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Evaluation of Structural Integrity and Cooling Performance of 4250 kVA Power Transformer with ONAN Mode

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ONAN 모드 4250kVA 변압기의 구조 건전성과 냉각 성능의 평가

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ABSTRACT

The main research content of this paper is to evaluate the structural integrity and the cooling performance of 4250 kVA power transformer with ONAN(Oil Natural and Air Natural) mode. The dynamic analysis is used to verify the structural safety of the transformer by seismic loading. The transformer structure is simplified and NX software is used to build a three-dimensional model, and ANSYS commercial software is used to calculate the stress and deformation by applying corresponding load. The analysis result was evaluated whether it satisfies the design requirements according to the IEEE Std 693 standard. In terms of thermal analysis to evaluate the cooling performance, the thermal physical model is used to calculate the heat exchange between the radiator and the tank in the steady state, and the result is input into the Fluent software to calculate the internal temperature field of the transformer tank, which reduces the calculation cost of thermal fluid. Comparing the simulated hot spot temperature and top oil temperature of the transformer with the calculation results of the IEC60076 classic model, it is found that the error is only 1.9%.

Key Words: Power Transformer(변압기), Seismic Analysis(지진해석), Thermal Analysis(열해석), Hot Spot Temperature(과열점 온도), Top Oil Temperature(상부 오일 온도)

1. Introduction

Earthquakes are one of the significant environments for electrical equipment. In the past few decades, high-voltage electrical equipment was damaged by earthquakes, which forced the power supply to be interrupted. Among them, the transformer of the power system is one of the main equipment in the power transmission and transformation system. If the transformer is destroyed in an earthquake, the power supply will be interrupted, which will have a huge impact on the rescue and reconstruction work after the earthquake[1,2]. Therefore, it is imperative to carry out seismic analysis and calculation of large power transformers. Seismic analysis can not only be used as a reference for the safety assessment of

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transformers, but also can analyze the dynamic characteristics of the transformer during an earthquake, which is of profound significance to the optimization of the seismic design of transformers[3].

Common transformer types can be divided into dry-type transformers and oil-immersed transformers according to the cooling method. Among them, oil-immersed transformers are widely used due to their excellent heat dissipation, low loss, large capacity, simple structure and comparative economic advantages. Oil-immersed transformers can be subdivided into forced oil circulation and natural oil circulation according to the way of circulating oil flow inside the tank. Forced oil flow transformers will produce noise disturbing people and oil flow electric shock during operation[4], forced oil flow transformers are gradually replaced by natural oil flow transformers. One of the most important factors influencing the safe operation of the transformer is the thermal performance of the transformer, especially the thermal state when the transformer is working at full load or overload[5]. According to the aging law of transformer insulation materials[6], when the temperature of the transformer is between 80 and 140℃, the aging rate of the transformer insulation layer will double for every 6℃ increase. Therefore, a very important parameter to measure the life of a transformer is the hot spot temperature in the transformer.

On the basis of the classical physical model[6-8], Lujia Wang et al. established a dynamic oil flow model using dual logarithmic regression optimization based on the principle of heat transfer and energy conservation[9]. Min-gu Kim et al. evaluated the cooling performance of ONAN (Oil Natural and Air Natural) and OFAN (Oil Direct forced and Air Natural) oil-immersed transformer radiators with CFD simulation and experimental research, and proposed a radiator performance prediction model[10]. Ruohan Gong et al. used the FVM (Finite Volume Method) to study the temperature distribution of a 110kV three-phase three-leg transformer, and compared the simulation data with the temperature rise experimental data[11].

This article takes the seismic evaluation and thermal performance analysis of 4250 kVA ONAN transformer which is a middle range of three-winding oil-immersed transformer produced by IEN Hanchang Co., LTD. This paper first conducts the static analysis of the transformer during daily work, considering the working pressure load of the internal insulating oil to the tank, and then loads the response spectrum according to the IEEE693 standard, and conducts the dynamic analysis under the seismic load, and performs a safety check. In terms of thermal performance analysis, this paper establishes a simplified model combining physical model and numerical simulation to calculate the temperature distribution and oil flow inside the transformer. The simplified model of the radiator based on the principle of heat transfer, energy conservation and momentum conservation are utilized to solve the temperature and flow of the oil flow into the transformer under steady-state conditions. The hot spot temperature and the top oil temperature obtained by the simulation are compared with the calculation results of the classic IEC model.

