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# Thermal management of a distribution transformer: An optimization study of the cooling system using CFD and response surface methodology

Leyla Raeisian[a], Hamid Niazmand[a,*], Ehsan Ebrahimnia-Bajestan[b], Peter Werle[c]

[a] Department of Mechanical Engineering, Faculty of Engineering, Ferdowsi University of Mashhad, Mashhad, Iran
[b] Department of Mechanical Engineering, Quchan University of Technology, Quchan, Iran
[c] Department of Electrical Power Systems, Schering-Institute, Leibniz University of Hannover, Hannover, Germany

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ABSTRACT

In this paper, a numerical scheme has been developed to examine the effective parameters on thermal management of distribution transformers and subsequently to optimize their cooling systems. In this regard, the response surface methodology (RSM) was used as the optimization method to minimize the hotspot temperature in the transformer as the response factor. A comprehensive three-dimensional computational scheme was employed considering the detailed geometrical specifications of an actual 200kVA distribution transformer to obtain the temperature field and the hotspot temperature. The accuracy of the numerical model was established via comparing the numerical results with the measured temperatures of a running transformer. The thermal variations of the thermo-physical properties of the transformer oil are determined experimentally and incorporated in the numerical modeling. A comprehensive parametric study among seven evidently effective parameters has been performed to identify the most effective parameters on the thermal performance of the transformer. It was found that fin height, length, and spacing are the more influential parameters among the examined parameters, which are also considered as the input variables in the optimization procedure. According to the RSM, the effects of the variations of these input variables in pre-specified ranges on the response, which is the hotspot temperature, are examined through the suggested runs by RSM. The results indicated that the hotspot temperature is more influenced by the fin height as compared to the fin length and spacing. Furthermore, the hotspot temperature decreases with the increase in fin height and length, while decreases as fin spacing increases. In addition, a correlation for the variations of the hotspot temperature as a function of the fin height ($H$), length ($L$), and spacing ($S$) is suggested using RSM. The significant finding is that the proposed optimum transformer configuration ($H = 0.9$ m, $L = 0.08$ m and $S = 0.036$ m) leads to the hotspot temperature reduction of about 16 °C as compared to the actual transformer geometry, which greatly affects the transformer life expectancy and safer performance.

## 1. Introduction

Electric transformers as an essential electric equipment perform a vital function in supplying the electric energy at required voltage levels to consumers. An under-loaded transformer not only meets an electrical process but also experiences a thermal activity that is impelled by heat generated due to the losses in core and windings. The generated heat is the major cause of transformer temperature rise and its aging [1] and should be removed by employing a suitable cooling system. Among the various parameters that affect the transformer performance, the location of the maximum temperature of the solid insulation named 'hotspot temperature' (HST) and its temperature level have been identified as the main reasons of the transformer aging and failures [2]. In the hotspot location the depolymerization process of cellulose insulation gradually occurs, which degrades the mechanical properties of cellulose paper such as tensile strength and elasticity, which in turn, makes the paper brittle and incapable of enduring electrical forces and vibrations. This irreversible deterioration strongly affects the transformer end of life [3]. Consequently, thermal management of transformers by means of appropriate cooling systems is the key factor of their safe operations and improving their productivities [4]. The thermal management efficiency of a transformer relies on various parameters such as dielectric strength and thermal properties of insulating media, operational conditions and geometrical design [5]. Among the mentioned factors that influence the hotspot and life expectancy of transformer, system configuration is the important one. The design of core and windings is

* Corresponding author.
*E-mail address:* niazmand@um.ac.ir (H. Niazmand).

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**Nomenclature**

| | |
|---|---|
| $A_s$ | cross sectional area ($m^2$) |
| $C_p$ | specific heat capacity ($J.kg^{-1}.K^{-1}$) |
| Ch | oil channel |
| CH | core height |
| CL | core length |
| CW | core square side |
| FT | fin thickness |
| g | gravitational acceleration ($m.s^{-2}$) |
| h | convective heat transfer coefficient ($W.m^{-2}.K^{-1}$) |
| H | fin height (m) |
| k | thermal conductivity ($W.m^{-1}.K^{-1}$) |
| $L_C$ | characteristic length (m) |
| L | fin length (m) |
| LVW | low voltage windings |
| HVW | high voltage windings |
| Nu | Nusselt number |
| p | pressure (Pa) |
| Ps | perimeter (m) |
| Ra | Rayleigh number |
| S | fin spacing(m) |
| T | temperature (K) |
| TH | tank height (m) |
| TL | tank length(m) |
| TW | tank width (m) |
| u | velocity in X direction ($m.s^{-1}$) |
| v | velocity in Y direction ($m.s^{-1}$) |
| w | velocity in Z direction ($m.s^{-1}$) |
| WH | winding height (m) |
| W | oil channel width (m) |
| Y1 | active part vertical position (m) |
| Y2 | fin vertical position (m) |

