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A kind of nonlinear PID controller for Refrigeration Systems based on Vapour Compression

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Abstract: There are different ways in making nonlinear PID controllers. In this paper, a kind of nonlinear PID controller designed by special usage of nonlinear function is introduced, which is called Han's nonlinear PID controllers for short according to the name of the original inventor. Typically, a fal function based nonlinear PID controller has been taken as an example for performance verification upon the Benchmark PID 2018 platform. The simulation results prove that, by parameters tuning for the performance of minimal control efforts, the fal function based nonlinear PID controller can achieve the desired cooling goal under more stable operating conditions yet holding nearly the similar quality steady-state performance.

Keywords: nonlinear PID; fal function; refrigeration system; vapour compression; Benchmark PID 2018;

1. INTRODUCTION

As widely known, Proportional-Integral-Derivative (PID) controllers are undoubtedly the most employed controllers in industry. However, it has been proved cannot adapt to all environmental occasions to achieve the desired control objectives. Consequently, different new techniques have been integrated into the PID based structure to improve its performance. Among all these work, nonlinear techniques have been taken as a kind of method effective and possessing clear physical meaning. Different kinds of nonlinear PID controllers have emerged in large numbers Vilanova and Visioli (2012), like fractional PID controllers in Vinagre et al. (2000), Nonlinear PID controller using neural networks in Matsukuma et al. (1997), Fuzzy-based nonlinear PID controller So and Jin (2018) and etc.

Nearly at the same time, a Chinese scholar Han Jingqing from Academy of Mathematics and Systems Science in Chinese Academy of Sciences had proposed an nonlinear PID controller in 1994 Jingqing (1994). This kind of PID controller was designed by using a kind of special nonlinear functions. This modification has been proved possessing with greater adaptability and robustness.

In this paper, the Han's nonlinear PID controller will be introduced and tested upon the Benchmark PID 2018. This paper is organised as follows. The nonlinear PID Controller description will be given in the second section. The simple introduction of the Benchmark PID 2018 will be described in the third part. The simulation comparison based on the Han's PID controller with the default controller will be given in the fourth part. Some conclusion remarks will be presented in the last section.

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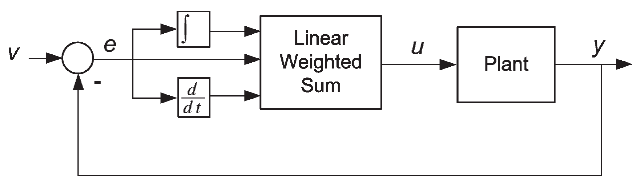

Fig. 1. The Classic PID control topology

2. NONLINEAR PID CONTROLLER DESCRIPTION

Han's nonlinear PID controller is a creative application of some special nonlinear functions for modification of PID based control structure.

2.1 The Structure of Han's Nonlinear PID Controller

Classical PID is presented as the following form:

$$u = k_0 \int_0^t e d\tau + k_1 e + k_2 \frac{de}{dt} \tag{1}$$

where, e represents the error between the setpoint $v =$ const and plant y, i.e. $e = v - y$. The control topology can be described as shown in Fig.1,

The linear combination of the tracking error e and its integration $\int_0^t e d\tau$ as well as its differentiation $\frac{de}{dt}$ constitutes

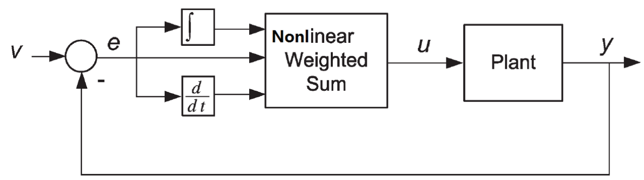

Fig. 2. The Han's nonlinear PID control topology

the control law, which covered the present, accumulative and predictive information of the tracking error.

Han questioned that there are four fundamental issues to be addressed in the PID framework Han (2009):
(1)Setpoint is often given as a step function, not appropriate for most dynamics systems because it amounts to asking the output and, therefore, the control signal, to make a sudden jump.
(2) PID is often implemented without the D part because of the noise sensitivity.
(3) The weight sum of the three terms in Equation 1, while simple, may not be the best control law based on the current and the past of the error and its rate of change.
(4) The integral term, while critical to rid of steady-state error, introduces other problems such as saturation and reduced stability margin due to phase lag.

