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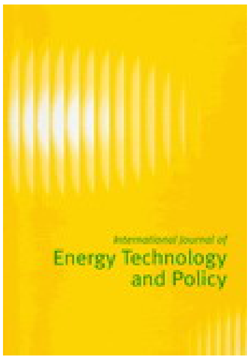

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Fuzzy PID-based temperature control method for power transformer coils

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Abstract: To improve the response speed and control stability of power transformer coil temperature control, a fuzzy PID-based power transformer coil temperature control method is studied. Based on the physical model of power transformers, a mathematical model for temperature control of power transformer coils is constructed. For the constructed mathematical model, the fuzzy PID control algorithm is used to control the temperature of the power transformer coil. The PID control part uses proportional, integral, and differential operations to control the coil temperature. The fuzzy control algorithm is used to set fuzzy rules for the PID control parameters, and the power transformer coil temperature control results are output through the fuzzy inference process. The results show that using this method, the coil temperature can be controlled at the target temperature within 0.1 seconds, with fast response speed and high control stability.

Keywords: fuzzy PID; power transformer; coil temperature; control methods.

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1 Introduction

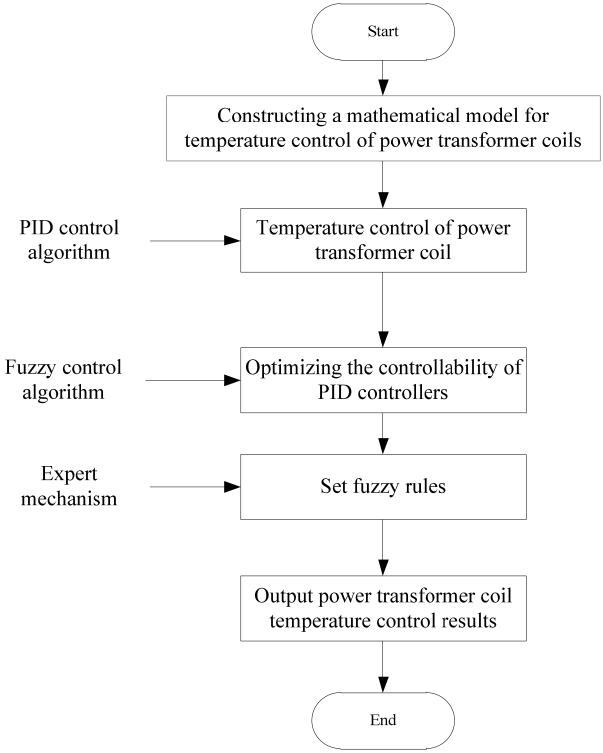
Power transformers are based on the principle of electromagnetic induction (Mikhak-Beyranvand et al., 2020). They use the same frequency between two or more windings to convert the same level of voltage into other levels of voltage, and have the function of adjusting the voltage level of the power system. Using power transformers to connect different voltage levels of power transmission and distribution networks, forming a complex electrical system. A coil is a wire turn that forms the electrical circuit of a transformer with a fixed voltage value (Kant and Singh, 2020). The coil is made of material wound with insulated round or insulated flat wire. The coil temperature control of power transformer is helpful to predict the temperature distribution of power transformer (An et al., 2020) and prevent the operation failure of power transformer. By collecting real-time data on the temperature of the power transformer coil as the basis for temperature control of the power transformer coil, the temperature of the power transformer is maintained within the ideal range to prevent power transformer faults. By controlling the temperature of the power transformer coil, the temperature of the power transformer coil is clarified (Meng et al., 2021), ensuring the safe and stable operation of the power transformer and achieving economic operation of the power transformer. The temperature of the power transformer coil is the main factor affecting the insulation capacity of the transformer, and there is a direct correlation between the temperature of the transformer coil and the service life of the power transformer. The temperature of the transformer coil is too high (Yazdani-Asrami et al., 2020), causing the polymer chains of the insulation material inside the transformer to undergo fission. Power transformers are prone to abnormal insulation and mechanical properties due to insulation aging (Ma and Jiang, 2022), and in severe cases, may cause deformation and damage to the power transformer.

When the temperature of the power transformer coil is too high, it affects the working state of the power transformer unit. Therefore, power transformer management personnel need to pay attention to the importance of temperature control and consider temperature as an important controlled parameter for the operation of power units. With the rapid development of intelligent technology, temperature control systems have been widely used in industrial production, and people’s demand for control accuracy and real-time control of temperature control systems is gradually increasing. Traditional temperature control systems cannot meet the stability requirements of power transformer coil temperature control (Wang et al., 2020), and the temperature control effect is poor, which cannot ensure the normal operation of power transformer units. The fuzzy PID control algorithm is an important control algorithm with high control performance (Chen and Yang, 2021). The fuzzy PID control algorithm is applied to the temperature control of power transformer coils, and combined with the efficient dynamic control characteristics and static control characteristics of expert mechanisms, the fuzzy PID control algorithm is used to control the temperature of power transformer coils. Through the adjustment process of control parameters in the fuzzy PID control algorithm (Conker and Baltacioglu, 2020), Adjust the entire process of fuzzy PID control based on temperature deviation and temperature deviation change rate, and use expert mechanisms to avoid oscillation of temperature control values. The fuzzy PID control algorithm can quickly achieve the target temperature value of the power transformer coil temperature, and can stabilise the temperature to the target temperature for a long time. The fuzzy PID control algorithm has the characteristic of small fluctuations (Guo et al., 2021) and can obtain good temperature response results of power transformer coils.

