http://ansinet.com/itj

ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

OPEN ACCESS Information Technology Journal

ISSN 1812-5638
DOI: 10.3923/itj.2016.1.9

Research Article
Design and Application of Constant Pressure Control Algorithm for Large Displacement and High Pressure Reciprocating Pump

Kai Li, Xiuting Wei, Zhenxian Wei and Leian Zhang

College of Mechanical Engineering, Shandong University of Technology, Zhangdian, Zibo, China

Abstract
According to the nonlinear and strong coupling characteristics of water-injecting process of large displacement and high pressure reciprocating pumps, the system for monitoring water injection with constant pressure was constructed and then the fuzzy rules for constant pressure control was obtained through site test. Furthermore, fuzzy Proportion Integration Differentiation (PID) gain conditioner (FPGC) control algorithm was put forward, with the error and its changing rate of outlet total pressure of injection station as input variables. Finally, the water-injecting experiments using conventional PID control algorithm and FPGC control algorithm were carried out respectively. Practical application proved that the former algorithm can ensure the outlet main pressure error (less than 0.1 MPa) and depress the system oscillation, with its feasibility applied to injection station of large displacement and high pressure reciprocating pump verified.

Key words: Water injection station, constant pressure control, mathematical model of water injection station, monitoring system, fuzzy rule, FPGC control algorithm

Received: September 28, 2015 Accepted: December 01, 2015 Published: December 15, 2015

Citation: Kai Li, Xiuting Wei, Zhenxian Wei and Leian Zhang, 2016. Design and Application of Constant Pressure Control Algorithm for Large Displacement and High Pressure Reciprocating Pump. Inform. Technol. J., 15: 1-9.

Corresponding Author: Xiuting Wei, College of Mechanical Engineering, Shandong University of Technology, No. 12 Zhangzhou Road, Zhangdian, Zibo, China

Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

In the oil field, to compensate for the loss of the underground reservoir pressure after producing oil and to ensure the stable and high oil production, high pressure water is usually injected into underground through water injection system to obtain higher oil productivity (Xu *et al*., 2009, 2011). Because of the randomness of underground reservoir, the characteristics of system included nonlinear, sluggish and time varying have showed. Controlling of outlet main water pressure will directly affect productivity and service life of the injection system (Liu, 2013; Wang, 2014). At present, the frequency conversion technology has become an important means to achieve constant pressure and the stability was improved. At the same time, effect of saving resource was more significant. Conventional PID controller with simple structure has been applied to system of large displacement and high pressure reciprocating pump injection station (Wang, 2007; Cheng *et al*., 2013; Pandey and Laxmi, 2014; De and Mudi, 2013), but the exact mathematical model of water injection station need to be known. For the characteristics of water injection system contradiction between static and dynamic has not solved, meanwhile, controlling performance was poor. The system without knowing the exact model has been good controlled by fuzzy controller and has been used in the water injection system (Luo *et al*., 2014; Zhang *et al*., 2013; Qin and Tan, 2005). However, only using fuzzy controller, the static performance of process of constant pressure water injection was not good (Patil *et al*., 2007; Sahraoui *et al*., 2012).

In this study, the process of injection was studied and FPGC control algorithm was designed, which retaining the advantages of conventional PID control and adding people's experience of adjusting the PID parameters. In order to verify the superiority of FPGC control algorithm, a set of experimental platform of constant pressure injection station was set up. Meanwhile, controlling performances of two control algorithms respectively tested through this platform. Finally, the effectiveness of the FPGC control system was verified by simulation experiments and this algorithm was successfully applied to water-injecting process of large displacement and high pressure reciprocating pumps. This study aims to design an effective control algorithm to reduce the outlet main pressure controlling error of constant pressure water injection station.

MATERIALS AND METHODS

Composition of monitoring system of large displacement and high pressure reciprocating pump injection station: Monitoring system was mainly composed of pump group, inverter, reservoir, injection pipe network, pressure transmitter, control system and other components, etc. Water injection pump group consist of three large displacement and high pressure reciprocating pumps and one was variable frequency pump. When the variable frequency pump working, motor was driven by inverter and the crankshaft was driven by reducer. Then, reciprocating movement of the plunger was achieved and high pressure was formed. The function of the water injected into underground has been achieved. The control system composed of controllers and man-machine monitoring interface which designed as a distributed structure include intelligent monitoring terminal, main control unit and data acquisition unit. Figure 1 showed the structure of

