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Numerical investigation of mechanical and thermal dynamic properties of the industrial transformer

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Abstract

Industrial transformer is one of the most critical assets in the power and heavy industry. Failures of transformers can cause enormous losses. The poor joints of the electrical circuit on transformers can cause overheating and results in stress concentration on the structure which is the major cause of catastrophic failure. Few researches have been focused on the mechanical properties of industrial transformers under overheating thermal conditions. In this paper, both mechanical and thermal properties of industrial transformers are jointly investigated using Finite Element Analysis (FEA). Dynamic response analysis is conducted on a modified transformer FEA model, and the computational results are compared with experimental results from literature to validate this simulation model. Based on the FEA model, thermal stress is calculated under different temperature conditions. These analysis results can provide insights to the understanding of the failure of transformers due to overheating, therefore are significant to assess winding fault, especially to the manufacturing and maintenance of large transformers.

Keywords: Transformer, Thermal analysis, Dynamic response, FEA

1. Introduction

Industrial transformer failures can cause enormous loss of revenue due to unscheduled maintenance, and great threat to environment [1, 2]. Moreover, power interruptions impose penalty due to the inability to provide continuous supply of electricity. According to an international IEEE survey carried out by Cigré [3], typical failure rates in large industrial power transformers is in the range of 1-2% per year (working voltage up to 300 KV). The increase of load has contributed to the sharply growing of transformer hottest spot temperature (HST) that boosts from 50 ˚C in 1974 to around 73 ˚C today [4], which reduces the remnant useful life of insulation system when transformers are operated at the peak load [5]. Therefore, in depth study of both mechanical and electrical properties, so as to diagnose and prognose the health condition of the transformer is significant in power and heavy industry.

Various methods are used for transformer condition monitoring, such as dissolved gas analysis (DGA), frequency response analysis (FRA), vibration analysis [6-11]. Among these techniques, online vibration analysis is relatively new, which is one of the safest on-line condition monitoring strategies for large transformers. Different mechanical damages, e.g., the loosen transformer core segments and faulty bearings on oil cooling pumps can result in abnormal vibration characteristics. Therefore, although vibration analysis itself cannot predict many faults explicitly at its early stage, it is a promising technology for diagnostics and health prediction to industrial transformers [10].

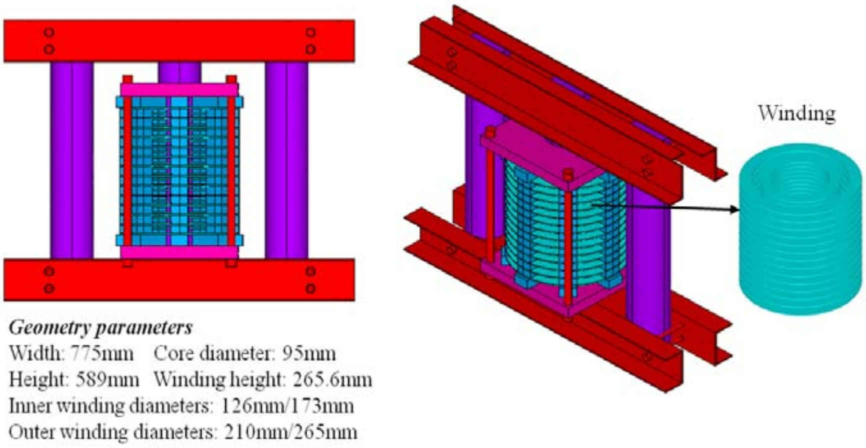
However, the vibration analysis is sensitive to the working conditions and noises associated with the structure, which can affect the boundary conditions in analysis and lead to considerable errors in the theoretical analysis. Due to the enormous cost of vibration experiments and aforementioned technical constraints, numerical modelling of transformer vibration is developed to evaluate the mechanical properties of the transformers [10, 12]. As a mature numerical method, Finite Element Analysis (FEA) is a powerful modelling method that can address the issue providing dynamic prediction of transformer under various fault conditions when adding work load and other noise factors. Wang, et al. [12] have developed a transformer FEA model based an experimental structure. The corresponding FEA model was employed to determine the mode shapes and natural frequencies.

