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FUZZY CONTROL FOR COMPRESSOR OF CO_2 HEAT PUMP WATER HEATER BASED ON DIGITAL SIGNAL CONTROLLER

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Abstract. *In this paper, controller design for compressor of CO_2 trans-critical water-water heat pump is researched; the hardware circuit of controller is designed based on dsPIC30F6010 of company MICROCHIP; conventional proportional-integral-derivative (PID) method and the design and completion of fuzzy PID controller are introduced; the control strategy is debugged by the model of brushless DC motor (BLDCM) built in MATLAB, also, corresponding experiments are done; experimental results and simulations verify the validity and rationality of the designed controller.*
Keywords: BLDCM, dsPIC30F6010, PID, Fuzzy PID

1. **Introduction.** Compared with conventional gas water heater and heat pump water heater, CO_2 trans-critical water-water heat pump has advantages of low energy consumption, environmental protection and wider temperature range of water supplying, etc.

Jiang et al. provided thermodynamic analyses of tans-critical CO_2 cycle with and without internal heat exchanger (IHX) [1], the experimental results of systems with and without IHX were analyzed and compared, indicating that IHX could improve the performance of the trans-critical CO_2 heat pump system. Ma et al. of Tianjin University analyzed the reliability of the trans-critical CO_2 air conditioning system [2], also, based on the built experiment rig of CO_2 trans-critical water-water heat pump, the control strategy and method were researched. Rubaai et al. of Howard University proposed an integrated environment for the rapid prototyping of a robust fuzzy PID controller that allowed rapid realization of novel designs [3]. Both the design of the fuzzy PID controller and its integration with the classical PID in a global control system were developed. Shanmugasundram et al. of University of Madras presented the design and implementation of fuzzy controller and its performance is compared with PID controller to show its ability to track the error and usefulness of fuzzy controller in control applications [4].

In order to improve the control performance of heat pump system, targeting at the compressor, the most significant part of electronic control system of CO_2 trans-critical water-water heat pump, in this paper, the hardware circuit of controller is designed combining fuzzy control strategy; the model of BLDCM is built in MATLAB and corresponding simulations are done; simulations and experimental results verify the validity of the proposed control strategy.

2. **Components of Electronic Control System of Water Heat Pump.** The diagram of electronic control system of researched water heat pump is shown as Figure 1.

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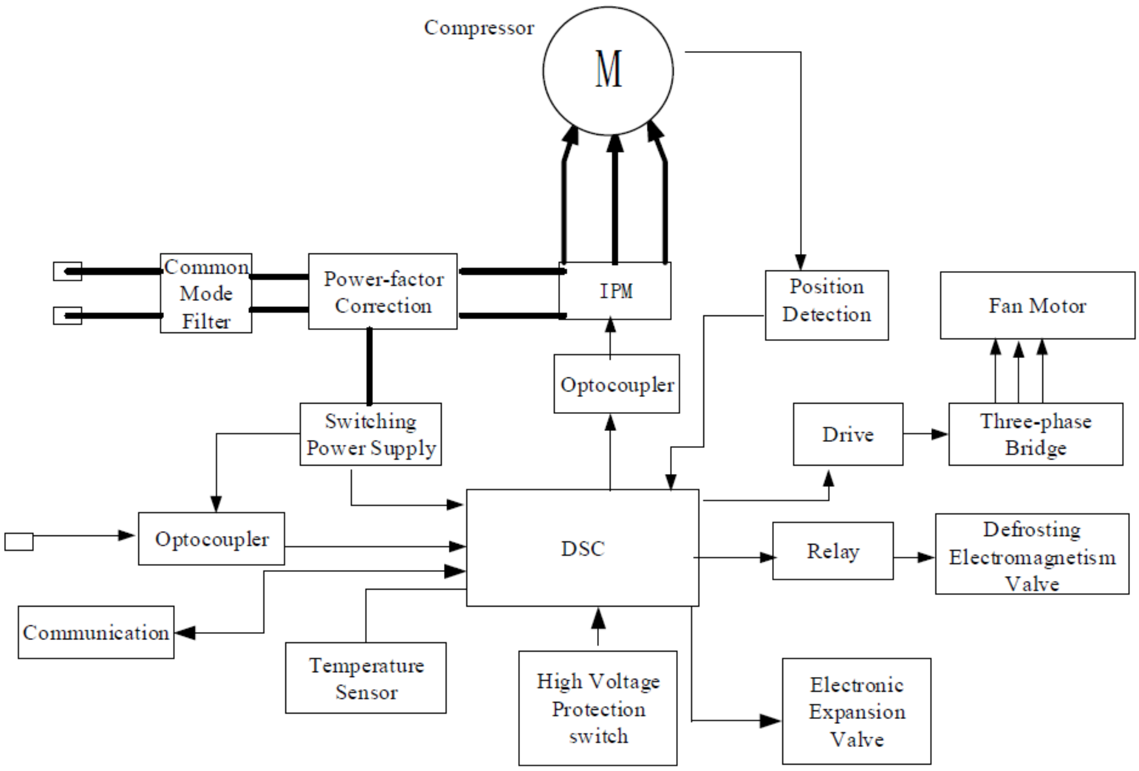

