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WINDING THERMAL ANALYZING OF DRY TYPE TRANSFORMERS

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Abstract- Transformers are the most important power conversion units used in the electrical systems considering their prices. The life of transformers has a considerable economic impact on the operation of electrical systems. Though the transformer life expectancy depends on the operating temperature, the life expectancy at various operating temperatures is not accurately known. The information regarding loss of life of insulation is considered to be the best way through which the transformer life expectancy can be expected. The most important parameter in transformers life expectancy is the insulation temperature value. The aim of this paper is to present a new and more accurate winding thermal model for dry-type transformers based on heat transfer theory, application of the lumped capacitance method and the thermal-electrical analogy. The proposed model is verified using experimental results, which have been obtained from temperature rise test performed on a 5 kVA dry-type transformer.

Keywords: Dry-Type Transformers, Thermal Resistance, Winding Temperature, Dynamic Model.

I. INTRODUCTION

The kilovolt-ampere output rating of a transformer is that it can deliver continuously at rated secondary voltage and rated frequency without exceeding the specified temperature rise under usual service conditions. The term "rated output" or "rated load" refers to nameplate rating of continuously operation [1]. In recent years, the variety of transformer types available for use in small and medium power applications has grown considerable. The major types are oil filled transformers, gas insulated transformers and dry type transformers [5]. In oil filled and gas insulated transformers, the oil and gas are acting as insulation and a cooling medium. But the dry type transformer lacks any fluid for cooling.

Dry-type transformers with standard classes corresponding to 80 °C, 115 °C, and 150 °C average winding rises have 150 °C, 185 °C, and 220 °C maximum hottest-spot operating temperatures, respectively [14]. Transformer life expectancy at various operating temperatures is not accurately known, but the information given regarding loss of life of insulation is considered to the best way through which the expectancy life can be expected using present knowledge of subject [1, 2, 5, 8].

Dry-type transformers are replacing liquid-immersed transformers in many commercial and industrial applications including power plants, hospitals, schools, multi-story buildings, paper and steel mills, mining, chemical plants and subway systems. They have several advantages over liquid-immersed transformers. The advantages are [13]:

- Fire risk is significantly reduced by using the dry-type transformers. Some liquid immersed transformers are filled with flammable oil, which should be avoided in commercial and industrial applications.
- Environmental concerns make the dry-type transformers more attractive. Liquid immersed transformers, especially PCB-filled transformers threaten the environment due to possible leakage. Since the leakage of such hazardous chemicals may contaminate drinking water and soil, and the resulting clean-up costs could be enormous.
- Even though the core and windings of dry-type transformers are larger than those of liquid-immersed transformers, the overall size of dry-type transformers is smaller since do not require space for cooling radiators.
- The installation cost for dry-type transformers are lower than that for liquid immersed transformers. Sometimes liquid immersed transformers require additional installation, which results in higher total installation cost, for example liquid-filled transformers require catch basins in case leakage occurs.
- The maintenance of dry-type transformers is easier and the costs of operation are lower. For liquid-cooled transformers, the core and coils have to be removed from the tank for repairs, which can be messy and costly.

Aging or deterioration of insulation is a function of time and temperature. Since, in most apparatus, the temperature is not uniform, the part of the winding insulation that is operating at the highest temperature will ordinarily undergo the greatest deterioration. Therefore, aging studies consider the aging effects produced by the highest temperature. The problem related to the accurate computation of heat transfer in power transformer applications is not particularly new [2]. It has been documented (extensively for oil-filled units, but sparsely for dry type units) in two main streams of the literature. Two main streams, mechanical engineering community and electrical engineering community do not necessarily emphasize on same aspects of phenomena under scope.

According to Previous studies [2, 3, 5, 8, 9, 11, 12], the variation of the temperature is described by an exponential equation based on the time constant of the transformer temperature rise model. In the thermal equivalent circuit model, the time constant is equal to multiplication of thermal capacitance and thermal resistance [2, 3, 5, 12]. The time constant used in this equation is equal to multiplication of the thermal capacitance and the thermal resistance of the temperature rise model. The thermal capacitance and thermal resistance of thermal equivalent circuit model are nonlinear and variable with temperature [3, 9]. The heat transfer theory, the lumped capacitance method and the thermal-electrical analogy are considered and used in this model [3, 9].

