

# A Top-oil Temperature Prediction Method for the Split Transformer Based on PSOGSA

XinZi<sup>1</sup>, Wei Bengang<sup>1</sup>, Liang Yongliang<sup>2</sup>, Xu Yanshun<sup>2</sup>, Guo Ruochen<sup>2</sup> and Lou Jie<sup>2</sup>

<sup>1</sup>Electric Power Research Institute, SMEPC, 171# Handan Rd., Shanghai, China

<sup>2</sup>School of Electrical Engineering, Shandong University, 27# South Shanda Rd., Jinan, China

391818095@qq.com

**Abstract.** Because of the complicated structure of cooling system, the heat radiation principle and top-oil temperature prediction of the split transformer is attracting more and more attention. This paper proposes a top-oil temperature prediction method for split transformer based on PSOGSA. Based on the thermal circuit of ordinary transformers, a thermal circuit for split transformers is proposed taking the heat radiation principle into account. Besides, the model is modified with the consideration of the non-linear heat resistance, load ratio and oil viscosity. Further, the parameters of the model are optimized by PSOGSA. Finally, the method proposed is tested by on-site temperature-rise experiment. The test results prove that the method could provide a high-precision prediction result of the top-oil temperature for split transformer.

## 1. Introduction

With the development of economy and urban construction, more and more split transformers have been used in the cities because of excellent structure. Now most underground substations which have large-scale application of split transformers concentrate in Beijing and Shanghai and other major cities [1-2]. However, as the load increases, the issue of transformer heat radiation has become increasingly prominent. Because of the complicated structure of split transformer and its cooling system, the key components of the heat transfer mode and heat radiation principle remains to be further studied. So it is of great significance to research the thermal circuit of split transformers for improving the operational reliability of split transformer [3-4].

For ordinary oil-immersed transformer, the most valuable reference temperature are winding hot-spot temperature, top oil temperature and bottom oil temperature[5-6], this is still suitable for split transformer. In order to ensure the heat radiation effect, split transformers are usually installed by upper and lower or horizontal layout, and often use water, oil, air and other means to cooling. Transformer heat radiation calculation of conventional cooling system has been carried out a large number of research works at home and abroad. In the past 90 years of last century, the classical calculation model of transformer thermal state parameters has been proposed in GB/T15164-1994[7-9]. There is a way of predicting the transformer oil temperature by using the thermal circuit model method which is obtained by the thermoelectric simulation method. The heat source is equivalent to the current source, and the voltage source represents the temperature difference that causes the heat transfer. This method has fewer parameters and the calculation process is simple [10-11]. There is also



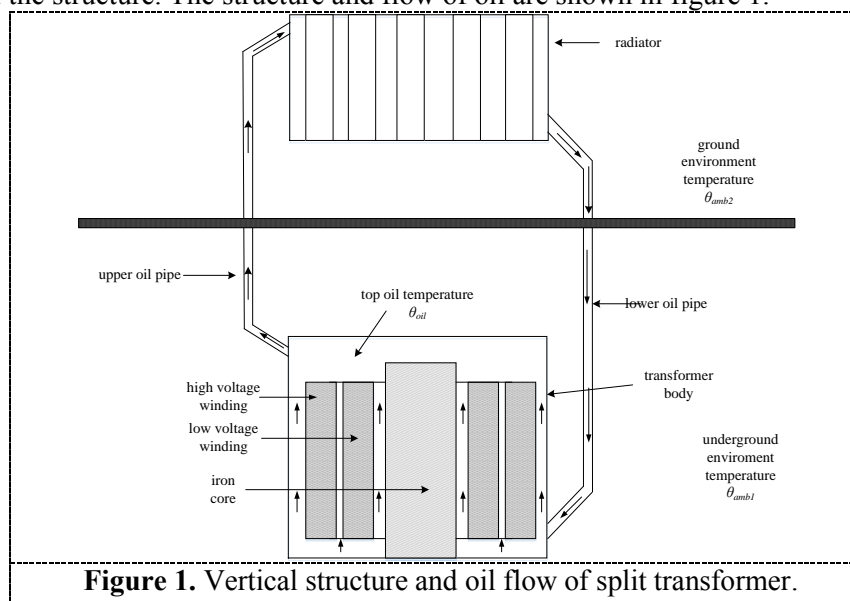
a way that using intelligent algorithms to predict. T-S fuzzy model is applied to the top of the power transformer oil temperature prediction, and the nonlinear system is linearized. The prediction accuracy has been improved compared with the IEEE empirical model [12]. Kalman filter algorithm is also applied to the top oil temperature prediction. On the basis of the thermal circuit model, the post-Eulerian formula is used to discretize the differential equation of the top oil temperature of the transformer linearly, which also improves the prediction precision [13-14]. The latter two methods are highly targeted but lack a clear physical meaning and hide the mapping relationship between influencing factors and internal temperature in the network. However, for the split cooling system, due to technical barriers and little in-depth relevant research, scientific basis is insufficient to calculate the top oil temperature and winding hot temperature.