Figure 1. The diagram of electronic control system of water heat pump

The core of the control system is digital signal controller (DSC) dsPIC30F6010, on the basis of its strong computing function and abundant integrated peripherals; therefore, the whole electronic control system of water heat pump can be accomplished.

The performance of the electronic control system is decided by the compressor, compressor is the heart of the heating system, and the flowing and recycling of the working medium (CO_2) are realized by the operation of the compressor. BLDCM is applied as the compressor of researched electronic control system.

3. Controller Design of BLDCM.

PWM scheme is applied to regulating the speed of sensor-less three-phase BLDCM, zero-crossing method of back EMF and position sensor are used to obtain the motor rotor position, the MCPWM module of dsPIC30F6010 of Microchip is used to output PWM wave to intelligent power module (IPM), and thus the control function is realized.

3.1. Conventional PID algorithm.

The control law of conventional PID controller is as follows:

$$u(t) = K_P \left[e(t) + \frac{1}{T_I} \int_0^t e(t)dt + T_D \frac{de(t)}{dt} \right] \tag{1}$$

In the actual computational process of DSC, the incremental PID formula is applied:

$$\begin{aligned} & u(k) - u(k-1) = K_P[e(k) - e(k-1)] + K_I e(k) + K_D[e(k) - 2e(k-1) + e(k-2)] \\ & \Delta u(k) = u(k) - u(k-1) \\ & (k = 0, 1, 2, \ldots) \\ & K_I = K_P T/\tau_I \\ & K_D = K_P \tau_D / T \end{aligned} \tag{2}$$

In Equations (1) and (2): $u(k)$ – The computer output value at the k^{th} sampling time, $e(k)$ – The input deviation value at the k^{th} sampling time, $e(k-1)$ – The input deviation value at the $(k-1)^{\text{th}}$ sampling time, K_P – Scale factor, K_I – Integral coefficient, K_D – Differential coefficient.

In this paper, the input and output of PID controller are motor rotor speed and duty of PWM respectively, and Ziegler-Nichols method is applied to regulating the PID parameters [5].

3.2. **On-line self-tuning fuzzy control algorithm.** The diagram of on-line self-tuning fuzzy control algorithm is shown as below.