As for the third mentioned issue, in the case of classic PID controller, no matter how the error changes, the gains of the controller will be consistence with the setting values. How the situation will be different if the controller's gains vary as the tracking error changes? By considering this, Han Jingqing proposed an nonlinear combination of the tracking error e and its integration $\int_0^t e d\tau$ as well as its differentiation $\frac{de}{dt}$ as a new PID controller in Jingqing (2008), which takes the form as shown in Fig.2,

In this form, the control law was decided by the tracking error and the nonlinear weighted sum, thus different nonlinear weighted sums will produce different nonlinear PID controllers.

2.2 One typical form of Han's Nonlinear PID controller

The fal function based nonlinear PID is the most widely used form among Han's nonlinear PID controllers, which can be presented as:

$$fal(e, a, \delta) = \begin{cases} e\delta^{a-1}, |e| \le \delta \\ |e|^a sign(e), |e| > \delta \end{cases} \tag{2}$$

where, $e(k) = z(k) - y(k)$, describing the system's tracking error; a deciding the non-linearity of the fal function; δ representing the interval length of linear segment.

The Characteristics of fal function The function fal's output is decided by three parameters, e, a and δ, and the way how they affect the function's output will be given in the following pictures which was discussed inHong et al. (2014).

(1) Take the Sine signal with the amplitude 1 and frequency 1 rad/s as the input signal, keep $\delta = 0.5$, change a, the fal function output's change according to the change of parameter a is shown in Fig.3.

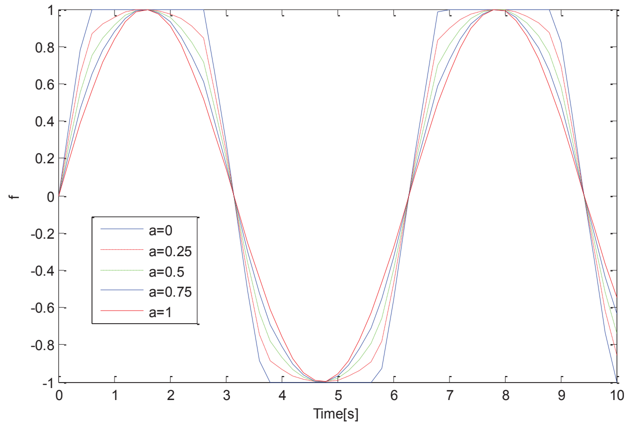

Fig. 3. The fal function output's change according to the change of parameter a

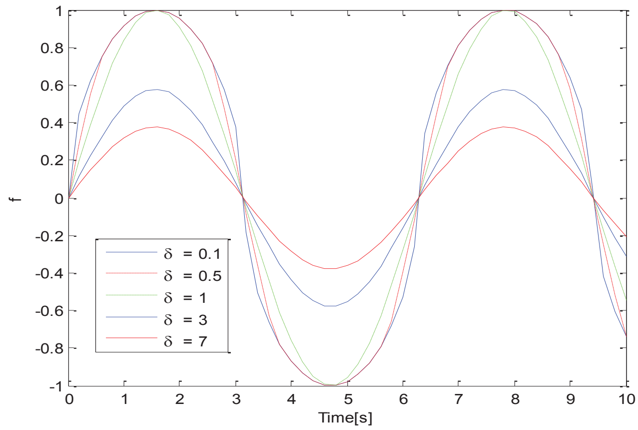

Fig. 4. The fal function output's change according to the change of parameter δ

(2) Take the Sine signal with the amplitude 1 and frequency 1 rad/s as the input signal, keep $a = 0.5$, change δ, the fal function output's change according to the change of parameter δ is shown in Fig.4.

As is shown in Fig.3, there will be a turning point when the amplitude of the Sine signal reach to 0.5, it is linear when lower than 0.5, nonlinear when higher than 0.5. Specifically, the value of parameter a deciding the nonlinearity of the fal function, which can be shown in the detailed image of fal function output's change according to the change of parameter δ given in Fig.5.

In conclusion, Yi and wenge (2002) pointed out that fal function can realise the engineers' experience of "Big tracking error, small gain; Small tracking error, big gain."

The fal function based nonlinear PID Controller The fal function based nonlinear PID Controller is given as:

$$u = k_1 fal(e_1, a_1, \delta) + k_2 fal(e_2, a_2, \delta) + k_3 fal(e_3, a_3, \delta) \tag{3}$$

where, e_1, e_2 and e_3 are the tracking error's integration, tracking error itself and tracking error's differential respectively. k_1, k_2 and k_3 are the controller's gains.