In addition to the mechanical deformation of industrial transformers, the overheating fault of transformer is another challenge for the reliability of transformers. The overheating fault of transformer can result in higher thermal stress on the transformer structure, which would directly lead to the mechanical failure of the transformers. Therefore, the thermal stress modelling of transformer has been another focus of research for years in industry. Tang, et al. [13] has developed a simplified transformer FEA model to conduct analysis of transformers based on thermal-electric analogy to calculate the transient-state temperatures and the stationary-state equilibria in the main parts of transformer. Preis, et al. [14] has also set up a FEA model to solve the thermal-electromagnetic coupling problem in the of power transformer. Swift, et al. [15] presented an equivalent circuit to represent the thermal heat flow equations for power transformer. However, the current thermal stress analysis models are simplified to reduce the computational complexity. These simplifications may serve the purpose of the existing research well, they are not sufficient for the purpose of accurate asset health prediction. Therefore this paper presented a modified FEA model with detailed design, especially on the contacts between winding and other components. This modified model is based on the laboratory test transformer in [12].

The modified FEA model is developed here can describe the detailed structural information, especially the characterization of the discrete windings, which is commonly assumed to be continuous in previous study. Modal analysis is conducted considering both thermal and mechanical properties of the test transformer, and the results will be compared with the experiment results to validate the FEA model. After the validation, thermal analysis is conducted to extract the characteristics of stress distribution on the transformer, which is the most critical factor for the overheating failure of transformer components.

2. Model Development

According to the vibration experiment conducted by Wang et al [12], they developed the modal tests on a 10kVA, single phase 415/240V step-down disk-type transformer. The nominal current in the primary winding is 20A with 240 turns and the secondary is 35A with 140 turns. Based on the transformer structure in the tests [12], a FEA model is developed to analyse the dynamic and thermal response of this transformer, as shown in Figure 1. The basic geometry parameters of the model follow the transformer structure in the experiment from literature [12] and the details are also provided in Figure 1. Since failures are frequently found in winding when the industrial transformers are in operation, more detailed structures of the windings and insulation blocks are made to better reveal the thermal and mechanical behaviours of windings, which is more detailed than the FEA model in [12].



Geometry parameters
Width: 775mm Core diameter: 95mm
Height: 589mm Winding height: 265.6mm
Inner winding diameters: 126mm/173mm
Outer winding diameters: 210mm/265mm

Figure 1 Transformer FEA model based on experiment in [12]

Materials properties are important in the simulation of transformer mechanical behaviours according to continuum mechanics theory. The transformer structure adopted in this paper mainly includes windings, core, brace, insulation blocks and clamping plates. Typical material parameters including both mechanical and thermal constants are provided in Table 1, which are obtained from literature [12] and material database [16].

Table 1 Material parameters of the transformer

Part	Material	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's ratio	Conductivity (W/m·K)	Thermal expansion (μm/m·°C)
Winding	Copper	8900	115	0.35	398	18.5
Core	Silicon Steel	7650	195	0.25	25.3	10.1
Brace	Steel	7850	210	0.3	25.3	10.1
Insulation block	Phenolic	820	20.72	0.4	0.51	52
Clamping plate	PBT	900	7.69	0.48	0.17	100

The FEA model is used to predict the dynamics characteristics of transformers. The numerical characterization obtained from FEA simulation is compared with experimental results from literature [12] to validate the FEA model.

Thermal stress distributions on transformers are then evaluated using this FEA model to predict the performances of the transformer under different temperature conditions. In the uniform temperature analysis, the temperature is evenly distributed on all the structure surfaces, based on which the structural stress can be predicted. In the non-uniform temperature analysis, the heat conduction simulation is first developed to extract the temperature distribution on the structure. By employing the temperature distribution from the heat conduction analysis, the stress distribution for different components on the transformer structure is calculated correspondingly.