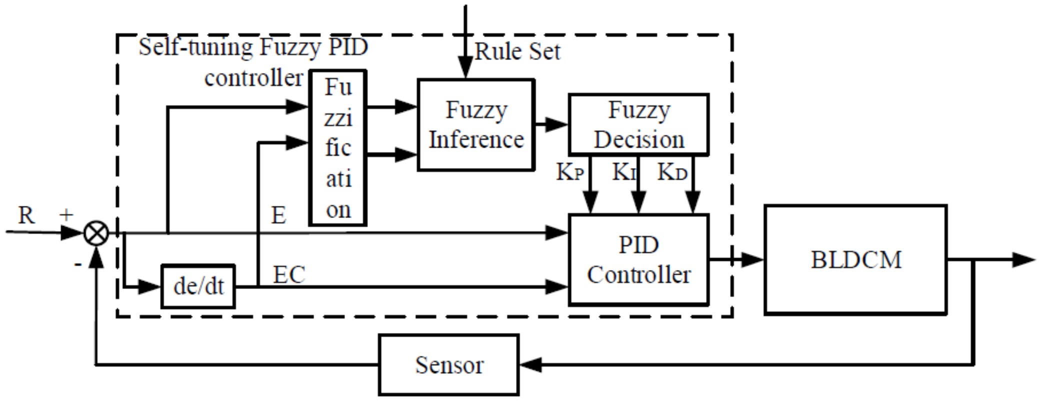

FIGURE 2. Diagram of on-line self-tuning fuzzy control algorithm

The key to realizing the self-tuning of PID parameters is figuring out the relation between three PID parameters (K_P, K_I, K_D) and error (E) or rate of change in error (EC).

The error is defined as the difference between the given speed and the actual speed, and the change in error is defined as the difference between the present error and the previous error. During the operating, E and EC are continuously detected, based on the principle of fuzzy control, three parameters are on-line regulated in time to satisfy the different requirements for controller parameters of different E and EC, and thus the controlled object can obtain good dynamic and static performance. The algorithm is easy for both computing and DSC implement.

The general fuzzy PID controller consists of three parts [6-8]. They are fuzzification, fuzzy rule base and fuzzy inference, defuzzification. The design steps are as follows.

3.2.1. *Fuzzification.*

1) Fuzzification of input.

The inputs of the fuzzy controller are error E and change in error EC, the outputs are three PID parameters K_P, K_I, K_D. The speed of BLDCM changes from 0-3000 rpm according to the specifications. Then the range of error is from -3000 to $+3000$ rpm; thus, the change in error is from -6000 to $+6000$ rpm.

Assuming that the range of original analog quantity is $[a, b]$, the setting formula is as (3).

$$y = \frac{1}{b-a}\left[x - \frac{a+b}{2}\right] \tag{3}$$

Thus, the setting formulas of E and EC are shown as follows.

$$E' = \frac{E}{6000} \tag{4}$$

$$EC' = \frac{DE}{12000} \tag{5}$$

Therefore, E', EC', fuzzification of input are obtained and quantized using the following linguistic terms negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), positive big (PB).

2) Fuzzification of output.

The outputs are three PID parameters K'_P, K'_I and K'_D, the range of which is set as $[-3, 3]$. According to the experience, let the three outputs multiple quantization factor respectively. The quantization factor can be regulated in time by experimental method according to various controlled objects.

The parameters are also quantized using the same terms as above.

3.2.2. *Fuzzy inference and rules.*

1) Membership function. The membership function of variables E', EC', K'_P, K'_I and K'_D in this paper is the combination of zmf function, triangular function and sigmoidal function, shown as follows.

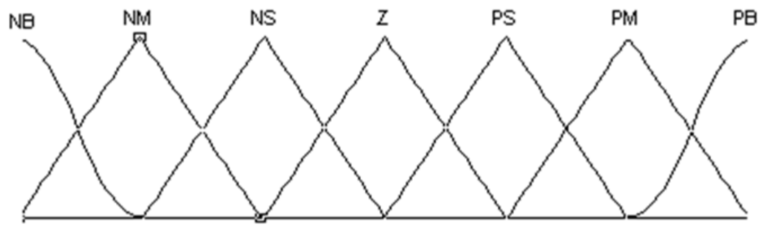

FIGURE 3. Membership function of variables E', EC', K'_P, K'_I and K'_D

2) Fuzzy rules. The outputs of fuzzy controller, K'_P, K'_I and K'_D, are obtained using the following 49 fuzzy rules:

1. If (E is NB) and (EC is NB) then (K_P is PB) (K_I is NB) (K_D is PS)
2. If (E is NB) and (EC is NM) then (K_P is PB) (K_I is NB) (K_D is NS)

⋮

48. If (E is PB) and (EC is PM) then (K_P is NB) (K_I is PB) (K_D is PS)
49. If (E is PB) and (EC is PB) then (K_P is NB) (K_I is PB) (K_D is PB)

The fuzzy sets of three parameters are shown as Tables 1, 2 and 3.

3) Fuzzy inference. Assume that there are two fuzzy rules as below:

R1: if x is A_1 and y is B_1, then Z is C_1
R2: if x is A_2 and y is B_2, then Z is C_2

If $x = x_0$, $y = y_0$, according to Mamdani's min-max inference rules:

$$\mu_C(Z) = \lfloor \omega_1 \wedge \mu_{C_1}(Z) \rfloor \vee \lfloor \omega_2 \wedge \mu_{C_2}(Z) \rfloor \tag{6}$$

where $\omega_1 = \mu_{A_1}(x_0) \wedge \mu_{B_1}(y_0)$, $\omega_2 = \mu_{A_2}(x_0) \wedge \mu_{B_2}(y_0)$.

TABLE 1. The fuzzy set of K'_P

$E' \backslash EC'$	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	Z	Z
NM	PB	PB	PM	PS	PS	Z	NS
NS	PM	PM	PM	PS	Z	NS	NS
Z	PM	PM	PS	Z	NS	NM	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	PS	Z	NS	NM	NM	NM	NB
PB	Z	Z	NM	NM	NM	NB	NB

TABLE 2. The fuzzy set of K'_I

$E'\backslash EC'$	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NM	NM	NS	Z	Z
NM	NB	NB	NM	NS	NS	Z	Z
NS	NB	NM	NS	NS	Z	PS	PS
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PS	PM	PB
PM	PS	Z	PS	PS	PM	PB	PB
PB	Z	Z	PS	PM	PM	PB	PB

TABLE 3. The fuzzy set of K'_D

$E'\backslash EC'$	NB	NM	NS	ZO	PS	PM	PB
NB	PS	NS	NB	NB	NB	NM	PS
NM	PS	NS	NB	NM	NM	NS	Z
NS	Z	NS	NM	NM	NS	NS	Z
Z	Z	NS	NS	NS	NS	NS	Z
PS	Z	Z	Z	Z	Z	Z	Z
PM	PB	PS	PS	PS	PS	PS	PB
PB	PB	PM	PM	PM	PS	PS	PB

3.2.3. *Defuzzification.* The fuzzy output of the controller should be converted to crisp value by the defuzzification. MOM method is applied in this paper, and the formula for the MOM defuzzification method is as below.

$$u_0 = \sum_{j=1}^{l} \frac{\omega_j}{l} \tag{7}$$

where ω_j: Outputs whose values reach to the maximum $m(\omega_j)$, l: Number of outputs.

4. Simulation of Motor Control System.

4.1. Simulation of current loop. The simulation model of current loop is shown as Figure 4, the PI integral separation regulator is applied to shortening overshoot and static error.

The wave of feedback current is shown as Figure 5.

4.2. Simulation of speed loop. The self-tuning fuzzy algorithm is applied to the speed loop to obtaining good static and dynamic performance. The diagram of simulation of speed loop with current loop is shown as Figure 6, the "Current Controller" is the current loop mentioned above, the "Saturation" is applied to limiting the maximum current reference, which is the output of speed loop, to 10A, and the "Filter" is a one level low pass filter.

The simulation results are shown in Figure 7, the command signals are square wave and 0-3000 pulse, and it can be seen that the designed control method has good tracking performance and quick response to speed mutation.