At present, many researchers have conducted research on temperature control of transformer coils. Luo et al. (2020) used the multi physical field calculation method to calculate the internal temperature changes of power transformers. Based on the temperature changes inside the transformer, a fuzzy neural network method is used to invert the temperature of the hot spot inside the transformer, determine the temperature change of the hot spot inside the power transformer coil, and achieve effective control of the power transformer coil temperature. However, this method did not consider the issue of noise interference, resulting in a high thermal aging rate during temperature control;

Zhang and Gao (2020) introduced Smith's predictive compensator to achieve self-tuning of PID control parameters, reduce overshoot of power transformer coil temperature control, and improve noise interference in the coil temperature control process, However, this method has the problem of slow response speed in transformer coil temperature control; Wu et al. (2020) applied the PID control algorithm and Nous control algorithm to the temperature control of transformer coils. This method selected a DC step-down transformer as the control object, and used the Nous algorithm to construct the transformer state space. In the transformer state space, the PID control algorithm was used to effectively control the temperature of the transformer coil. However, this method failed to effectively suppress noise interference, resulting in strong fluctuation in transformer coil temperature control.

Figure 1 Schematic diagram of technology roadmap



Therefore, in response to the shortcomings of the above methods, a fuzzy PID-based power transformer coil temperature control method is proposed to address the issues of susceptibility to noise interference and poor robustness during transformer coil temperature control, resulting in high volatility and slow response speed in the process. This method utilises proportional, integral, and differential operations to control the coil temperature. In order to solve the problem of PID controllers being susceptible to noise interference and causing strong fluctuations, a fuzzy control algorithm is introduced to improve the stability of temperature control and optimise the controllability of PID controllers. And set fuzzy rules to project the control range of the expert mechanism onto the fuzzy domain, in order to obtain rich and accurate rules, so that the rule library can cover multiple input situations and produce accurate outputs. Finally, the fuzzy PID control algorithm outputs the temperature control results of the power transformer coil through the fuzzy inference process based on the set fuzzy rules, achieving the temperature control of the power transformer coil. This control method has ideal transient response effect on coil temperature control, effectively improving the temperature control performance of power transformer coils, and has important guiding significance for the reliable operation of power transformers. The specific Technology roadmap is shown in Figure 1.

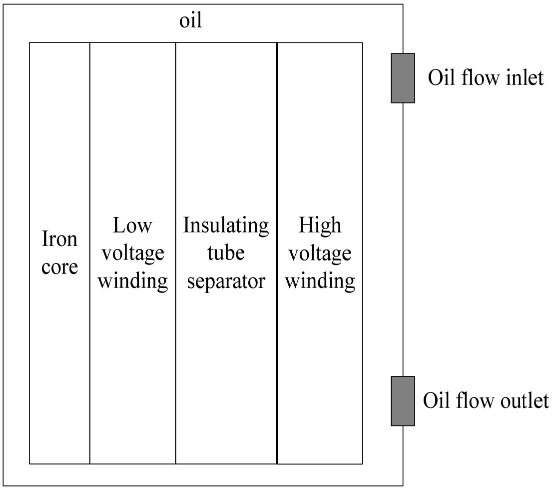
2 Material method

2.1 Power transformer coil temperature control model

By analysing the temperature and heat conduction process of the internal coils of power transformers, a temperature control model for power transformer coils is constructed. After the inner coil of a power transformer forms heat, it is transferred to the oil of the transformer through a heat conduction process. The eddy current loss of the transformer core is transmitted to the oil of the transformer through the process of heat conduction. The oil inside the transformer is transmitted to the radiator and oil tank walls through the vertical and horizontal oil ducts in the power transformer (Li et al., 2022), using convection. The radiator and oil tank walls use heat conduction to transfer heat to the air, completing the heat dissipation process of the power transformer.

The physical model of the power transformer is shown in Figure 2.

Figure 2 Physical model of power transformer



Analysing the physical model of the power transformer in Figure 2, the iron core, high-voltage winding coil, and low-voltage winding coil are the main heat sources inside the transformer. When constructing the mathematical model of a power transformer, it is assumed that the heat generation per unit volume of the coil heat source of the transformer is constant per unit time. The heat dissipation and generation of the power transformer are assumed to be in a steady state (Jin et al., 2020), and the temperature of the winding coils and oil inside the power transformer is fixed. At this time, the flow velocity of the oil does not change. Assuming that the external environment temperature of the power transformer is constant, energy, mass, and momentum transfer control the flow field and temperature field changes of the oil inside the power transformer. The initial velocities of the upper and lower oil ports of the power transformer are both 0.

The energy differential equation expression for the temperature change of the inner coil of a power transformer is as follows:

$$\rho c_p\left(u\frac{\partial t}{\partial x}+v\frac{\partial t}{\partial y}\right)=\lambda\rho\left(\frac{\partial^2 t}{\partial x^2}+v\frac{\partial^2 t}{\partial y^2}\right) \tag{1}$$

The continuity equation expression for the temperature change of the power transformer coil is as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{2}$$

The momentum differential equation expression for the temperature change of the power transformer coil in the x-direction is constructed as follows:

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=Fx-\frac{\partial p}{\partial x}+\gamma\rho w\left(\frac{\partial^2 u}{\partial x^2}+v\frac{\partial^2 u}{\partial y^2}\right) \tag{3}$$

The momentum differential equation expression for the temperature change of the power transformer coil in the y-direction is constructed as follows:

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=F_y-\frac{\partial p}{\partial y}+\gamma\rho\left(\frac{\partial^2 v}{\partial x^2}+v\frac{\partial^2 v}{\partial y^2}\right) \tag{4}$$

In the above formula, F_x and F_y respectively represent the forces in x and y directions on the oil in the power transformer, c_p and λ respectively represent the specific heat capacity of the oil and the thermal conductivity coefficient of the winding coil, ρ and p respectively represent the density and pressure of the oil in the power transformer, γ and w respectively represent the absolute viscosity and temperature of the oil, u and b respectively represent the speed of the oil in x and y directions, and t represents the time of temperature change.

