Acta Technica 62 (2017), No. 5B, 579–590

Study on simulation cooling test for oil-immersed split cooling type transformers

Wei Bengang[1,5], Huang hua[1], Wang Liming[2], Yao Zhoufei[1], Zhu Qingmin[3], Dai Mingqiu[4]

Abstract. In order to investigate the heat dissipation efficiency of the of the split-cooling type transformers used in underground substation, the layout modes of the cooling systems were investigated. The typical split cooling system layouts of transformers were investigated and concluded Test methods of changing the horizontal distance between the transformer and the panel-type radiator and lifting the panel-type radiator vertically are designed to simulate the ONAN cooling type. An 80MVA/110kV oil-immersed transformer were tested and the temperature of top oil, high and low voltage windings, the oil inlet and outlet of panel-type radiator are measured and analyzed. It can be concluded that the ODWF, OF/OF/AN and ONAN cooling types were applied in actual application, and the cooling effects of them decrease progressively. In the horizontal layout, changing distance from 5.2m to 6.4UnitNamem6.4m between the transformer and the panel-type radiator had little influence on the cooling effects. However, lifting the panel-type radiator to 5.75m high could slow the oil flow in cooling system and thus reduce the cooling effect. In addition, conditions that the temperature rise of top oil were within limit while the temperature rise of windings were much higher would appear.

Key words. Transformers; placeCitySplit cooling type; Simulation; Temperature rise, Underground substation.

[1]Workshop 1 - Shanghai Municipal Electric Power Company Electric Power Research Institute, 200437 Shanghai, China

[2]Workshop 2 - Shanghai Municipal Electric Power Company Electric Power Research Institute, 200437 Shanghai, China; e-mail: dsy_wanglm@163.com

[3]Workshop 3 - Wujiang Transformer Co., LTD., 215200 Suzhou, China; e-mail: 18962599997@163.com

[4]Workshop 4 - Shanghai Jiaotong University, 200030 Shanghai, China; e-mail: daimingqiu@163.com

[5]Corresponding author: Wei Bengang; e-mail: wbgsj@126.com

1. Introduction

Large cities have been densely covered with population, high-rise buildings and high power load, while the land resources of the urban load center are scarce, the construction of high-voltage high-capacity substation under the ground has became a solution to meet the city's growing demand for power load[1-5]. Underground substation has the characteristics of a large capacity of transformer, compact equipment distribution in station, reliability of equipment operation, and the high noise control requirements. Using the one-piece cooling method requires the transformer room to set a larger inlet and outlet area and take strong exhaust measures to improve heat dissipation, which increases the difficulty of site design and noise control[6,7]In order to meet the cooling needs of power equipment, and adapt to space constraints and noise control, the transformers in underground and indoor substation often separately arranged the transformer body and radiator with split cooling method. The cooling performance of transformer cooling device is related to the reliable operation and life of the transformer the transformer temperature rise test results must comply with the provisions of GB1094.2 [8]. At present, the research on transformer split cooling system is mainly focused on the field installation, operation performance and economic benefits of the cooling device [1,6,9-11] . Study of the application on the numerical calculation method of the transformer internal temperature distribution which is used for the integral-cooling transformers on analyzing the cooling effect of split -cooling transformers need to be further[12-18]. The temperature rise test is still the most direct method to analyze the cooling effect of the split-cooling transformer. For large-capacity oil-immersed split cooling type transformer, due to the different circumstances between factory test and the actual operation, it is difficult to fully arranged in accordance with the operation of the test and the equivalent of test is difficult to control, the current large-capacity transformer split cooling device test lack the effective test method. In order to ensure the reasonable selection of the transformer cooling system and the safe operation of the later stage, it is necessary to do some research on the effectiveness of the miniaturization simulation experiment according to the actual transformer split cooling system structure, which is provided for the transformer temperature rise test and the cooling system selection.

This paper investigates the operation of the split cooling device in placeCityShanghai underground substation, and summarizes the arrangement of the typical split cooling device. Based on the results and the conditions of field test, the test scheme of cooling effect of split cooling device under the ONAN cooling mode of the oil - immersed transformer in the actual substation is designed. A 800kVA / 110kV oil-immersed transformer was used as the test object. The arrangement of transformer body and the chip radiator were changed in the test: The heat dissipation center was the same as the height of the transformer center; the horizontal distance was different; the height of the heat dissipation center and transformer center was different. The temperature of the top of the transformer, the temperature rise of the radiator inlet, the temperature of the outlet of the radiator, the temperature rise of the high voltage winding and the temperature of the radiator were measured under the different test conditions. The influence of the radiator arrangement on the temperature rise of the transformer under the test conditions is analyzed, and the simulation test method of the cooling effect of the split cooling device is studied. The test results have an important reference for the layout of the split cooling device in the actual construction and the factory temperature rise test.