The photos of designed controller and test bench are shown as Figures 8 and 9.

The software test platform is built in LabWindows, the speed signal is given as 2700rpm, 3Hz sin wave, and experimental result is shown as Figure 10. It can be seen that the designed fuzzy controller can obtain better tracking performance than conventional PID controller.

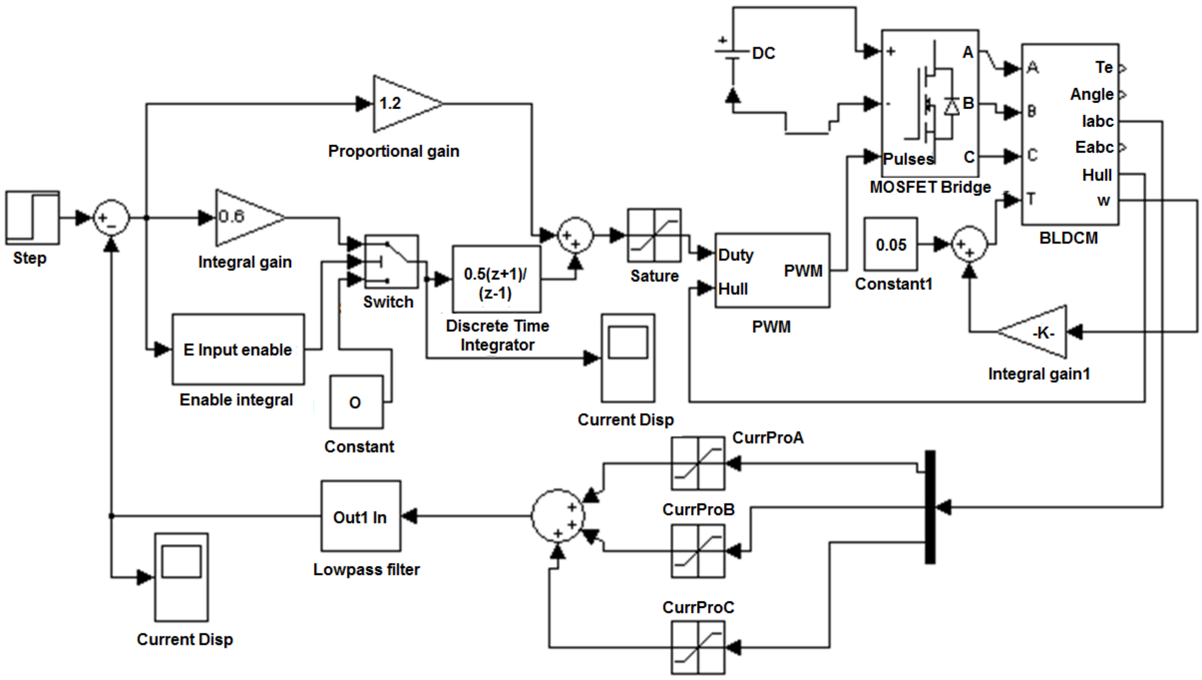

Figure 4. Simulation model of current loop

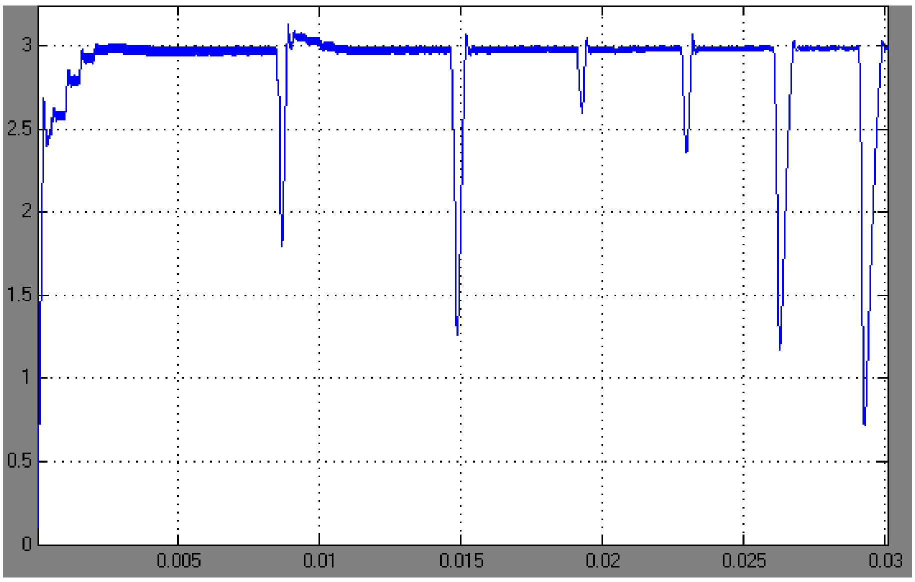

Figure 5. The wave of feedback current