This article is based on the thermal circuit models which has actual physical meaning, proposed a split transformer top oil temperature thermal circuit model by analogizing with the thermal circuit of ordinary transformers. The model considers the influence of nonlinear thermal resistance, actual load, oil viscosity variation and other parameters on the thermal resistance and heat capacity of the model. After the model parameters are reasonably simplified, the corresponding parameters are optimized based on the PSOGSA algorithm to obtain the optimal Model parameters.

## 2. The top oil temperature thermal circuit model for split transformer

### 2.1. The top oil temperature prediction thermal circuit model for split transformer

Split transformer applied in underground substation generally take the body and radiator vertical distribution of the structure. The structure and flow of oil are shown in figure 1.

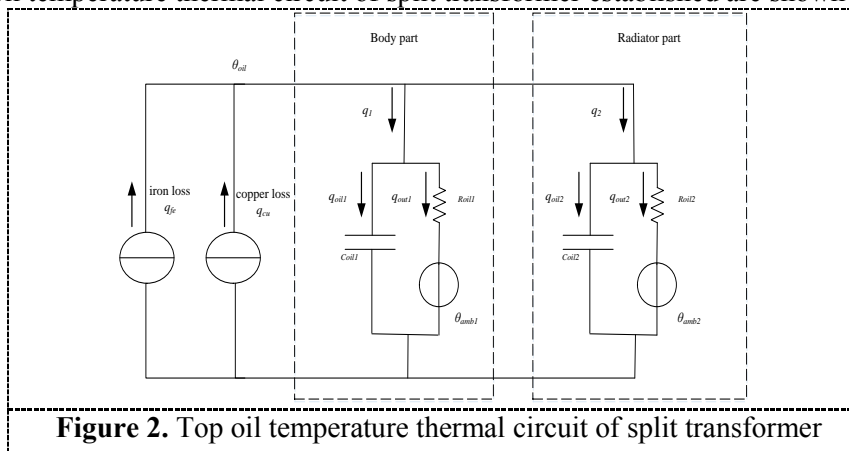


**Figure 1.** Vertical structure and oil flow of split transformer.

The key thermal parameters of the split transformer also select the hot spot temperature and the top oil temperature, namely "ambient temperature - top oil temperature - hot spot temperature" double-layer thermal circuit model. Among them, the part of "top oil temperature - hot spot temperature" is located in transformer body, it can be assumed with the ordinary cooling transformer, so the paper mainly research in the establishment of "ambient temperature - top oil temperature" thermal circuit and calculation of parameters. The difference of cooling process between split and ordinary transformer mainly comes from the structure, where there is a large vertical height difference between the radiator and the body of split transformers, distance between the two parts is far and their working environments are different. About the thermal calculation method, we can refer to ordinary transformers, but also to fully distinguish the difference. As for the selection of transformers body structure model, since there is no significant difference between the two structures, the ordinary transformer thermal circuit model can be directly used. The heat radiation process of radiator and

transformer body were considered separately, parallel analyzing through the path of heat radiation, and the radiator part taking a simplified treatment similar to the traditional ordinary transformer radiator. We may think that winding outlet temperature and the radiator inlet temperature of split transformer are the same, the transformer winding inlet temperature and radiator outlet temperature are the same. The temperature of the transformer oil in the body heated by the heating element is equal to the temperature at which it is cooled in the radiator so as to achieve the balance of heat generation and heat dissipation of the split-type transformer in steady-state operation. That is to say, the transformer oil flowing through the closed heating and cooling oil system and the temperature profile along the geometric height of the oil circulating system of the transformer are closed curves when the split transformer operates in steady state.

