Energy Saving Control of Integrated Energy Multi-Energy Complementary Coupling Space Heating System Based on Fuzzy Theory

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Abstract—Because the traditional solar-ground source heat pump heating system uses temperature difference controllers to control most, it causes the problem of large energy consumption of the equipment. In order to improve such problems, the complexity of the space heating control system is considered comprehensively, and the fuzzy strategy is used to improve the previous control system. TRNSYS was used to build a heating system simulation model, MATLAB was used to build a solar heating system fuzzy controller model, and the two models were coupled to jointly simulate the internal temperature change and energy consumption of the space under the same environmental conditions and different controllers. Experiments show that under the design conditions, the solar collector is greatly affected by the light, the temperature of the hot water storage tank is controlled between 58℃ and 65℃. Using the traditional temperature difference controller, the system COP (Coefficient Of Performance) is low and the energy consumption is large, and the economic benefits are not high; the use of the fuzzy controller can increase the system COP by 6.1%, reduce the energy consumption by 22.85%, and save 8.71 yuan in the daily economic benefits of the system.

1. INTRODUCTION
At present, building energy consumption is increasing year by year, among which the energy consumption of building heating and cooling is the most, accounting for 55% of the total building energy consumption. Compared with the last century, the proportion of building energy consumption in the total energy consumption has increased from 10% to 46%. Therefore, reducing building energy consumption is a problem to be solved in recent years. The 14th Five-year Plan emphasizes the modern energy system of "clean, low-carbon, safe and efficient", speeds up the realization of energy transformation, strengthens the mutual combination and complement of "wind, light, water, fire and storage" to enhance the utilization rate of energy, solves the problem of the difficulty of absorbing renewable energy, and reduces energy consumption and energy cost. Therefore, strengthening the application of solar energy and ground source heat pump technology in buildings has become the main popular way of cooling and heating. Solar energy is an inexhaustible natural resource. It is clean, renewable and easy to collect. Sunlight can be irradiated to the absorber through the transparent cover
plate and then converted into heat energy for heating. The ground source heat pump can transfer energy from low temperature heat source to high temperature heat source after the input of a small amount of high grade energy, to achieve cooling or heating, not only good stability, energy saving and efficient, long service life, but also a multi-purpose machine, environmental protection and renewable. But correspondingly it is very limited by the field, there is not enough space to realize the energy exchange is very difficult. Therefore, the combined application of solar energy and ground source heat pump for heating can solve each other's shortcomings, and give full play to each other's advantages [1].

In terms of single solar space heating system, literature [2] has analyzed the heating in cold regions, and the heat collection can be effectively improved from the Angle of installation angle. As for the heating system of a single ground source heat pump, literature [3] optimized the analysis from the depth of buried pipe, and concluded that the heat exchange effect of buried pipe increases with the increase of drilling depth, geothermal gradient and soil thermal conductivity. Coupling space in solar energy - ground source heat pump heating technology, the literature [4] studied the heating characteristics, indicates that the system, when combined with heating only high soil temperature can better ensure its effective operation, improve the COP of the system, the solar heating subsystem can make the soil temperature quick recovery after joining, the problem of soil temperature imbalance after long-term operation of the unit is avoided.

In recent years, in most space heating coupling systems, the traditional temperature closed-loop control method is basically used to achieve the system temperature variation flow control function, which is not high in intelligence, high energy consumption and uneconomic. Therefore, this paper takes a building in Beijing as the object to study the control strategy of comprehensive energy multi-energy complementary coupling space heating system. The TRNSYS model and MATLAB model are used for mutual coupling [5-7], and the traditional temperature closed-loop control method and fuzzy control algorithm [8] are proposed for joint control. The simulation effect of the system is analyzed. Compared with the traditional control results, the effectiveness and advantages of the proposed algorithm are verified.