2. Arrangement of Transformer placeCitySplit Cooling System

2.1. placeCitySplit Cooling Arrangement in Underground Substation

In the oil-immersed transformer, the internal heat of the transformer body is transmitted to the body and the radiator surface through the internal cooling medium by conduction and convection, and is further dissipated by the radiator through the external cooling medium. The heat transfer mode is related to the cooling mode of the radiator. According to the internal oil circulation of the transformer, the oil-immersed transformer can be divided into natural circulation type, forced circulation type and strong oil-oriented type. According to the external radiator cooling method can be divided into natural air-cooled, forced air cooling and forced water cooling. Transformer cooling system design integrated transformer capacity, voltage level, substation site conditions and other factors to take different internal cooling and external cooling combination.

This paper investigates the operation of the main transformer substation cooling system in the typical underground substation of placeCityShanghai, which is responsible for the design of the split cooling system. The layout of the transformer cooling system and the split cooling device in the practical application is shown in Table 1.

Table 1. Split Cooling System for Typical Substation in placeCityShanghai

cooling method	Substation	Cooling system device
	220kV Square Substation	
	220kV Jimo Substation	
ONAN	220kV Wanping Substation	Chip radiator
	220kV Tilanqiao Substation	
	220kV placePlaceNameDadu PlaceTypeRiver Substation	

In the three cooling methods, ODWF has the highest cooling efficiency. The cooling system includes oil to-water heat exchanger, closed cooling towers, circulating water pumps and water sprinkler systems and fire control, protection systems, etc., These structure are complex, construction and failure Maintenance costs are high; cooling towers and circulating pumps cause greater noise. The cooling efficiency, construction costs and system complexity of OF / OF / AN cooling method is moderate, but need to be equipped with more circulating pump (including transformer oil circulation and cooling oil circulation), and the circulating pump are located in the transformer room, when the load is high and the circulating pump is fully operational, a large noise level is generated. ONAN cooling method is easy to arrange, low construction costs, but the cooling effect is relatively weak; due to the higher pressure, there have the risk of fire caused by transformer tank oil leakage.

The actual layout of the Wanping substation with ONAN cooling is the transformer interior of the transformer body located at 11.95 meters underground (2 floors underground). The radiator is arranged the height of chmetcnvTCSC0 SourceValue1.5UnitNamem1.5m above the ground. The transformer and the radiator are connected directly through the tubing. The cooling system utilizes the thermodynamic power generated caused by the different temperature between the upper and lower oils for natural circulation cooling.

3. Transformer split cooling simulation test

3.1. split cooling system layout

The influence of different factors on the heat dissipation effect of the ONAN cooling mode of the oil-immersed transformer is simulated. Therefore, the transformer body and the chip radiator are designed to be splitat different distances on the same horizontal plane and the radiator center of the chip radiator is raised by a certain height, Horizontal arrangement and vertical arrangement are shown below.

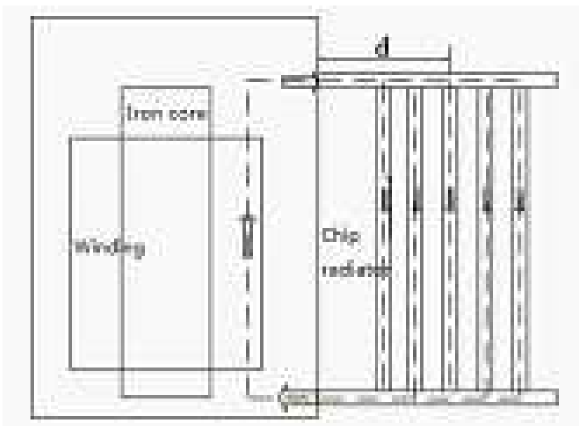

Fig. 1. Schematic diagram of the horizontal arrangement

Use stent to raise the bottom of the chip radiator 5.75m from the ground in vertical arrangement, the field test layout is shown in Figure 3.