For the mathematical model of power transformers, set the boundary conditions as follows:

$$q=-\lambda_1\left(\frac{\partial t}{\partial x}+\frac{\partial t}{\partial y}\right) \tag{5}$$

$$\alpha(w-w_\alpha)=-\lambda_1\left(\frac{\partial t}{\partial x}+\frac{\partial t}{\partial y}\right) \tag{6}$$

In the above formula, q and w_α respectively represent the heat generation rate of the power transformer's heat source and the external air temperature; α and λ_1 represent the heat transfer coefficient between the air and the oil tank wall of the power transformer and the heat conduction coefficient of the oil tank wall of the power transformer respectively.

The temperature control model of the power transformer coil is a typical nonlinear time-varying delay model, which uses a second-order inertia pure delay link to construct the temperature control model of the power transformer coil. Convert the second-order system into a first-order system based on the parameter identification process. The mathematical model for temperature control of power transformer coils is represented by a first-order inertial hysteresis loop, and the expression is as follows:

$$G(S) = Ke^{\tau S} / Ts + 1 \tag{7}$$

In formula (7), τ and k represent the pure lag time parameter and amplification coefficient, respectively, T represents the inertia link time parameter, and S represents the transfer coefficient.

The temperature control of power transformer coils belongs to the branch of process control, and the dynamic characteristics of temperature changes in power transformer coil temperature control have the characteristic of high initiative (Wang et al., 2022), with a relatively slow change time. The dynamic changes in coil temperature exhibit high nonlinear characteristics. The temperature rise of the power transformer coil requires certain conditions to be met. The temperature rise of the power transformer coil depends on the continued heat of the power transformer, the material of the power transformer coil, and the ventilation condition of the transformer environment. When the temperature of the power transformer coil exceeds the set value, it takes a long time to cool the power transformer coil.

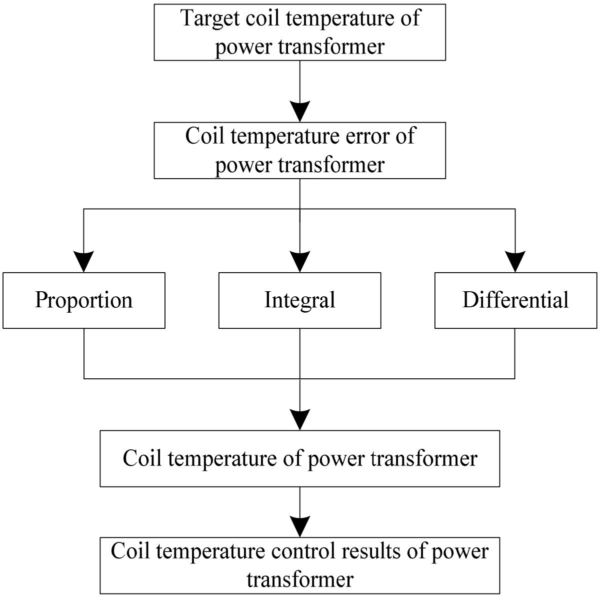
The use of conventional power transformer coil temperature control methods can easily lead to overheating of the coil temperature. Building an accurate power transformer coil temperature control model can meet the coil temperature control requirements.

2.2 Power transformer coil temperature control based on PID control algorithm

PID control algorithm is a control algorithm that estimates the future temperature of power transformer coils based on their historical temperature. The proportional control process using PID control algorithm (Liang et al., 2021) can improve the response speed of the power transformer coil, an inertial system, and reduce the temperature error of the power transformer coil. By utilising the integral control process of PID control algorithm, the temperature control deviation should be reduced to zero. During the integral control process, overshoot of temperature control should be avoided. When the integral effect is too high, it is easy to increase the overshoot of the PID control algorithm. Therefore, through the differential control process of the PID control algorithm, the rate of change of the error signal is adjusted to reduce overshoot during the control process and avoid oscillation of the PID controller.

The principle structure diagram of using PID control algorithm to control the temperature of the power transformer coil is shown in Figure 3.

Figure 3 PID control principle diagram of power transformer coil temperature control



From the PID control principle diagram of the power transformer coil temperature control in Figure 3, it can be seen that the power transformer coil temperature is the controlled object of the PID controller. The PID control algorithm belongs to a linear controller, where $r(t)$ and $c(t)$ represent the set value and feedback value of the power transformer coil temperature, respectively. The deviation $e(t)$ between the set value $r(t)$ of the power transformer coil temperature control and the feedback value $c(t)$ is used as the input signal of the PID control algorithm. After proportional, integral, and differential operations are performed on the deviation value $e(t)$, the control quantity of the PID control algorithm is formed by adding the calculation quantity, Apply the determined control quantity to the temperature control of the power transformer coil, which is the control process of the PID control algorithm.