2. Seismic Analysis

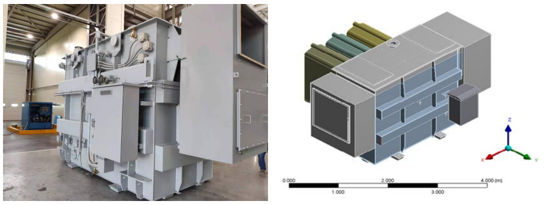
The structural integrity of the 4250 kVA transformer under seismic loads can be verified by the dynamic analysis according to IEEE Std.693-2018[2].

2.1 Finite element modeling

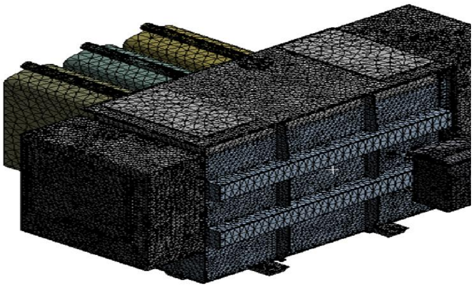
The design size of the transformer body is 4100 mm×3040 mm, the height is 2600 mm, the total weight of the transformer is 12530 kg, the weight of tank assembly with oil is 5667 kg, and the weight of core and coil assembly is 4980 kg. The

Table 1 Main parameters of transformer

Capacity	4250 kVA
Phase	3
Frequency	60Hz
Cooling Type	ONAN
Insulating Oil	Mineral Oil



(a) Assembled transformer (b) 3D model



(c) Finite element mesh shape

Fig. 1 Transformer modeling and mesh shape

main structural parts of the transformer include: core and coil assembly, radiator, HV bushing, LV bushing, foundation, panel and tank assembly. The main parameters of the transformer are shown in Table 1.

Fig. 1 shows an assembled transformer, modeling and FE mesh shape. NX software is used to build the three-dimensional model of the transformer structure. The ANSYS workbench software is used in the finite element analysis.

The load combination for ASD (Allowable Design Method) methodology according to the IEEE Std 693-2018, Annex D is as follows.

$$ASD = 1.0D + 1.0E_{RSS} + 1.0OP \qquad (1)$$

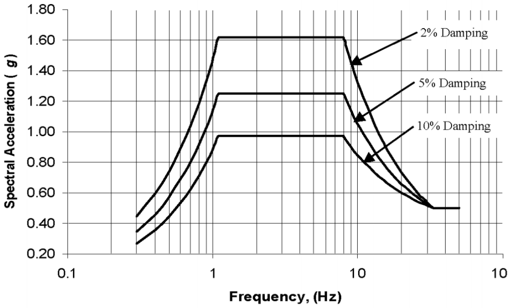


Fig. 2 High required response spectrum, 0.5g (acceleration of gravity)

where D is the dead load; E_{RRS} is the earthquake load demand from the design level spectra; OP is the normal operating load.

The earthquake load is defined as response spectrum shown in Fig. 2. The same response spectrum is applied in three directions to get the conservative results. The acceptable damping value is 2% damping in IEEE Std. 693-2005.

For response spectrum analysis, in which each of the three spatial components are calculated separately and the representative maximum response of interest of the structure can be satisfactorily obtained by taking the SRSS of the corresponding representative maximum response for each of the three components calculated separately per IEEE 693-2018.

The periodic modal responses and the periodic components of modal responses are combined using the double sum complete quadratic combination (CQC). The natural frequencies are included up to 25th mode. The sum of modal participating mass is lower than 90%. Thus, the missing mass technique is applied in analysis. Table 2 lists the natural frequencies and participating ratio of the structure, and its behavior is greatly affected by the participation quality ratio in a specific mode.