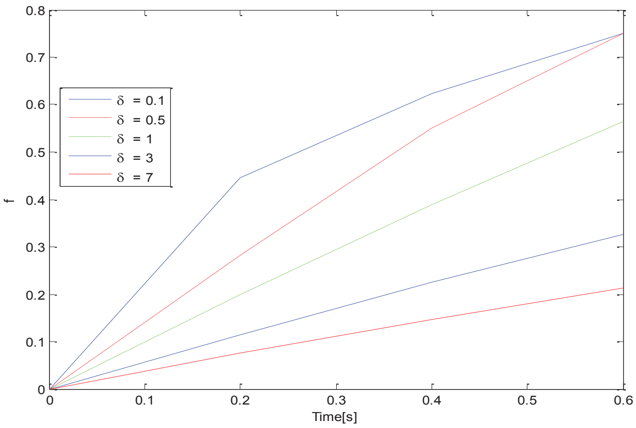

Fig. 5. The detailed image of fal function output's change according to the change of parameter δ

3. THE BENCHMARK PID 2018 DESCRIPTION

The benchmark PID 2018 set up by Bejarano et al. (2017) is a control problem of refrigeration systems based on Vapour compression, the benchmark platform is established based on an one-compression-stage, one-load-demand vapour- compression refrigeration cycle.

The main control objective is to provide the desired cooling power $\dot{Q}_e$. Furthermore, the generation of this cooling power is intended to be as efficient as possible, which implies controlling the degree of superheating T_{SH}. As widely known, energy efficiency is usually described in refrigeration field using the Coefficient of Performance (COP), which is defined as the ratio between the cooling power generated at the evaporator $\dot{Q}_e$ and the mechanical power provided by the compressor $\dot{W}_{comp}$, as indicated in Equation 4.

$$COP = \frac{\dot{Q}_e}{\dot{W}_{comp}} = \frac{\dot{m}(h_{e,out} - h_{e,in})}{\dot{m}(h_{c,in} - h_{e,out})} = \frac{h_{e,out} - h_{e,in}}{h_{c,in} - h_{e,out}} \quad (4)$$

In the Benchmark PID 2018 a particular application of refrigeration systems is considered. The cycle, working with R404a as refrigerant, is expected to provide a certain cooling power $\dot{Q}_e$ to a continuous flow entering the evaporator as secondary flux. The evaporator secondary fluid is a 60% propylene glycol aqueous solution, whereas the condenser secondary fluid is air.

The Benchmark PID 2018 provides the Simulink model of Fig.6 for control strategy development and research, where the manipulated variables, the controlled variables, and the disturbances are indicated. Two variables (the outlet temperature of the evaporator secondary flux $T_{e,\sec,out}$ and the degree of superheating T_{SH}) are to be controlled by manipulating two variables (the compressor speed N and the expansion valve opening A_v), considering also the disturbances Bejarano et al. (2017). The Coefficient of Performance COP is used as quality steady-state performance variable.

In this paper, the simulation study is carried out by comparing with the default controller based upon this simulation platform.