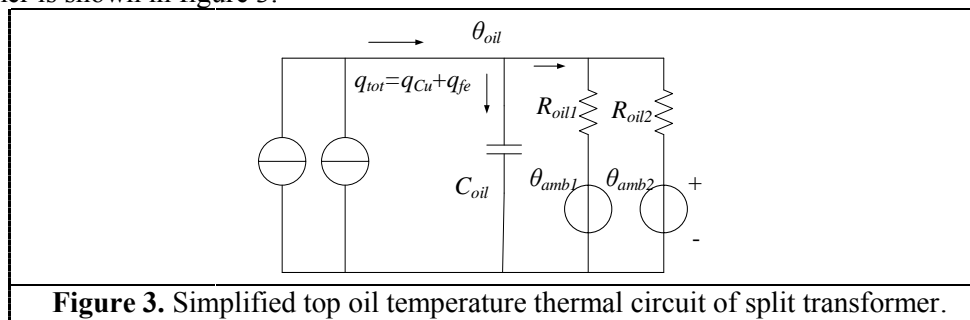
Transformer and radiator parts are used in the form of RC circuit, and the two branches are in parallel. Top oil temperature thermal circuit of split transformer established are shown in figure 2.



**Figure 2.** Top oil temperature thermal circuit of split transformer

Where  $q_{Fe}$  is the transformer iron loss,  $q_{Cu}$  the transformer copper loss,  $\theta_{amb1}$  and  $\theta_{amb2}$  represent ambient temperature underground and above ground, the heat dissipated through the body and heat sink is  $q_1$  and  $q_2$ . Among them,  $q_{oil1}$  and  $q_{oil2}$  represent heat dissipated to body transformer oil and radiator transformer oil,  $q_{out1}$  and  $q_{out2}$  represent heat dissipated to the environment underground and above ground.  $Coil1$ ,  $Coil2$  and  $Roil1$ ,  $Roil2$  are the capacitance and resistance of the body transformer and heat sink separately.

By simplifying the capacity branch, the simplified top oil temperature thermal circuit of split transformer is shown in figure 3.



**Figure 3.** Simplified top oil temperature thermal circuit of split transformer.

Based on the simplified top oil temperature thermal circuit of split transformer, According to Kirchhoff's law:

$$q_{Fe} + q_{Cu} = C \frac{d\theta_{oil}}{dt} + \frac{(\theta_{oil} - \theta_{amb1})}{R_1} + \frac{(\theta_{oil} - \theta_{amb2})}{R_2} \quad (1)$$

## 2.2. Analysis and correction of influencing factors of the thermal circuit

As the oil temperature changes during the operation of the transformer, the oil density and viscosity change with heat transfer. Therefore, it is necessary to consider the influence of the non-linear heat resistance, load ratio and oil viscosity [15-16].

(1)Non-linear heat resistance correction. The factor  $1/n$  is introduced to describe the non-linear variation of heat resistance, so:

$$q = \frac{\Delta\theta_{oil}^{\frac{1}{n}}}{R} \quad (2)$$

Where  $n$  is a constant, often take  $n = 0.8 \sim 1$ ,  $1/n$  is used to characterize the heat resistance and the non-linear relationship added at both ends of the heat resistance.

Substituting (2) into (1):

$$q_{Fe} + q_{Cu} = C \frac{d\theta_{oil}}{dt} + \frac{(\theta_{oil} - \theta_{amb1})^{\frac{1}{n}}}{R_1} + \frac{(\theta_{oil} - \theta_{amb2})^{\frac{1}{m}}}{R_2} \quad (3)$$

Among them,  $m$  and  $n$  have the same value range, but the values may not be the same.