2. Space heating system

2.1. Composition of space heating system

In this paper, the system is mainly composed of solar collector, layered heat storage water tank, variable frequency water pump, fixed frequency water pump, flow divider, confluent three-way valve, heater, buried pipe and heat pump, which makes full use of natural resources to realize heating in winter and realize the heating demand of users all year round.

As showned in Figure 1, there are mainly two heating modes in this system. The first heating mode is night heating, when the solar heating system is closed, and the heater heating system assists the ground source heat pump heating system. If the heating quantity is sufficient, the heating system is closed, otherwise it is turned on. The second kind of daytime heating, at this time, the solar heating system is open, mainly by the heater heating system auxiliary ground source heat pump and solar heating system combined heating, if the solar energy and the ground source heat pump heating volume is sufficient, the heater will not start, otherwise open. The specific process is that the solar collector absorbs the heat energy released by the sun and heats the fluid internal heat source, while the fluid heat source is heated by the heater. The heat source of the two parts is gathered into the stratified water tank 1 through the confluence valve, and the cold working medium after heat exchange flows to the respective heating system for heating again through the shunt valve. In addition, the heating medium at the outlet of the stratified water tank 1 and the ground source heating medium simultaneously enter the heat pump for heat exchange, and the heating medium at the outlet of the heat pump enters the stratified heat storage tank 2 for heat supply to the room.
2.2. Control principle of space heating system

The operation of each subsystem of the space heating system is showed in Figure 2-5.

2.2.1. Solar heating system

Figure 2 is the logical topology of the solar heating system. The controller collects two kinds of data, namely, the outlet temperature of the heat transfer working medium of the solar collector and the outlet temperature of the heat transfer working medium of the heat storage tank, calculates the logical difference value, and controls the start and stop of the water pump, so that the heat transfer working medium can carry out circulation heating in the system.

2.2.2. Ground source heat pump heating system

Figure 3 is the logical topology of the ground source heat pump heating system. The input of the controller has two kinds of data, namely the temperature of the heat transfer working medium and the expected temperature. The 0/1 signal is calculated by the controller to control the start and stop of the water pump.

2.2.3. Heater heating system

Figure 4 is the logical topology of the heating system of the heater. The main controller receives two signals, namely the temperature of the heat exchange medium required by the heat storage tank and the expected temperature, and outputs the control signal through internal calculation to control the start and stop of the water pump and auxiliary heating equipment at the same time.

2.2.4. Circulation heating system for working area

Figure 5 logical topology for work area circulation heating system, heating area air temperature set point and the working area of the actual air temperature feedback quantity input to the controller at the same time, through the controller calculates the signal, the start-stop control pump.
Figure 2. Logic diagram of solar heating system

Figure 3. Logic diagram of ground source heat pump heating system

Figure 4. Logic diagram of heating system of heater
Figure 5. Logic diagram of circulation heating system in working area

2.3. Mathematical model of solar heating system

2.3.1. Mathematical model of solar collector
Solar collector is a collection of optical radiation energy and convert it into heat energy of a collection device, if according to the solar collector internal vacuum space form classification, mainly divided into two major categories of flat type vacuum tube collector and collector, it is on the basis of the first law of thermodynamics, the collection efficiency as an important index of performance evaluation of collectors, The collector efficiency is shown as follows:

\[
\eta = F \left( \alpha \tau - U_L \left( \frac{T_p - T_a}{H_T} \right) \right) \tag{1}
\]

Where, \(H_T\) solar radiation flux, \(W/m^2\); \(T_p\) is the average temperature of solar collector, \(\degree C\); \(T_a\) is the ambient temperature, \(\degree C\); \(U_L\) is heat dissipation loss coefficient, \(W/(m^2\cdot \degree C)\); \(\alpha\) is the absorption rate of solar radiation by the endothermic plate; \(\tau\) is the transmittance of solar radiation from endothermic plate; \(F\) is heat collection efficiency factor; \(\eta\) is the thermal efficiency of solar collector.

