PRACTICAL VALIDATION FOR THE FREQUENCY DOMAIN APPROACH TO STUDY THE THERMAL BEHAVIOR OF TRANSFORMERS UNDER NONSINUSOIDAL OPERATION CONDITIONS

Antonio C. Delaiba  Josè C. de Oliveira  Jose R. Cardoso  Paulo F. Ribeiro

Federal University of Uberlandia  University of São Paulo  BWX Technologies
Electrical Engineering Department  USP - São Paulo  Product Development Dept.
Av. João Naves de Ávila, 2100 - Uberlandia - MG - Brazil  Brazil  Lynchburg, VA, USA
Fax/Phone: (034) 236-5099 - email: jcoliveira@ufu.br

Abstract - This paper is focused in the direction of practical and theoretical aspects of thermal performance of transformers under distorted operating conditions. Using the superposition method, the thermal conditions are estimated through the frequency domain technique. To validate the theoretical results, practical measurements are made using a 15 KVA transformer prototype supplying a 6 pulse rectifier. The results are then used to validate the proposed method to investigate transformer thermal behavior.

Keywords: Power Transformers, Harmonic Distortion, Thermal Behavior, Power Quality.

I. INTRODUCTION

Power transformers have an insulating system which consists of organic materials, and they can suffer degradation effects due to several reasons. The most well known are: heat, mechanical forces, contamination, etc. Transformer oil is also affected by chemical degradation. Various studies have been made to evaluate the thermal effect on a transformer under sinusoidal and non-sinusoidal conditions. As power transformer are usually the interface between the supply and non-linear loads, the effect of harmonics on the performance of this component represents a matter of major importance. Reference [1] deals with traditional methods to predict the loss of life of transformers supplying non-linear loads. On the other hand, reference [2] compares winding losses calculation from a finite element method with measured losses in single phase distribution transformers. Comparisons between winding temperature prediction from a finite element based method for a 10 KVA single phase distribution transformer model are made in [3]. In [4] methods are established to determine the capability of transformers to supply non-sinusoidal load currents of known characteristics, without normal life expectancy variation. Reference [5] discusses the influence of incremental temperature rise on transformer’s lifetime and in [6] expressions for the transformer’s core and winding losses as a function of the total harmonic distortion are experimentally obtained. Analytical and experimental investigations on single and three-phase transformers under distorted voltage are described in [7].

II. THEORETICAL ASPECTS

HYSTERESIS LOSSES

According to [1] the losses associated to the hysteresis phenomena, under non-sinusoidal conditions, are calculated by:

\[
P_{Hn} = \left[ 1 + \sum_{n=2}^{\infty} \left( \frac{V_n}{V_1} \right)^2 \right] P_{H1}
\]

where:

- \(P_{Hn}\) - harmonic hysteresis losses;
- \(P_{H1}\) - fundamental hysteresis losses;
- \(n\) - harmonic order;
- \(V_n\) - \(n^{th}\) harmonic voltage;
- \(V_1\) - fundamental voltage,
- \(\phi_n\) - harmonic voltage phase-angle
- \(s\) - “Steinmetz” coefficient

EDDY CURRENT LOSSES

The effect of voltage distortion upon eddy current losses, in relation to the fundamental value, can be evaluated [1] through:

\[
\frac{P_{Fn}}{P_{F1}} = \left[ 1 + \sum_{n=1}^{\infty} \left( \frac{V_n}{V_1} \right)^2 C_{en} \right]
\]
\[ C_{se} = 1 - 0.00173^3, 3.6 < \xi \leq 3.6 \]  
\[ C_{se} = \frac{3}{\xi}, \xi > 3.6 \]  
\[ \xi = \Delta \sqrt{n \mu / \nu f} \]  
where:
- \( P_{he} \) - harmonic eddy current losses;
- \( P_{hu} \) - fundamental eddy current losses;
- \( \Delta \) - magnetic core thickness;
- \( \mu \) - magnetic core permeability;
- \( \gamma \) - magnetic core electrical conductivity;
- \( n \) - harmonic order;
- \( f \) - fundamental frequency