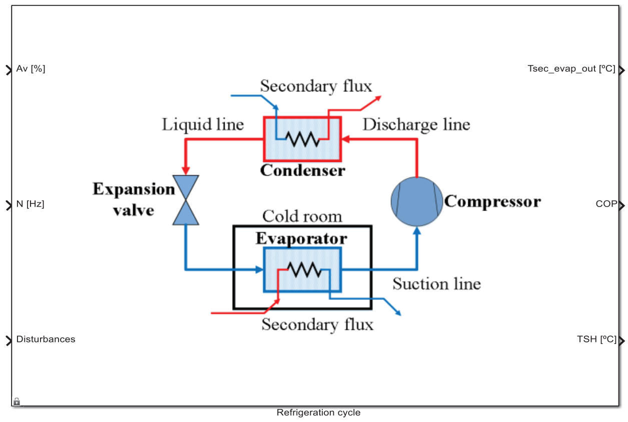

Fig. 6. Refrigeration Control System

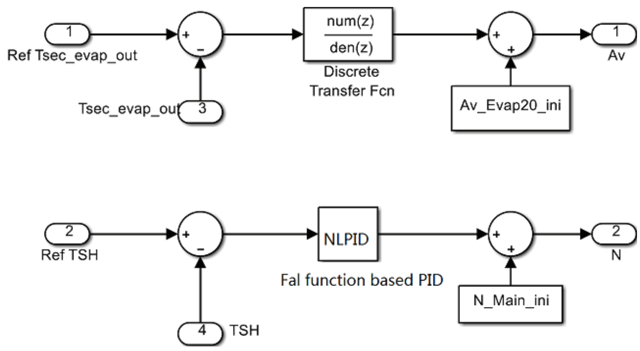

Fig. 7. Schematic picture of the proposed nonlinear PID Controller Structure

4. THE SIMULATION COMPARISON WITH THE DEFAULT CONTROLLER

4.1 The proposed Nonlinear PID Controller structure

In order to verify the performance of the fal function based PID control on the Benchmark PID 2018 problem, we keep the defaulted settings unchanged, and only replace the discrete PID controller in the second loop with the fal function based PID controller, thus the simulink model of the new control part is given as shown in Fig.7.

4.2 The Simulation comparison results

To test the performance of the fal function based nonlinear PID controller on the given Benchmark platform is the main goal of this work. Thus, the control goal and the setting disturbances as well as the controller of the first loop remain unchanged, the employment of fal function based nonlinear PID controller will affect the system in many aspects, including the tracking performance, the control effort, the condenser pressure, the evaporator pressure, compressor efficiency and COP.

In order to further analyse the performance of the proposed nonlinear PID controller, eight individual performance indices and one combined index are employed in the comparison. The first two indices are the Ratios of Integrated Absolute Error (RIAE), taking into account that both the outlet temperature of evaporator secondary flux ($T\sec\_evap\_out$) and the degree of superheating (TSH) should follow their respective references. The third is the

Ratio of Integrated Time multiplied Absolute Error (RITAE) for the first controlled variable ($T\sec\_evap\_out$), taking into account that the standard simulation only includes one sudden change in its reference. The fourth, fifth, and sixth indices are the Ratios of Integrated Time multiplied Absolute Error (RITAE) for the second controlled variable (TSH), taking into account that the standard simulation includes three sudden changes in its reference. The seventh and eighth indices are the Ratios of Integrated Absolute Variation of Control signal (RIAVU) for the two manipulated variables, the valve opening (Av) and the compressor speed (N). The combined index is obtained as the mean value of the eight individual indices using a weighting factor for each index. The expressions of the indices are given as below.

$$\mathrm{IAE_i} = \int_0^{time} |e_i(t)|\, dt \tag{5}$$

$$\mathrm{ITAE_i} = \int_0^{time} \left|\frac{\mathrm{du_i(t)}}{\mathrm{dt}}\right| dt \tag{6}$$

$$\mathrm{RIAE_i(C_2{,}C_1)} = \frac{\mathrm{IAE_i}(C_2)}{\mathrm{IAE_i}(C_1)} \tag{7}$$

$$\mathrm{RITAE_i(C_2{,}C_1{,}t_c{,}t_s)} = \frac{\mathrm{ITAE_i(C_2}{,}t_c, t_s)}{\mathrm{ITAE_i(C_1}, t_c, t_s)} \tag{8}$$

$$\mathrm{RIAVU_i(C_2{,}C_1)} = \frac{\mathrm{IAVU_i(C_2)}}{\mathrm{IAVU_i(C_1)}} \tag{9}$$

$$J(\mathrm{C_2{,}C_1}) = \frac{\begin{array}{l} w_1\,\mathrm{RIAE_1(C_2{,}C_1)}+\mathrm{w_2\,RIAE_2(C_2{,}C_1)} \\ +\mathrm{w_3\,RITAE_1(C_2{,}C_1{,}t_{c1}{,}t_{s1})} \\ +\mathrm{w_4\,RITAE_2(C_2{,}C_1{,}t_{c2}{,}t_{s2})} \\ +\mathrm{w_5\,RITAE_2(C_2{,}C_1{,}t_{c3}{,}t_{s3})} \\ +\mathrm{w_6\,RITAE_2(C_2{,}C_1{,}t_{c4}{,}t_{s4})} \\ +\mathrm{w_7RIAVU_1(C_2{,}C_1)} \\ +\mathrm{w_8RIAVU_2(C_2{,}C_1)} \end{array}}{\sum_1^8 w_i} \tag{10}$$

According to the simulation process, the following discussion was divided into two parts - research for the optimal combined index and the optimal control efforts since all the performance indices cannot be easily met up at the same time.

