Fuzzy control simulation of hot water supply system for ground source heat pump

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Abstract. Aimed to the hysteresis, time-varying, nonlinear characteristics of ground source heat pump systems, a fuzzy controller has been designed and simulation calculation is implemented with Matlab software. The results indicate that compared to the traditional PID control system, the adjustment time of the fuzzy control method is found shorter by 40%. The system with the fuzzy controller can reduce the steady-state error and enhance the resistance to disturbance.

1. Introduction

Due to the limited resources of the earth, ground source heat pumps have been increasingly used in heating and air conditioning systems. The heat pump is an energy-saving product that uses low-grade heat source to provide energy for building, by heating the building in winter and cooling it in summer. For the purpose of saving energy and reducing the consumption of fossil fuels, it is necessary to find the optimal configuration of heat pump unit and improve the performance of the refrigeration and air conditioning system[1]. Establishing a mathematical model of a heat pump system and performing a computer simulation is a widely used research method.[2][3][4]

Although the research on the main components and equipment of the ground source heat pump air conditioning system is basically mature, most of the traditional heat pump systems use simple controls which result in low control precision, poor control quality and stability. In traditional controller design, one must first understand and analyse the whole system, and then derive accurate dynamic equations based on system characteristics to describe the controlled system. However, it is often difficult to establish mathematical models for systems in a parameter-determined manner since the real systems are more complicated. Besides the estimated system model cannot be applied to larger control range, it is thus inevitable to cause errors when applying the model to a real system. As a result of the complicated characteristics of the ground source heat pump control system, it is difficult to establish a relatively accurate mathematical model for the traditional controller, therefore, introducing a more intelligent control becomes a reasonable and appropriate solution.
2. Principle of frequency conversion control of ground source heat pump

The relationship between the frequency and speed of the compressor of ground source heat pump is shown in the formula (1), and the relationship between the heat supply and the speed of the compressor is described in formula (2). The heating load keeps changing randomly and the output heat of the compressor changes with the heating load.

\[ n = \frac{60f}{p} (1 - s) \]  
\[ Q_k = q_v V_R = q_v V \eta_F n z / 60 \]  
\[ Q_k = c m (t_{out} - t_{in}) \]

In the formulas, \( f \) represents the frequency of the input AC power, \( p \) is the number of pole pairs of the motor, \( s \) stands for the slip rate of the asynchronous motor, \( n \) is the motor speed, \( q_v \) is the volumetric heat of the compressor, \( V \) is the actual and theoretical displacement of the compressor, respectively, \( z \) is the number of cylinders, \( \eta_F \) is the volumetric efficiency, \( n \) is the motor speed, \( c \) is the specific heat of water, \( t_{out}, t_{in} \) is the temperature of water out and in of the heat pump, respectively, \( m \) is the flow rate of water. In this paper, to achieve the purpose of the set hot water temperature, the fuzzy control of the frequency conversion of the compressor is studied.

![Figure 1: System structure of fuzzy controller](image)

3. Design of the fuzzy control

The control mode of the ground source heat pump has two inputs and a single output, which means that it uses the deviation between the actual outlet water temperature and the set value as the first input, and uses the change rate of the water temperature deviation as the second input. The output frequency converter finally sends the control signal to variable frequency actuator after the calculation is done by the fuzzy controller. Figure 1 shows the system structure of fuzzy controller.

![Figure 2: Mamdani fuzzy reasoning system diagram](image)

3.1. Mamdani type fuzzy logic control
Mamdani type fuzzy logic controller is one of the most widely used fuzzy controllers. Its structure is showed in figure 2: $e$ represents the deviation of the input temperature, that is, the deviation of the instantaneous value of the water supply temperature from its set value; $e_c$ represents the change rate of the temperature difference, that is, the ratio of the difference between the instantaneous value of the water temperature at a certain time $t_1$ and at its previous time $t_0$ and the sampling period $T$; $u$ represents the output frequency of the heat pump compressor.

Defuzzification is the process of producing a quantifiable result, given fuzzy sets and corresponding membership degrees. There are three commonly used methods of defuzzification: middle of maxima, center of gravity and last of maximum membership degree method\[5\]. In this paper, the last method is implemented. The fuzzy domain is generally described by 7 linguistic variables: positive big(PB), positive medium(PM), positive small(PS), zero (NO), negative small(NS), negative medium(NM) and negative big(NB). These variables construct the fuzzy language variables $E$, $E_c$ and $U \{PB, PM, PS, NO, NS, NM, NB\}$. Then a membership function need to be chosen based on the linguistic variables, which can be done by summarising the operator’s experiences and using fuzzy statistical methods. Figure 3 is the triangular-shaped membership function curve of temperature deviation.