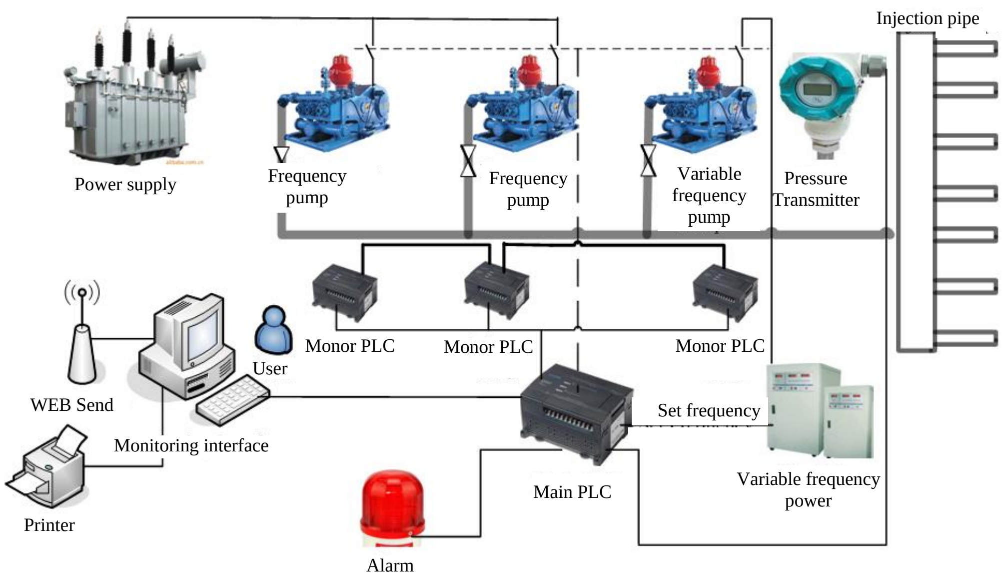

Fig. 1: Monitoring system of water injection station

monitoring system. Using the pressure sensor which installing at the end of water injection network, the change of outlet main water pressure was measured and the pressure signal was transmitted to the main PLC controller. According to different pressure demand at different times and the changing of outlet main pressure, after algorithm calculated, controlling signal was imported into inverter. Then, the speed of reciprocating pump motor was adjusted and adjustment for outlet main water pressure of injection station system was completed.

Mathematical model of water injection station: Analysis of mathematics transfer function of each component showing in Fig. 1, then the mathematical model of all system was got.

When the water from the initial state to the outlet pipe network, water injection process can be divided into rising pressure process and the constant pressure. The process of water pressure rising was approximated as a first-order inertia link with a large time constant. So the mathematical model of water pipe network is $e^{-\tau s}$. Where, $e^{-\tau s}$ is a pure lag process and τ is the time of pure lag process.

The transfer function of water pressure sensor was regarded as a proportion link because the bandwidth of water pressure sensor can meet the requirements of general system.

The working frequency range of inverter was 20~50 Hz. Under the condition of high frequency converter, rotor leakage impedance was ignored and controlling of frequency ratio of inverter was constant voltage. So, the mathematical model of inverter was expressed by Eq. 1:

$$\frac{E_g}{f_1} = \frac{U_S}{f_1} = a \text{ (constant)} \tag{1}$$

where, f_1 is the working frequency of the inverter, E_g is electromotive force of the inverter, U_S is voltage of motor stator phase and a is constant.

For the process of adjusting motor speed was nonlinear, so it was not realistic to obtain a precise mathematical model to describing the whole dynamic working process. Making some assumptions on the motor, the mathematical model of the motor was obtained by the partial-differential linearization near the point of the steady working state. And this point was obtained through mechanical characteristic equation of the motor properties. When the rotor resistance (R_2') was large, it considered that:

$$R_1 << \frac{R_2'}{s}$$

and:

$$\omega_1^2 (L_{l1} + L_2') << \frac{R_2'}{s}$$

In other words, R_1 and ω_{12} ($L_{l1}+L'_{l2}$) were all zero while comparing with the $R_{2'}/s$. On this condition, Eq. 2 turned into Eq. 3:

$$T_e = \frac{3n_p U_1^2 R_2' / s}{\omega_1 \left[\left(R_1 + \frac{R_2'}{s} \right)^2 + \omega_2^2 \, (L_{l1} + L_{12}')^2 \right]} \tag{2}$$

$$T_e \approx \frac{3n_p U_1^2 s}{\omega_1 R_2'} \tag{3}$$

where, from Eq. 2-3, T_e is the electromagnetic torque of approximate linear mechanical properties of motor, R_1 and R_2 are resistances of motor, U_1 is the stator voltage, n_p is the speed of motor, ω_1 is the angular velocity of motor and s is slip of motor.

