Journal of Energy and Power Engineering 5 (2011) 972-977

A Tool for the Assessment of the Electromagnetic Forces in Power Distribution Transformers

A. da Costa Lopes[1], M.A. Sanz-Bobi[1], L. Rouco[1], R. Palacios[1], L. Flores[2] and P. Cirujano[2]

1. Institute of Technological Research-IIT, ICAI-School of Engineering, Comillas Pontifical University, Madrid E 28015, Spain

2. ORMAZABAL, Polígono El Caballo - Parcela 56, E 28890 Loeches, Madrid E 28015, Spain

Received: November 12, 2010 / Accepted: March 31, 2011 / Published: October 31, 2011.

Abstract: This paper compares the estimated electromagnetic forces due to short circuits in power transformers using two computational models. The first model is based on approximate analytical expressions of the electromagnetic forces as they have been compiled in earlier versions of the IEC standard 60076-5. The second model is based on a finite element model of the transformer using the software FEMM (Finite Element Method Magnetics). The paper shows how valid the analytical model is for design purposes. Results have been obtained and compared from both models in a number of actual power distribution transformers. It is possible to conclude that the analytical formulation provides satisfactory results for the design of power transformers compared to detailed finite element models. A tool has been designed for this purpose and the main features of it will be described in the paper.

Key words: Electromagnetic forces, power transformer, short-circuit, IEC 60076-5.

1. Introduction

The estimation of the electromagnetic forces inside a power transformer in operation has been the main objective of many technical references [1-3]. Specially, the estimation of their value in short circuit conditions is very valuable in order to design more robust and reliable transformers able to withstand such electromagnetic forces [4-6].

In particular, the IEC standard 60076-5 [1] includes a set of recommendations which are very important in order to design power transformers which are able to withstand short circuit forces. In earlier versions of the above mentioned IEC standard, analytical expressions for the calculation of electromagnetic forces were included, but in the newest version they are not included because the mathematical expressions are only approximations of the real values of the electromagnetic forces.

At present only some limits and thresholds for the forces are included, leaving the estimation of the electromagnetic forces to be carried out using the best method that the interested company has available. There are many manufacturers of power distribution transformers interested in the application of the above mentioned IEC standard, but normally they do not have the required sophisticated tools and sufficient human resources to perform accurate models for the calculation of electromagnetic forces. A tool is needed to complement the design process of a power distribution transformer.

2. Tool Developed: Objectives and Features

The objective of this paper is to describe the process followed for the development of a simple tool oriented to be used by a manufacturer, able to estimate the electromagnetic forces inside a power distribution transformer. The base of this tool is made up of the analytical equations included in earlier versions of the IEC standard 60076-5 [7]. In order to confirm that

Corresponding author: M.A. Sanz-Bobi, professor, research fields: maintenance, diagnosis, fault detection and artificial intelligence. E-mail: masanz@upcomillas.es.

these equations are valid, a comparison was made using two different computational models of the electromagnetic forces due to short circuits in power transformers.

The first model is based on approximate analytical expressions of the electromagnetic forces as they were compiled in earlier versions of the IEC standard 60076-5 and used in some publications such as Ref. [1]. The second model is based on a finite element model of a power distribution transformer using a free software package of finite element analysis for electromagnetic analysis (FEMM, Finite Element Method Magnetics [7]).

The advantage of the first model lies on its simplicity. Hence, it can be easily incorporated into the usual design process of a power transformer by a manufacturer. Moreover, the sensitivity analysis of design alternatives can be undertaken with little effort.

In contrast, the advantage of the second model is its accuracy due to the detailed representation of both the core and windings. The electromagnetic forces are computed using the actual magnetic field distribution throughout the windings.

The next sections of this paper will describe how valid the analytical model is for design purposes. The results of the estimation of electromagnetic forces have been compared for both models in several power distribution transformers. The results obtained have also been compared with others presented in the technical literature ([8, 9]). The main conclusion of the comparative analysis was that the analytical formulation suggested in earlier versions of the standard IEC 60076-5 and other sources ([10, 11]) provides satisfactory results for the design of power distribution transformers compared to detailed finite element models. Once this conclusion was reached, a simple tool was developed coded in Matlab.

A description of the main features of the tool developed will be included in another section of this paper. This tool is very valuable in the design of power distribution transformers, not only to ensure that the limits of the IEC standard are not over-passed, but also to observe how far the design is from these limits.