**Winding Losses**

The total winding losses due to the primary and secondary distorted current flowing through the winding, can be calculated using the superposition method:

\[ P_{jn} = \sum_{n=0}^{\infty} R_n(p) I_n^2(p) + \sum_{n=0}^{\infty} R_n(s) I_n^2(s) + P_{BC} + P_{OSL} \]  

where:
- \( R_n(p) \) - primary winding harmonic resistance;
- \( R_n(s) \) - secondary winding harmonic resistance;
- \( I_n(p) \) - rms primary harmonic current;
- \( I_n(s) \) - rms secondary harmonic current;
- \( P_{BC} \) - harmonic eddy current losses;
- \( P_{OSL} \) - additional losses associated to non-sinusoidal conditions.

**The Theoretical Evaluation of Transformer Temperature**

**Top-oil temperature rise in relation to the ambient temperature**

According [1], the final top-oil rise of temperature in relation to the ambient temperature, can be calculated as:

\[ \theta_{o,f} = \theta_{o,1} \left[ \frac{(P_{he} + P_{hu} + P_{jn})}{P_{01} + P_{1j}} \right]^{m_1} \]  

where:
- \( \theta_{o,1} \) - top-oil temperature rise in relation to the ambient with linear load[°C];
- \( m_1 \) - coefficient varying from 0.8 to 1.0 - the lower limit applies to self-cooled transformers and higher limit to forced-oil-cooled ones.

- \( P_{he} \) - harmonic hysteresis losses;
- \( P_{hu} \) - harmonic eddy-current losses;
- \( P_{01} \) - harmonic ohmic losses;
- \( P_{01} \) - harmonic iron losses (\( P_{he} + P_{hu} \));
- \( P_{hl} \) - fundamental ohmic losses;
- \( n \) - harmonic order;
- \( T_0 \) - thermal oil time constant;
- \( \theta_{o,1} \) - initial oil temperature rise;

**Winding temperature rise in relation to the final top-oil temperature.**

The final temperature rise at the transformer winding hottest-spot can be estimated by equation (9). This equation calculates the temperature rise in relation to the final top-oil temperature:

\[ \theta_{e,F} = \theta_{e,1} \left[ \frac{P_{jn}}{P_{1j}} \right]^{m_2} \]  

The corresponding winding temperature transient is described by equation (10).

\[ \theta_{e} = \theta_{e,1} \left( 1 - e^{-\frac{-\Delta t}{T_e}} \right) + \theta_{e,1} e^{-\frac{-\Delta t}{T_e}} \]  

where:
- \( \theta_{e,F} \) - winding temperature rise with non-linear load;
- \( T_e \) - thermal winding time constant;
- \( \theta_{e,1} \) - instantaneous winding temperature rise;
- \( \theta_{e,1} \) - winding temperature rise with linear load;
- \( m_2 \) - practical coefficient, varying from 0.8 to 1 - the lower limit applied to for self-cooled transformers and the higher limit for forced-oil-cooled ones.

**III. EXPERIMENTAL RESULTS**

In order to validate the above methodology, an experimental investigation was carried out using a prototype. The transformer used for the experiment was a special unit which consisted of a three-phase, 15KVA, 220/220V, Y/Y, mineral oil insulation material. To obtain the transformer temperature at different points, two methods were applied. For the winding measurements, a PT-100 (sensor) classical unit was used and a J type of thermal sensor was utilized to derive the top-oil temperature. Figure 1 shows the practical arrangement which was set up in the laboratory. The system comprises an AC supply, a transformer and a six pulse rectifier. The main parameters are shown in the figure.
Once the experiment was set up, several steady state measurements were carried out. The variables taken and here described are the waveform and harmonic spectrum for the primary and secondary voltage and current. Figures 2 to 7 indicate part of the results. It must be emphasized that three phase monitoring was made and only phase A results are given.
The harmonic content predictable for a six pulse rectifier contains the classical 5th, 7th, 11th, 13th, etc., orders. These are easily verified by looking at figures 3, 5, and 7, the most expressive one being the 5th. The 5th harmonic shows 22% of the fundamental value and the total harmonic distortion level found is of 2.5%. On the other hand, the supply voltage has shown 2.8% of total distortion and the same harmonic orders are found in the current waveform. On the secondary side, the voltage distortion achieved 6.4%. The temperature measurement procedure took into consideration the transient behavior till the thermal equilibrium and the local temperature were obtained using standard recommendations [8]. The temperature results are given in figures 8, 9 e 10, which correspond respectively to the oil, primary and secondary winding temperatures during the transformer operating period. Besides, the temperature was measured in four different positions along the winding extension.