Supposing the point of M was a steady working point on approximate linear mechanical properties of the motor and existing a small deviation in this point, then the specific relationship of parameters was expressed by Eq. 4. After content of Eq. 4 introduced into Eq. 3, then Eq. 5 was got. The polynomials which containing ΔU_{12} and $\Delta U_1 \Delta s$ ignored, Eq. 6-7 was gotten:

$$\begin{cases} T_e = T_{eM} + \Delta T_e \\ U_1 = U_{1M} + \Delta U_1 \\ s = s_M + \Delta s \end{cases} \tag{4}$$

$$T_{eM} + \Delta T_e \approx \frac{3n_p (U_{1M} + \Delta U_1)^2 (s_M + \Delta s)}{\omega_1 R_2'} \tag{5}$$

$$T_{eM} + \Delta T_e \approx \frac{3n_p (U_{1M} s_M + 2U_{1M} s_M \Delta U_1 + U_{1M}^2 \Delta s)}{\omega_1 R_2'} \tag{6}$$

$$\Delta T_e \approx \frac{3n_p (2U_{1M} s_M \Delta U_1 + U_{1M}^2 \Delta s)}{\omega_1 R_2'} \tag{7}$$

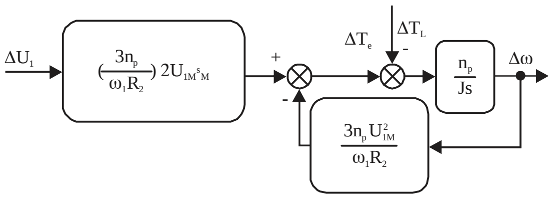

Fig. 2: Structure of approximate partial-differential linearization dynamic of asynchronous motor

$$s = 1 - \frac{n}{n_0} = 1 - \frac{\omega}{\omega_1} \tag{8}$$

$$\Delta s = -\frac{\Delta\omega}{\omega_1} \tag{9}$$

The ratio of between the difference value of asynchronous motor synchronous speed and rotor speed and synchronous speed is called slip. Using electrical angle, ω was synchronous angular velocity and ω_1 was practical angular velocity. So, the slip was expressed by Eq. 8. Combining Eq. 7 with Eq. 9, the relationship on the point of steady state operating between micro deviator (ΔTe), ΔU_1 and Δω was expressed by Eq. 10:

$$\Delta T_e \approx \frac{3n_p(2U_{1M}s_M\Delta U_1 - \frac{U_{1M}^2}{\omega_1}\Delta\omega)}{\omega_1 R_2^{'}} \tag{10}$$

$$\begin{cases} T_{eM} - T_{lM} = \frac{J}{n_p} \cdot \frac{d\omega_M}{dt} \\ T_{eM} + \Delta T_e - (T_{lM} + \Delta T_l) = \frac{J}{n_p} \cdot \frac{d(\omega_M + \Delta\omega)}{dt} \\ \Delta T_e - \Delta T_l = \frac{J}{n_p} \cdot \frac{d(\Delta\omega)}{dt} \end{cases} \tag{11}$$

If small deviation existing near the point of M, the motion equation of electric drive system with constant torque loading at the point of M was expressed by Eq. 11. Ignoring the electromagnetic inertia and combining Eq. 11 with Eq. 9, the approximate partial-differential linearization dynamic structure of motor was got, as showed in Fig. 2:

$$\frac{\frac{n_p}{Js}}{1 + \frac{3n_p U_{1M}^2}{\omega_1 R_2^{'}} \cdot \frac{n_p}{Js}} = \frac{1}{\frac{J}{n_p}s + \frac{3n_p U_{1M}^2}{\omega_1 R_2^{'}}} \tag{12}$$

$$\begin{aligned} &= (\frac{3n_p}{\omega_1 R_2^{'}}) \cdot 2U_{1M}s_M \cdot \frac{1}{\frac{J}{n_p}s + \frac{3n_p U_{1M}^2}{\omega_1 R_2^{'}}} \\ &= \frac{2s_M\omega_1}{\Delta U_M} \cdot \frac{1}{\frac{J\omega_1{}^2 R_2^{'}}{3n_p U_{1M}^2}s + 1} \\ &= \frac{K_{MM}}{T_m s + 1} \end{aligned} \tag{13}$$

where, from Eq. 4-13, letters including Δ are the corresponding different value. The letters including M are the corresponding value at the point of M. The K_{MM} is transfer coefficient of asynchronous motor. T_m is the electromechanical time constant value of asynchronous motor driving system.