In this study, a simple model is presented based on parameters that can be calculated using the manufacture data of the transformer and routine test results. The value of the thermal equivalent capacitances is calculated from dry-type properties. The value of the thermal equivalent resistance is initially extracted from experimental data and to increase the model accuracy, this value is adjusted via simple procedure [5, 9].

II. TRANSFORMER LIFE EXPECTANCY

The insulation aging phenomenon has been well documented as a thermal deterioration process in the literature. The application of loading on a transformer, i.e., the load current in the transformer coils, results in heating and, consequently, reduction in the age of the transformer.

Loading capability of power transformers is limited mainly by winding temperature [1]. As part of acceptance tests on new units, the temperature rise test is intended to demonstrate that at full load and rated ambient temperature, the average winding temperature will not exceed the limits set by industry standards. However the temperature of the winding is not uniform and the real limiting factor is actually the hottest section of the winding commonly called winding hot spot. This hot spot area is located somewhere toward the top of the transformer, and not accessible for direct measurement with usual methods. Recommendations in IEEE C57.94 guide are based on life expectancy of transformer insulation affected by operating temperature-time [14].

The Permissible loading of transformers for normal life expectancy depends on the design of the particular transformer, its temperature rise at rated load, temperature of the cooling medium, duration of the overloads, the load factor, and the altitude above sea level air is used as the cooling medium. Transformers are designed on the basis rise above the ambient temperature as determined by average winding resistance and are so rated on the nameplate, However, In actual operation, the hottest-spot temperature should be used as the limitation rather than the average winding temperature rise. Transformers may be operated continuously at hottest-spot temperatures up to 150 °C, 185 °C, and 220 °C maximum for 80 °C, 115 °C, and 150 °C average winding rises rated transformers, respectively [14].

III. LOSS COMPUTATION

Temperature rise inside a transformer is the result of power losses. The transformer losses are composed of no-load and load losses. The no-load losses are almost entirely core iron losses. These are calculated by the FEM by the summation of the uniform loss densities within the elements [7, 10]. The loss density distribution is obtained by estimating the iron loss values as a function of the magnetic flux density. The load losses, which are mostly Joule losses, can be split into three types [7]:

- Resistive losses
- Additional AC losses (eddy current losses)
- Stray losses (in structural parts)

Current harmonics cause an increase of the additional AC losses and the stray losses. For a stranded winding, with a non-prominent skin effect, the additional AC losses rise proportionally to the square of the harmonic order, which led to the traditional definition of the K-factor [7]. The stray losses are very much construction dependent. The Joule losses in the windings are calculated by the summation of the integrated loss densities in the different finite elements in the windings. However, a different approach is chosen for the massive (foil) windings and stranded windings [7].

Foil windings: Both source and eddy current densities are present in the FEM magnetic field model. The total Joule loss is obtained by Equation (1).

$$q_{foil} = R_{AC}(w)I^2 = \sum_e q_e = \sum_e \left(\int_{\Omega_e} \frac{\left(J_s^2 + jw\sigma A\right)^2}{\sigma} d\Omega \right) \quad (1)$$

Stranded windings: Since the eddy currents are neglected in this type of winding, only the DC losses are modelled. The contribution of the additional AC losses is to be estimated separately. This is accomplished by calculating the losses in an individual strand, subject to a leakage flux, modelled as a small massive conductor in additional FEM calculations. By varying the leakage flux strength, the additional loss function f_{ec} can be estimated and added [7]. This set of separate limited FEM calculations has to be performed only once for a certain strand dimension [7, 10].

$$q_{wire} = R_{AC}(w)I^2 = \sum_e q_e = \sum_e \left(\frac{J_s^2}{\sigma} + f_{ec}(w)B^2 \right) \Omega_e \quad (2)$$

Temperature rise is one of the most crucial parameters that affect the transformer lifetime. Temperature rise can easily leads to the serious damages. This makes temperature estimation an important priority for engineers and companies. Different methods have been suggested. Among them, measurement of winding resistance according to IEEE/ANSI standards, usage of Fiber Optic for measurement of Hot-Spot temperature and software's simulations can be mentioned [1, 2, 3, 5, 7, 9, 11, 12].