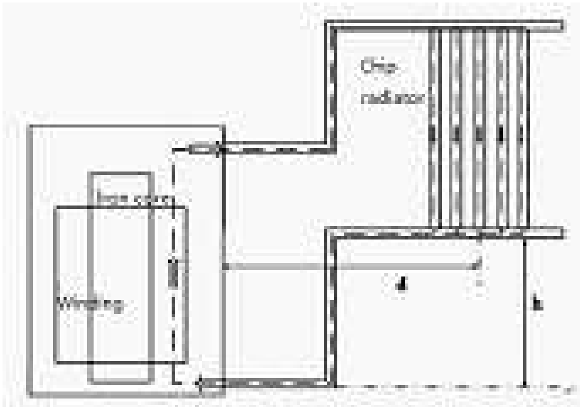

Fig. 2. Schematic diagram of vertical arrangement

Fig. 3. Live vertical layout

3.2. Test device

Three-phase 80MVA/110kV oil-immersed split cooling transformer is used in this test. The transformer is equipped with 22 groups of gilled radiator, specification of each group of gilled radiator is PC2000-31/520 , while center distance is 2000mm, slice width is 520mm and slices is 31mm. The transformer body oil outlet, which is connected with the gilled radiator oil inlet, is located in the top of the transformer, as shown in Figure 3(b). The transformer body return port, which is connected with the gilled radiator oil outlet, is located in the lower side of the body, as the diagonal distribution with the body oil output, as shown in Figure 3(a).

Temperature measuring devices include the use of patch-J-type thermocouple temperature sensor and infrared thermal imager. Connect the temperature sensor at one end of the thermocouple to the specified position on the wall of the transformer body housing, the sensor is showed in next figure. The whole temperature distribution of the transformer body and the radiator is observed by the FLIR infrared temperature imager, and it is used as a reference for the thermocouple temperature measurement data. The ambient temperature measuring point is arranged at 4 places and is located at 1/2 of the height of the transformer and 2 meters away from the surface of the tank and the measurement in the liquid is used to avoid direct heat radiation effect on the ambient temperature. At the same time, in order to avoid the impact of air flow on the temperature measurement data, the thermocouple temperature sensor placed in the liquid, as shown in Figure 4.

Fig. 4. Thermocouple measuring ambient temperature

In the horizontal arrangement mode, the distance between the heat dissipation center of the transformer body and the chip radiator is changed, respectively 5.2m, 5.8m, and 6.4UnitNamem6.4m, and start the transformer temperature rise test; Raise the chip radiator in the vertical direction to a height of 5.75 m from the ground and perform the same temperature rise test. In the test, the load level of the transformer and the configuration of the heat sink are kept unchanged. Each test measures the top of the transformer oil temperature, the radiator inlet oil temperature, the radiator outlet oil temperature, the high pressure winding temperature, and the temperature of the radiator.

Test process in accordance with GB1094.2 short circuit method of the transformer temperature rise test implementation [5]. First applying the total loss of the transformer, when the top layer temperature change is less than 1K and maintained for 3 hours, that the temperature reached a stable, down the load to rated current, and lasted for 1 hours. The difference between the temperature of each part and the ambient temperature at the end of the total loss is defined as the temperature rise of the transformer. Measure the winding temperature using the resistance method, the first valid data measured within 2 min after the power supply is cut off, and measuring the thermal resistance value every half minute. The measurement time lasts for 20 min. The temperature of the instantaneous winding is calculated by extrapolation method, as shown in formula (1), and the average temperature rise of the winding$\theta\omega$ is calculated according to the formula (2)

$$\theta_2 = \frac{R_2}{R_1} 235 + \theta_1 - 235 \tag{1}$$

$$\theta_\omega = \theta_2 + \Delta\theta_{ofm} - \theta_a \tag{2}$$

R1, R2 is the resistance value in stability of the winding temperature and power supply instantaneous; θ2 is the winding average temperature at the moment of the power supply turn off. θofm is the reduced value of the liquid average temperature at the stage of applying a rated current. θa is the temperature of the external cooling medium at the end of the total loss.