Considering only the transfer function between the ΔU_1 to Δω, ΔT_L was defined zero and the closed-loop transfer function in Fig. 2 was expressed by Eq. 12. Then, the approximate linearization transfer function of asynchronous motor was expressed by Eq. 13. In the system of constant pressure water injection, some control and detection section, such as the control conversion to relay and the time constant of the pressure conversion can be regarded as the proportion link. Therefore, the mathematical model of system can be equivalent to two inertial linking in series with pure lag and the dead zone. Finally, the mathematical model of the water injection system was expressed by Eq. 14:

$$G(s) = \frac{Ke^{-\tau s}}{(T_1 s + 1)(T_2 s + 1)} \tag{14}$$

where, K is the overall gain of the water injection system, T_1 is the inertial time constant of system, T_2 is the time constant of motor and converter and τ is the pure lag time of system.

Design for constant pressure control algorithm for large displacement and high pressure reciprocating pump: Figure 3 showed the structure of FPGC controller. Using fuzzy rules and reasoning to adjust the three parameters include K_p, K_i and K_d, FPGC control algorithm was very suitable for the object of constant pressure injection system (Ning *et al*., 2010). According to the linear relationship between the speed of the reciprocating pump and the change of the outlet main water pressure, the pressure control can be transformed to the control of the motor speed of the reciprocating pump. Using two-dimensional FPGC controller, the signal of input control was error (e MPa) and error rate (ec), meanwhile, the signal of output control was the motor speed (V, rpm).

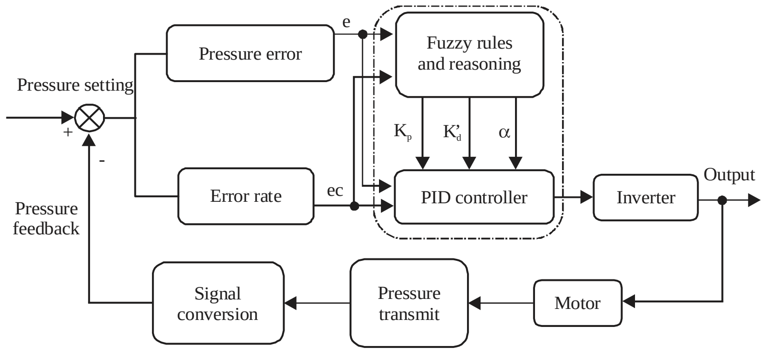

Fig. 3: Structure of FPGC controller

Table 1: Fuzzy adjustment rules of K_p'

	de (k)						
	NB	NM	NS	ZE	PS	PM	PB
e (k)							
NB	B	B	B	B	B	B	B
NM	S	B	B	B	B	B	S
NS	S	S	B	B	B	S	S
ZE	S	S	S	B	S	S	S
PS	S	S	B	B	B	S	S
PM	S	B	B	B	B	B	S
PS	B	B	B	B	B	B	B

Table 2: Fuzzy adjustment rules of Kd'

	de (k)						
	NB	NM	NS	ZE	PS	PM	PB
e (k)							
NB	S	S	S	S	S	S	S
NM	B	B	S	S	S	B	B
NS	B	B	B	S	B	B	B
ZE	B	B	B	B	S	B	B
PS	B	B	B	S	B	B	B
PM	B	B	S	S	S	B	B
PS	S	S	S	S	S	S	S

Table 3: Adjustment rules of α

	de (k)						
	NB	NM	NS	ZE	PS	PM	PB
e (k)							
NB	2	2	2	2	2	2	2
NM	3	3	2	2	2	3	3
NS	4	3	3	2	3	3	4
ZE	5	4	3	3	3	4	5
PS	4	3	3	3	3	4	5
PM	3	3	2	2	2	3	3
PS	2	2	2	2	2	2	2