The mathematical model of solar collector is expressed as [9]:

\[
C_e K \frac{dT_{f,o}}{dt} = F_K \left[ S - U_L \left( T_{f,i} - T_a \right) \right] \tag{2} + G C_p \left( T_{f,i} - T_{f,o} \right)
\]

Where, \(C_e\) is the effective heat capacity per unit area of the solar collector, \(kJ/(m^2\cdot \degree C)\); \(F_K\) is the heat transfer factor of solar collector; \(S\) is solar irradiance, \(kJ/m^2\); \(T_a\) ambient temperature, \(\degree C\); \(T_{f,i}\) is the inlet temperature of the solar collector, \(\degree C\); \(T_{f,o}\) is the outlet temperature of the solar collector, \(\degree C\); \(C_p\) is the specific heat capacity of water at constant pressure, \(kJ/(kg\cdot \degree C)\); \(G\) is the flow rate of solar collector per unit area, \(kg/h\).

2.3.2. Mathematical model of stratified heat storage tank
Stratified heat storage tank is a kind of heat storage device which can not only store excess heat but also make the working medium temperature of heating side and load side in a reasonable range. And on the basis of heat transfer working medium is different, the heat storage tank has a sensible heat storage, phase change thermal storage, chemical storage hot three thermal storage mode, the most common heat transfer working medium is water, due to poor thermal effect causes high temperature and low density of water to rise, high density in low temperature water drop, at this point in the heat storage water tank in the upper temperature is high, the lower the temperature low stratification, which is beneficial to
improve the heating performance of the system. Improve the heat utilization rate. If the heat transfer working medium in the heat storage tank is evenly mixed, the temperature balance equation is [9]:

\[
\left( mc_p \right)_s \frac{dT_s}{d\tau} = F_j \left( mc_p \right)_G \left( T_{r,0} - T_r \right) - (UA)_s \left( T_s - T_a \right) - Q
\]

(3)

Where, \( Q \) is the heating load provided by the heat storage tank, kW; \( F_j \) is the collector control function; \( T_r \) is the temperature of heat storage tank, °C; \( T_a \) is the ambient temperature, °C; \( U \) is the average heat loss coefficient of water tank, \( W/(m^2\cdot K) \); \( A \) is the external area of the water tank, \( m^2 \); \( m \) is the water volume of the tank, kg; \( (US)_s(T_s - T_a) \) refers to heat loss of heat storage tank.

2.3.3. Mathematical model of water pump

Water Pump in HVAC is an essential type of circulation equipment, which is mainly by receiving the control signal of the controller, judging and adjusting its speed, and then regulating the output flow, so as to meet the change of the load side demand. Pumps can be divided into fixed frequency pumps and frequency conversion pumps according to frequency, fixed frequency pump speed, energy consumption, has a greater impact on energy; Frequency conversion pump speed can be regulated according to the load, variable speed, low energy consumption, is the main trend of the industrial and agricultural field for circulation system equipment in today’s era.

Variable frequency pump characteristic curve equation:

\[
h = k_1 q^3 + k_2 q^2 + k_3 q + k_4
\]

(4)

The relationship between power, flow, head and speed of variable frequency water pump in operation is as follows:

\[
\frac{P_1}{P_2} = \left( \frac{n}{n'} \right)^3
\]

(5)

\[
\frac{h_1}{h_2} = \left( \frac{n}{n'} \right)^2
\]

(6)

\[
\frac{q_1}{q_2} = \frac{n}{n'}
\]

(7)

Where, \( k \) is the fitting coefficient of the pump characteristic curve equation; \( P \) is water pump power, kW; \( N \) is the pump motor speed,(r/min); \( H \) is the pump head; \( Q \) is the flow rate, kg/h.

Variable frequency pump effective power equation:

\[
P_e = \frac{\rho g q h}{3.6 \times 10^6}
\]

(8)

Where, \( P_e \) is the effective power of the variable frequency water pump, kW; \( \rho \) is the fluid density of heat transfer working medium, \( kg/m^3 \); \( G \) is the acceleration of gravity, \( m/s^2 \).