The PID control algorithm is used to perform proportional, integral, and differential operations on the temperature of the power transformer coil, and the calculation amount is superimposed to output the superimposed control amount. The expression is as follows:

$$u(t) = \left[K_p e(t) + \frac{1}{T_i} \int_0^t e(t) d\tau + T_d \frac{de(t)}{dt} \right] \tag{8}$$

On the basis of the above formula (7), when using the PID control algorithm to control the temperature of the power transformer coil, the transfer function expression is as follows:

$$G(S) = K_p + \frac{SK_p}{T_i} + K_p T_d \times S \tag{9}$$

In the above formula, $e(t)$ represents the input of the PID controller, $u(t)$ represents the output superposition control quantity, T_i and T_d represent the integral time constant and differential time constant, respectively, and K_p represents the proportional coefficient.

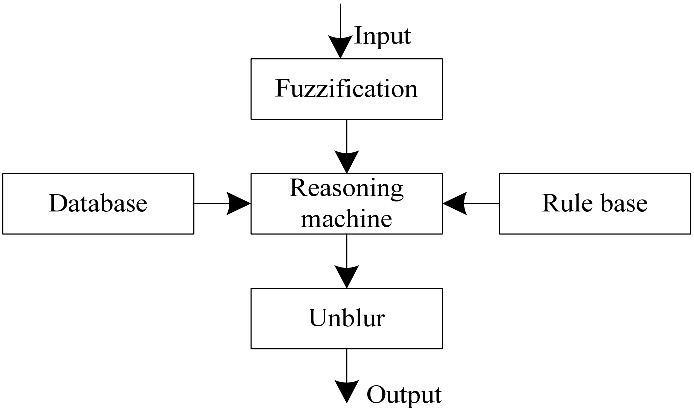
The real-time performance of proportional control in PID controllers is strong. When there is an error in the temperature of the power transformer coil, the proportional control parameters can be quickly adjusted to respond and reduce the error in the temperature of the power transformer coil. The proportional control process of PID controller can only respond when there is an error in the coil temperature of the power transformer. When the temperature error of the power transformer coil is 0, the proportional control does not respond, and at this time, the proportional control process cannot eliminate the steady-state error of the power transformer coil. Using an integral controller to integrate the error of the power transformer coil, the error signal is accumulated to obtain the output control quantity of the PID controller (Gheisarnejad and Khooban, 2021), eliminating the control error of the power transformer coil temperature. When there is an error in the temperature of the power transformer coil, the integral part of the PID controller quickly responds and adjusts the temperature of the power transformer coil until the error drops to 0. At this point, the output of the PID controller is fixed. The above process shows that the integral controller can effectively eliminate the steady-state error of power transformer coil temperature. When the integration effect is too high, it is easy to increase the overshoot of the PID control algorithm. Use a differential controller to adjust the rate of change of the error signal. The differential controller can introduce the correction amount in advance, reduce overshoot during the control process, avoid oscillation in the PID controller, improve the stability and dynamic response speed of the PID controller, and shorten the adjustment time of the PID controller (Verma and Padhy, 2020). The PID controller, through the differentiation process, is prone to amplifying the noise signal during the temperature control process of the power transformer, causing the PID controller to be easily affected by noise interference. When the PID controller constant is too high, it is easy to experience fluctuations in the PID controller, which affects the stability of the power transformer temperature control. Therefore, in order to improve the stability of temperature control, a fuzzy control algorithm is introduced to optimise the control performance of the PID controller.

2.3 Introducing fuzzy inference mechanism into PID control algorithm

When only using PID control algorithm to control the temperature of power transformer coils, due to the strong coupling characteristics of multiple inputs and multiple outputs, the temperature parameters exhibit nonlinear and variable characteristics, making it difficult to control the temperature of power transformer coils. Therefore, in order to solve the problem of PID controllers being susceptible to noise interference and causing strong fluctuations, a fuzzy control algorithm is introduced to improve the stability of temperature control and optimise the controllability of PID controllers. The fuzzy control algorithm uses numerical operations to replace the control conditions of fuzzy temperature, meeting the problems existing in the temperature control of power transformer coils. Fuzzy control theory consists of fuzzy reasoning mechanism, fuzzy rule base and fuzzy data. Introduce fuzzy control theory into PID control algorithm and apply it to temperature control of power transformer coils. Use fuzzy controller instead of analogue controller, and use computer control technology and fuzzy control algorithm to construct a control system with feedback channel closed-loop structure.

The structure diagram of the fuzzy controller applied in the temperature control of power transformer coils is shown in Figure 4.

Figure 4 Fuzzy control structure diagram



The fuzzification process in fuzzy controllers converts the input data of the fuzzy controller into fuzzy vectors that can be applied to the fuzzy inference process in fuzzy control algorithms.

The fuzzy language conversion process for temperature control of power transformer coils is as follows: use e and e_c to represent the temperature deviation and deviation transformation of the power transformer coil, respectively, while u represents the output of the fuzzy controller. The arguments for the three parameters are {–3, –2, –1, 0, 1, 2, 3}, and the relative fuzzy subsets of each argument belong to A_i, B_j and C_k. The relative linguistic values of A_i and C_k belong to {NB, NM, NS, 0, PS, PM, PB}, while the linguistic values of B_j belong to {NB, NS, 0, PS, PB}. Using the above process, the linguistic values are represented by membership functions.

Using a database of fuzzy control algorithms to store the membership vector values of all fuzzy subsets of conveying variables in the temperature control of power transformer coils. Select an expert mechanism, utilise the historical research results of experts, form fuzzy rules from the content stored in the database, and construct a fuzzy rule library.