*Subscripts*

| | |
|---|---|
| a | air layer |
| s | surface |
| ∞ | ambient |

*Greek letters*

| | |
|---|---|
| β | thermal expansion coefficient |
| ρ | density ($kg\,m^{-3}$) |
| μ | viscosity (Pa s) |
| α | thermal diffusivity ($m^2\,s^{-1}$) |
| ν | Kinematic viscosity ($m^2\,s^{-1}$) |

usually performed by two main structures, which are the layers model for distribution transformers and disks for power ones, while reviewing the literature indicates that various designs can be used for cooling systems.

A number of researchers have investigated the effects of cooling system design on the overall performance of the transformers. These efforts can be categorized according to the methodology of the investigation into three main groups as: (i) estimation of the hotspot temperature and location as well as the lifetime of transformers; (ii) study of temperature distribution in windings, and (iii) simulation of convective heat transfer of insulating media in transformers.

In the first group of studies, simplified forms of energy equation are usually solved along with the proper boundary and operational conditions, where the complications of the realistic geometry are ignored. This method of study provides the possibility of fast prediction of the hotspot. For instance, Taghikhani and Gholami [6] investigated the location and value of a power transformer's hotspot by solving the partial differential form of heat conduction equations numerically for a winding disk transformer, which were well compatible with the results of the actual tests on site. Pradhan and Ramo [7] also presented a theoretical model to examine the hotspot, based on a boundary value problem of heat conduction in windings employing the finite integral transform technique. Susa and Nordman [8] presented a simple model, based on the exponential iterative calculation procedure, for calculating the hotspot temperature by relating the hotspot temperature to the top oil temperature. They also compared their results with the IEEE Annex G method, where reasonable agreements were observed.

Furthermore, Hajidavalloo et al. [9] assessed the effect of sun shield on the hotspot temperature of a transformer, both experimentally and numerically. It was observed that the oil temperature under the shadow mode was remarkably lower than that of the normal mode, as the reduction of hotspot temperature in summer was as high as 7 °C and the lifetime enhancement by the sun shield was nearly 24%. Souza et al. [10] applied an evolving fuzzy model to study the lifetime of distribution transformers. Koufakis et al. [11] developed a theoretical method to calculate the insulating resistance of the insulation paper in distribution transformers at several temperatures, which strongly influenced the transformer lifetime. They also presented a method to calculate the transformer life cycle. In a similar research, Abu-Alanian and Salama [12], presented a method of estimating the lifetime of transformer insulation according to some artificial histories for the ambient temperature and the transformer load, which were used as the inputs to the Monte Carlo simulation technique in order to find the thermal lifetime of the insulation of a given transformer.

Although, estimation of maximum temperature and lifetime of transformers are of great practical importance, simplifications of the governing equations and geometrical models in above-mentioned studies lead to the case sensitive and relatively low accurate results.

Literature review shows that most of the previous studies are belong to the second group, where the impacts of geometry and coolant flow inside the channels of the windings are considered on the temperature distribution of windings, using a 2D or an axisymmetric model. Clearly, in these models, which are mostly developed for power transformers, the geometry of windings are basically examined not the entire transformer. In the following, some of the papers related to this category are briefly reviewed. Hosseini et al. [13] investigated the effects of oil channels thickness and washer arrangements on the hotspot and also temperature distribution in windings using the FLUENT software. Besides, Torriano et al. [14] numerically studied the impacts of the operational parameters, such as the mass flow rate and boundary conditions on the flow and temperature distributions of the windings. They concluded that in higher flow rate, the better cooling of the windings is obtained, since the windings temperature distributions become more uniform and the hotspot temperature reduces. Similarly, Zhang and Li [15] demonstrated that the coolant flow path arrangement plays a vital role on the cooling of winding disks, such that the maximum temperature usually occurs in the disks surrounded by the ducts with minimum coolant flow rate. Toriano et al. [16] also performed a three dimensional (3D) conjugate heat transfer simulation of oil flow through the cooling ducts and demonstrated the importance of 3D modeling. They reported the weakness of the axisymmetric modeling due to the missing of annular velocity and temperature gradients in oil channels of windings. Campelo et al. [17] applied Computational Fluid Dynamic (CFD) and Thermal-Hydraulic Network Models (THNMs) to study and compare the flow and temperature distributions in the 2D and 3D modes. Skillen et al. [18] investigated the oil flow and temperature distributions in the low voltage winding of a power transformer using the CFD approach along with the temperature dependent coolant

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