Fig. 3 shows the 8th modal shape with the largest mass participating ratio in the y-direction. The stress distributions of tank assembly, radiator and core assembly are shown in Fig. 4. Table 3 shows the results of each component of the transformer and the maximum stresses are compared with the allowable stresses. Allowable stress values are referred form ASME Boiler & Pressure Vessel, Sec. II Part D Materials Properties. The maximum stress of all components is lower than the allowable stress respectively. Based on this result, the safety of the transformer under earthquake conditions is evaluated.

Table 2 Frequency and modal participating ratio

No.	Frequency [Hz]	Modal participating ratio (%)		
		x	y	z
1	14.88	2.17	0.00	0.00
2	15.86	1.27	0.01	0.00
3	16.09	6.72	0.00	0.00
4	27.03	0.08	0.34	0.01
6	31.47	0.01	30.09	2.08
7	33.03	0.02	6.79	0.51
8	34.99	0.00	32.51	0.00
9	35.81	0.37	0.00	0.03
10	36.50	1.14	0.03	0.10
⋮	⋮	⋮	⋮	⋮
25	60.73	0.01	0.03	0.00
Sum of effective mass		14.55	80.82	10.77

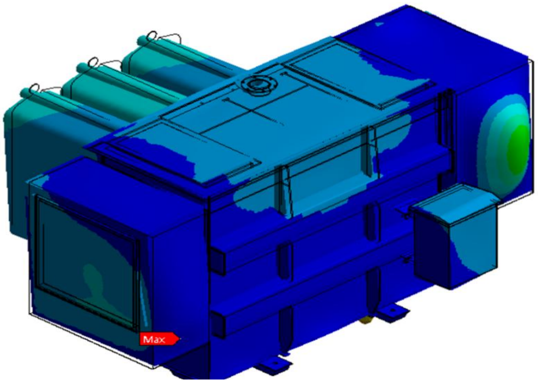
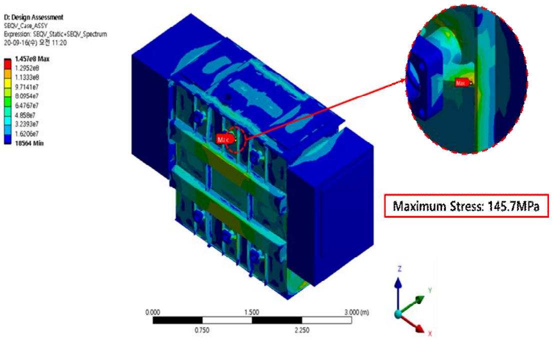
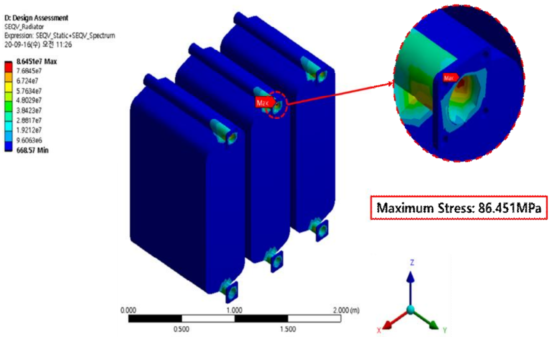


Fig. 3 8th mode shape (34.99Hz)



(a) Tank assembly



(b) Radiator

Fig. 4 Distribution of von Mises stress

Table 3 Maximum stress of each component

Part	Calculated stress [MPa]	Allowable stress [MPa]
Case Assembly	145.6	150
Radiator	85.72	150
HV bushing	5.1	40
LV bushing	15.63	40
Core and Coil	54.45	150
Foundation	109.2	150
Panel	36.38	150

3. Thermal analysis

The main driving force of the flow inside the natural oil circulation transformer is the thermal buoyancy lift of the oil. The schematic diagram of the natural oil flow transformer is shown in Fig. 5.