The process of constructing fuzzy rules in fuzzy control algorithms is as follows: use e, B_j, and u to represent the constraints of A_i and e_c, as well as the constraints of C_k, respectively. Assuming there are $i \times j$ fuzzy inference rules, merge the rules that satisfy the fuzzy inference results into 1 rule. Using the fuzzy reasoning mechanism in the fuzzy control algorithm, according to the fuzzy rules, the power transformer coil temperature control is carried out fuzzy reasoning according to the fixed fuzzy rules, and the fuzzy control quantity of the power transformer coil temperature control is obtained. By solving the fuzzy process, the fuzzy inference output of the power transformer coil temperature control is transformed into the output result of the power transformer coil temperature overheating control.

2.4 Fuzzy PID control of power transformer coil temperature

Combining fuzzy control algorithm with PID control algorithm to reduce the oscillation characteristics in the coil temperature control process, improve the stability of temperature control, and shorten the control time of power transformer coil temperature control. Once fuzzy rules and membership functions are established, they cannot be adjusted in real-time and cannot meet the hysteresis and time-varying requirements of the power transformer coil temperature control system. Introduce expert mechanisms into the fuzzy PID controller algorithm, construct a fuzzy adaptive PID control algorithm, and improve the hysteresis and time-varying performance of the fuzzy PID controller in controlling the temperature of power transformer coils. Expert mechanisms are often used in processes such as fault diagnosis and process control, as well as in solving difficult problems in industrial control. They are common and important methods in industrial processes. The fuzzy PID adaptive control algorithm mainly includes two parts: a fuzzy PID controller and an expert controller. The fuzzy PID adaptive control algorithm uses a mode selection switch to select a fuzzy PID controller and an expert controller, which act on the temperature control of the power transformer coil. In the process of implementing transformer coil temperature control using this algorithm, the control range of the expert mechanism is projected onto the fuzzy domain to obtain rich and accurate rules, enabling the rule library to cover multiple input situations and produce accurate outputs.

The transfer function of using a PID controller to control the temperature of the power transformer coil in formula (9) is transformed as follows:

$$G(S) = K_p\left(1+1/T_jS\right)+T_zS \tag{10}$$

In formula (10), K_p, T_j and T_z represent the proportional parameters, integral time parameters, and process time parameters of the control process, respectively.

The discretisation method is selected as the control process of the PID control algorithm. The continuous time t of the power transformer coil temperature control is expressed as kT by the sampling time. The process formula (8) of the PID control algorithm is replaced by a first-order backward differential process. The power transformer coil temperature control process of the PID controller is transformed as follows:

$$\int_0^t e(t)dt \approx T\sum_{j=0}^{k} e(jT) = e(k)-e(k-1)/T \tag{11}$$

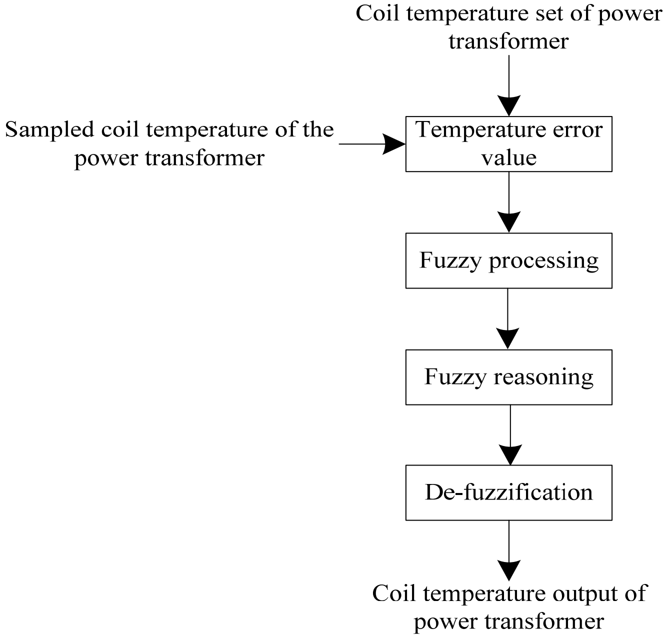
The PID controller is discretisation, and the expression of the discrete PID controller is as follows:

$$u(k) = K_pe(k)+k_i\sum_{j=0}^{k} e(j)TK_D\left(e(k)-e(k-1)\right)/T \tag{12}$$

By using dual frequency AC input, the difference e and difference e' between the target temperature of the power transformer coil and the actual temperature are calculated. The control value u is used as a single output of the controller to improve the accuracy and real-time performance of the power transformer coil temperature control.

The fuzzy domains of E, E' and U are represented by e, e' and u, and the control process of the fuzzy PID controller is shown in Figure 5.

Figure 5 Control flow chart of fuzzy PID controller



Using the adaptive fuzzy PID control algorithm, output a fuzzy subset of temperature control value *U*, and define the domain of this fuzzy subset as follows: use NB, NM, NS, ZO, PS, PM, PB to represent the fuzzy subsets of *E* and *U*. The elements in the fuzzy control subset represent negative large, negative medium, negative small, zero, positive small, positive medium, and positive large, respectively. The domains of *E*, *E′* and *U* are within the range of {–5, –3, –1, 0, 1, 3, 5}. Select S-shaped and Z-shaped membership functions as the membership functions for subsets NB and PB. For other subsets of fuzzy control, triangular membership functions are used to represent them, and genetic algorithms are used to optimise the parameter configuration of peaks, starting points, and ending points in the membership functions. Using the above process, a control table of fuzzy rules is constructed to achieve better control performance. Use a fuzzy controller to convert the range of error *E* in power transformer coil temperature control [–7, 7] to 0 in the fuzzy domain.