3. Analytical Model

The IEC international standard for power transformers 60075-5 (third edition 2006-02) in part 5 “Ability to withstand short circuit” identifies the requirements for power transformers to sustain without damage, the effects of overcurrents originated by external short circuits. This standard recommends a procedure in order to conclude if a power transformer could be able or not to withstand a short circuit according to a set of characteristics and design parameters of a power transformer. This third edition canceled and replaced the second edition published in 2000 which included an annex B titled “Calculation method for the demonstration of the ability to withstand short circuit”. However, this annex included a specific analytical model for the calculation of electromagnetic forces that could be useful as a reference to obtain some values required in the current version of the standard. The calculation of electromagnetic forces is based on approximate formulae for the radial and axial forces. This analytical model was described a long time ago in the literature related to the calculation of electromagnetic forces in power transformers such as for example in Refs. [11, 12].

In this paper, the main equations of this analytical model have been reused for the estimation of radial and axial electromagnetic forces in the windings of a power transformer such as those which were included in the previous version of the standard 60075-5 and used by other authors such us Azevedo [9, 10]. These equations have been applied to a set of core-type power distribution transformers in the range between 250 and 1000 kVA.

The approximate formula for the estimation of radial force in a winding of a core-type power transformer is the following:

$$F_r = 1.256\frac{(NI_r)^2}{H_w}\pi D_m 10^{-6}\ [N] \qquad (1)$$

Where:

1.256×10^{-6} is the air permeability [H/m];

N is the number of electrical turns of the winding;

I_r is the r.m.s. value of winding rated current [A];

H_w is the geometrical average length [m];

D_m is the mean diameter of the winding [mm].

When an external short circuit occurs, the first peak amplitude of the current is k*r times higher than the peak of the rated current and in this case the radial force from Eq. (1) for the complete winding during short circuit is the following:

$$F_r = 0.628 \frac{(NI_r)^2}{H_w} \pi D_m r^2 \left(k\sqrt{2}\right)^2 10^{-6} \ \text{[N]} \qquad (2)$$

Where:

k is the asymmetry factor;

r is the over-current factor.

Radial forces that appear in the windings of a power transformer due to the circulation of the current through them cause a tensile stress. The tensile stress has to be lower than that corresponding to the material of the windings in order to be sure that no failure will occur. Using Eq. (1) or (2), it is possible to estimate the mean hoop stress or tensile stress on an outer or inner winding of a core-type transformer. Eq. (3) corresponds to the case of the tensile stress caused in the conductors of a winding due to the radial forces when an external short circuit occurs.

$$\sigma_t = 0.314 \frac{(NI_r)^2}{H_w^2 a} D_m r^2 \left(k\sqrt{2}\right)^2 10^{-6} \ \text{[N/mm}^2\text{]} \qquad (3)$$

Also the current circulating through the windings of a power transformer creates an axial force, but its estimation is more difficult. An approximation of the estimation of the axial force, less rigorous than that used for the estimation of the radial force, is expressed by Eq. (4).

$$F_a = 0.628 \frac{(NI_r)^2}{H_w^2} \pi D_m \left(d_0 + \frac{d_1 + d_2}{3}\right)(2K-1) r^2 \left(k\sqrt{2}\right)^2 10^{-6} \qquad (4)$$

Where:

F_a is axial force [N]

I_r is the r.m.s. value of winding rated current [A];

H_w is the geometrical average length [mm];

D_m is the mean diameter of the pair of windings [mm];

K is the Rogowski factor;

d_0 is the width of the main duct [mm];

d_1 and d_2 are the radial width of winding #1 and 2 respectively (concentric windings) [mm].

Other important equations can be deduced in order to analyze the effect of electromagnetic forces in the windings of a power transformer, but they will not be included here in order to respect the length of this paper. They can be found in the literature previously cited in this section.

4. Finite Element Model

An important question to be evaluated is if the equations of the analytical model presented in the previous section are reasonable approximations to the real values of electromagnetic forces or how far they are from the estimated values.

In order to answer this question a different method has been used to estimate the electromagnetic forces in a power transformer. This alternative method of calculation was based on the use of a finite element model. The creation of this model uses a completely different procedure and could be an interesting method of comparison.

FEMM (Finite Element Method Magnetics) [8], a free software tool, was used to obtain finite element models for several real power transformers. FEMM is only able to create models in 2-D and some approximations are required in order to develop the models. The basic steps required for building the finite element models are the following: definition of geometrical characteristics of the power transformer, creation of the finite element net, assigning of material properties, definition of current sources, definition of boundary conditions, processing and analysis of results.