4. Test results

The layout of different distance under the horizontal and vertical arrangement have the same trend in transformer top oil temperature and inlet and outlet oil temperature of the chip radiator. when the distance between transformer body and cooling center are 6.4m and heat center vertical lifting 5.75m, the temperature rise curve as shown below

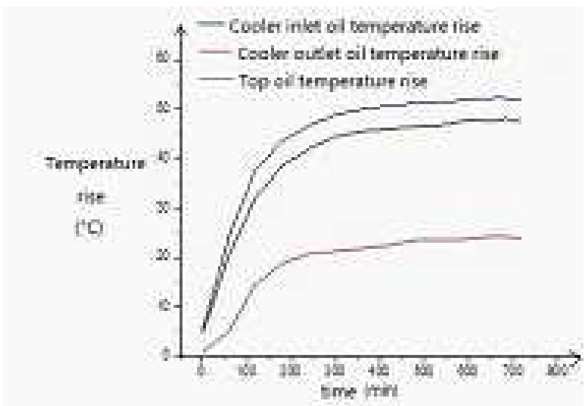

Fig. 5. Temperature rise curve when horizontal arrangement (distance 6.4m)

According to the standard, when the temperature reaches a stable condition, it can be seen from Fig. 5 and Fig. 6 that the stable temperature rise time is about 540min for the horizontal and vertical arrangement. When the arrangement is different, the temperature rise and the average temperature rise of the windings

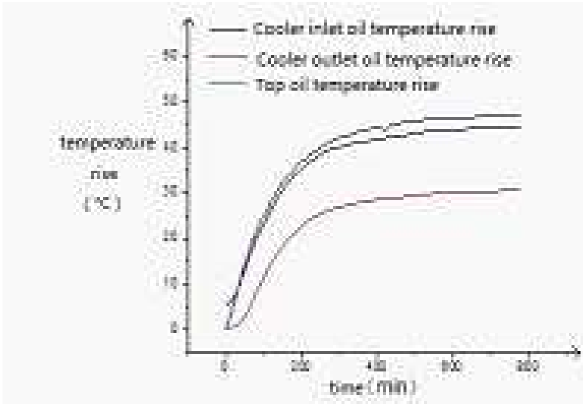

Fig. 6. The temperature rise curve when vertical arrangement (height 5.75m)

are shown in Table 2.

Table 2. Steady temperature rise and winding average temperature rise in different arrangement

Arrangement	**Top temperature rise**	**Chip of the inlet temperature rise**	**Chip of the outlet temperature rise**	**High voltage winding temperature rise**	**Low voltage winding temperature rise**
Type1	52.3	47.7	24.3	63.4	63.9
Type2	49.5	45.7	24.0	60.6	60.8
Type	46.7	40.9	20.7	58.9	57.8
vertical	46.6	44.0	30.3	64.5	65.6

5. The analysis of test results

5.1. Analysis of heat dissipation process

The transformer top oil temperature rise and winding temperature rise are related to the performance and life of the transformer insulation material and also reflect the working state of the transformer. [12-14] Radiator inlet and outlet oil temperature difference reflects the heat dissipation heat of the radiator and can predict the oil flow rate in the heat sink. In the case of the same amount of oil content, the greater the heat dissipation of the chip heat sink, the greater the oil flow rate. [19]

Before the start of the temperature rise test, the oil circulation path between the transformer and the radiator is in a quiescent state. After the total loss is applied, the transformer windings and the core are heated and the heat is transferred to the surrounding transformer oil by convection and cause the oil temperature rises. Transformer oil density decreased with the increase of temperature, the temperature distribution caused oil flow driving force (buoyancy), so the hot oil flows up to the top of the transformer body and enters the chip radiator through the connecting pipe. The transformer oil density at a certain temperature is calculated by the formula (3), [9] and the pressure difference of the oil flow along the pipeline can be calculated by the formula (4). [17]

$$\rho_{\vartheta}=\rho_0/(1+\beta_0\theta) \approx \rho_0(1-\beta_0\theta) \tag{3}$$

$$\Delta F = \Delta P \cdot S \tag{4}$$

S represents the internal cross-sectional area of the oil flow conduit.

With the increase of oil temperature in the transformer body, the oil temperature gradient increases, the oil flow driving force increases, the oil flow rate increases gradually, the radiator efficiency gradually increases, resulting in the oil temperature rising speed slows down. When the steady temperature rise is gradually reached, the transformer loss power is balanced with the heat dissipation power of the cooling system. The buoyant force generated by the temperature difference along the oil flow pipe is balanced with the resistance of the pipe wall to the oil. The oil flow rate in the oil circulation system is stable. In horizontal and vertical arrangement, the temperature rise test of the chip radiator inlet and outlet oil temperature difference changes as shown below, reflecting the chip radiator cooling power gradually increased to stabilize in test process.