Table 1 Fuzzy rules for coil temperature control

	NB	*NM*	*NS*	*ZO*	*PS*	*PM*	*PB*
NM	NM	NM	NM	PB	PS	PM	PM
NS	NB	NS	NS	PS	PM	PB	PS
ZO	NS	ZO	NB	ZO	ZO	PS	NS
PS	PS	PS	PS	NB	PS	NS	NM
PM	PM	NB	NB	NM	PB	PM	NB
PB	PB	PB	PS	NS	NM	NB	PB
NB	NB	PM	PM	PB	NS	NM	PB

Calculate the fuzzy domain of parameters for temperature control of power transformer coils using a fuzzy rule table. The fuzzy rule table settings for coil temperature control are shown in Table 1.

In the expert control of power transformer coil temperature using the fuzzy adaptive PID control algorithm, the projection content of the expert control range onto the fuzzy domain is shown in Table 2.

Table 2 Projection contents of expert control scope and fuzzy domain

Range	*Mapping result*
[8, 11]	1
[–11, –8]	–1
[12, 17]	2
[–17, –12]	–2
[8, 17]	3
[–18, –7]	–3

The process of defuzzification in fuzzy control algorithms is as follows: using the centre of gravity method as the deblurring process of a fuzzy PID controller. Taking parameter ΔK_p as an example, the expression for solving the membership degree $\mu_{\Delta K_p}$ of the first fuzzy rule of parameter ΔK_p is as follows:

$$\mu_{\Delta K_p} = \mu_{NB}(e) * \mu_{NB}(e') \tag{13}$$

In formula (13), * represents the symbol for taking small operations, $\mu_{NB}(e)$ and $\mu_{NB}(e')$ represent the membership values of the temperature difference e and the difference value e' in the fuzzy rules, respectively. $\mu_{\Delta K_p}$ represents the membership values of the temperature control deviation and the change rate of the temperature control deviation of the power transformer coil. Formula (13) can be converted as follows to ensure that the error in temperature control is minimised:

$$\mu_{\Delta K_p} = \min\{\mu_{NB}(e), \mu_{NB}(e')\} \tag{14}$$

After inputting the temperature control amount of the power transformer coil, the expression for obtaining the output ΔK_p of the adaptive fuzzy PID controller is as follows:

$$\Delta K_p = \frac{\sum_{j=1} \mu_{\Delta K_p} \times \mu_{pj}}{\sum_{j=1} \mu_{pj}\left(\Delta K_p\right)} \tag{15}$$

In formula (15), μ_{pj} represents the combined membership degree corresponding to output quantity ΔK_p.

The parameter adjustment expression of the adaptive fuzzy PID control algorithm for power transformer coil temperature control is as follows:

$$\begin{cases} K_p = K_{p0} + \Delta K_p \\ K_i = K_{i0} + \Delta K_i \\ K_i = K_{i0} + \Delta K_i \end{cases} \tag{16}$$

Use formula (16) to obtain the output of the adaptive fuzzy PID control algorithm, which is the actual control parameters of the power transformer coil temperature control, to achieve efficient and stable power transformer coil temperature control.

3 Experimental testing

3.1 Scheme and parameter settings

In order to verify the effectiveness of the coil temperature control method for power transformers studied, this method was applied to the operation of a power transformer in a certain power system, which was equipped with 8 oil immersed transformers. The power transformer in the power system adopts a cake like structure as the high-voltage winding coil. The coil is formed by continuous winding, with a total of 40 cakes and 18 turns of coil winding per cake. The horizontal oil passage length of the power transformer is 50mm. The average temperature rise of the winding coils inside the power transformer is 70K. The power transformer used in the experiment is a single-phase transformer, which is equipped with a circulating oil pump and heat dissipation fins, making it convenient for the power transformer to use various heat dissipation processes for flexible heat dissipation. The electrical parameter settings of the power transformer are shown in Table 3.

Table 3 Electrical parameters of power transformer

Device name	*Parameter name*	*Numerical content*
Power transformer	Model number	YD-100KVA/10 kV
	Rated capacity	100 KVA
	Rated high voltage	10 kV
	Rated low voltage	500 V
	Rated high voltage current	20 A
	Rated low voltage current	230 A
	No-load loss	488 W
	Load loss	1,325 W
Iron core	Core diameter	200 mm
	Core window width	350 mm
	High core window	550 mm
	material	Silicon steel sheet
Coil	High voltage line length	550 m
	Low pressure line length	30.5 m
Radiator	Model number	PG350-5
	Heat dissipation area	1.85 m^2

To ensure the reliability of the test results, the parameters related to the test should be set before the start of the test, as shown in Table 4.