3. Results and discussion

3.1 Modal Analysis of Transformer

A dynamic response experiment has been conducted by Wang [12] as aforementioned, and the first three orders natural frequencies in testing are respectively 52.0Hz, 131.5 Hz and 240Hz. In this paper, the dynamic response of the transformer is also estimated by the FEA model that is developed in Section 2. The first three order simulated natural frequencies are respectively 56.5Hz, 137.5Hz and 192.8Hz, and the corresponding mode shapes are extracted, as shown in Figure 2. For the 1st and 2nd order natural frequencies, the FEA prediction is extremely close to the experimental results. However, for higher order natural frequencies (e.g. 3rd order in Figure 2), the simulation results are not as accurate as lower orders, which is consistent with common results in FEA simulation, especially for complex industry systems [17].

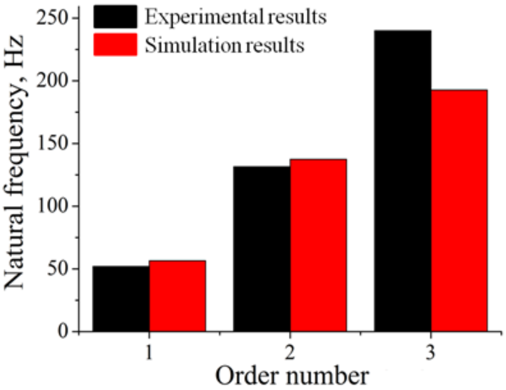
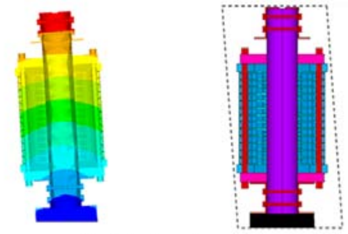
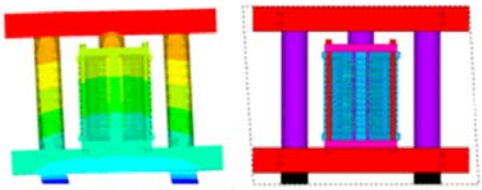


Figure 2 Comparison of the experimental and simulated natural frequency

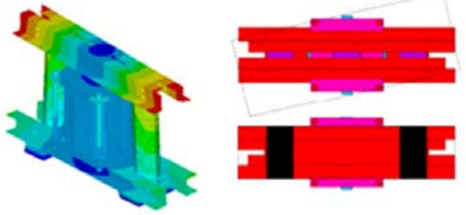
The mode shapes of the transformer are shown in Figure 3. The mode shape of the 1st order vibration is the out-of plane rotation of the global structure, and the 2nd order mode shape is the in-plane rotation of the transformer. For both of these two mode shapes, the windings move in-phase. This phenomenon might be caused by the location of the supports, as the in-plane support length is longer than that of out-of-plane direction, which results in the resonance frequencies for the in-plane vibration are higher due to the addition stiffness. For the 3rd order vibration mode shape, the core window distorts in opposite direction with the windings assembly. Since the model can accurately predict the first two orders of natural frequency, it is arguable that this model is capable of capturing the dynamic response of transformers. Therefore, this model will be further utilized to analyse the thermal stress on the transformer structure under different temperature conditions.



(a) Simulation result of 1st order mode shape at 56.5Hz



(b) Simulation result of 2nd order mode shape at 137.5Hz



(c)Simulation result of 3rd order mode shape at 192.8Hz

Figure 3 Simulated mode shapes of the first three orders

3.2 Thermal stress analysis of transformer using FEA

According to the operating conditions of transformers, the thermal stress analysis of transformers can be divided into two types: uniform temperature distribution and non-uniform temperature distribution. In the uniform temperature distribution analysis, heat conduction is not considered since all the parts are working under the same temperature condition. For instance, the main structures of oil-immersed transformers are working in the oil, and the temperature distribution is uniform on the surfaces of all the parts, which is the same as the oil due to heat transfer. However, in the case of gas filled dry-type transformers, the working parts are exposed to the gas, and the heat that is generated by these working parts (e.g. windings) cannot be completely released to the air only by heat convection, which results in the non-uniform distribution of the temperature on the transformer structure. In this paper, both uniform temperature and non-uniform temperature conditions are studied to understand the thermal stress distribution on the structure and analyse the overheating fault mechanism of transformers.

