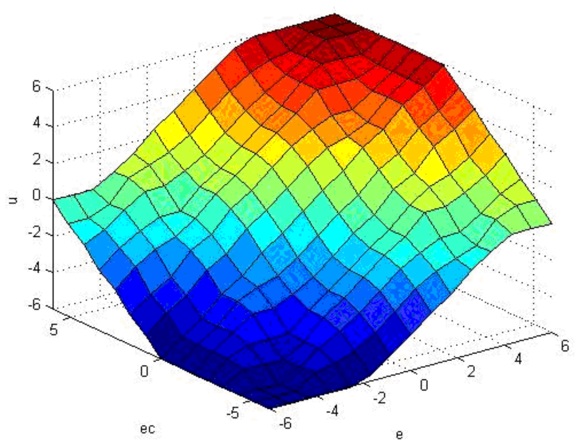

Fig.9 Control Surface of Two-dimensional Fuzzy Controller

From the figure above, note that an apparent fluctuation arose in the control surface shape as the input signal expanded. This indicated the controller response characteristics to nonlinearity.

V. Analysis of Simulation Results of Pressure Fuzzy Controller

Fig.10 was the simulation wave of the pressure fuzzy controller under the step input. And Fig.11 was the simulation wave of the fuzzy controller with random interference under the step input. From figures, note that without interference the system response time was shorter, its overshoot was severely small and the system could rapidly trace the given signal and adjusted the velocity value to reach the stability within the regulated time. In addition, the system pressure output could also achieve stability promptly after the certain interference was added. Hence the controller effectively improved the reliability, stability and robustness for the overall system.

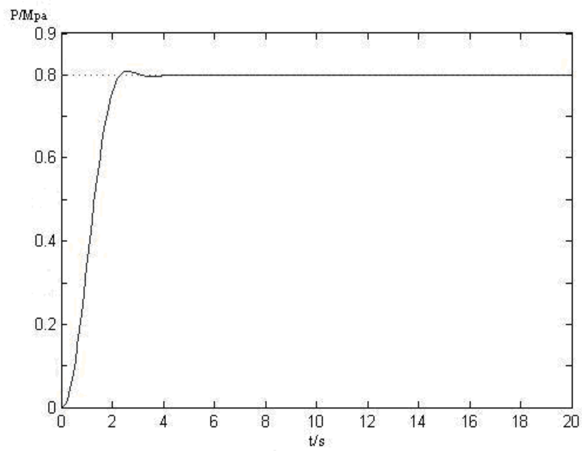

Figure 10. Simulation wave of fuzzy controller under step input

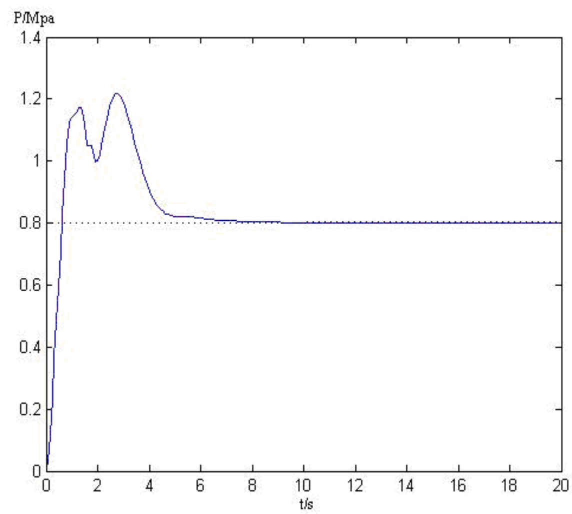

Figure 11. Simulation wave of fuzzy controller with random interference under step input

VI. CONCLUSIONS

This paper aiming at defects in the intrinsic control system of air compressors, the ECS-700 system from the DCS technology was applied to designing the monitoring system of the air compressor system which offered data required for the system controller design.

The monitoring system was guaranteed in effective, safe and steady operation since a scientific and reasonable control project was chosen. Its main effects were shown in several aspects as follows: 1) The fluctuation range of air pressure at the outlet was diminished and air-supply quality was improved by implementing effective loading/unloading operation on each air compressor in the unit. 2) Arranging start and stop of each compressor rationally according to the working state, the case that resources were utilized reasonably, energy consumption was decreased and cost was saved was achieved. 3) Interlocking shutdown of compressors was accomplished automatically to downsize equipment damage when time of outlet pressure higher than the assigned value in air compressors was too long. 4) Faults appearing during the system operating could be located quickly and then manipulator working intensity was reduced. 5) It possessed satisfactory HMI and abundant flow charts exhibited real-time parameter value of each components. The system management function was powerful.

Aiming at variation of outlet pressure of the air compressor, a pressure fuzzy controller was designed by utilizing the fuzzy control theory. It was calculated and analyzed to obtain the curved surface of the output control and control rule table through applying fuzzy tool in Matlab. So not only did air-supply control at the constant pressure in the air compressor system become more reliable and steady, but also the control efficiency was improved.

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