Energy dissipation equation of variable frequency water pump:

\[
P = \frac{P_e}{\eta} \left( \frac{f}{f_0} \right)^3 + P_n
\]

(9)

Where, \( f_0 \) is the power supply frequency, Hz; \( P_n \) is the frequency converter power, kW.
3. Controller design

3.1. Principle of fuzzy control
When using fuzzy controller, it is important to determine the input and output signals of the controller. The heating system is in a variable flow conditions, the fuzzy controller of the input signal is the temperature setting of the system and solar collector export working medium temperature, the output signal is of variable frequency pump control signal, when the fuzzy controller input signal is detected, the blur processing first, then on the basis of the designed fuzzy rules of fuzzy reasoning, Then the specific output control signal of the variable frequency pump is obtained by anti-fuzzy processing, and then the speed of the variable frequency pump is adjusted to obtain the different outlet flow rate of working medium. The fuzzy control block diagram is shown in Figure 6.

3.2. Fuzzy model building
3.2.1. Define the membership function
The triangular membership function is used to fuzzily transform the input variable set value (trimf) and divides the set value temperature into three fuzzy sets: SD (low temperature), MD (moderate temperature) and LD (high temperature). The value range is [65, 80]. The membership function is as following:

\[
\mu_{SD}(x) = \frac{73 - x}{73}
\]

\[
\mu_{MD}(x) = \begin{cases} 
\frac{x}{73} & \text{if } 65 \leq x < 73 \\
\frac{80 - x}{73} & \text{if } 73 \leq x \leq 80 
\end{cases}
\]

\[
\mu_{LD}(x) = \frac{x - 73}{73}
\]

The input variable solar collector outlet temperature (trimf) is blurred by triangular membership function. The outlet working medium temperature of the solar collector is divided into three fuzzy sets: NG (low temperature), MG (medium temperature), and LG (high temperature). The value range is [-5, 95], and the membership function is as follows:

\[
\mu_{NG}(y) = \frac{50 - y}{50}
\]

\[
\mu_{MG}(y) = \begin{cases} 
\frac{y}{50} & \text{if } -5 \leq y < 50 \\
\frac{95 - y}{50} & \text{if } 50 \leq y \leq 95 
\end{cases}
\]
The triangle membership function is used to fuzzier the output variable control signal (trimf), and the control signal is divided into five fuzzy sets: VS (very small), S (small), M (medium), L (large), VL (large), and the value range is [0, 1]. The membership function is as follows:

\[ \mu_{VS}(z) = \frac{0.1 - z}{0.2} \]  (16)

\[ \mu_{S}(z) = \begin{cases} \frac{z}{0.2} & 0 \leq z \leq 0.2 \\ \frac{0.4 - z}{0.25} & 0.2 < z \leq 0.4 \\ \end{cases} \]  (17)

\[ \mu_{M}(z) = \begin{cases} \frac{z - 0.2}{0.25} & 0 \leq z \leq 0.2 \\ \frac{0.7 - z}{0.25} & 0.2 < z \leq 0.7 \\ \end{cases} \]  (18)

\[ \mu_{L}(z) = \begin{cases} \frac{z - 0.4}{0.25} & 0 \leq z \leq 0.4 \\ \frac{1 - z}{0.3} & 0.4 < z \leq 1 \\ \end{cases} \]  (19)

\[ \mu_{VL}(z) = \frac{z - 0.7}{0.3} \]  (20)

The fuzzy controller rules are shown in Table 1 below:

| Control signal z | Set temperature x/°C |
|------------------|----------------------|
|                  | SD       | MD       | LD       |
| Solar collector temperature y/°C | NG | VS | M | L |
|                  | MG | S | M | L |
|                  | LG | M | L | VL |