The range of outlet main pressure was 0-P_{max}. Therefore, the basic theory of the pressure error was set as [-P_{max}, P_{max}] and the discrete domain of e (error) was defined as {-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6}. The change error rate was set as [-5, 5] and the discrete domain of ec was defined as {-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6}. The lingual variables of e and ec were forest as seven fuzzy subsets {NB, NM, NS, ZO, PS, PM, PB}. Triangle function was applied to subordinate function of e and ec (Feng *et al*., 2010; Johnson and Smartt, 1995). The fuzzy rules were expressed by conditional statements (if e(k) is A_i and ec(k) is B_i then K_p' is C_i, K_d' is D_i, α is α_i). A_i B_i C_i and D_i were in the corresponding fuzzy sets and α was a constant. Table 1-3 were the fuzzy rules of K_p' K_d' and α.

The K_p' K_d' and α were got from Table 1-3. The parameters of FPGC controller were obtained from Eq. 15 (Ning *et al*., 2010):

$$\begin{cases} K_d = (K_{d,max} - K_{d,min})K'_d + K_{d,min} \\ K_p = (K_{p,max} - K_{p,min})K'_p + K_{p,min} \\ K_i = K_p^2 / (\alpha K_d) \end{cases} \tag{15}$$

Under proportional controlling, K_μ was the period of gain and the T_μ was the period of oscillation. The range of K_p and K_d were obtained from Eq. 16 (Qin and Tan, 2005):

$$\begin{cases} K_{p,min} = 0.32K_u \\ K_{p,max} = 0.6K_u \\ K_{d,min} = 0.08K_u T_u \\ K_{d,max} = 0.15K_u T_u \end{cases} \tag{16}$$

RESULTS

Results of numerical simulation: The test process of control system was simulated by Matlab/Simulink (Yan *et al*., 2006; Xue and Chen, 2007). In Eq. 14, K was set 20, T_1 was set 10, T_2 was set 0.6, τ was set (-4). A set of ideal PID parameters were selected: K_p = 0.082, T_i = 0.065; T_d = 0.065. The test main pressure was set 12.5 MPa and the simulation time was set

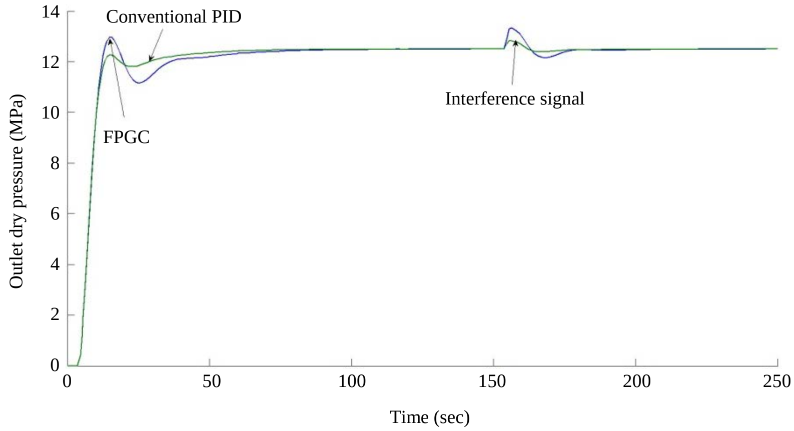

Fig. 4: Simulation curves with two control algorithm

Fig. 5: Water injection station

Table 4: Parameters of system

Parameters	Values
Reciprocating plunger pump	3
Flow rate (L min^{-1})	120
Plunger diameter (cm)	30
Number of water pump plunger	6
Power of induction motor (KW)	120
Max speed of motor (rpm)	1500
Temperature (°C)	27
Humidity (RH)	32

250 sec. The jamming signal occurred at the time of 150 sec. Simulation result was showed in Fig. 4. As the Fig. 4 showed, with the algorithm of conventional PID controlling, the overshoot σ was 8.33% and the settling time t_s was 73 sec. By contrast, with the algorithm of FPGC controlling, overshoot of σ was 2.4% and settling time was 56 sec.

Industrial experiment: As Fig. 5 showed, conventional PID control algorithm and FPGC control algorithm were test in water injection station. The monitoring system was composed of two parts, the data acquisition system and the upper computer monitoring system. Control system consisted of a main controller (PLC S7-200) and three subordinate controllers. And communication between them were realized through CAN bus network. The PC monitor interface was developed by Kingview software. The communication between main controller and PC were realized through RS485 bus. After A/D conversion and filtering jamming signal, the signal of control system collecting by many sensors (water pressure sensor, lubricating oil pressure sensor, temperature sensor and so on) will transmit to PC monitor interface.