3.2.1 Uniform temperature analysis

The thermal stress and elastic strain of the transformer at different temperatures are simulated by using the FEA model that is introduced in section 2. As shown in Figure 4, the thermal stress on the transformer increases with temperature. The maximum thermal stress happens at the bolt part, which is used to fix the windings and clamping plates.

Winding is one of the most important functional components on industrial transformers. The failure of windings (e. g. insulation breakdown) is common in industrial transformers and can cause enormous economic loss. Therefore, we extracted the thermal stress distribution on windings specifically to illustrate the mechanisms of winding failures due to the overheating of transformers. For the windings, the thermal stress boosts with temperature. Stress concentration happens at the interfaces between insulation blocks and windings. This stress concentration is caused by the uncoordinated thermal deformation of the transformer components due to the contact constraints. This characteristic should be focused on for future design of optimized industrial transformer structures to reduce the potential damage caused by the overheating of transformers.

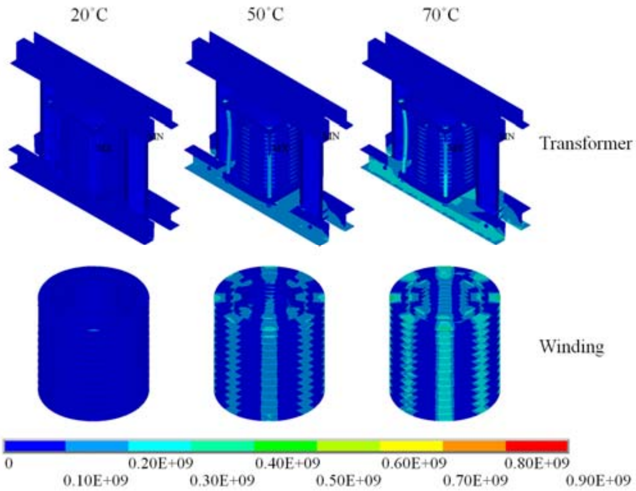


Figure 4 Thermal stress in the transformer during the temperature arising process

The elastic strain of the transformer is shown in Figure 5. For the entire transformer, the maximum value happens at the clamping plate, mainly because the thermal expansion of this part is relatively larger than other parts. For the windings, the thermal expansion at the insulation block/winding interface is larger comparing to the other contact free regions, which explains the stress concentration in these related regions. Therefore, future attentions should be paid to monitor the winding/insulation block contact areas, where structural damage due to overheating is more likely to propagate from.

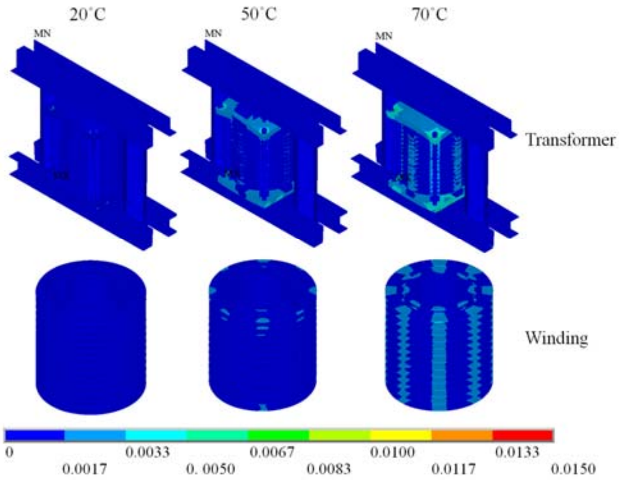


Figure 5 Elastic strain of the transformer during the temperature arising process

