TOWARDS THE EFFICIENT REFRIGERATION OF TRANSFORMER SUBSTATIONS BY MEANS OF COMPUTATIONAL FLUID DYNAMICS

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ABSTRACT

The use of simulation tools has allowed companies to streamline their new product development processes reducing both cost and time-to-market. However, these virtual experimentation tools can be too complex and time consuming to be used by designers - that usually need a quick answer to compare and contrast different design solutions. This drawback is especially important when CFD (Computational Fluid Dynamics) is used to calculate the natural (non-forced) convection of a fluid, such as the oil inside an ONAN (Oil Natural Air Natural) distribution transformer or the air circulating in a transformer substation during the temperature-rise test.

To address the situation described above, a customized simulation tool has been developed with the aim of reducing the computational cost that would require a model with the complete geometrical description. As a consequence both time-to-experiment and knowledge acquisition cost are reduced.

INTRODUCTION

Transformer substations (TS) are used for electrical power distribution in public networks and private installation load-centres. These buildings are usually made of prefabricated concrete, having a personnel access and some ventilation grilles. Inside the enclosure, one or two distribution transformers with their Low Voltage (LV) boards, Medium Voltage (MV) cubicles, and interconnecting and auxiliary devices are found. In the transformer and the LV boards there is heat generation due to power losses occurring in the conversion of the distributed electrical energy from MV to LV for domestic and industrial applications. This heat must be removed by the natural convection flow of air that enters and leaves the substation through the ventilation grilles and by the radiation exchanges with the walls of the substation.

The International Standards [1-2] indicate that the criterion of good performance of a TS is given by the maximum temperature reached by the top oil of the transformer. This temperature must be limited to extend the operation life of the transformer. As the experimental tests must be done with the real substation, an above limit temperature would invalidate the already built substation, requiring a new design and a modification of the enclosure casts. In order to avoid this slow and expensive "build-test-fail" design procedure, it would be very useful to have a mathematical model of the ventilation of the TS able to determine the temperatures in the design stage prior to the experimental tests.

Fig. 1. Ormazabal's Transformer Substation

TEMPERATURE-RISE TEST

As stated above, the purpose of this test is to check that the design of the prefabricated substation enclosure operates correctly and does not impair the life expectancy of the substation components[1]. In particular, the test shall demonstrate that the temperature rises of the transformer inside the TS enclosure do not exceed those measured on the same transformer outside the TS enclosure more than the value which defines the TS enclosure class, in the studied cases 10 K, i.e. a maximum increment of 10 ºC.

[1] The rate of ageing doubles for every increment of 6 K of the winding hot-spot temperature. According to IEC 354 [3].

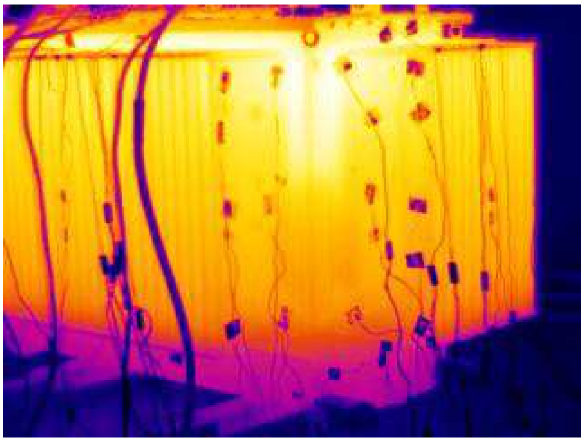

Fig. 2. Temperature-rise test over a distribution transformer (thermographic image)

MODELS OF THE VENTILATION OF TRANSFORMER SUBSTATIONS

Simplified models

One of the first models of the ventilation of a TS that can be found in the literature is the one of Menheere [4]. This is a very simplified model that uses one equation for the heat transferred to the ventilation air and another equation for the heat dissipated through the walls of the substation, and results can be used only as a "rule of thumb" in the design stage of a TS because the model does not give the enclosure class of the substation required by the Standard [2].

Dynamic network models

Another possible approach to the thermal modelling of TS is the transient equivalent thermal circuit model developed by Radakovic and Maksimovic in [5]. This model is based on a short number of characteristic temperatures inside the TS and it relies on some parameters whose values have to be determined by means of experimentation for each new design. The same authors in [6] present an improvement of the model including solar irradiation and wind velocity. Besides, Iskender and Mamizadeh in [7] use the same methodology but improving the previous models by considering the variation with time of the thermal resistances and capacitances of the top-oil, of the ventilation air and of the different components of the substation enclosure. However, these dynamic network models can not analyse and optimise the performance of a TS in the design stage in order to determine the enclosure class.

Differential equations based models

There are other types of mathematical models based on a more exhaustive description of the mass and heat transfer phenomena taking place in a flow domain under the restriction of some conditions imposed in its boundaries, i.e. by means of differential equations, that are able to deal with design and optimisation objectives. To solve these differential equations there are different numerical techniques that can be employed.