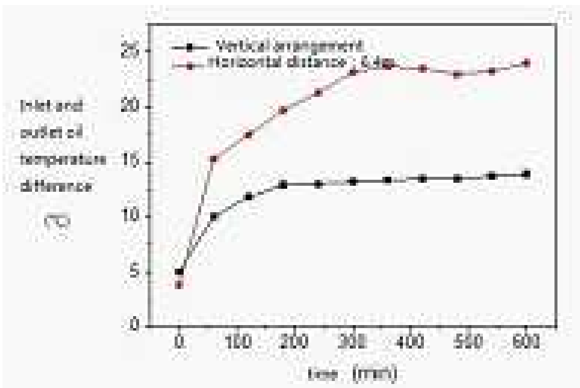

Fig. 7. Radiator inlet and outlet oil temperature difference time curve

5.2. *Analysis of stable temperature rise*

In contrast to the horizontal arrangement, the following figure shows the steady temperature rise in each part of the transformer and the average temperature rise of the winding with the horizontal distance between the transformer body and the cooling center, and the temperature rise after the vertical arrangement also showed in this figure.

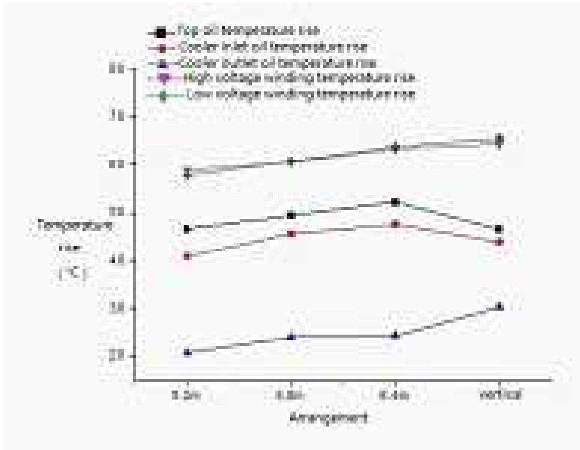

Fig. 8. stable temperature rise at different points in different arrangement

According to the figure 8, the winding temperature is higher than the top oil temperature under different arrangement modes. With the horizontal distance of the transformer body and the cooling center increases, the stable temperature rise in the top of the transformer and cooler inlet and outlet of the oil, and high pressure and low pressure winding temperature rise is slightly increased, while the temperature difference between the inlet and the outlet of the cooler is also increased, and the temperature change rate is less than 6%. . Considering the influence of the ambient temperature and the measurement error, it can draw a conclusion that change the horizontal distance between the transformer body and the heat dissipation center has little effect on the cooling effect.

In the vertical arrangement, there are no difference with horizontal arrangement between the temperature rise in the top of transformer and inlet and outlet of radiator, but the temperature rise of the high and low voltage winding is obviously higher than horizontal arrangement, and the temperature difference between the inlet and outlet of radiator is obviously smaller than horizontal arrangement. It is shown that when the transformer heating power is constant, the heat sink of the radiator is raised chmetcnvTCSC0NumberType1Negative5.75UnitNamem5.75m, which reduces the oil circulation speed and reduces the heat dissipation of the radiator; while due to the decrease of the oil flow rate, the heat transfer between windings of transformer body and the transformer oil around is weakened, then the temperature rise of the top oil and inlet-outlet oil of radiator increase a little but the windings temperature is obviously larger in compare of the horizontal arrangement

6. Conclusion

This paper summarizes the typical installation of typical split cooling device layout in the underground substation, and designs experimental scheme for cooling effect of split cooling device in oil-immersed transformer combined with the research results. And then carried out the test of changing horizontal distance between the transformer body and the center of radiator at the situation of horizontal arrangement, and the temperature rise test at the arrangement of lifting the radiator chmetcnvTCSC0NumberType1NegativeFalseHasSpaceFalseSourceValue5.75UnitNamem5.75m in vertical distance. In this paper, the difference of heat dissipation effect under different experimental schemes and the influence factors of the radiator arrangement on the temperature rise of the transformer are analyzed. The following conclusions are obtained:

(1) Three cooling methods of ODWF??OF/OF/AN and ONAN occurred in practical applications. ODWF has the highest cooling efficiency but the system complex construction and maintenance costs are higher. OF/OF/AN has the moderate cooling efficiency and system complex construction and maintenance costs, but the circulation pump noise when operation is much louder; ONAN has easier layout ??lower construction costs and relatively lower cooling effect, but the transformer body needs to withstand high oil pressure.