Research for the optimal combined index The control parameters of the employed fal function based PID controller are chosen as below:

$$k_1 = 0.5, k_2 = 10, k_3 = 0.01$$
$$a_1 = 0.001, a_2 = 0.01, a_3 = 0.55$$
$$\delta = 0.1$$

With the parameters setting, the simulation of tracking performance comparison was obtained as shown in Fig.8, and that of the corresponding control effort comparison was given as shown in Fig.9.

Generally, there are two indices to evaluate the system performance, one is the tracking performance, the other is the system energy efficiency, which is COP in this benchmark problem.

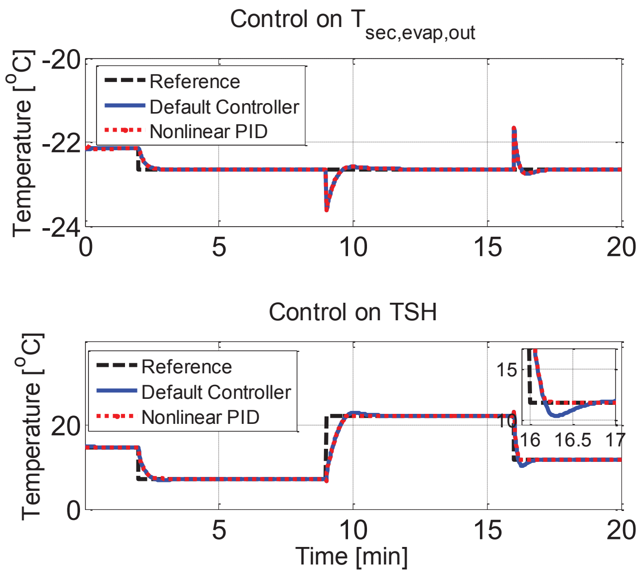

Fig. 8. The simulation comparison results of the tracking performance

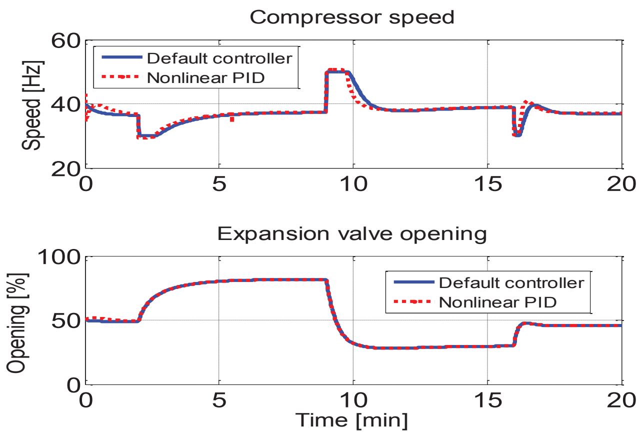

Fig. 9. The simulation comparison results of the control effort

From the above curves, we can tell that with the fal function based nonlinear PID controller, the system can reach nearly the same desired goal with similar control effort changes yet without any overshoot in the tracking for the degree of superheating.

Correspondingly, the comparison results of compressor efficiency and COP are shown in Fig.10.

From the curves, it can be seen that the overall energy efficiency of both the proposed controller and the defaulted one are nearly the same. Specifically, there are differences in several partial details, for example, at around 3 second and 16 second, the COP of system with defaulted controller are higher than the proposed controller, which might be resulted by the evaporator pressure difference which is shown in Fig.11 at each corresponding time. While at around 10 second, the COP of the proposed controller is higher than the defaulted controller.

The proposed controller produced slightly less evaporator pressure, thus make a bigger pressure difference between the evaporator and the condenser, then consequently result