The heat exchange process in the transformer is complex. The heat transfer cycle includes the convective heat exchange between winding and oil, core and oil, and the external radiator and air. Therefore, the hot spot temperature of the transformer is mainly determined by the total loss and the oil flow rate[12].

3.1 Radiator reduced model

During the operation of the natural oil flow transformer, the core and coil generate heat and release it to the cold oil. The cold oil absorbs the heat and the temperature rises to produce a density difference, which leads to the generation of buoyancy and driving under the action of buoyancy lift, the core oil passage and the coil oil passage flow upwards to the top of the oil tank and merge into the radiator. After the radiator is cooled, the cold oil flows into the oil tank from the inlet at the bottom of the oil tank to form a circulation. In the steady state, the heat generated by the iron core and the coil is transferred to the oil flow in the form of convection, and the oil flow then dissipates this part of the heat to the outside in the form of heat conduction, convection and radiation through the fuel tank and radiator.

The equations for oil momentum balance, oil heat transfer, air momentum balance, air heat transfer, and heat transfer from oil to air are described in Eq. (2). [13] The winding material of the 4250 kVA natural oil circulation transformer studied in this paper is copper, and the iron core material is steel. The main parameters of the winding and iron core materials are shown in Table 4. The cooling medium is transformer oil, and its physical parameters are variables related to temperature, as shown in Table 5.

The air temperature around the transformer radiator is assumed to be 303K, and its related physical parameters are shown in Table 6.

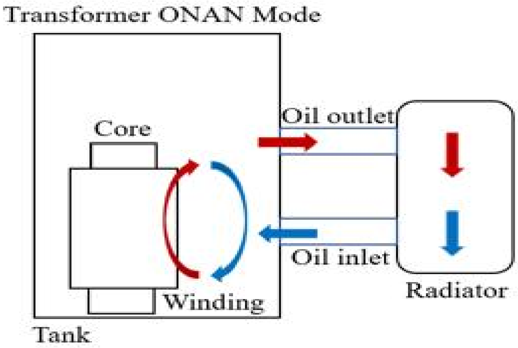


Fig. 5 Schematic diagram of oil flow

$$
\begin{aligned}
&R_{mom,oil}\left(T_{oil\ 1}, T_{oil\ 2}, Q_{oil}\right) = 0,\\
&R_{ener,oil}\left(T_{oil\ 1}, T_{oil\ 2}, Q_{oil}\right) = 0,\\
&R_{mom,air}\left(T_{air\ 2}, U_{air}\right) = 0,\\
&R_{ener,air}\left(T_{air\ 2}, U_{air}\right) = 0,\\
&R_{hex}\left(T_{oil\ 1}, T_{oil\ 2}, T_{air\ 2}, U_{air}, Q_{oil}\right) = 0.
\end{aligned}
\tag{2}
$$

Table 4 Transformer solid material parameters

Material	Density (kg/m^3)	Specific heat(J/kg·K)	Thermal conductivity(W/m·K)
Copper	8700	385	400
Steel	7650	460	42

Table 5 Fitting function of transformer oil properties

Property of oil	Fitting function
Density(kg/m^3)	1055.4-0.584T
Specific heat(J/kg·K)	807.163+3.58T
Thermal conductivity(W/m·K)	$0.1509-7.1\times10^{-5}T$
Viscosity(kg/m·s)	$0.08467-4\times10^{-4}T+5\times10^{-7}T^2$

Table 6 Air properties

Property of air	Value
Kinematic viscosity(m^2/s)	1.5610^{-5}
Density(kg/m^3)	1.17
Thermal conductivity(W/m·K)	3.310^{-3}
Specific heat(J/kg·K)	1005
Thermal coefficient(1/K)	0.03

Table 7 Calculated result by reduced model

Description	Value
Ambient temperature(K)	303
Inlet oil temperature(K)	325
Outlet oil temperature(K)	336
Oil flow rate(m^3/s)	5.0510^{-4}
Air inlet temperature(K)	303
Air outlet temperature(K)	315
Air mean velocity(m/s)	1.04

In geometry of radiator, the height, width and thickness are 1.5m, 0.52m and 1.25mm, respectively. The radiator has 26 panels, each panel has six oil channels, and the cross-sectional area of the oil channel is 0.3* $10^{-4}$$m^2$, the width between the panel and the panel is 0.03m, the distance between the middle level of the radiator and that of the winding is 0.6m. Solving Eq. (2) can obtain the relevant working parameters of the natural oil flow transformer, as shown in Table 7.