The finite elements of the active part of the power transformer are based on the use of the Maxwell equations applied to magnetostatics problems establishing a relationship between electromagnetic flux and current density in the finite element [8, 13, 14]. In order to estimate the electromagnetic forces in a power transformer, FEMM has two methods available: Lorentz forces and the Maxwell stress tensor both applied to the finite elements defined previously. The Lorentz forces are obtained using electromagnetic flux and current density circulating through the windings. The Maxwell stress tensor is obtained from the Lorenz forces replacing the current density by the magnetic field.

As an example of an application of the FEMM tool for the estimation of electromagnetic forces in a power transformer, Table 1 presents the main characteristics of a real power transformer analyzed and Fig. 1 shows the electromagnetic density flux in a winding.

The profile of electromagnetic fluxes per winding shown in Fig. 1 is the same as the profiles of radial distribution forces due to the direct relationship between both variables.

Several cases of real power transformers were analyzed using the method of finite elements in the range between 250 and 1000 kVA and finally the instruments to be used to answer the question raised at the beginning of section 4 are available.

The comparison of values obtained for the electromagnetic forces using the analytical model and the finite element model were compared for the power transformers analyzed. As an example, Table 2 shows the results obtained for the case of the transformer described in Table 1.

In all the cases studied the difference between the values obtained for the electromagnetic forces using both methods of estimation never surpassed 10% and for this reason it is reasonable to use the equations of the analytical models because of their simplicity and possibility to be easily incorporated to the usual design process of power transformers. Moreover, the sensitivity analysis of design alternatives can be undertaken with little effort using the analytical model.

Table 1 Characteristics of a power transformer.

Transformer power [kVA]	630	
Number of phases	3	
Percentage of impedance	4%	
	Low voltage winding	High voltage winding
Voltage [V]	420	20.000
Number of turns	20	1650
Mean diameter [mm]	236.5	319.3
Winding height [mm]	340	330

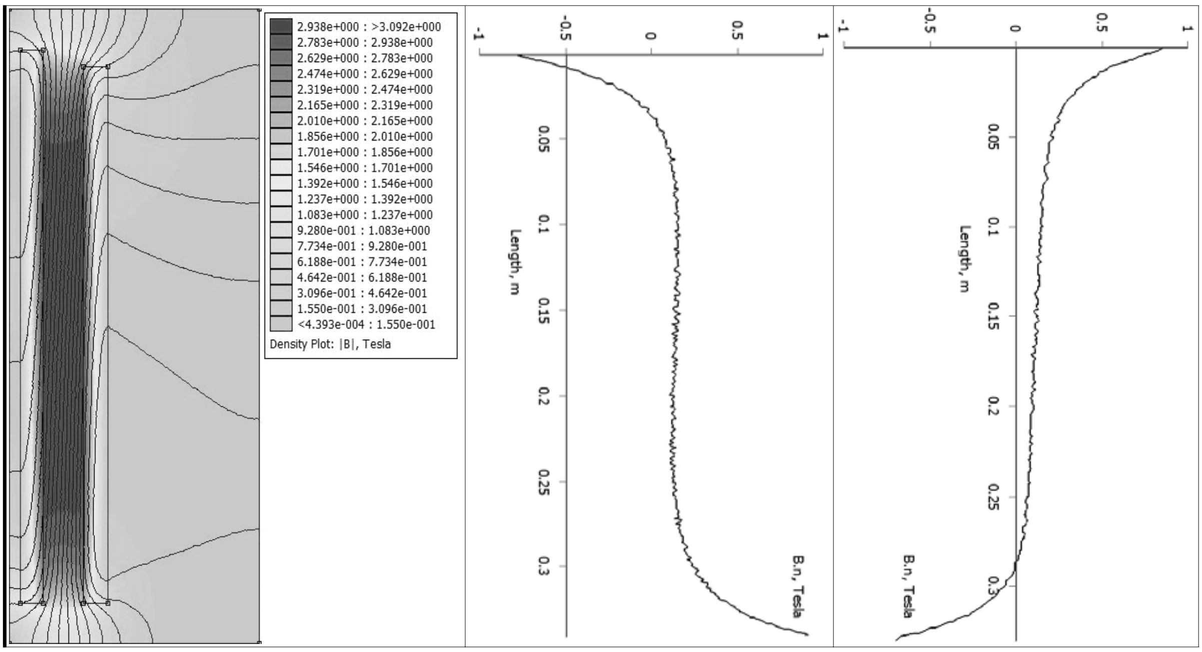

Fig. 1 Electromagnetic density flux distribution along the axes of windings (left) and per low (center) and high (right) voltage windings.