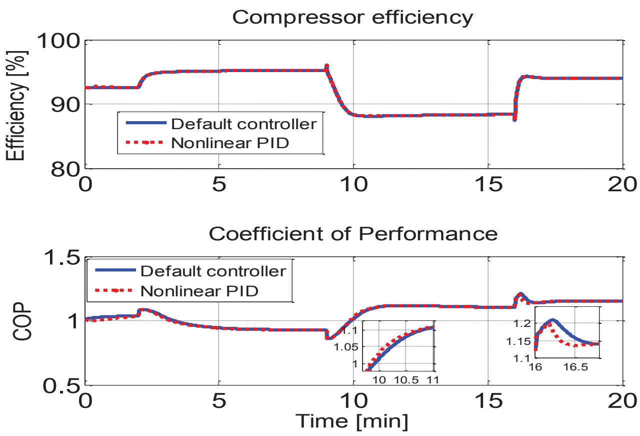

Fig. 10. The simulation comparison results of compressor efficiency and COP

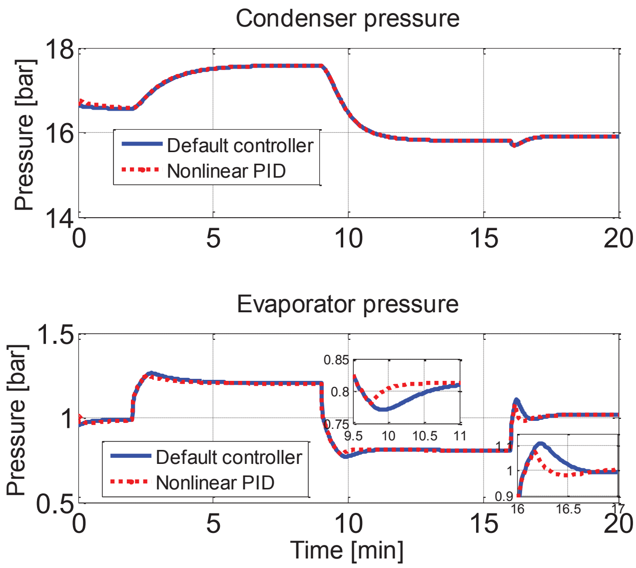

Fig. 11. The simulation comparison results of condenser and evaporator pressure

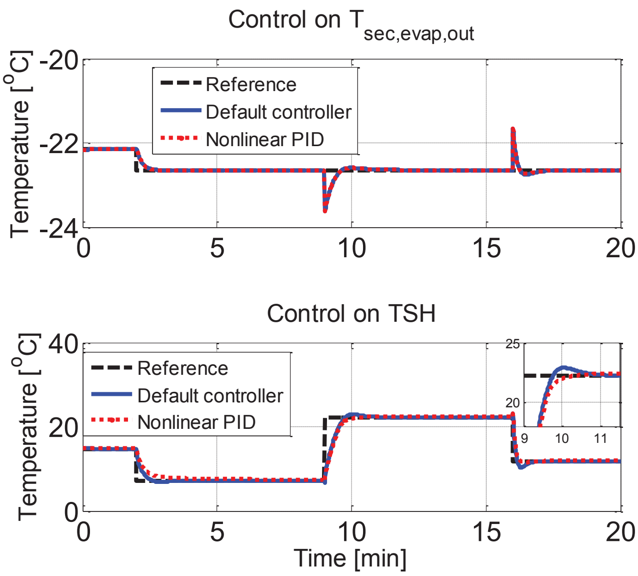

Fig. 12. The simulation comparison results of the tracking performance

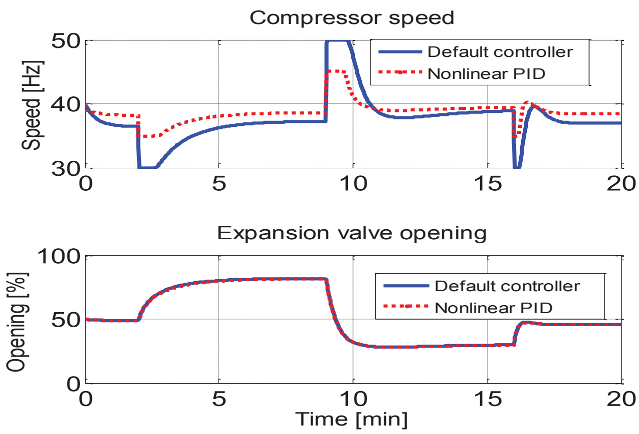

Fig. 13. The simulation comparison results of the control effort

in a lower COP in the corresponding time point according to the COP equation 4.

The quantitative comparison indices are presented in table 2.

Table 1. Performance Indices

Index	Value
$RIAE_1(C_2,C_1)$	1.03
$RIAE_2(C_2,C_1)$	0.86
$RITAE_1(C_2,C_1,t_{c1},t_{s1})$	0.97
$RITAE_2(C_2,C_1,t_{c2},t_{s2})$	1.12
$RITAE_2(C_2,C_1,t_{c3},t_{s3})$	0.76
$RITAE_2(C_2,C_1,t_{c4},t_{s4})$	0.87
$RIAVU_1(C_2,C_1)$	1.01
$RIAVU_2(C_2,C_1)$	1.30
$J(C_2,C_1)$	0.97

The performance indices show that the overall performance of the proposed Controller possesses a better combined index $J(C_2, C_1)$, while the Integrated Absolute Error , Integrated Time multiplied Absolute Error and Integrated Absolute Variation of Control signal are slightly worse.