3.2 IEC transformer dynamic thermal model

In the classic thermal model IEC 60076-7 are provided to calculate the hot spot temperature and the top oil temperature, as shown in Eq. (3). In the IEC classic thermal model, the hot spot temperature is as follows.

$$\begin{aligned}&\theta_h(t)=\theta_a+\varDelta\theta_{Oi}+\left\{\varDelta\theta_{\mathrm{or}}\times\left[\frac{1+R\times K^2}{1+R}\right]^x-\varDelta\theta_O\right\}\times\\&f_1(t)+\varDelta\theta_{hi}+\left\{Hg_rK^y-\varDelta\theta_{hi}\right\}\times f_2(t)\\&f_1(t)=\left(1-e^{\frac{-t}{(k_{11}\times\tau_0)}}\right)\\&f_2(t)=k_{21}\times\left(1-e^{\frac{-t}{(k_{22}\times\tau_w)}}\right)-\\&(k_{21}-1)\times\left(1-e^{(-t)/(\tau_0/k_{22})}\right)\end{aligned}\qquad(3)$$

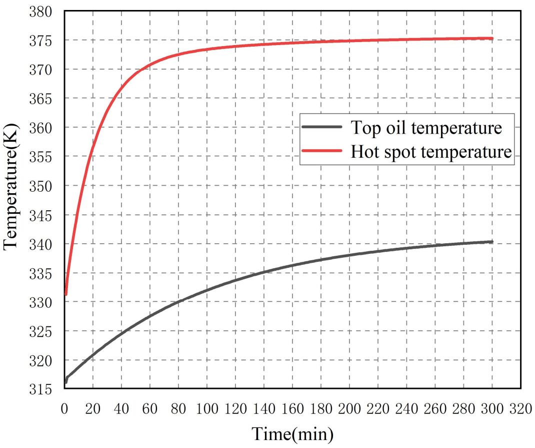


Fig. 6 IEC model top oil and hot spot temperature

where ambient temperature $\theta_a=303K$, top oil rise rated losses $\varDelta\theta_{\mathrm{or}}=38K$, ratio of load losses at rated current to no-load losses $R=1000$, hot-spot factor $H=1.0$, average winding to average oil (in tank) temperature gradient at rated current $g_r=14.5K$, top oil (in tank) temperature rises at start $\varDelta\theta_{oi}=13.5K$, load factor $K=1.4$.

In this set of calculation models, winding index and oil index are the main parameters. In the classic thermal model of IEC, the winding index is a parameter used to describe the non-linear relationship between the winding and the average oil temperature gradient and the winding loss, and the oil index is used to describe the relationship between the top oil rises with the ambient temperature and the load loss.

This article studies a large transformer in the form of 4250 kVA ONAN, the calculation result of the IEC model is shown in Fig. 6. After the transformer reaches a steady state, the top oil temperature is 340.3K and the hot spot temperature is 375.3K.

3.3 Fluid-thermal analysis

The numerical simulation method reduces the costs and time of experiments. Compared with the thermal formula calculation model, the numerical simulation method can describe the fluid dynamics and temperature distribution and heat transfer process inside the transformer tank in more detail. However, for large oil-immersed transformers, if the overall thermal simulation is required, calculation the cost is very large, and because of the many calculation boundary conditions of the model, the calculation accuracy will be reduced. Therefore, this paper constructs a simplified numerical model. The temperature and flow of the oil flow into the transformer under steady-state conditions solved by the simplified model of the radiator are invoked as the initial values for solving the CFD simulation model of the thermal field in the oil tank under steady-state conditions.