(2) At the horizontal arrangement, when the horizontal distance between the transformer body and the center of the radiator is in the range of chmetcnvTCSC0,the effect of horizontal distance on the cooling effect of the radiator is much smaller.

(3) At the vertical arrangement, it will reduce the oil circulation speed between transformer and radiator and the cooling efficiency of radiator. At the same time, the heat transfer between the transformer windings and the transformer oil is slow down, resulting in the situation which the temperature rise of the oil layer is in accordance with the temperature rise standard but the temperature rise of the windings may have exceeded the standard, thus bringing great security risks. In view of the vertical arrangement of the separate cooling method, most of the existing theoretical means of calculation didn't make the appropriate amendments, which is the next step in the research program.

References

[1] J. S. Tomar, D. C. Gupta, N. C. Jain: *Operation Analysis of Transformer Cooling Mode in Shanghai Underground Substation.* Operation Analysis of Transformer Cooling Mode in Shanghai Underground Substation *51* (2014), No. 11, 211–220.

[2] J. S. Tomar, A. K. Gupta: *Application of gas insulated transformers to underground substations in Japan.* Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES. IEEE *98* (1985), No. 2, 257–262.

[3] R. H. Gutierrez, P. A. A. Laura: *Discussion on heat dissipation of transformer in underground substation.* Forum on Electrical safety of Jiangsu Institute of Electrical Engineering *18* (1985), No. 3, 171–180.

[4] R. P. Singh, S. K. Jain: *Analysis of the cooling system for underground transformers.* Telecom Power Technology *7* (2004), No. 1, 41–52.

[5] M. N. Gaikwad, K. C. Deshmukh: *Review and prospect of underground substations design in Shanghai.* East China Electric Power *29* (2005), No. 9, 797–804.

[6] S. Chakraverty, R. Jindal, V. K. Agarwal: *Contrast application of transformer's hanging and split radiator.* Electric Engineering *12* (2005) 521–528.

[7] N. L. Khobragade, K. C. Deshmukh: *Development analysis of split type energy-*

saving low noise power station. Movable Power Station and Vehicle *30* (2005), No. 4, 555–563.

[8] Y. F. Zhou, Z. M. Wang: *Power Transformers Part 2: Temperature rise for liquid immersed transformers.* Beijing: Standards Press of China *316* (2008), Nos. 1–5, 198–210.

[9] R. Lal: *A Method of Temperature Rise Calculation for Discrete Type ONAN Transformer.* Transformer *34* (2003), No. 4, 587–606.

[10] R. Lal, Y. Kumar: *Location of the oil pump in the oil forced separated cooling.* Mechanics of Advanced Materials and Structure *20*, (2013), No. 4, 264–275.

[11] Y. Kumar: *Application Analysis of transformer and radiator distributed up and down.* Technology Innovation and Application *18* (2013), No. 2, 589–597.

[12] J. R. Kuttler, V. G. Sigillito: *Calculation and test of hot -point temperature -rise in transformer windings.* Transformer *78* (1981), No. 4, 585–590.

[13] K. M. Liew, K. Y. Lam: *Analysis of Calculation Theory for Transformer Temperature Rise.* Transformer *27* (1991), No. 2, 189–203.

[14] K. M. Liew: *Influence factor analysis and improvement of the thermal model for predicting transformer top oil temperature.* High Voltage Engineering *29* (1992), No. 24, 3087–3097.

[15] K. M. Liew, C. W. Lim: *Transformer winding hot-spot temperature prediction model of support vector machine optimized by genetic algorithm.* Transactions of China Electrotechnical Society *114* (1994), Nos. 3–4, 233–247.

[16] M. S. Qatu, N. A. Jaber, A. W. Leissa: *An Improved Dynamic Thermal Circuit Model of Oil- Immersed Power Transformer.* Power System Technology *167* (1993), No. 1, 183–191.

[17] A. K. Gupta, P. Sharma: *Three-dimensional thermal simulation of separated cooling transformers based on finite volume method.* Shanghai Electric Power *1* (2010), No. 5, 357–365.

[18] A. K. Gupta, P. Sharma: *Improvement and Discussion on the box edge structure of separated-type concentrated cooling transformer.* Shandong Industrial Technology *7* (2011), No. 20, 1–17.

[19] A. K. Gupta, P. Sharma: *Thermal analysis on frequencies of non-homogeneous trapezoidal plate of variable thickness and density.* Acta technica CSAV *58* (2013), No. 2, 189–205.

Received November 16, 2017