Parameters setting: Parameters setting of constant pressure controlling were realized in the main PLC and the man-machine information real-time was exchanged on monitoring interface. In the industrial experiment, outlet main water pressure was set as 12.5 MPa and PID parameter: K_p = 0.148, T_i = 0.107, T_d = 1.672. Other experimental parameters were shown in Table 4.

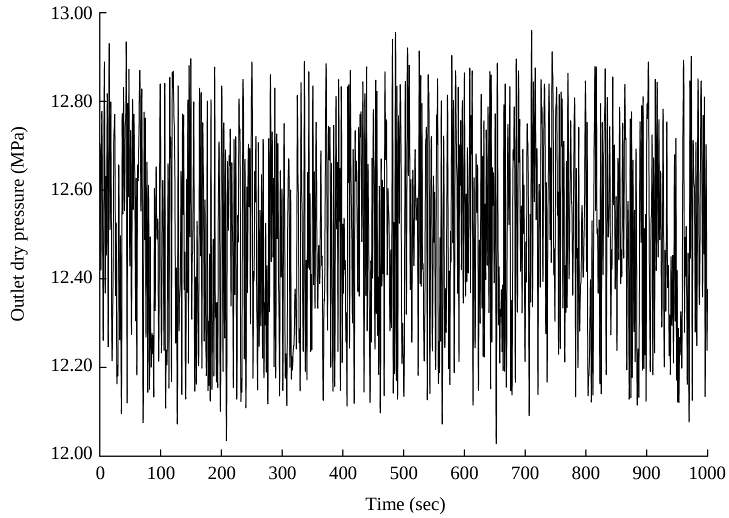

Fig. 6: Main pressure curve under conventional PID

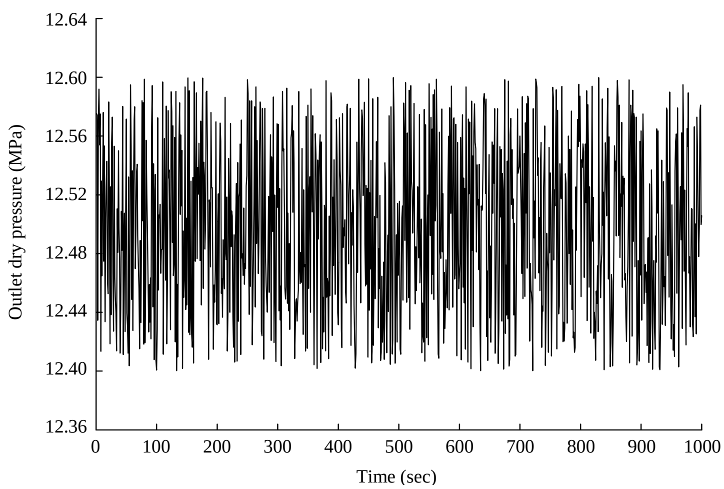

Fig. 7: Main pressure curve under FPGC

Result of industrial experiment: When the system stable, the value of outlet main water pressure was random selected from sample database. The curves of pressure change and pressure error under two algorithms were, respectively showed in Fig. 6-8.

As these curves showed, in the test of constant pressure injection, the outlet main pressure error under conventional PID algorithm control was $\pm$0.4 MPa. The outlet main pressure error under FPGC algorithm control was $\pm$0.1 MPa, which keeping in the vicinity of the preset pressure (12.5 MPa) and changing smoothly. So, FPGC algorithm can meet the control requirement of constant pressure control of oilfield injection-production.

DISCUSSION

At present, majority of oil field has entered the period of high water content and the water injection system must work day and night. So, the system consumed a lot of energy. In the whole oil field, the annual energy consumption of water injection system accounts for 33-56%, while in some, even more than 50% (Huang *et al*., 2012; Chang *et al*., 2013; Sahraoui *et al*., 2012).