5. **Conclusions.** In this paper, controller for the most significant part of electronic control system of CO_2 heat pump water heater, compressor, is researched. The hardware circuit of fuzzy controller is designed; we build the model of BLDCM in MATLAB, and on that basis, corresponding simulations are done, as well as necessary experiments that can verify the validity of designed controller. In the future, with the development of digital signal processor (DSP), the designed controller in this paper can be replaced by DSP to obtain better functions.

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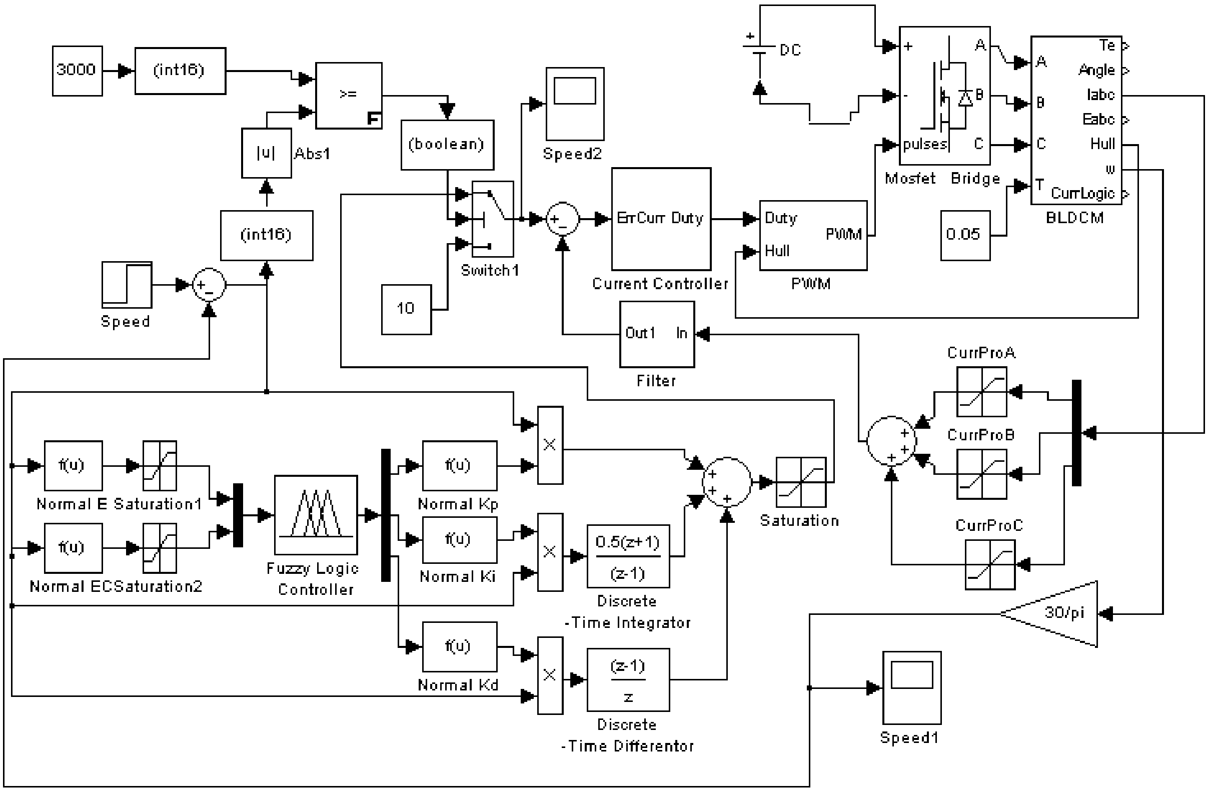