(2)Correction of the actual load: In non-rated load conditions, it is necessary to correct the equation of transformer model based on real-time load, the relationship between load current and rated current as follows:

$$K = \frac{I}{I_{rated}} \quad (4)$$

$$\beta = \frac{q_{Cu}}{q_{Fe}} \quad (5)$$

In practice, the iron loss basically does not vary with the load; the copper loss is proportional to the square of the current, so the total loss after correction is:

$$q_{Fe} + q_{Cu} = (q_{Fe} + q_{Cu})_{rated} \times \frac{\beta K^2 + 1}{\beta + 1} \quad (6)$$

(3)Correction of oil viscosity: among the parameters which determine the heat resistance, the oil viscosity, which changes the most with temperature, has the greatest impact on the changes of heat resistance. As the temperature changes, the variety of oil viscosity is reflected through the heat resistance.

$$R = \frac{1}{\gamma_1 \cdot \left( \frac{\Delta\theta_{oil}}{\mu} \right)^n \cdot A} \quad (7)$$

where  $\gamma_1$  is a constant, determined by the oil density, oil heat expansion coefficient, oil heat conductivity, oil specific heat capacity and so on;  $\mu$  is the oil viscosity which changes with temperature.

In actual operation, oil viscosity is usually difficult to obtain, and its variation is reflected by heat resistance. Therefore, in actual treatment, heat resistance is directly taken as model identification parameter. And the formula (3) becomes as follows:

$$(q_{Fe} + q_{Cu})_{rated} \times \frac{\beta K^2 + 1}{\beta + 1} = C^* \frac{d\theta_{oil}}{dt} + \frac{(\theta_{oil} - \theta_{amb1})^{\frac{1}{n}}}{R_1^*} + \frac{(\theta_{oil} - \theta_{amb2})^{\frac{1}{m}}}{R_2^*} \quad (8)$$

### 3. Parameter optimization of a top-oil temperature prediction method for split transformer based on PSOGSA

In equation (8), once the parameters of the model can be determined, the value of the top oil temperature can be solved. The parameters to be optimized are [C \*, R1 \*, R2 \*, n, m]. PSOGSA is used to optimize the parameters.

### 3.1. Parameter optimization of a top-oil temperature prediction method for split transformer based on PSOGSA

PSOGSA composed by particle swarm optimization algorithm and gravitation search algorithm is aimed to combine the optimization ability of PSO and the search ability of GSA[17-18]. There are unique advantages in solving the optimization problem. The particle acceleration  $a(t)$  and the global extreme number  $gbest$  are introduced into the calculation formula of the particle velocity. The final  $gbest$  is the optimization result we need. The convergence speed is better than PSO and GSA.

In a D-dimensional search space, supposing there are N particles, so the position of the  $i$ th particle is:

$$X_i = (x_i^1, \dots, x_i^d, x_i^D) \quad i = 1, 2, \dots, N \quad (9)$$

At the  $t$ th iteration, the inertial mass  $M_i(t)$  of the  $i$ th particle is defined as:

$$m(t) = \frac{f_i(t) - f_{worst}(t)}{f_{best}(t) - f_{worst}(t)} \quad (10)$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^N m_j(t)} \quad (11)$$

where  $f_i(t)$  is the fitness value of particle  $i$  at the  $t$ th iteration, and  $f_{best}(t)$  and  $f_{worst}(t)$  are the optimal value and the worst value of fitness in the  $t$ -th iteration.

The gravitational force of particle  $j$  on particle  $i$  is defined as:

$$F_{ij}(t) = G(t) \frac{M_{pi}(t) \times M_{aj}(t)}{\|p_i(t), p_j(t)\|_2} [X_j(t) - X_i(t)] \quad (12)$$

Where  $G(t)$  is the gravitational time constant,  $M_{pi}(t)$  and  $M_{aj}(t)$  are the passive inertial mass of particle  $i$  and the active inertial mass of particle  $j$ , respectively. It is generally assumed that the passive inertial mass is equal to the active inertial mass.

For particle  $i$ , its attraction by the rest of the particles is represented by a random weighted sum:

$$F_i(t) = \sum_{j \neq i} rand_j F_{ij}(t) \quad (13)$$

Based on Newton's second law, the acceleration generated by particle  $i$  is:

$$a_i(t) = \frac{F_i(t)}{M_i(t)} \quad (14)$$

Then the particle's velocity and position can be updated as:

$$v_i(t+1) = rand_i \times v_i(t) + a_i(t) \quad (15)$$

$$p_i(t+1) = p_i(t) + v_i(t+1) \quad (16)$$

Where  $p_i$  is the position of the  $i$ th particle,  $v_i$  is the velocity of the  $i$ th particle,  $a_i$  is the acceleration of the  $i$ th particle, and  $rand_i$  is a random number between [0,1].