Table 4 Related parameter settings

Parameter	*Content*
Scale	0.8
Integral time parameter	0.5
Differential time parameter	0.2
Controller output signal range	0–10

Based on the above parameter settings, the effectiveness of the proposed method is first verified, and its control response and adaptive control are tested. Finally, in order to verify the superiority of the proposed method, the Luo et al.'s (2020) method, Zhang and Gao's (2020) method and Wu et al.'s (2020) method are used as comparison methods, and the root-mean-square deviation of the temperature control result, the response of the temperature control and the thermal aging rate of the control power transformer are selected as performance test indicators respectively to conduct control performance comparison tests with the proposed method. Among them, the calculation formula of root-mean-square deviation is shown in the following formula. The smaller the calculation result is, the higher the control precision of the model is, and the stronger the adaptability and reliability are.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|\hat{y}_i - y_i\right| \tag{17}$$

In the equation, $\hat{y}_i$ is the control result, y_i is the expected result, and n is the number of samples.

The faster the response speed of temperature control, the faster the method can adjust and maintain the set temperature, and improve energy utilisation efficiency.

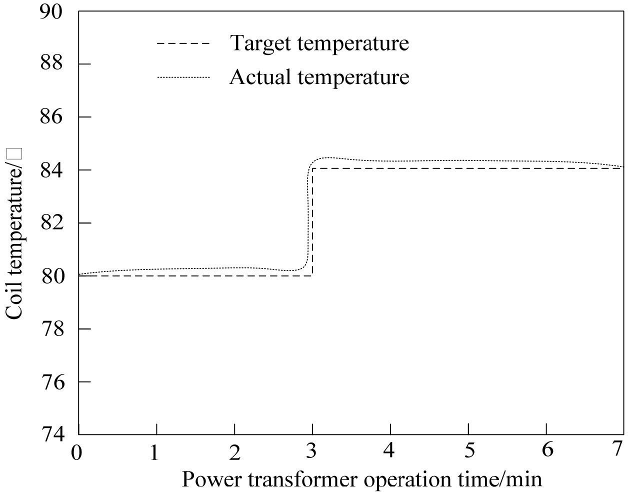
The lower the thermal aging rate of power transformers, the better the suppression of noise interference by this method. It can effectively adjust the fluctuation of transformer coil temperature control process, ensure the safe operation of power transformers, and has strong application performance.

3.2 Result analysis

The method proposed in this paper is applied to the temperature control of power transformer coils. The response results of the power transformer coil temperature controlled by this method are shown in Figure 6.

The experimental results in Figure 6 show that the method proposed in this paper can control the power transformer coil and quickly respond within the ideal temperature range. Using the method described in this article to control the temperature of the power transformer coil, the difference between it and the ideal temperature of the power transformer coil is minimal. The experimental results verify that the method proposed in this paper can quickly control the power transformer coil within the ideal temperature range and has a high temperature control effect. This article adopts the fuzzy PID control algorithm, combining the advantages of fuzzy controller and PID controller in temperature control, to achieve rapid adjustment of power transformer temperature.

Figure 6 Coil temperature control results of power transformer



The maximum limit for the temperature of the power transformer coil is 95°C. When the temperature of the power transformer coil exceeds 90°C, the method in this article timely initiates an alarm and operates the temperature control method to control the temperature of the power transformer coil. The method described in this article is used to implement adaptive control of the coil temperature of power transformers. The control results of the coil temperature of power transformers in the power system from August 1 to August 30, 2021 are shown in Table 5.

Table 5 Coil temperature control process of power transformer

Date	*Alarm time*	*Alarm threshold value (°C)*	*Alarm value (°C)*	*Temperature control value (°C)*	*Whether a heat fault occurs*
On 5 August	17:25:11	90	90.5	88.5	no
On 12 August	12:12:08	90	90.6	88.4	no
On 14 August	9:54:23	90	90.3	88.6	no
On 16 August	7:15:19	90	90.2	88.1	no
On 18 August	8:16:31	90	90.4	87.5	no
On 21 August	9:23:18	90	90.5	86.5	no
On 24 August	14:15:52	90	90.4	85.7	no
On 27 August	16:13:18	90	90.3	86.4	no
On 28 August	15:23:47	90	90.1	87.5	no
On 29 August	16:25:33	90	90.4	86.5	no

From the experimental results in Table 5, it can be seen that this method can quickly start the fuzzy PID control algorithm when the temperature of the power transformer coil exceeds the set threshold, and quickly adjust the temperature of the power transformer coil to the ideal state. When the coil temperature of the power transformer is in an ideal state, it can maintain the power transformer in the ideal operating state, providing a good temperature foundation for the reliable operation of the power system, and avoiding overheating faults of the power transformer.

In order to further verify the control performance of this method on power transformer coil temperature, the Luo et al.'s (2020) method, Zhang and Gao's (2020) method and Wu et al.'s (2020) method are selected as comparison methods, and different methods are used to control the power transformer coil temperature. The root-mean-square deviation of each method is calculated through the above formula (17), and the calculation results are statistically analysed to illustrate the applicability and reliability of the proposed model, the statistical results of its root-mean-square deviation are shown in Table 6.