Table 2 Comparison of radial and axial magnitude of the electromagnetic forces.

[kN]	Values obtained from FEMM	Values obtained from analytical model
Radial force-low voltage winding	925	988
Axial force-low voltage winding	85	84
Radial force-high voltage winding	1186	1328
Axial force-high voltage winding	85	84

5. Tool for the Assessment of the Electromagnetic Forces in Power Distribution Transformers

Using the results obtained in section 4, a tool was developed in MATLAB oriented to be used in the design phase of power distribution transformers. This tool was conceived to assess the electromagnetic forces that can appear in a power distribution transformer and how far its design is from the limits recommended by the IEC standard 60076-5 is its current version. The tool developed is an easy and very valuable complement for the manufacturer of power transformers in order to verify the robustness of the transformer designs. The main window of the developed tool is shown in Fig. 2. It shows three main sub-windows that will be briefly described. The sub-window titled "Input Data" presents the characteristics of the transformer to be analyzed. These characteristics are read from the transformer design files prepared by the manufacturer.

Once a transformer is loaded, it is possible to press the button "Estimate Forces" on top of the sub-window "Output Data" in order to proceed to perform all the calculations related to forces and stress in the power transformer.

The sub-window titled "Output Data" can show different kinds of information according to the option selected in the menu "Type of results" located in the bottom of the sub-window. Fig. 2 shows the case of the selection of "Radial stress" in the winding conductors. In this sub-window, normally three types of results are

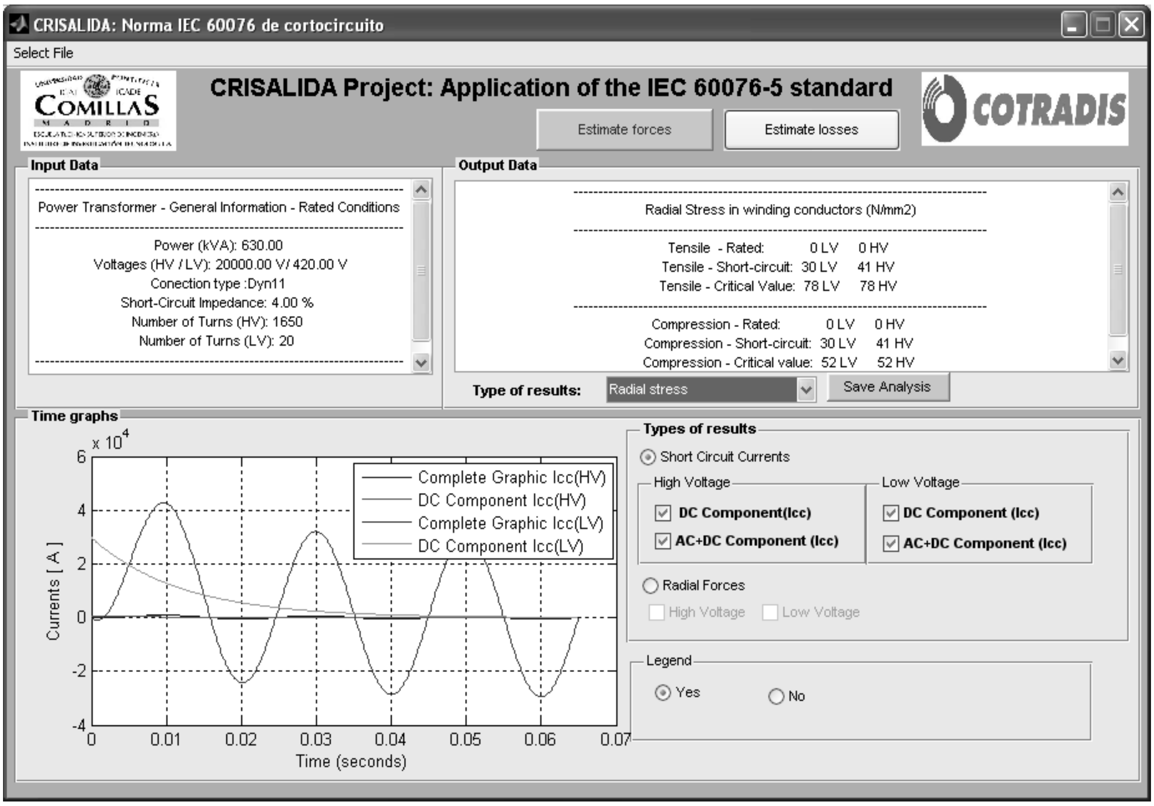

Fig. 2 Main window of the tool for estimation of electromagnetic forces in a power distribution transformer.

presented: estimations for the rated conditions, for short-circuit conditions and the critical values suggested to not be over passed by the current version of the IEC Standard 60076-5. This information can be observed in Fig. 2 for the loaded power transformer.