Research for the minimal control efforts The control parameters of the employed fal function based PID controller are chosen as below:

$$k_1 = 0.01, k_2 = 5, k_3 = 0.01$$
$$a_1 = 0.01, a_2 = 0.01, a_3 = 0.01$$
$$\delta = 0.1$$

With the parameters setting, the simulation of tracking performance comparison was obtained as shown in Fig.12, and that of the corresponding control effort comparison was given as shown in Fig.13.

From the above curves, we can tell that with the fal function based nonlinear PID controller, the system can reach nearly the same desired goal with less control effort changes yet without any overshoot. In other words, the system can realise the control target under more stable operating conditions comparing with the defaulted controller, which may result in a longer operating life of the compressor. Furthermore, the bigger magnitude of change produced by the defaulted controller may increase the compressor's energy consumption. Thus, for the same con-

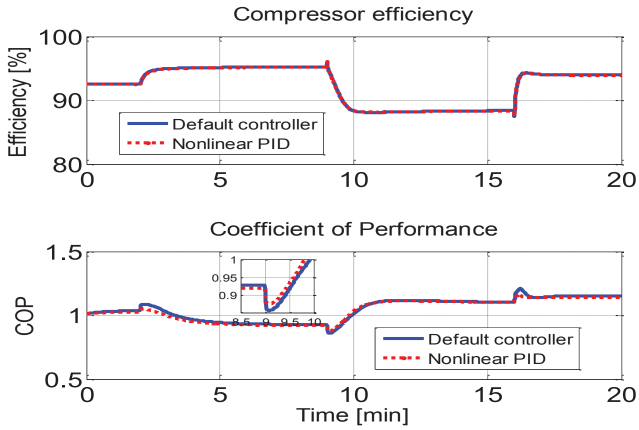

Fig. 14. The simulation comparison results of compressor efficiency and COP

trol goal, the fal function based nonlinear PID controller may be more favorable in the industry.

Correspondingly, the comparison results of compressor efficiency and COP are shown in Fig.14.

The curves show that the overall energy efficiency of both the proposed controller and the defaulted one are nearly the same with some slight differences in several partial details ,just like the results of the former chosen parameters.

The quantitative comparison indices are presented in table 2.

Table 2. Performance Indices

Index	Value
$RIAE_1(C_2,C_1)$	0.98
$RIAE_2(C_2,C_1)$	1.18
$RITAE_1(C_2,C_1,t_{c1},t_{s1})$	0.81
$RITAE_2(C_2,C_1,t_{c2},t_{s2})$	3.25
$RITAE_2(C_2,C_1,t_{c3},t_{s3})$	1.01
$RITAE_2(C_2,C_1,t_{c4},t_{s4})$	1.43
$RIAVU_1(C_2,C_1)$	0.99
$RIAVU_2(C_2,C_1)$	0.62
$J(C_2,C_1)$	1.26

The data shows that less control effort will be achieved at the cost of the Integrated Absolute Error, Integrated Time multiplied Absolute Error and the combined index.

From the comparison research, it can be noted that an overall better performance with eight better relative indices and a better combined performance is hard to obtain via the proposed method. The search for one optimal performance index would usually take cost of the other indices. As a result, the designer should choose parameters according to the designing requirements.

5. CONCLUSION

In this paper, a kind of nonlinear function based Han's nonlinear PID controller is introduced. Under this framework, the PID controller's gain will be decided not only by the linear gains but also by the nonlinear function's characteristics. Typically, the fal function based nonlinear PID controller was taken as an example to apply for the control of the Benchmark PID 2018 simulation platform.

The simulation results reflect the Han's nonlinear PID controller is able to achieve the desired control target with less control effort variation without any overshoot yet holding the similar quality steady-state performance. However, the other performance indices will be sacrificed sometimes. Moreover, it is worth noting that the parameters tuning is a problem for the promotion of this approach, which is realized by trial and error by now. In conclusion, the Han's idea of nonlinear PID making possesses a great potential in the industrial application, which deserves further exploration.

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