In accordance with figure 12, the temperature for the secondary winding was 33°C under linear loading and 42°C under non-linear loading. Table 1 compares the final temperature increase under the above two conditions. In addition, it is also given the results derived from the traditional short-circuit test to evaluate transformer temperature rise. As can be seen, this method yields to lower temperature levels.

Table 1 - Experimental temperature comparison.
Laboratory and Theoretical Results Comparison

In order to validate the proposed theoretical methodology, figures 13 and 14 provide means of comparison between computational and experimental results. The so-called theoretical values were obtained from a computer program elaborating use of the previous equations.

By comparing the laboratory and computational results, it can be easily seen they are in a very close agreement. Thus, it follows that the frequency approach of estimating transformer temperature rise has been validated by the experimental results.

V. Conclusions

This paper was focused towards the validation of the frequency domain approach to evaluate thermal behavior of transformers under distorted supply conditions and non-linear loading. Besides, the results are useful to verify the adequacy of using the superposition method as proposed with the frequency method. To achieve these targets several practical and computational results were shown in relation to temperature rise at different transformer locations under linear and non-linear loading. The tests were performed in a three-phase transformer prototype specially built. This transformer allowed for temperature measurements at different oil and winding locations. Both theoretical and laboratory results were close enough to show that the frequency/superposition method has an appropriate accuracy for transformer thermal estimation. This conclusion is supported by oil and windings results as well as the hottest spot temperature. As expected, under non-linear loading, the transformer was led to higher temperature rise and this is of major concern in considering life expectancy. Also, it has been shown that the classical methodology to determine transformer temperature, i.e. the short-circuit procedure, produced lower values than the load test. This, of course, will result in optimistic life expectancy calculations.

VI. Acknowledgments

The authors are in deep gratitude to W.T.W. Transformers-Fernandópolis/SP- Brazil for providing the transformer prototype.

VII. References


VIII. BIOGRAPHIES

Antônio Carlos Delailha was born in Botucatu- Brazil. He received the B.S. degree in electrical engineering from Fundação Educacional de Barretos-Brazil, the M.S. and Dr. degrees from University of São Paulo- USP- Brazil. He is presently lectures in the electrical engineering department, Federal University of Uberlândia- Brazil. He has authored several papers on the subjects of electrical power systems.

José Carlos de Oliveira was born in Itajubá- Brazil. He received the B.S. and M.S. degrees from Federal University of Itajubá- Brazil, and PhD degree from University of Manchester-Institute of Science Technology- Manchester-UK. He is currently research in the electrical engineering department, Federal University of Uberlândia- Brazil. He has taught and published in a variety of subjects, including electrical power systems and power quality.

José Roberto Cardoso was born in São Paulo- Brazil. He received the B.S., M.S. and Dr. Degrees from University of São Paulo-USP- Brazil. He is presently lectures in the electrical engineering department, University of São Paulo- Brazil. He has taught and published in a variety of subjects, including electrical power systems, numerical techniques and finite elements.

Paulo F. Ribeiro was born in Recife, Brazil. He received a BS in Electrical Engineering from the Universidade Federal de Pernambuco, Recife, Brazil, completed the Electric Power Systems Engineering Course with Power Technologies, Inc. (PTI), and received the Ph.D. from the University of Manchester - UMIST, England. Dr. Ribeiro is a Senior Member of the IEEE, member of the CIGRE Voltage Quality WG, and Vice Chairman of the IEEE TF on Harmonics Modeling and Simulation.