The steady-state CFD simulation solution model of the transformer oil tank is constructed to analyze the interior of the transformer. Oil flow conditions and hot spot temperature values and distribution, so as to avoid solving the conjugate heat transfer model of the entire transformer. The calculation process is shown in Fig. 7.

First, the following assumptions are made: (1) The transformer is a three-phase transformer, and the structural components that have little effect on the result are ignored, such as gaskets, leads and bushings. (2) The insulating cylinder is next to the winding, and its thickness is very thin to ignore it. The high and low voltage windings are simplified to a single cylinder structure with equal height. (3) The iron yoke and iron core are simplified as cylinders. (4) The radiator outside the oil tank is not considered. In order to study the oil flow and convection heat transfer process inside the transformer, the vertical oil passage between the windings is considered, and the non-slip condition is considered on the surface of the vertical oil passage.

In order to save the calculation cost, the horizontal oil passage inside the winding is ignored. The model built is shown in Fig. 8.

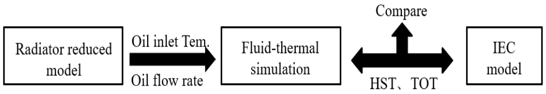


Fig. 7 Fluid-thermal calculation process

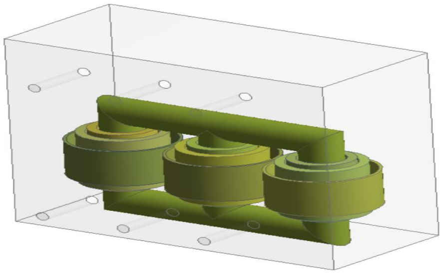


Fig. 8 CFD simulation calculation model

The total number of grids divided by the entire natural oil circulation transformer model is about 5.27 million. After verification of grid independence, the total number of grids can be a good balance between the calculation accuracy and the calculation time.

The natural oil circulation transformer structure model, the winding material is copper, the core material is silicon steel, the main parameters of the winding and iron core material are shown in Table 4. The cooling medium is transformer oil, and its physical parameters are variables related to temperature, as shown in Table 5. Regarding the heat source conditions, both the core and windings in the transformer will produce heat loss. Here, the internal heat source is used. The total heat loss is shown as Eq. (4) from the load experiment and the no-load experiment. [11]

$$P_{total} = P_{iron} \cdot U_r(\%)^2 + P_{copper} \cdot k^2 \qquad (4)$$

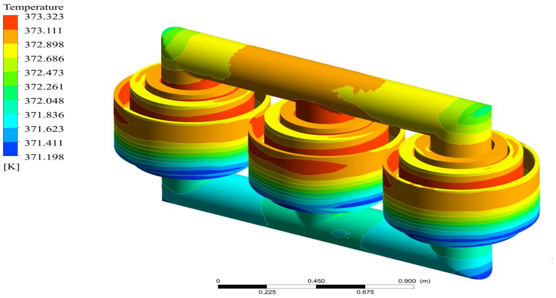
where the total losses of transformer; $U_r(\%)$is the voltage percentage; P_{iron} stands for no-load losses; P_{copper} represents the load losses; and k is the load factor which is set to be 1.0 in this experiment.

The convection inside the transformer adopts turbulence calculation and the k-omega SST model is selected[14,15]. The SST model considers the advantages of better combining k-epsilon and k-omega models. A hybrid function based on wall distance is used, the wall distance is used as a switch, the k-omega model is used in the near-wall area, and the k-epsilon model is used in the far-away area.