Thermal stress is one of the major causes of deterioration of insulation material for power transformers resulting in the failure of electrical distribution systems.

IV. FUNDAMENTAL THEORY OF THERMAL ELECTRICAL ANALOGY

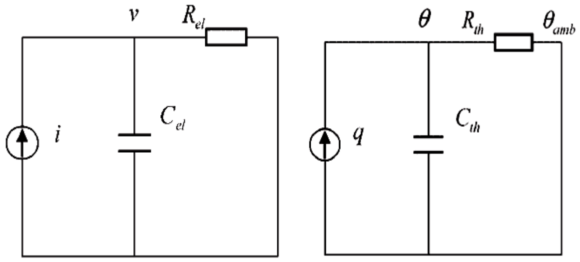
The analogy between thermal and electric process is briefly given below to analyze the thermal conditions inside the power transformers [2, 3, 4, 5, 8, 11, 12]. A thermal process can be defined by the energy balance (Figure 1-a) given in Equation (3) [2, 5, 8, 11].

$$q = C_{th} \frac{d\theta}{dt} + \frac{(\theta - \theta_{amb})}{R_{th}} \quad (3)$$

Equation (4) is similar to Equation (3) corresponding to a simple electric RC circuit shown in Figure 1-b.

$$i = C_{el} \frac{dv}{dt} + \frac{v}{R_{el}} \quad (4)$$

where *i* is electric current, C_{el} is the electric capacitance, R_{el} is the electric resistance and *v* is the electric voltage.



(a) analogous thermal (b) RC circuit

Figure 1. The electric and thermal-electric circuits.
(a) electric RC circuit, (b) analogous thermal circuit

Table 1 shows the parameters obtained from the thermal-electric analogy by comparing Equations (3) and (4) [2, 3, 4, 5, 8, 11, 12]. The electrical analogy to one-dimensional (1-D) heat flow makes it convenient to set up a heat transfer network corresponding to the actual thermo hydraulic structures, and to adjust the thermal parameters for the actual area. The equivalent thermal circuit includes the heat conductors, heat capacitors, and heat current sources.

Table 1. Thermal-electrical analogous quantities

Variables	Thermal	Electrical
Through variable	Heat transfer rate, *q*, watts	Current, *i*, amps
Across variable	Temperature, *θ*, deg (C)	Voltage, *v*, volts
Dissipation element	Thermal resistance, R_{th}, deg (C)/watt	Elec. Resistance, R_{el}, ohms
Storage element	Thermal capacitance, C_{th} , joules/deg (C)	Elec. Capacitance, C_{el} , farads

V. DYNAMIC THERMAL MODELING

Power losses in a transformer are converted into heat. These losses are comprised of core losses, resistive losses of windings and stray losses [2, 5, 8, 12]. The heat transfer in a dry-type transformer (from heat source to ambient) is achieved by three different ways as i-convection, ii-conduction and iii-radiation. The real-time thermal model of a dry-type power transformer is developed by considering the transformer to be comprised of two components i- the core and coil assembly and ii- the cooling medium [2, 5, 8].

Heat is a form of energy and is always transferred between two communicating systems, arising solely from a temperature difference. In simple cases, the rate of heat flow can be quantitatively determined by applying the basic principles of thermodynamics and fluid mechanics [2, 5, 11]. The thermal equivalent circuit of a dry type transformer should include nonlinear heat resistances, heat conductors, heat capacitors and heat current sources. The winding thermal circuit of a power transformer is shown in Figure 2. The total losses can be written as Equation (5):

$$q_{tot} = q_s + q_{fe} + q_{wind} \quad (5)$$

In this model the thermal capacitances of transformer core is obtained from Equation (6).

C_{fe} = 0.449 (weight of core in kg) (6)

The thermal capacitance of the structural parts of transformer is obtained from Equation (7).