In the oil field, water injection pump is usually two kinds-reciprocating pump and centrifugal pump (Wu *et al*., 2014). Changing fluid pressure in the volume of suction trap, the outlet main water pressure was increased by the

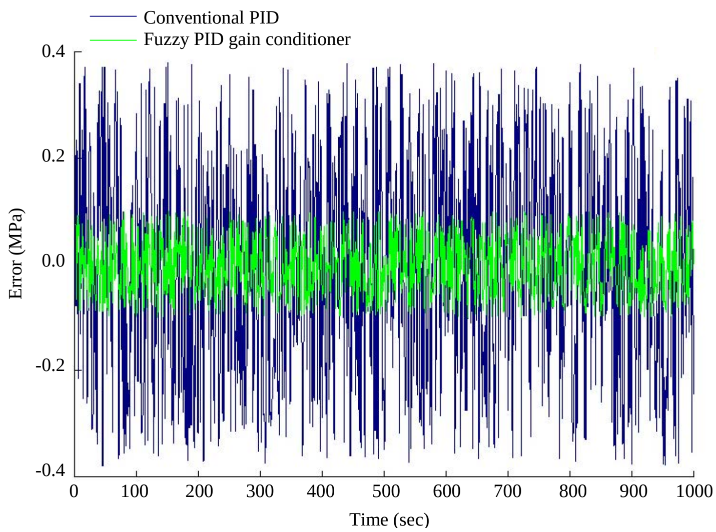

Fig. 8: Error curves of main pressure under two algorithms

reciprocating pump through periodically compressing the water flow. Through elevating the speed of centrifugal pump, the centrifugal force of water was increased. Then, the outlet water pressure of the centrifugal pump was promoted by the flow of kinetic energy. The reciprocating pump was paid more attention to because of higher efficiency (Liu, 2013; Wang, 2014). Large displacement and high pressure reciprocating pumps which were energy-saving and efficient were used widely and even has the trend of replacing the centrifugal pump (Wu *et al*., 2005, 2014).

The dead zone was existed in pipe network of water injection system and the water pipe laying was more complex. In addition, there were many unstable factors in the underground oil reservoir. The variable frequency pump needs to carry out the conversion between power frequency and variable frequency when the outlet main water pressure needs to be changed. So, the outlet main pressure value was influenced by many factors. Compared to previous research, the mathematical model of system was analyzed in detail in this study (Xu *et al*., 2009, 2011; Ning *et al*., 2010; Feng *et al*., 2010). In this study, an effective constant pressure control algorithm and monitoring system was designed. The unmanned injection station and intelligent monitoring were achieved, such as online reflecting the operation of water injection station, realizing visual monitoring, fault automatic alarming and stopping pump, automatic collecting and recording field data. The function of artificial intelligence have a great progress compared to previous research (Xu *et al*., 2009, 2011; Liu *et al*., 2014; Wang, 2007).

In the large displacement and high pressure reciprocating pump injection station, the goal of keeping outlet main water pressure stably was most important. Conventional PID controller and fuzzy controller have been applied to more injection station, but the controlling performance for outlet main constant pressure were not ideal (Cheng *et al*., 2013; Pandey and Laxmi, 2014; De and Mudi, 2013; Wang, 2007; Luo *et al*., 2014; Zhang *et al*., 2013; Qin and Tan, 2005; Patil *et al*., 2007; Sahraoui *et al*., 2012). As it is found through this study, controlled by conventional PID algorithm, the outlet main pressure error was $\pm$0.4 MPa. In contrast, the outlet main pressure under FPGC algorithm control can keep in the vicinity of the preset pressure 12.5 MPa (the error is less than 0.1 MPa).

CONCLUSION

On account of the problem that complex nonlinear and strong coupling process of constant pressure control of large displacement and high pressure reciprocating pump, the system of constant water pressure injection was built and the control law about system was obtained by field test. Then algorithms of conventional PID control and fuzzy gain conditioner PID control designed in this article were simulated and experimental analyzed and the algorithm of fuzzy gain conditioner PID control was applied in the constant pressure water injection control system successfully. Test results and the actual application showed that the algorithm of fuzzy gain conditioner PID control can greatly improve the stability of outlet main pressure of water injection station and control accuracy and meeting the demand of the oil field. Theoretical basis and detailed test data were provided for the next step of researching and designing for large displacement and high pressure reciprocating pump.

ACKNOWLEDGMENTS

This study is sponsored by National Natural Science Foundation of China (No. 51375284) and Shandong Provincial Natural Science Foundation (No. ZR2014EL027).

REFERENCES

Chang, Y.R., S.H. Wang and R.X. He, 2013. Water injection station design based on one-for-several rotor VVVF technique. Adv. Mater. Res., 722: 585-590.