For example, Loucaides et al. [8] use the Finite Element Method (FEM) to solve the energy and the Navier-Stokes equations in a flow domain corresponding to the air inside a TS. The model is used to analyze the influence of the aperture of the ventilation grilles, the transformer load and the ambient temperature in the air temperature distribution inside the substation. Other works in this sense are the ones by Ramos et al. in [9, 10], where they develop a differential model of the ventilation (air circulation and heat transfer) of a half-buried [9] and underground [10] TS solved by means of the Finite Volume Method (FVM). Both models yield the enclosure class of the substations and allow an analysis of the air velocity and temperature distributions.

CFD SIMULATIONS

The FVM is applied to discretize the differential equations (Navier-Stokes and energy equations) of the mathematical model using a segregated implicit solver to solve the generated algebraic equation system. Equations are linearized and then sequentially solved using the Gauss-Seidel algorithm accelerated by an Algebraic Multigrid method. The pressure-velocity coupling is achieved through the use of the SIMPLE algorithm. Diffusive terms of the equations are discretized using a second-order centred scheme, and the convective terms are discretized using a second-order upwind scheme. A body force weighted scheme is chosen in the discretization of pressure to deal with this buoyancy-driven flow. All this numerical procedure has been implemented in the unstructured CFD code Fluent V.6.3.

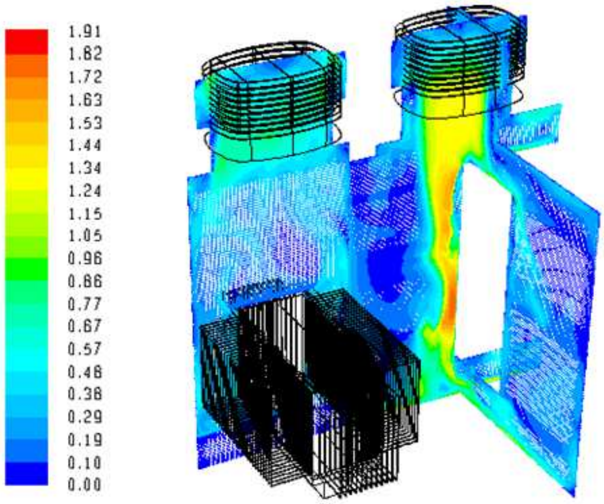

Fig. 3. Velocity vectors coloured by velocity magnitude in m/s at two perpendicular planes. Simulation of the temperature-rise test over a transformer substation.

On the one hand, CFD models provide results that can be obtained neither experimentally nor with other types of models: the air flow pattern and temperature distributions, the air mass flow rate or the heat transfer coefficients on the transformer surfaces. On the other hand, the principal handicap of these differential models is the high computational resources that are needed to perform a single simulation and the long time period that is required to obtain results.

ZONAL THERMAL MODEL

To deal with the former drawback, all the information obtained from the simulation of the differential models can be used to develop an intermediate level model, the approach known as zonal modelling [11-12], that requires less computational resources and simulation time, so as to allow its implementation in a software tool oriented to the design and optimization of the thermal performance of TS.

This methodology has been successfully applied to the modelling of the cooling of distribution transformers by Gastelurrutia et al. In [13] they develop a detailed numerical model of the movement by natural convection of the oil inside distribution transformers and, based on the oil flow and temperature patterns obtained, they produce in [14] an algebraic zonal thermal model that can be used for design and optimization purposes. References [13, 14] describe how to build a zonal thermal model of the ventilation of TS which lower computational resources and easier to implement in a design-oriented software.

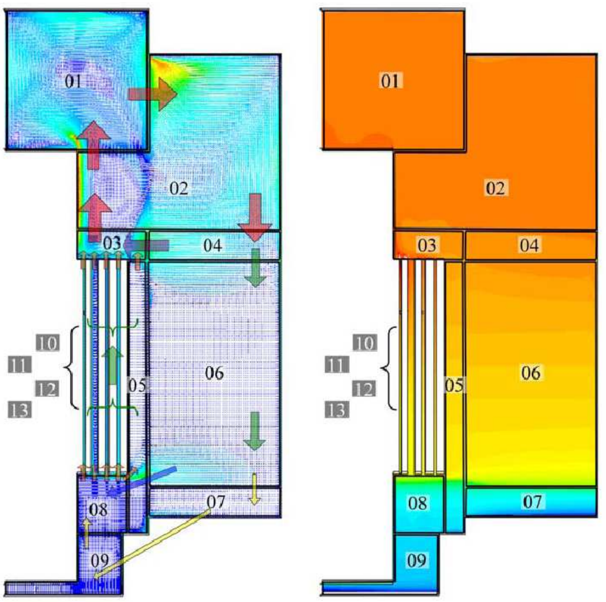

Fig. 4. Definition of the control volumes of the zonal model of the transformer based on the mass flow interchanges (left) and oil temperature distribution (right) in the differential model [13-14]

The usage of the zonal models has allowed the parametrization of the most typical designs of both transformers and TS enclosures.

CUSTOMIZED SIMULATION TOOL

The mathematical zonal model has been implemented in a software application[2] to check its real performance. The customized simulation tool can calculate the thermal behaviour of the transformer both inside and outside the TS in order to assess the enclosure class.