C_{tm} = 0.449 (weight of iron fittings in kg) (7)

The differences between specific thermal capacitances of Al, Cu and Fe for different temperatures are given in Table 2 [5].

Table 2. Thermal capacitance of Al and Cu

Temperature (K)	Conductor substance		
	Aluminum	Copper	Iron
298.15	897 J/kg-K	385 J/kg-K	449 J/kg-K
350	930.6 J/kg-K	392.6 J/kg-K	470.6 J/kg-K
400	955.5 J/kg-K	398.6 J/kg-K	490.5 J/kg-K

In most transformers the primary and secondary windings conductor is copper, but now transformers are designed and constructed with aluminum as conductor in both primary and secondary windings, or one of them may be aluminum and the other copper. The thermal capacitance of transformer winding is obtained from Equation (8).

C_{wind} = 0.385 (weight of Copper windings in kg)
+ 0.910 (weight of Aluminum windings in kg) (8)

The stray losses and winding losses vary with load and can be simplified as load losses and load capacitance. The simplified nonlinear winding thermal circuit of a dry type transformer is shown in Figure 3. The total losses can be written as Equation (9)

$$q_{load} = q_s + q_{wind} \quad (9)$$

The thermal capacitance of transformer load can rewritten as Equation (10).

C_{load} = 0.449 (weight of iron fittings in kg)
+ 0.385 (weight of Copper windings in kg) (10)
+ 0.910 (weight of Aluminum windings in kg)

The transformer winding thermal model given in Figure 3 is derived from the thermal-analogy and heat transfer theory. The differential equation corresponding to Figure 3 is as Equations (11) and (12).

$$q_{fe} = C_{fe} \frac{d\theta_{fe}}{dt} + \frac{\theta_{fe} - \theta_{amb}}{R_{fe-amb}} + \frac{\theta_{fe} - \theta_{wind}}{R_{fe-wind}} \quad (11)$$

$$q_{load} = C_{load} \frac{d\theta_{wind}}{dt} + \frac{\theta_{wind} - \theta_{amb}}{R_{wind-amb}} - \frac{\theta_{fe} - \theta_{wind}}{R_{fe-wind}} \quad (12)$$

