International Journal of Thermal Sciences 116 (2017) 224–233

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

A validated online algorithm for detection of fan failures in oil-immersed power transformers

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ARTICLE INFO

Article history:
Received 26 October 2016
Received in revised form
13 January 2017
Accepted 21 February 2017

Keywords:
Online monitoring
Thermal modelling
Detection of changes
Cooling system
Air-forced power transformer

ABSTRACT

With the integration of the renewable energy-based power plants into the power system, and due to their volatile nature, the overloading of power transformers is inevitable for economical reasons. Under a specified loading condition, the operation of fans leads to increase the heat transfer coefficient on the air-side of the cooling system resulting in decreasing of the temperature of the oil entering the winding, and consequently decreasing the winding temperature and increasing the lifetime of the transformer. Therefore, the healthy operation of fans should be guaranteed when a transformer is subjected to a loading condition.

In this paper, a new online algorithm is proposed for detection of fan failures in power transformer based on the detection of changes in the estimated parameters of a thermal model; moreover, an allowed band is provided for triggering the alarm signal which is able to be applied on every oil-immersed transformer with AF cooling system. Furthermore, an empirical-based thermal model is proposed which uses different temperature-dependent thermal resistances corresponding to different heat transfer phenomena. Furthermore, the proposed algorithm is validated using the measured data of a 333 MVA ODAF and a 600 MVA OFAF power transformer including ambient temperature, load factor, number of operative pumps and fans, and top-oil temperature.

1. Introduction

1.1. Motivation and state-of-the-art

Certainly, power transformers are of the most important components and large capital items of power systems. Their operation affects both economical and technical issues of power systems and their sudden failures increase both economical and technical costs [1,2]. Moreover, the loading capability of a transformer is limited by its winding temperature which should not exceed the maximum allowed temperature [3,4]. As an example, according to IEC loading guide [3], the aging rate of the insulation is doubled for each 6° of temperature increase above the maximum allowable insulation temperature. Nevertheless, in this context the measurement of the winding and the Hot-Spot Temperature (HST) would not be competent measured values in an online monitoring system. Since it is time consuming, very expensive, and cannot be done on transformers already installed. However, the HST can be calculated using two different ways as follows:

– Physical and semi-physical modeling approach describing the complex heat transfer modes in a transformer with simple differential equations. The inputs of such models can be measured during operation of a transformer. These models can be used in an online monitoring system.
– Computational Fluid Dynamic (CFD) modeling approach which is very accurate but time consuming and needs the design details of the transformer for modeling [5]. Using these models, in addition to the HST, the hydraulic behavior of a transformer can be investigated [6,7]. However, such models cannot be used in an online monitoring systems which are considered to be almost independent of the monitored transformers. The thermal behavior of a transformer under dynamic loading is very hard to investigate and needs high performance computers.

On the contrary, the measurement of the Top-Oil Temperature

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http://dx.doi.org/10.1016/j.ijthermalsci.2017.02.012
1290-0729/

Nomenclature

A	Surface area of convection heat transfer (m^2)
A_{rad}	Effective surface area of radiation (m^2)
C	Empirical factor
C_{th}	Thermal capacitance (W•s/K)
cp	Specific heat (W•s/(kg•K))
Dt	Time difference between two measurements (h)
d	Characteristic diameter of the oil duct (m)
$E(\cdot)$	Expected value
Gr	Grashof number
G	Gravitational acceleration (m/s^2)
J	Jacobian matrix
j	Jacobian vector
k	Load (%)
m, n	Empirical factors
P_0	No load loss (W)
P_K	Short circuit loss (W)
P_{loss}	Total losses (W)
Pr	Prandtl number
p, q	Empirical factors
R_{th}	Thermal resistance (K/W)
Re	Reynolds number
u	Proportionality constant
V_m	Average velocity of the fluid (m/s)
X	Input matrix of the model
Y	Output matrix of the model

Greek

α	The heat transfer coefficient
β	Volumetric thermal expansion coefficient (1/K)
$\Delta\theta$	Temperature gradient between a solid material and a fluid (K)
$\Delta\theta_{to}$	Top-oil temperature rise over ambient temperature (K) at any load
$\Delta\theta_w$	Winding temperature gradient (K) at any load
$\in$	Independent additive error (K)
ε	Emissivity
θ_{to}	Top-oil temperature(°C)
θ_a	Ambient temperature (°C)
θ_{o-a}	Logarithmic average temperature of the oil and the air (K)
λ	Thermal conductivity (W/(m•K))
ν	Kinematic viscosity (m^2/s)
ρ	Fluid density (kg/m^3)
σ	Stefan-Boltzmann constant ($W/(m^2K^4)$)
τ_{to}	Oil time constant (h)
Φ	Vector of unknown parameters

Indices

$\hat{}$	Estimated value
a	Number of iteration
air	Air-side
i	Time step
oil	Oil-side
T	Temperature-dependent value

(TOT) is cost effective, can be done on the transformers already installed, and provides adequate information about the thermal condition of a transformer.

The performance of the cooling system has a direct impact on the temperature of the winding and consequently on the lifetime of the power transformer. The early detection of fan failures in a power transformer based on a proper real-time online algorithm leads to increase the availability of the transformer which is not well reported in the literature. A systematic fault diagnosis method for power transformers based on Petri Net is proposed in Ref. [8]. The calculated nominal thermal resistance of a transformer has been investigated in Ref. [9]; in addition, big changes in the estimated parameters of a TOT model can be used for fast failure detection of the cooling system [10]. Moreover, the error in the calculation of the top-oil temperature can also be a fast method for malfunction detection of the cooling system [11].

In order to use an online algorithm for detection of fan failures, a simple and accurate TOT model should be used. CIGRÉ Brochure A2.38 [12] provides a comprehensive review on the thermal modeling of power transformers, where the IEEE [4] and IEC loading guides [3,13] have been introduced as the thermal models for the dynamic loading of power transformers; in addition, the issues of the calculation of the TOT using a thermal model and the affecting parameters and their applications have been investigated in the literature. These thermal models can be divided into the following groups:

- The IEEE C57.91 [4], IEC 60076-7 [3], and IEC 60354 [13] loading guides which provide very simple equations for calculation of the TOT based on the real-time measurements during the normal operation of a transformer. However, their accuracy is limited, since they consider the thermal resistance of a transformer independent of the loading condition and do not account for the changing of the number of operative fans and pumps directly [11].
- Other conventional models based on the physical phenomena namely Susa [14] [15], and swift [16] models, which do not account for the forced convection; and therefore, their accuracies are limited in these cases.
- Advanced thermal models based on physical phenomena which have been proposed to overcome the deficiencies of the loading guides and the conventional models [11,17–19].
- Thermal models using advanced mathematical methods such as neural networks [20,21], genetic algorithm for the parameter identification of thermal models [22,23], and evolving fuzzy systems [24]. Due to the complexity of these methods, it is hard to use them in an online monitoring system.

1.2. Contributions

In this paper, a new online algorithm based on the detection of changes in the estimated parameters of a TOT model for failure detection of fans in oil-immersed power transformers is proposed which is significantly faster than the previous work of the authors in Ref. [11]. Moreover, the algorithm is validated using real-time measurements of two power transformers. In addition, in comparison with the other methods of the failure detection of fans [9,10], an allowed band is provided in this paper which is applicable for all transformers with AF cooling system. Moreover, a TOT model is proposed which uses temperature-dependent thermal resistances corresponding to the natural and forced convections of