In the traditional GSA, each update is based on the result of one iteration calculation, which leads GSA to have strong search ability but not global optimization ability. Therefore, considering the global optimal concept in PSO, the optimal location  $gbest$  is obtained and (15) is changed to:

$$v_i(t+1) = \omega v_i(t) + c_1 \times r \times a_i(t) + c_2 \times r \times (gbest - p_i(t)) \quad (16)$$

Where  $\omega$  is the inertia factor; the learning factors  $c_1$  and  $c_2$  are non-negative constants,  $r$  is a random number between [0,1],  $gbest$  represents the global optimum.

### 3.2. Optimization of parameters based on PSOGSA

The parameters to be optimized are  $[C^*, R1^*, R2^*, n, m]$ , which form a 5D search space, and the number of particles is set 20. Before the parameters are optimized, the range of parameters should be set rationally.

The variation range of  $C^*$ ,  $R1^*$ ,  $R2^*$  should be near their rated value, and the calculation method of rated R value is:

$$R_{rated} = \left( \frac{\Delta\theta_{oil}}{q_{Fe} + q_{Cu}} \right)_{rated} \quad (17)$$

Therefore, the optimization range of  $R1^*$  and  $R2^*$  is  $[0.5R_{rated}, 2R_{rated}]$ . The calculation formula of rated  $C$  is:

$$C_{rated} = 0.48 \cdot M_{FLUID} \quad (18)$$

The  $M_{FLUID}$  is the quality of the oil. Therefore, the optimization range of  $C^*$  is  $[0.5C_{rated}, 2C_{rated}]$ .

The range of  $n$  and  $m$  values is generally  $[0.8, 1.2]$ .

The optimal fitness function is the average absolute percentage (MAPE) error of the calculated and tested values, which is:

$$MAPE = \frac{1}{k} \sum_{i=1}^k \left| \frac{y_i - y_{it}}{y_i} \right| \times 100\% \quad (19)$$

## 4. Verification based on an example

In this paper, a split transformer which has not been put into operation is chosen as an example to validate the model proposed in this paper.

The transformer parameters are shown in table 1. The transformer rated capacity is 80000kVA, refrigeration mode of which is ONAN. The weight of its oil and winding respectively are 28400kg and 14818kg. Specific volume heat of the transformer oil and winding (copper) respectively are 2569 (20°C) [J / kg·°C] and 390 (20°C) [J / kg·°C].

**Table 1.** The parameters of SZ11-80000/110 split transformers.

Item	Content
Refrigeration mode	ONAN
Type	SZ11-80000/110
Rated Capacity	80000kVA
Rated Voltage	110kV/10.5kV
Rated Current	419.9A/2539.7A
Oil Weight	28400kg
Winding Weight	14818kg
Specific volume heat of oil	2569(20°C)[J/kg.°C]
Specific volume heat of winding(copper)	390(20°C)[J/kg.°C]
Item	Content

According to the test results in transformer factory, because the split transformer has not yet been put into operation, still in the pilot phase, the body and the radiator are at the same ambient temperature. And oil viscosity and other factors cannot be measured. According to the definition of the

thermal resistance concept, the rated thermal resistance is the ratio of the steady temperature change (under rated loss) and the total loss. The rated loss is 370360W ( $P=370360W$ ), the rated thermal resistance can be obtained according to the existing formula:

$$R_{rated} = \left( \frac{\Delta\theta_{oil}}{q_{Fe} + q_{Cu}} \right)_{rated} = \frac{59.8-13.5}{370.36 \times 10^3} = 1.25 \times 10^{-4} \cdot C / W \quad (20)$$