Table 6 Comparison results of MSE values

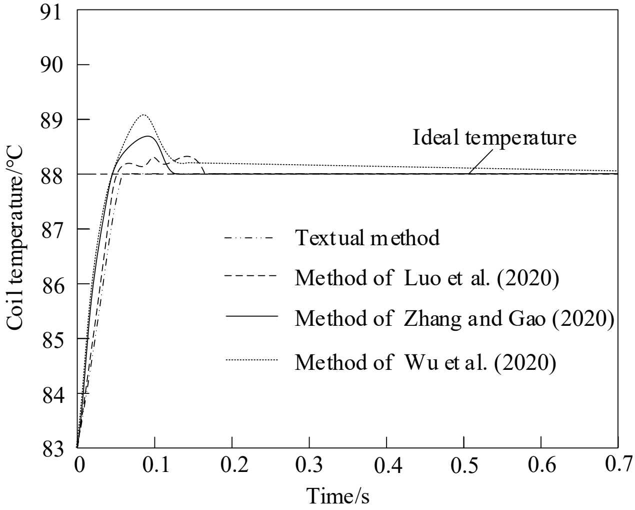
Number of samples	*Root mean square error*			
	Proposed method	*Luo et al.'s (2020) method*	*Zhang and Gao's (2020) method*	*Wu et al.'s (2020) method*
200	0.21	0.51	0.52	0.52
400	0.22	0.53	0.53	0.54
600	0.23	0.56	0.57	0.57
800	0.25	0.59	0.58	0.59
1,000	0.27	0.62	0.63	0.64

According to the results in Table 6, with the increase of the number of samples, the root-mean-square deviation results of the four methods show some differences. When the number of samples reaches 1,000, the root-mean-square deviation results of the proposed method, Luo et al.'s (2020) method, Zhang and Gao's (2020) method and Wu et al.'s (2020) method are 0.27, 0.62, 0.63 and 0.64 respectively. Compare the results obtained by four methods. The root-mean-square deviation of the proposed method is small, which indicates that the control accuracy of the model in the proposed method is high, and it has applicability and reliability. It can be said that the control of power transformer coil temperature provides reliable support.

Subsequently, different methods were used to control the temperature of power transformer coils, and the response results of temperature control are shown in Figure 7.

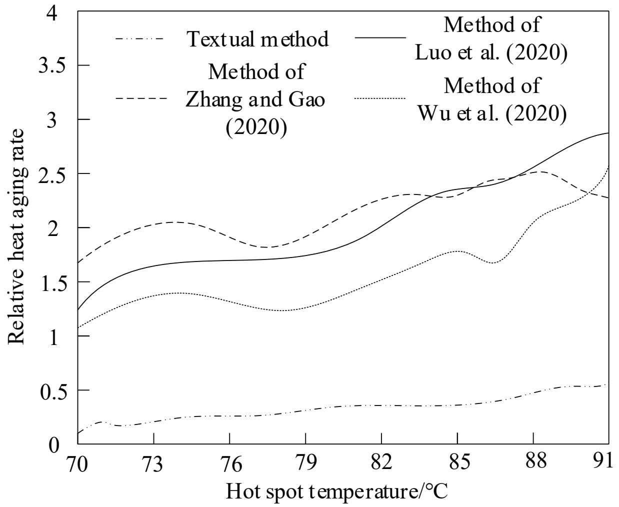
From the response results of the power transformer coil temperature control in Figure 7, it can be seen that using this method to control the power transformer coil temperature has a fast response speed. Within 0.1 seconds, the coil temperature can be controlled at the ideal temperature. The temperature of the power transformer coil only has a very small amount of overshoot, quickly reaching the ideal temperature, and then maintaining it at the ideal temperature for a long time. Using the methods of Luo et al. (2020), Zhang and Gao (2020), and Wu et al. (2020) to control the temperature of the power transformer coil, there is a significant overshoot situation, and the fluctuation of the control response results is obvious. Using the above three control methods to control the temperature of the power voltage transformer coil has high oscillation, and the control effect is not ideal. The comparison results verify that the proposed method has an ideal control effect. The method used in this article to control the coil temperature of power transformers has high effectiveness, which can improve the working efficiency of power transformers and meet the temperature control requirements of power transformer coils. Compared to other methods, this method has control advantages such as short response time, fast reaction speed, and small overshoot.

Figure 7 Coil temperature control response results



The method used in this paper is used to control the temperature of the power transformer coil and the changes in the thermal aging rate of the power transformer. The thermal aging rate of the power transformer controlled by this method is compared with the methods in Luo et al. (2020), Zhang and Gao (2020), and Wu et al. (2020). The comparison results are shown in Figure 8.

Figure 8 Comparison of thermal aging rate of power transformer



From the experimental results in Figure 8, it can be seen that when the temperature of the power transformer coil is controlled using the method proposed in this paper, the relative thermal aging rate of the power transformer is lower than 1, and the relative thermal aging rate of the power transformer is significantly lower than the other three methods. This method can control the coil temperature of power transformers within the safe temperature rise range. The higher the temperature of the power transformer coil, the higher the thermal aging rate. When the thermal aging rate increases to a certain extent, it affects the normal operation of the transformer. The method described in this article can control the coil temperature of a power transformer within an ideal range, which is of great significance for ensuring the safe operation of the transformer and avoiding overheating faults due to the high temperature of the transformer coil.

4 Conclusions

The temperature control of power transformer coils has the characteristics of high complexity and nonlinearity. By controlling the temperature of power transformer coils, the production efficiency of power transformers can be improved. By controlling the temperature of power transformer coils, the process requirements for power transformer operation can be met. The use of fuzzy PID control algorithm effectively improves the defects of large inertia and serious hysteresis in the temperature control process. This method combines PID control algorithm with fuzzy control algorithm, introduces expert mechanism to construct an adaptive fuzzy PID controller, and adjusts the temperature of the power transformer coil. This method is applied to the power transformer of a certain power system. Through experimental verification, it can achieve effective control of the coil temperature of the power transformer, with the characteristics of small overshoot and high real-time control. The relative thermal aging rate of the power transformer is less than 1. Utilising precise control of the coil temperature of power transformers to maintain ideal operating conditions is an efficient control method with high intelligence.

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