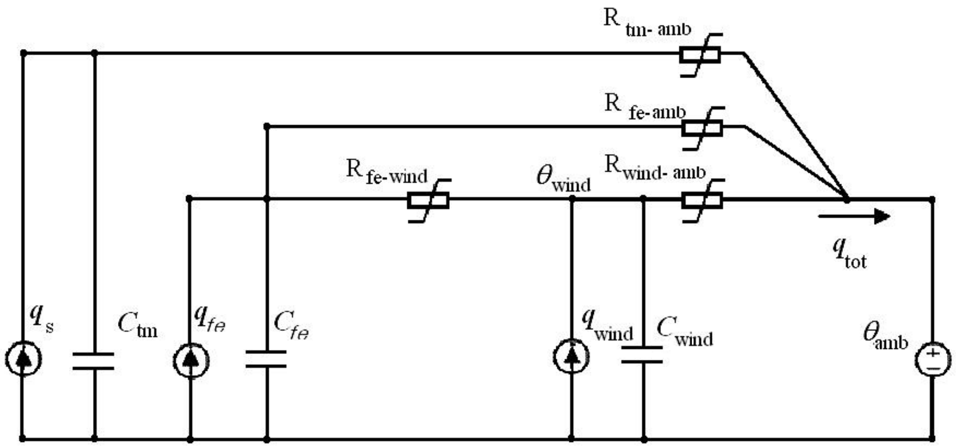


Figure 2. The winding temperature thermal circuit

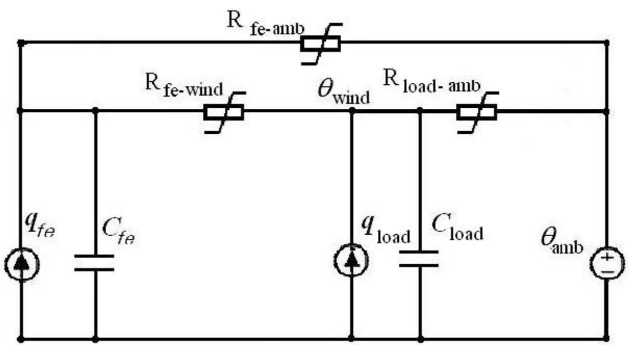


Figure 3. The simplified equivalent winding thermal model

Figure 4. Experimental verification test setup

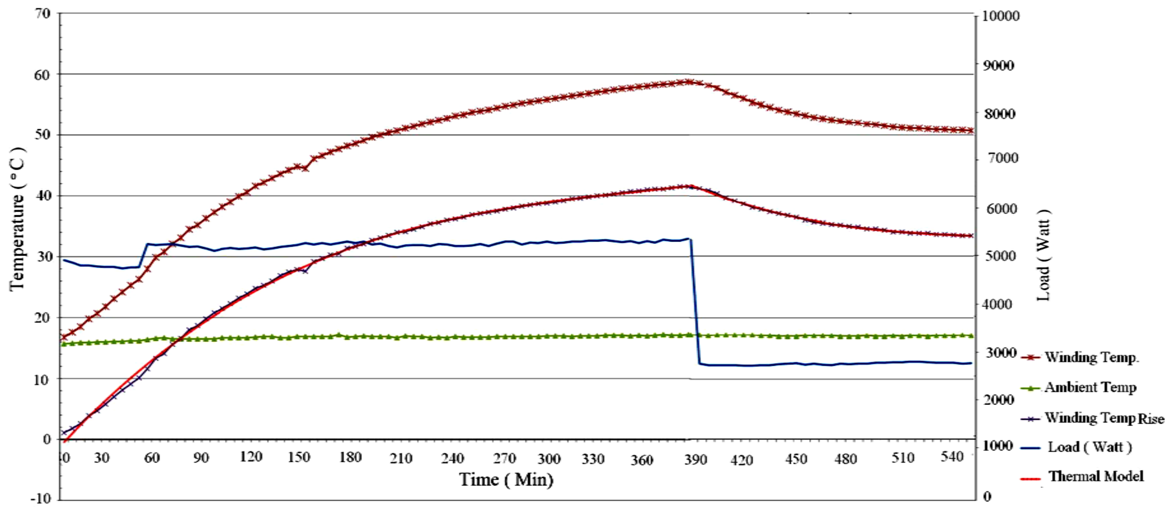


Figure 5. Experimental and theoretical results of the winding temperature rise for a dry-type transformer

VI. EXPERIMENTAL VERIFICATION

To verify the nonlinear thermal model derived for winding temperature of dry-type transformers the experiments were carried out on a 5 kVA Dry-type transformer (Figure 4). The load and no-load losses experiments performed in laboratory were carried out at principle tapping according to IEEE Standard IEEE Std C57.91-2001 [6, 11].

During temperature rise tests the secondary side of transformer is connected to a resistive load bank and the rated voltage is applied from primary side [2, 5, 12]. During test, the temperature of eight different points was measured using eight separate temperature transducers. Five of them were mounted at winding of the transformer to measure the winding temperature and the next three temperatures were used to measure the ambient temperature at three different points which have 30 cm distance from the transformer corners [7].

During experiments LM type temperature transducer were used due to their advantages as: i- higher sensitivity (the highest mV output per degree of temperature change-10 mV per centigrade), ii- higher reliability, iii- small dimension (easy mounting in windings). The measured and theoretical results of the winding temperature rise for dry-type transformer are shown in Figure 5.

VII. CONCLUSIONS

The thermal model of a dry type transformer was derived considering the nonlinear thermal resistance and the adequate value of thermal capacitance. The ambient temperature change was also considered in deriving the thermal-electric analogy model.

The experiment works were carried out in laboratory to verify the suggested model. The experiment was done on a 5 KVA Dry-type transformer. The results show that the error between the experimental and theoretical results is very low and the results obtained from the dynamic thermal modeling of winding temperature rise are in a good accordance with the results of experiments.

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BIOGRAPHIES

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