FIGURE 6. The diagram of simulation of speed loop with current loop

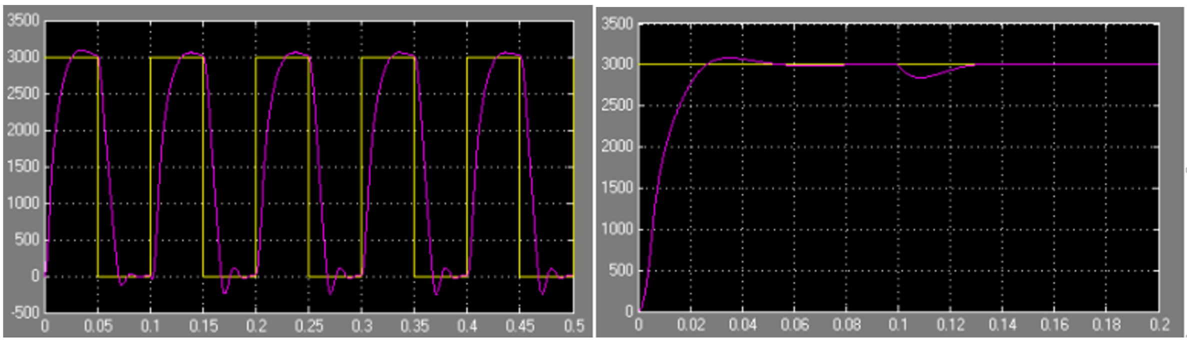

FIGURE 7. Tracking performance and response of designed fuzzy control method

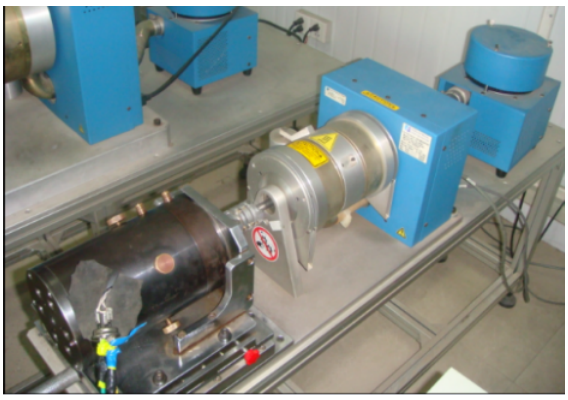

FIGURE 8. Photo of test bench

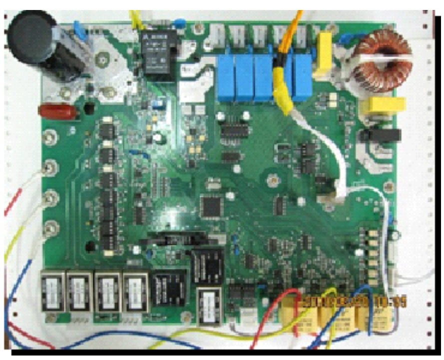

FIGURE 9. Photo of designed controller

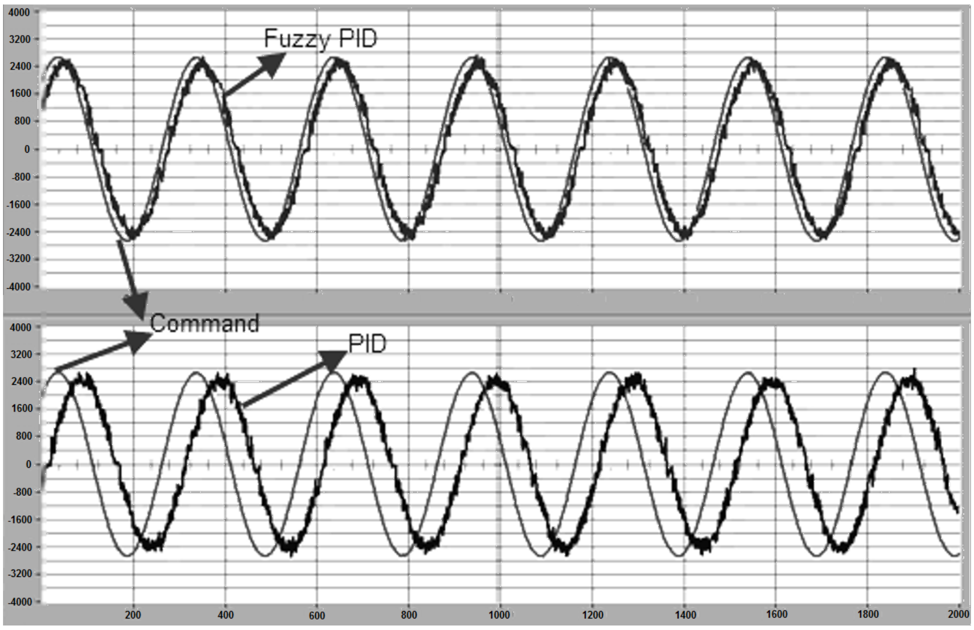

Figure 10. Comparison of tracking performance of fuzzy PID and conventional PID

REFERENCES

[1] Y. Jiang, Y. Ma, M. Li and L. Fu, An experimental study of trans-critical CO_2 water-water heat pump using compact tube-in-tube heat exchangers, *Energy Conversation and Management*, vol.76, pp.92-100, 2013.
[2] Y. Ma, J. Yang, H. Guan and M. Li, Theoretical analysis of heat transfer performance for heat absorbing process in trans-critical carbon dioxide cycle, *Journal of Thermal Science and Technology*, vol.2, no.4, pp.297-301, 2003.
[3] A. Rubaai, M. J. Castro-Sitiriche and A. R. Ofoli, Design and implementation of parallel fuzzy PID controller for high-performance brushless motor drives: An integrated environment for rapid control prototyping, *IEEE Trans. Industry Applications*, vol.44, no.4, 2008.