The relationship between thermal stress and the environment temperature based on FEA modeling is summarized in Figure 6. The thermal stress on the transformer increases linearly with the temperature, which is a result of the constant coefficients of the thermal expansion for all the transformer components, as provided in Eq (1). As mentioned in the literature [4], the sharp increase of loads has increased the HST of transformers, from 50 ˚C in 1974 to around 73 ˚C today. According to our FEA model, the maximum thermal stress at room temperature (20˚C) is 256 Mp, which increases to 639 MPa at 50 ˚C and 933MPa at 73 ˚C, as shown in Figure 6.

$$\alpha = \frac{1}{L} \cdot \frac{\Delta L}{\Delta T} \tag{1}$$

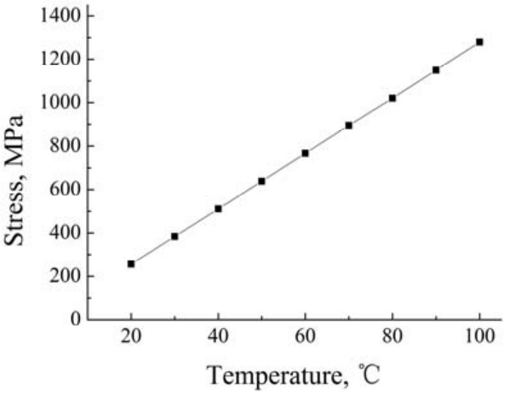


Figure 6 Relationship between thermal stress and temperature

According to the abovementioned data, the thermal stress and thermal elastic strain have increased 46.0% for uniform temperature condition transformers during the last 40 years. Therefore, the increase of industrial transformers temperature, which is detected by condition monitoring techniques, has significantly increased the risk of transformers as the thermal stress on the transformers dramatically increases. Correspondingly, the reliability of industrial transformers reduces and proper maintenance is therefore needed to extend the remnant useful life of transformers.

However, the constitutive relations of thermal expansion of all transformer parts are simplified as linear equations to reduce the complexity of modeling, which could reduce the accuracy of the FEA prediction. Future efforts on FEA modeling are needed to more accurately characterize the mechanical performances of transformers under different temperature conditions.

3.2.2 Non-uniform temperature analysis

For dry-type transformers which are filled with gas, the temperature is not uniformly distributed on the structure surfaces as introduced in the beginning of section 3. Therefore, heat conduction analysis is needed to provide detailed temperature distribution on transformers for the thermal stress analysis. In the heat conduction simulation, the surface of the braces which are exposed to air is set to be room temperature. However, as the heat can be generated on the windings, which is the working part of transformers, the temperature on windings is higher than the other parts. We designed a number of numerical scenarios whose winding temperature ranges from 20°C to 100 °C. The temperature and stress distribution on the transformers are extracted, and the corresponding maximum stress on windings are compared with the results from uniform temperature distribution.

The temperature distribution in the transformer under 30 °C, 50 °C and 70 °C are shown in Figure 7. It can be found that, besides windings and insulation blocks, the temperatures at the contact part of the clamping plate and bolts on the structure is higher comparing to the other parts, which is similar to uniform temperature scenarios. The temperatures of braces and cores are not as high as clamping plate and bolts because they are not directly connected to the windings that generate heat in working.

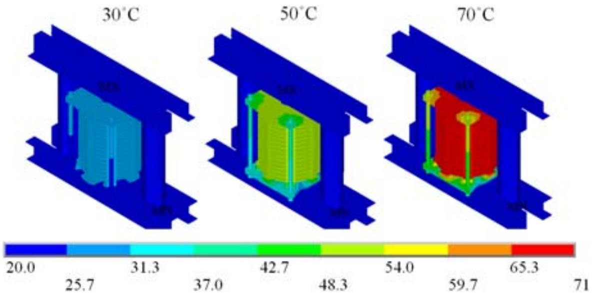


Figure 7 Temperature distribution on the transformer

The thermal stress distribution pattern under uniform temperature condition and non-uniform temperature conditions are similar, which is shown in Figure 8. The stress concentration always happens on the interfaces between windings and insulation blocks. However, the maximum stress value on windings dramatically increases (by approximately 30%) when the temperature distribution on the transformers is non-uniform, as shown in Figure 9.