3.2.2. Fuzzy control reasoning

- Rule matching

Assume that the sampling is carried out on the SDHW system at a certain time, the set temperature is 33 °C, and the working medium temperature at the outlet of the solar collector is 30 °C. After calculation, the membership degree can be obtained as following:

\[ \mu_{SD}(33) = \frac{40}{73} \quad \mu_{MD}(33) = \frac{33}{73} \quad \mu_{NG}(30) = \frac{2}{5} \quad \mu_{MG}(30) = \frac{3}{5} \]
TABLE II. SDHW SYSTEM RULE MATCHING TABLE

| Control signal z | Set temperature x/°C |
|------------------|----------------------|
|                  | SD | MD | LD |
| NG               | $\mu_{Y}(x)$ | $\mu_{Y}(x)$ | 0 |
| MG               | $\mu_{X}(z)$ | $\mu_{X}(z)$ | 0 |
| LG               | 0  | 0  | 0  |

- Determination of rules

According to the fuzzy controller rule table, the following four rules can be triggered:

If (x is SD) and (y is NG) then (z is VS)
If (x is SD) and (y is MG) then (z is M)
If (x is MD) and (y is NG) then (z is S)
If (x is MD) and (y is MG) then (z is M)

- Credibility of rules

In the same rule, the rule conclusion can be obtained through the relationship between the premises and. The credibility of the general premise of each rule can be obtained by taking small operation between the premises: the credibility of the premise of rule 1 is $min\left(\frac{40}{73}, \frac{2}{5}\right) = \frac{2}{5}$. The credibility of the premise of rule 2 is $min\left(\frac{3}{73}, \frac{3}{5}\right) = \frac{3}{73}$ ……Thus, the prerequisite credibility table of SDHW system rules is shown in Table 3:

TABLE III. RELIABILITY TABLE

| Control signal z | Set temperature x/°C |
|------------------|----------------------|
|                  | SD | MD | LD |
| NG               | 2/5 | 2/5 | 0 |
| MG               | 40/73 | 33/73 | 0 |
| LG               | 0  | 0  | 0  |

- The reasoning of each rule.

Combine the above two tables to get the output of each rule (the confidence of the rule)

TABLE IV. RULES CREDIBILITY TABLE

| Control signal z | Set temperature x/°C |
|------------------|----------------------|
|                  | SD | MD | LD |
| NG               | $min\left(\frac{2}{5}, \mu_{Y}(x)\right)$ | $min\left(\frac{2}{5}, \mu_{Y}(z)\right)$ | 0 |
| MG               | $min\left(\frac{40}{73}, \mu_{X}(z)\right)$ | $min\left(\frac{33}{73}, \mu_{X}(z)\right)$ | 0 |
| LG               | 0  | 0  | 0  |

- The total output of the fuzzy system (aggregation), take the union of the inference results of each rule, namely:
\[
\mu_{all} = \max\{\min\left(\frac{2}{5}, \mu_1(z)\right), \min\left(\frac{2}{5}, \mu_2(z)\right), \min\left(\frac{40}{73}, \mu_3(z)\right), \min\left(\frac{33}{73}, \mu_4(z)\right)\}
\] (21)

- Deblurring.

The total output of the fuzzy system is actually the union of the inference results of the three rules. Use the maximum average method.

4. Simulation system analysis based on TRNSYS

4.1. Analysis of solar heating system

The figure below shows the temperature change of the heat transfer working fluid at the outlet of the solar collector and the hot water storage tank during a certain whole day during the heating season. It can be seen from Figure 7 that at night from 0:00 to 6:00, because there is no sun, the temperature of the working fluid at the outlet of the heat collector is continuously decreasing. At this time, the solar heat collection system is not circulating, and the control signal of the variable frequency pump is 0 as shown in Figure 8. After 6 o'clock, the temperature of the outlet of the heat collector gradually rises, and the control signal gradually when the temperature reaches about 50°C at 11 o'clock, the control signal tends to be between 0.9 and 1. The temperature reaches about 90°C at 15 o'clock. At this time, because the temperature is too high, the control signal of the variable frequency pump is reduced to reduce the flow output; After 15:00, the temperature of the collector outlet gradually decreases, and the control signal increases to meet the heating demand; Until the variable-frequency pump stops running at night, the collector temperature approaches 0°C. The hot water storage tank has been kept between 58°C and 65°C because the solar heat collection system is turned off at night, and the ground source heat pump alone may cause insufficient heat supply. At this time, the heater is turned on to keep the temperature of the water tank stable and supply Enough heat.