The sub-window "Time graphs" shows the first cycles for the short circuit currents or alternatively for the radial forces. Fig. 2 shows the selection of short circuit currents for the high and low voltage windings and both components AC and DC. The bigger curves observed correspond to the components AC and DC of the low voltage winding.

6. Conclusions

This paper has demonstrated that the use of the equations proposed by the analytical model included in the previous version of the IEC standard 60076-5 (year 2000 annex B) and published in many different publications can give a reasonable approximation to the values of electromagnetic forces and stresses caused in a power transformer by the current circulation, especially in short-circuit conditions. This is based on good concordance between the results obtained with the analytical model and other tests performed using element finite techniques. The advantage of the use of the analytical model lies on its simplicity. Hence, it can be easily incorporated into the usual design process of a power transformer. Moreover, the sensitivity analysis of design alternatives can be undertaken with little effort. A tool has been developed in order to complement the instruments that are being made available by the power transformer manufactures now in the process of design.

Acknowledgments

This paper has described a part of the research activities developed within the project named CRISALIDA belonging to the program CENIT (part of the program INGENIO 2010) supported by CDTI office inside the Spanish Ministry of Science and Innovation. The authors are grateful for this support.

References

[1] M. Waters, The measurement and calculation of axial electromagnetic forces in concentric transformer windings, Proceedings of the IEE-Part II: Power Engineering 101 (1954) 35-46.

[2] J.H. Harlow, Electric Power Transformer Engineering, CRC Press, 2007.

[3] B.H.E. Limited, Transformers, McGraw-Hill, 2004.

[4] K. Najdenkosk, D. Manov, Electromagnetic forces calculation on power transformer windings under short circuit, The International Journal for Computation and Mathematics in Electrical and Electronic Engineering 17 (1998) 374-377.

[5] Y. Liu, S. Wang, X. Meng, J. Qiu, B. Feng, C. Wei, et al., Kinetic characteristics of transformer windings under short circuit condition, International Journal of Applied Electromagnetics and Mechanics 33 (2010) 457-464.

[6] Y.Q. Tang, J.Q. Qiao, Z.H. Xu. Numerical calculation of short circuit electromagnetic forces on the transformer winding, IEEE Transactions on Magnetics 26 (1990) 1039-1041.

[7] IEC 60076-5 Ability to withstand short circuit, current version (2006), and Annex B Calculation method for the demonstration of the ability to withstand the dynamic effects of short circuit, in version (2002).

[8] Finite Element Method Magnetics, available online at: http://femm.foster-miller.net/wiki/HomePage.

[9] A. de Azevedo, I. Rezende, A. Delaiba, J. de Oliveira, B. Carvalho, H. de Bronzeado, Investigation of transformer electromagnetic forces caused by external faults using FEM, in: Transmission & Distribution Conference and Exposition, Latin America, 2006.

[10] A.C. Azevedo, A.C. Delaiba, J.C. Oliveira, B.C. Carvalho, H. de S Bronzeado, Transformer mechanical stress caused by external short-circuit: A time domain approach, in: Internacional Conference on Power Systems Transients (IPST'07), Lyon, France, 2007.

[11] G. Bertagnolli, Short-Circuit Duty of Power Transformers, 2nd ed., ABB Trasformatori, Milano, Italy, 1998.

[12] K. Karsai, D. Kerenyi, L. Kiss, Large Power Transformers, Elsevier Science Ltd., 1987.

[13] D. Meeker, Finite Element Method Magnetics–User's Manual Version 4.0, available online at: http://femm.foster-miller.net/.

[14] S. Jamali, M. Ardebili, K. Abbaszadeh, Calculation of short circuit reactance and electromagnetic forces in three phase transformer by finite element method, in: Proceedings of the Eighth International Conference on Electrical Machines and Systems 2005, ICEMS 2005, 2005, Vol. 3, pp. 1725-1730.