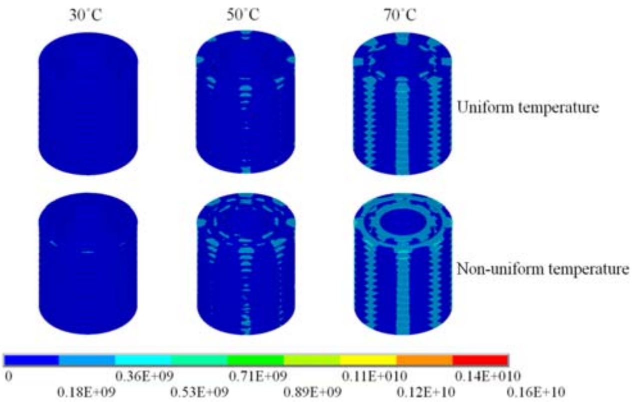


Figure 8 Thermal stress comparison under uniform and non-uniform temperature conditions

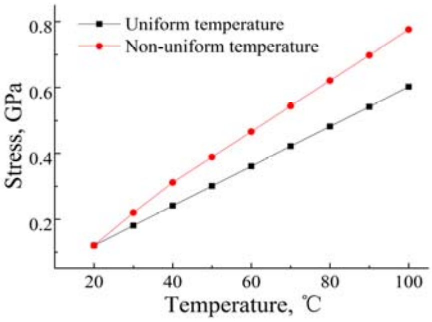


Figure 9 Relationship between thermal stress and temperature

From Figure 9, it can be found that the stress increases with respect to the temperature, for both of the uniform and non-uniform temperature distribution cases. However, for the non-uniform distribution case, the rate of stress increase is higher, indicating that temperature distribution is crucial to the absolute value of thermal stress on the structure. This stress increasing characteristic for non-uniform temperature distribution case is due to the uncoordinated thermal strain of different transformer parts, which result in higher failure probability of transformers.

4. Conclusion

In this paper, a detailed FEA model is developed to predict the dynamic response and thermal stress of a laboratory transformer. Compared with existing models in literature, this FEA model is purposely created to include specific structural details (e.g. idealized continuous winding block is replaced by a combination of discrete windings) due to their criticality to the failure of transformer. This design allows in depth study of both thermal and mechanical stress distribution on the transformer, especially on the windings, which can provide evidence to investigate the mechanism of failures caused by transformer overheating. Based on the numerical simulation results, the following conclusions can be made:

- The natural frequencies are predicted by using the specifically designed FEA model. The first three orders natural frequencies obtained from simulation are consistent with the experimental results from literature, which indicates that this FEA model is reliable in capturing the structural responses of transformer.
- The FEA model is then used to predict the thermal stress on transformers with both uniform and none-uniform temperature distributions. The behaviours of windings, which are considered as an integral part of the whole transformer, are focused on in this paper. The thermal stress on windings mainly concentrates at the interface between windings and insulation blocks. Non-uniform temperature distribution results in higher thermal stress on the transformer structure.

The above findings are valuable for optimizing the structural design of the transformer, especially for the parts where thermal stress concentration could happen. This design approach can assist to significantly improve the existing FEA simulation of transformer structures under both mechanical and thermal conditions. In addition, maintenance plan can be optimized by monitoring the specific susceptible parts to prevent potential failures due to transformer overheating.

The FEA model presented in this paper can foster future studies on more complex industrial transformers due to the build-in technical details. It provides a powerful platform for the mechanical and thermal analysis of industrial transformers and prediction of the performances of industrial transformers under various external or internal loadings. Further FEA study is needed to investigate the way in which real industrial transformers perform under multi-field coupling conditions, and to provide evidences for transformer diagnosis and prognosis.

Acknowledgments

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