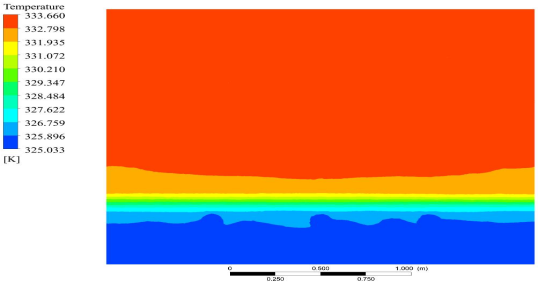
According to the assumption (5) when the model was established: The external radiator of the transformer is not considered, the result of the simplified radiator model in Chapter 3.1 is used as the initial value of the steady-state model, and the oil flow inlet oil velocity is set to 0.085m/s, The oil outlet is set so that the pressure outlet flows freely. The ambient temperature is assumed to be 303K.

The software Fluent is used to numerically simulate the steady-state temperature field of the natural oil circulation transformer. The distribution of the temperature field in the transformer is obtained, as shown in Fig. 9. It can be seen from Fig. 10 that the hot spot temperature (HST) of the transformer is 373.3K. The top oil temperature (TOT) in the tank is 333.7K. The oil flow velocity distribution inside the transformer is shown in Fig. 10. It can be seen that the maximum velocity in the oil tank is 0.10m/s, which appears inside the vertical oil channel between the MV windings and HV windings.

Table 8 compares the internal hot spot temperature and top oil temperature of the transformer calculated by the IEC60076 classic thermal model and the numerical simulation, and the error is found to be 1%. It is proved that the accuracy of the simplified calculation scheme proposed in this paper is reliable. Even though the model in this paper is relatively simple, it can still give researchers a clear understanding of the hot-spot temperature distribution and internal oil flow of the transformer

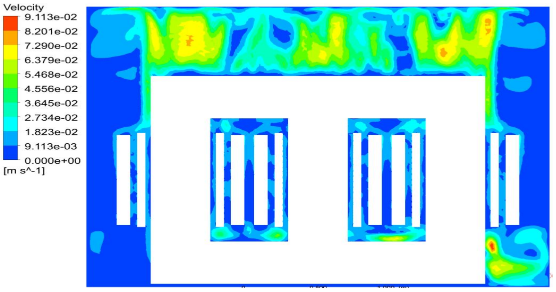


(a) Core and winding

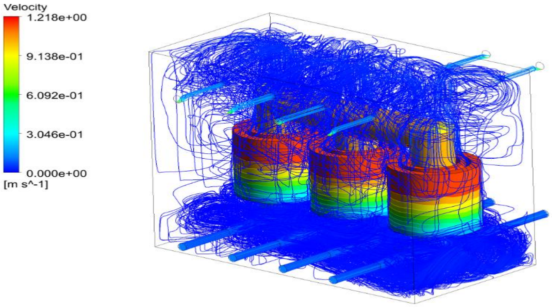


(b) Oil

Fig. 9 Temperature distribution



(a) Transformer inside



(b) Three-dimensional streamline

Fig. 10 Oil flow velocity distribution

Table 8 Comparison between IEC model and simulation results

Temperature	IEC(K)	Simulation(K)	Relative error(%)
HTS	375.3	373.3	0.53
TOT	340.3	333.7	1.9

4. Conclusion

4.1 Seismic analysis

In this paper, the dynamic analysis method is used to carry out seismic analysis and calculation of 4250 kVA power transformer. A three-dimensional simulation model of the transformer is established, and the overall stress distribution of the transformer is simulated. According to the requirements of IEEE Std 693-2018, the stress analysis of the key parts such as the top, bottom and base of the transformer is carried out. The analysis proves that the seismic performance of the transformer meets IEEE Std 693-2018 standard requirements.

4.2 Thermal analysis

In terms of transformer thermal physical model calculation and numerical simulation, this paper proposes to first calculate the working condition of the radiator using the thermal physical model to obtain the heat exchange between the transformer tank and the radiator, and secondly use the calculation result as the study of the internal temperature field of the transformer tank under steady state conditions. The input value of the situation greatly reduces the calculation cost of fluid mechanics. Finally, the hot spot temperature value of the simulation is compared with the calculation result of the IEC model, and the error is only 1.9%, which proves that the accuracy of the simplified calculation scheme proposed in this paper is reliable.

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