3.2. Fuzzy logic rule design
Fuzzy control makes it possible to derive the experiences from manual control and then set up rules according to these experiences, so as to realize automatic control by computer\[6\]. In general, the principle of establishing fuzzy control rules is: when the error is large or relatively large, the control variable is selected for the purpose to eliminate the error as soon as possible; when the error is small, the stability of the system should be concerned in the first place, so the control variable should be chosen to prevent overshoot. Based on the actual operation control experiences, the fuzzy control rules have been established for the frequency of the ground source heat pump compressor. These rules are shown in table 1. The fuzzy controller de-fuzzes and outputs to the next-level control object. The characteristic curve of the fuzzy controller is shown in figure 4. It can be seen from figure 4 that this controller is a nonlinear controller whose spatial surface is nearly smooth and the output surface is continuous, which is one of the main features of fuzzy control.

| $e_c$ | NB | NM | NS | NO | PS | PM | PB |
|------|----|----|----|----|----|----|----|
| NB   | PB | PB | PB | PM | PS | NO | NO |
| NM   | PB | PM | PM | PS | NO | NO | NS |
| NS   | PB | PM | PS | PS | NO | NS | NM |
| NO   | PM | PS | PS | NO | NS | NS | NM |

Table 1. Fuzzy control rule table
Based on operational experience, the fuzzy control rules are determined. If \( e=\text{NB} \) and \( e_c=\text{NB} \) or \( \text{PM} \), then \( U=\text{PB} \). Since each input is quantized into 7 fuzzy subsets, there should be 49 rules, and each rule corresponds to a fuzzy relationship. In this way, the computer completes the fuzzy reasoning process by looking up the table operation as shown in table 1. The designed fuzzy controller can be used in the fuzzy module in the Matlab/Simulink.

4. Matlab/Simulink simulation analysis
The Matlab software is used to simulate the heat pump control system. In the simulation, both the compressor frequency model and the water flow model can be seen as a large inertial first-order system, as shown in equation (4)\(^7\). In order to facilitate the study, according to the literature\([8,9]\), the compressor frequency model takes the formula (5), the water flow model takes the formula (6).

\[
G(s) = \frac{k}{1+Ts} e^{-\tau s} \quad (4)
\]

\( G(s) \) — compressor frequency model or temperature model
\( T \) — inertial time constant
\( \tau \) — pure lag time constant
\( k \) — gain coefficient
\( s \) — complex variable

\[
G(s) = \frac{0.5}{1+2600s} e^{-60s} \quad (5)
\]

\[
G(s) = \frac{0.4}{1+220s} e^{-40s} \quad (6)
\]

![Figure 5. Fuzzy control simulation model](image)

![Figure 6. The relationship between water temperature and time with fuzzy control mode](image)

![Figure 7. The relationship between water temperature and time with PID control mode](image)
Fuzzy control simulation model is shown in figure 5. It can be seen from figures 6 and 7 that the fuzzy control mode adjustment curve first passes a short lag and then rises rapidly, and the overshoot water temperature phenomenon does not occur, that is, the steady state is reached, and time to establish the equilibrium is about 2500 s. The PID control mode adjustment curve has a short lag first, then rises rapidly, and then gradually attenuates the oscillation after a large overshoot, until it reaches the stable control state, and the time of this procedure is about 3500 s. Although both control methods can achieve the final control requirements, the fuzzy control method has better control precision and stability, short transition time, small overshoot or almost no overshoot, so its stability suits the need of control system better.

5. Experimental verification of fuzzy control mode
In order to verify the effectiveness of fuzzy control, experiments were carried out in the laboratory. The temperature of output hot water was set at 30 ℃, and hot water temperature range was 24 to 36 ℃. The experimental results were shown in figure 8. As can be seen from the results: when the hot water temperature was below the set value 30 ℃, and the water temperature change rate was positive, the compressor operated at 55 Hz frequency, when the water temperature reached to 30 ℃, the compressor running frequency was 50 Hz, as the water temperature continued to rise, the compressor frequency, in turn, reduced to 45 Hz, 40 Hz, 35 Hz, respectively. When the water temperature reached the upper limit of set value 36 ℃, the compressor frequency operated at 35 to 40 Hz. It can be seen that the outlet temperature of hot water did not exceed the set value in the fuzzy control mode, and the compressor frequency changed with the change rate of temperature and temperature difference in a timely manner, with a very small delay, which is consistent with the expected control effect. It proved that the designed fuzzy control was effective and correct.

6. Conclusions
In this paper, a fuzzy control method is designed for the deficiency of the traditional ground source heat pump control system. The simulation calculation of this fuzzy controller was realised by Matlab/Simulink. The comparison between the fuzzy control and PID control shows that the fuzzy control has a better performance than that of the latter: the overshoot of the fuzzy control mode is much smaller than the PID control, and the time required for the control parameters to stabilise is also smaller than the PID control mode. The experimentl results proved that the designed fuzzy control was effective and correct. The fuzzy control method can better meet the needs of stable
temperature for hot water supply, which not only saves energy but also improves comfort. This conclusion can provide reference for further research of ground source heat pump fuzzy control.

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