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Experiments and modeling of heat transfer in oil transformer winding with zigzag cooling ducts

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Abstract

In natural oil-cooled (ON) electric transformers, cooling fluid flow and heat transfer process depend on each other. A coupled thermal/hydraulic model has been developed to investigate 2-D axi-symmetric temperature field in solid heating components (transformer windings) and hydraulic and thermal fields in network of oil cooling ducts. The convective heat transfer at solid/fluid interface was taken as coupling element between the heat generating windings and the cooling oil flow. An experimental study has also been conducted to investigate oil and disk temperatures in ON transformer windings. The results have been used to validate and then calibrate the developed simulation model, with an implicit nonlinear optimization approach. Consequently two empirical correlations for local convection heat transfer coefficient have been developed, corresponding to cooling ducts with heating on one-side and both-side walls, respectively. The correlations are valid for Reynolds numbers ranging from 7.5 to 75.9 in both-side heating ducts and from 1.5 to 218.4 in one-side heating ducts. The improved thermal model is in good agreement with the experimental results. It is also found from the experimental study that the conductor temperature gradients in circumferential direction is small and can be neglected, and therefore a two-dimensional axi-symmetric model is sufficiently accurate for the thermal simulation of the winding disks.

Keywords: Electric transformer; Heat transfer; Hydraulic; Coupling; Modelling; Experiment

1. Introduction

Electric transformer is a key component in the transmission and distribution of electrical energy. The reliability, lifetime, performance and design of transformers are intimately related to and affected by the formation and temperature of the hottest spot in the transformer winding disks. Due to the requirement in security and reliability, the application of mineral oil as a dielectric and coolant is becoming increasingly important to transformer performance. Consequently, investigation for the hottest spot in oil transformer windings has attracted particular attention from both manufacturers and user sectors. Accordingly, IEEE Standard C57.12.00-2000 requires that the hottest spot temperature and its location be determined by either measurement or calculation method. The determination of the hottest spot location and temperature by measurement is a daunting task for working transformers because of the expense, effort and difficulty involved.

From the geometrical constructions, transformer windings can be classified into two basic forms, layer and disk type. The disk-type winding with zigzag cooling duct arrangement is more popular in practice, but a difficulty arises in hydraulic and thermal predictive calculations due to complex oil fluid flow paths in it. The present study is focused on the prediction of the hottest spot temperature in this type of transformer windings. In oil transformer, the cooling oil is in practice heated in winding disks and cooled in radiators, and average winding temperature is mainly determined with oil circulation condition and

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Nomenclature

a_1, a_2	decision variables in heat transfer correlations
b_1, b_2	decision variables in heat transfer correlations
c_1, c_2	decision variables in heat transfer correlations
c_p	specific heat at constant pressure, J/(kg °C)
D_h	hydraulic diameter, m
h_x	local heat transfer coefficient, W/(m^2 °C)
H_a	height of a disk, m
H_b	height of a horizontal duct, m
H_s	height of a spacer, m
IMAX	number of measurements corresponding to an experimental condition
K	thermal conductivity, W/(m °C)
L_h	length of a horizontal duct, m
LMAX	total number of experimental conditions
M_i	mass flow rate at ith duct, kg/s
N	number of disks per pass
Nu_x	local Nusselt number
O	observed value
P	predicted value
Pr	Prandtl number
Q_o	heat output at disk surface, W
Re	Reynolds number
T	temperature, °C
V_c	center-to-center distance between sticks, m
V_s	spacer width covering disk surface, m
V_w	width of a stick, m
W_h	width of a straight horizontal duct, m
W_{min}	minimum width of a tapered horizontal duct, m
W_{max}	maximum width of a tapered horizontal duct, m
W_v	width of a vertical duct, m
x	distance, m
x^*	dimensionless distance

Subscripts

I	numbering disk and loop, or measurement location
i	concerning node numbering in radial direction, $i = 1, 2, \ldots, m$
in	concerning inlet of a duct
ins	concerning insulation paper
j	concerning node numbering in axial direction, $j = 1, 2, \ldots, n$
L	numbering experimental condition
N	concerning northern node
out	concerning outlet of a duct
S	concerning southern node
W	concerning western node
x	concerning local value

temperature level. In forced oil-cooled transformer, the oil circulation condition and hence cooling capacity is mainly affected (such as OF, the oil is pumped through the transformer, with natural oil circulation in the windings), and determined (such as OD, the oil is pumped and forced through the windings), by oil pump in the circulation loop, but inappropriate flow distribution across the horizontal ducts may cause a local overheating in the windings. As a result, the coupling between fluid flow and heat transfer in the windings must be taken into consideration for the accurate prediction of the hottest spot temperature in magnitude and location. With no application of oil pump, natural oil cooling (ON) technique has the highest reliability and is hence frequently adopted in transformer design. In ON transformer cooling loop, the circulation oil is driven with thermal driving force, referred to as thermosyphon. At steady state, the thermal driving force should be equal to total flow resistances along the thermosyphon loop, and therefore higher oil temperature rise is necessary to maintain the oil circulation while the hottest spot temperature in the windings must be under control. Because of such globally coupled phenomena between the fluid flow and heat transfer along the thermosyphon circulation loop, the prediction of the hottest spot in the ON transformer windings is involved with hydraulic pressure losses in winding ducts, as well as the interaction between fluid flow and heat transfer.

Mufuta [1–3] employed commercial software to simulate flow phenomena in the winding ducts, and conjugated heat transfer analysis was conducted with the thermal boundary condition of constant heat dissipation rate through the disk surface. But temperature field in the disk was neglected in the analysis, and a difficulty in model formulation may result from the complex duct geometry in the windings. At present, hydraulic piping network analysis is more popular for the prediction of fluid flow distribution, because of its simple formulation and easy coupling to thermal simulation for the disk temperature field [4]. Its accuracy has been verified with experimental and numerical results [5]. Oliver [6,7], Burton et al. [8], and Del Vecchio and Feghali [9] have utilized the hydraulic network approach to develop coupled thermal models. The boundary condition required by the hydraulic network models was the heat flux through unit surface area of the duct. Temperature dependent oil properties and temperature and velocity dependent heat transfer and friction coefficients were taken into consideration. But heat conduction within each disk was neglected, and hence the disk temperature in the analyses was assumed uniform. It is not in agreement with Allen and Childs experimental results [10], as the temperature variation along the radial direction within the disk was found to exceed 10 °C. In addition, all of above models neglected cylindrical geometry involved, and approximately treated it as Cartesian. Declercq and Van der Veken [11] formulated a computer model with cylindrical analysis and accounted for the heat conduction within the disk. But the temperature variation in the disk was simply described as wall