Cheng, H.X., D.S. Zhang and L. Cheng, 2013. Comparative study on fuzzy PID controller and conventional PID controller. Applied Mech. Mater., 328: 112-116.

De, R.R. and R.K. Mudi, 2013. Fuzzy self-tuning of conventional PID controller for high-order processes. Adv. Intell. Syst. Comput., 247: 41-48.

Feng, Y.X., Y.M. Feng and Z.H. Li, 2010. Fuzzy-PID control water-supplying system based on PLC for constant pressure. Electric Mach. Control Applic., 2: 36-40.

Huang, Z.Q., Z. Chen, G. Zheng, J.Q. Xue and X.Y. Li, 2012. The key technology research of the water injection system energy saving for super low permeability reservoir in changqing oil field. Adv. Mater. Res., 524-527: 1217-1222.

Johnson, J.A. and H.B. Smartt, 1995. Advantages of an alternative form of fuzzy logic. IEEE Trans. Fuzzy Syst., 3: 149-157.

Liu, H.J., Y.W. Liu and L.A. Zhang, 2014. Design of large capacity high-pressure reciprocating pump distributed monitoring system. Mod. Manuf. Technol. Equipment, 3: 1-2.

Liu, M.H., 2013. Analysis of the packing leakage of high pressure reciprocating pump and its improvement measures. Guangzhou Chem. Ind., 41: 209-211.

Luo, Y.F., Y. Liu and J.L. Cheng, 2014. Climbing method of fuzzy control in the wind power system. Control Eng. China, 3: 378-381.

Ning, Y.B., S.M. Li and X.X. Sun, 2010. Variable frequency constant pressure water supply system based on gain-schedule fuzzy-PID control. J. Xi'an Univ. Technol., 26: 207-211.

Pandey, S.K. and V. Laxmi, 2014. Control of twin rotor MIMO system using PID controller with derivative filter coefficient. Proceedings of the IEEE Students Conference on Electrical, Electronics and Computer Science, March 1-2, 2014, Bhopal, pp: 1-6.

Patil, N.J., R.H. Chile and L.M. Waghmare, 2007. Implementation of model reference adaptive fuzzy controller. Proceedings of the IET-UK International Conference Information and Communication Technology in Electrical Sciences, December 20-22, 2007, Tamil Nadu, pp: 100-104.

Qin, X.P. and G.J. Tan, 2005. Development and prospect of fuzzy control theory. Control Eng. China, 12: 137-139.

Sahraoui, M., M. Salem, M.F. Khelfi and T. Self, 2012. Fuzzy controller of nonlinear systems. Proceedings of the 6th International Conference on Sciences of Electronics, Technologies of Information and Telecommunications, October 22-25, 2012, Florida, USA., pp: 912-916.

Wang, H.Z., 2014. Research on force analysis and fatigue resistance check of triple plungers pump crank shaft. Manuf. Automat., 12: 83-86.

Wang, R.L., 2007. The frequency control water supply system based on PID fuzzy control algorithm. J. Weifang Univ., 6: 16-19.

Wu, X., H. Lu, S. Wu, K. Huang, J. Wan, W. Li and Z. Liu, 2014. Stress analysis of reciprocating pump pipeline system in oil station. J. Chem. Pharmaceut. Res., 7: 2026-2032.

Wu, Y.D., G.N. Qi, Q.S. Xie and Y.J. Lu, 2005. Research on networked manufacturing system for reciprocating pump industry. Proceedings of the SPIE Mechatronics, MEMS and Smart Materials, September 20-23, 2005, Chongqing, China.

Xu, H.F., J. Cao and X. Wu, 2011. Design of reverse osmosis water treatment monitoring system base on MCGS and PLC. J. Comp. Applic., 12: 204-207.

Xu, X.F., H.S. Yin, Y.Q. Hou and Q. Zhong, 2009. Fault diagnosis system for oilfield water flooding pumps based on virtual instrument. J. Daqing Petroleum Inst., 3: 86-88.

Xue, D.Y. and Y.Q. Chen, 2007. MATLAB Solutions to Mathematical Problems in Control. Tsinghua University Press, Beijing, China.

Yan, X.Y., Q.C. Ren and Q.L. Meng, 2006. A self-tuning PID controller design and simulation. J. Syst. Simul., 8: 753-756.

Zhang, G., F. Tian and J.P. Wang, 2013. Study of DTC system based on fuzzy control. Control Eng. China, 6: 1023-1026.