[4] R. Shanmugasundram, K. M. Zakariah and N. Yadaiah, Implementation and performance analysis of digital controllers for brushless DC motor drives, *IEEE/ASME Trans. Mechatronics*, vol.19, no.1, 2014.
[5] A. Oveisi and M. Gudarzi, Adaptive sliding mode vibration control of a nonlinear smart beam: A comparison with self-tuning Ziegler-Nichols PID controller, *Journal of Low Frequency Noise Vibration & Active Control*, vol.32, nos.1-2, pp.41-62, 2013.
[6] Y. He, Y. Tang, D.-H. Lee and J.-W. Ahn, Suspending control scheme of 8/10 bearingless SRM based on adaptive fuzzy PID controller, *Chinese Journal of Electrical Engineering*, vol.2, no.2, 2016.
[7] J.-W. Jung, Y.-S. Choi, V. Q. Leu and H. H. Choi, Fuzzy PI-type current controllers for permanent magnet synchronous motors, *IET Electric Power Applications*, vol.5, no.1, pp.143-152, 2011.
[8] R. Shanmugasundram, K. M. Zakariah and N. Yadaiah, Digital implementation of fuzzy logic controller for wide range speed control of brush-less DC motor, *Proc. of IEEE International Conference on Vehicular Electronics and Safety*, Pune, India, pp.119-124, 2009.