![Figure 7. Temperature changes heating collecting system](image-url)
4.2. System performance analysis

4.2.1. System COP comparison
COP of a heat pump system is a value used to evaluate whether a system is efficient and energy saving. The value is the ratio of the total heating power of the heat pump to the power of the compressor. The larger COP of the system is, more energy saving the system will be.

Figure 8. Frequency conversion control signals

Figure 9 shows the comparison of COP changes of heating units in a whole day with and without the fuzzy control system. The fuzzy controller controls the frequency conversion system, while the system without the fuzzy control is controlled by temperature difference control, which controls the fixed-frequency system. When the controller detects that the water supply temperature is higher than the set value of water supply temperature by 1°C, the heating side of the system stops working, and when the
water supply temperature is lower than the set value of water supply temperature, the system is in working state. In the figure, the green line is the change of COP without fuzzy control system, and the blue line is the change of COP with fuzzy control system. Can be clearly in the figure than the fixed frequency inverter system COP to an average about 0.2, this is because solar collector stop working at night, the ground source heat pump and auxiliary heater to work, if the amount of ground source heat pump heating is enough, the auxiliary heater does not need to open, or the auxiliary heating auxiliary heater. During the day, when the solar heat collection system is on, solar heating is preferred, and auxiliary heating is carried out on the ground source side. Making full use of solar energy to reduce the use of the ground source side can promote the recovery of underground temperature and improve the COP of the system. On the other hand, when operating under partial load, the flow rate of heat transfer working medium decreases and the flow resistance of heat transfer working medium in the heat exchanger decreases, making the decrease rate of heat supply lower than that of compressor power, so the COP of unit is improved.

4.2.2. Total energy consumption analysis of the system

Figure 10 heat pump for heating during the day, energy consumption, red curve with fuzzy control system part total energy consumption, all pumps blue curve for fuzzy control system does not contain all the pump total energy consumption, the figure can be seen that the energy dissipations of the red curve in the day is about 38.5 kWh, and blue curve energy consumed in a day is about 47.3 kWh. Pump energy consumption per day can reduce energy consumption by 22.85%. Figure 11 shows the total price in different time periods in Beijing and the total price of the whole system under different controls within a day. The blue curve is the case without fuzzy control of the total electricity price, the total electricity price in a day is 112.78 RMB, the yellow curve is the case with fuzzy control of the total electricity price, the total electricity price in a day is 104.07 RMB, which can reduce 8.71 RMB a day. In the same working condition, when the frequency system is given the control signal, because the unit water temperature is fixed, when the temperature changes, the pump speed is still constant, often running at full speed, resulting in energy waste; The frequency conversion system can change the flow according to the required temperature, so as to control the pump speed can change freely between zero and rated speed according to the demand, and reduce the energy consumption of the system.

Figure 10. Comparison of total energy consumption of pumps in the system
5. CONCLUSIONS
In view of the operation characteristics of multi-energy complementary coupling space heating system of comprehensive energy, this paper proposes the control combining traditional control and fuzzy algorithm, and uses TRNSYS and MATLAB platform to carry out simulation verification, and draws the following conclusions:

(1) For the solar heating subsystem, the fuzzy algorithm can effectively control the operation of the water pump, realize the variable flow operation of the system, and effectively reduce the energy consumption of the system.

(2) For the overall multi-energy complementary heating system, the combined control of fuzzy and traditional control, compared with the single traditional control, better reflects the advantages of collaborative control, energy saving and emission reduction, system COP increased by 6.1%, overall energy consumption reduced by 22.85%, saving 8.71 yuan per day.

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