According to the transformer parameters, the rated heat capacity can be obtained:

$$C_{th-oil} = 0.48 \cdot M_{FLUID} = 0.48 \times 28400 = 13632 Wh/^{\circ}C \quad (21)$$

so the optimal range of model parameters is

$$0.625 \times 10^{-4} \cdot C / W \leq R_1^*, R_2^* \leq 2.5 \times 10^{-4} \cdot C / W$$

$$6816 Wh/^{\circ}C \leq C^* \leq 27264 Wh/^{\circ}C \quad (22)$$

$$0.8 \leq n, m \leq 1.2$$

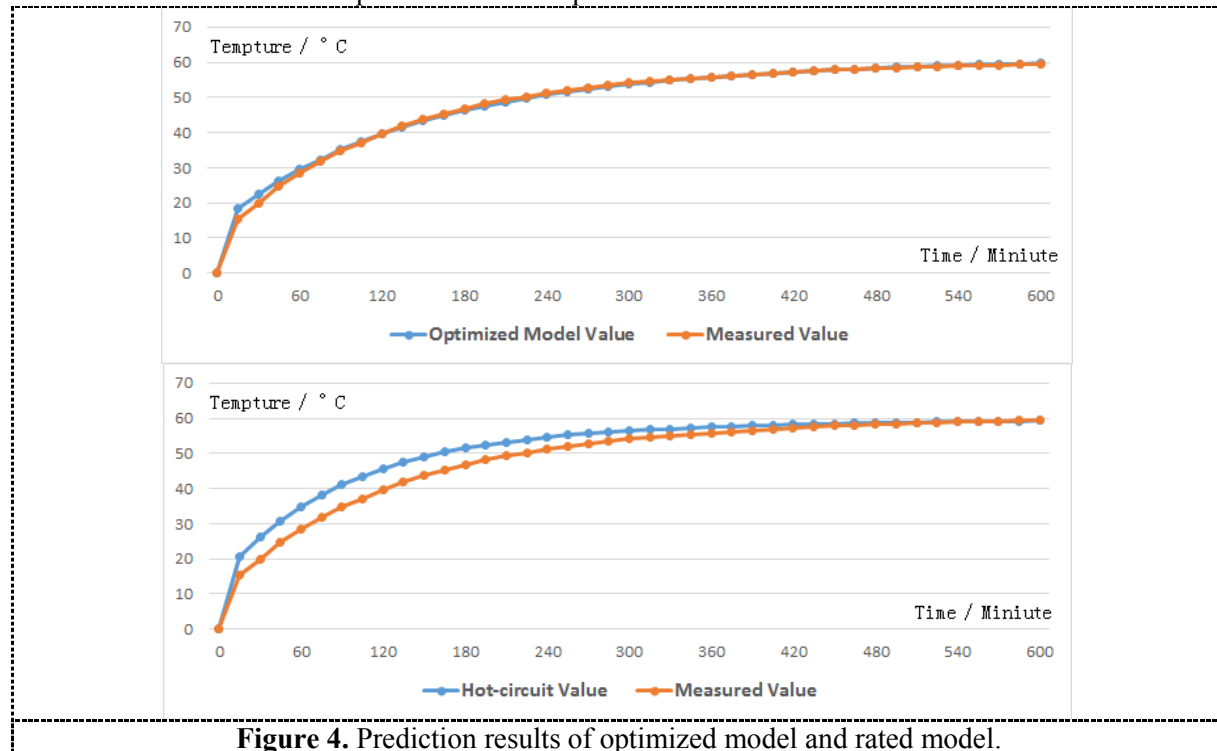
Based onsite temperature-rise experiment data sampled every 15 minutes from 9:00p.m. to 7:00 a.m. the next day, under the constant power state of the transformer, the optimization of the model parameters is finished by PSOGSA. The results are showed in table 2.

**Table 2.** Optimized parameters of model.

$R1^*$	$R2^*$	$C^*$	$n$	$m$
$1.7 \times 10^{-4}$	$1.28 \times 10^{-4}$	19268	1.01	1.09

The results of the calculation of the top-oil temperature are shown in figure 4, which is using the optimized parameter model ( $n=m=1$ ).

The orange indicates the measured value and the blue indicates the calculated value of the hot-circuit model. It's obvious that the final steady state temperature is both consistent in figure 4. But the temperature rise fitting of the optimization parameter is more accurate than that of the rated values model. It illustrates that the optimization of the parameter model is effective.



**Figure 4.** Prediction results of optimized model and rated model.

## 5. Conclusion



Aiming at the prediction of top-oil temperature of split transformer, a method based on PSOGSA is proposed. Firstly, according to the split transformer structure, heat radiation principle and the ordinary transformer thermal circuit model, the thermal circuit model of the split transformer top-oil temperature is proposed. Besides, model parameters are revised by non-linear heat resistance, load ratio and oil viscosity. Then, on the premise of not affecting the calculation results, the model is further simplified and the five model parameters to be optimized are extracted. Further, PSOGSA hybrid optimization algorithm is used to optimize the model parameters. The model proposed in this paper is verified by on-site temperature-rise experiment data. The results show that the proposed method can effectively improve the calculation accuracy of the thermal circuit model of the top-oil temperature. The proposed method provides a feasible solution for the calculation of the top-oil temperature and the hot spot temperature of the split transformer, which will help to improve the operational reliability of split-type transformers.

## Reference

- [1] Ye Jun, Hu Wangrong, Xu Ping. Arrangement and Application of Split Transformer in 110 kV and 35 kV Substation[J]. Electrical World, 2007, 48(7):14-15.
- [2] Yang Zhengyan. Improvement the Operation Condition of 35kV Substation with Split Transformer. Shanghai Electric Power, 2001, 5:55-56.
- [3] Shao Zhiwei. Investigation on Loss and Heat Dissipation Characteristics for Power Transformer Systems[J]. Electric Power, 2016, 49(6):132-136.
- [4] Fu Chenzhao, Ji Shengchang, Wang Shishan, et al. 2D Numerical Calculation of Temperature Field of Winding in Transformer[J]. High Voltage Engineering, 2002, 28(5):10-12.
- [5] Pan Chong. Study on insulation fault diagnosis and thermal state parameters prediction model of power transformers[D]. Chongqing University, 2009.
- [6] Zhao Yinhan. Application of Optical Fiber Temperature Measurement Technology to Transformer[J]. Electric Power, 1990(11):48-49.
- [7] GB/T 15164-1994 loading guide for oil-immersed power transformers[S], d94.
- [8] Huang Xiaofeng, Zhou Lijun, Wu Guangning. Comparative Analysis on Classical Thermal Models for Calculating Transformer Hot-spot Temperature and Its Improvement[J]. Modern Electric Power, 2013, 30(2):69-73.
- [9] Su Xiaoping. Investigation into the calculation model and prediction method of hot-spot temperature for oil-immersed transformers[D]. Chongqing University, 2012.
- [10] Jiang Taosha, Li Jian, Chen Weigen, Sun Caixin. Thermal model for hot spot temperature calculation in oil-immersed transformers[J]. High Voltage Engineering, 2009, 35(7): 1635-1640.
- [11] Tang Yan, Liu Chengyuan, Hao Zhongyan, et al. Calculation and test of hot—point temperature-rise in transformer windings[J]. Transformer, 2001, 38(2): 1-5.
- [12] Xiong Hao, Chen Weigen, Du Lin, Sun Caixin, Liao Ruijin. Study on prediction of top-oil temperature for power transformer based on T-S model[J]. Proceedings of the CSEE, 2007, 27(30): 15-19(in Chinese).
- [13] Wang Yongqiang, Yue Guoliang, He Jie, Liu Hongliang, Bi Jiangang, Chen Sufen. Study on prediction of top oil temperature for power transformer based on Kalman filter algorithm[J]. High Voltage Apparatus, 2014, 50(8):74-79+86.
- [14] Su Xiaoping, Chen Weigen, Xi Hongjuan. Winding Hot-spot Temperature Prediction for Oil-immersed Power Transformer Based on Kalman Filter Algorithm[J]. High Voltage Engineering, 2012, 38(8):1909-1916.
- [15] Wei Bengang, Huang Hua, Fu Chenzhao, Li Honglei, Liu Jiayu. Algorithm for transformer top-oil temperature and winding hot-point temperature based on modified thermal circuit model[J]. East China Electric Power, 2012, 40(3):444-447.
- [16] Wang Fenghua, Zhou Xiang, Gao Pei, et al. Improved Thermal Circuit Model of Hot Spot Temperature in Oil-immersed Transformers Based on Heat Distribution of Winding[J]. High Voltage Engineering, 2015, 41(3):895-901.
- [17] Ma Li, Liu Litao. Analysis and Improvement of Gravitational Search Algorithm[J]. Microelectronics & Computer, 2015(9):76-80.
- [18] Mirjalili S, Hashim S Z M. A new hybrid PSOGSA algorithm for function optimization[C]// International Conference on Computer and Information Application. IEEE, 2012:374-377.