The input to the model consists of the ambient temperature, the most relevant geometrical characteristics of both the transformer and the TS, and finally, the power losses that are generated in conjunction with their distribution. The main output of the model consists of the top oil temperature rise (from outside to inside the TS), along with the rest of the model temperatures, pressures, mass flow and heat flux distributions.

There are three resolution types for the zonal model:
1) The calculation mode: The model is solved for a specific geometry of the transformer and the TS.
2) The redesign mode: An objective top oil temperature value is prefixed. The objective is achieved by means of changing the geometric parameters of the transformer and the TS.
3) The optimisation mode: In this case the objective function to be minimised can be the cost of the transformer. As in the previous mode, the top oil temperature is fixed.

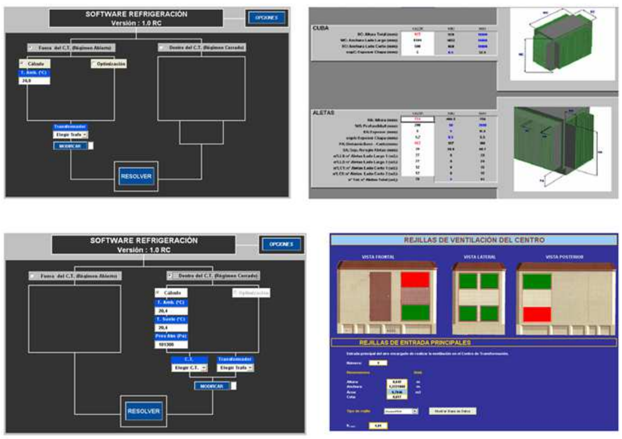

Fig. 5. Overview of the customized simulation tool

Whilst the CFD of a whole electric substation natural ventilation can take 4 weeks, with the customized simulation tool it is possible to assess one design in just 20 minutes.

[2] The Microsoft Excel® spreadsheet has been selected, with its built-in Solver®.

Once the more promising designs are detected, they are assessed by means of CFD models and physical testing to achieve the optimized final solution.

VALIDATION

The devised simulation tool has been validated, during a long virtual-physical correlation process that has lasted 8 years (2005-2012), by comparing the numerical results with the experimental ones obtained for different TS, distribution transformers and power losses.

For example in [10], the ventilation by natural convection of two underground TS has been numerically modelled and validated with the experimental results of eight temperature-rise tests carried out under different conditions of ventilation and transformer power losses. Afterwards, there is a further validation comparing the CFD model results with the zonal model ones, such as [14], checking that the correlation is accurate enough for design purposes.

CONCLUSIONS

The developed customized simulation tool has proven to be an efficient tool that can be used to study the natural convection of the oil inside distribution transformers and the ventilation of transformer substations, allowing the improvement and optimization of the designs from a thermal point of view. The customized simulation tools allow designers to check different design solutions quickly and cost-efficiently, speeding up the designers´ learning curve by means of reducing both time-to-experiment and the knowledge acquisition cost [15-17].

REFERENCES

[1] IEC 60076-2:1997: Power Transformers. Part 2: Temperature Rise, second edition, IEC Standard, 1997.

[2] IEC 62271-202:2006: High-voltage switchgear and controlgear. Part 202: High voltage/low voltage prefabricated substations, IEC Standard, 2006.

[3] IEC 354: Loading Guide for Oil Immersed Power Transformers, 2nd Edition, 1991.

[4] W. M. M. Menheere, 1995, "Transformer stations and natural ventilation", CIRED 13th International Conference on Electricity Distribution, Brussels (1995) Paper no. 1-23.

[5] Z. Radakovic, S. Maksimovic, 2002, "Non-stationary thermal model of indoor transformer stations", Electrical Engineering 84 (2002) 109-117.

[6] Z. Radakovic, S. Maksimovic, 2009, "Dynamical thermal model of oil transformer placed indoor", CIRED 20th International Conference on Electricity Distribution, Prague (2009) Paper no. 0304.

[7] I. Iskender, A. Mamizadeh, 2011, "An improved nonlinear thermal model for MV/LV prefabricated oil-immersed power transformer substations", Electrical Engineering 93 (2011) 9-22.

[8] N. Loucaides, Y. Ioannides, V. Efthymiou, G. E. Georghiou, 2010, "Thermal modeling of power substations using the finite element method", 7th Mediterranean Conference and Exhibition on Power Generation, Transmission, Distribution and Energy Conversion, 7-10 November 2010, Agia Napa, Cyprus, Paper no. MED10/188.

[9] J. C. Ramos, A. Rivas, and J. M. Morcillo, 2005, "Numerical thermal modelling of the natural ventilation of a half-buried transformer substation using CFD techniques", R. Bennacer (Ed.), Progress in Computational Heat and Mass Transfer vol. II, Lavoisier, Paris, 2005, pp. 929-934.

[10] J. C. Ramos, M. Beiza, J. Gastelurrutia, A. Rivas, R. Antón, G. S. Larraona, I. De Miguel, 2013, "Zonal thermal model of distribution transformer cooling, Numerical modelling of the natural ventilation of underground transformer substations", Applied Thermal Engineering 51 (2013) 852-863.

[11] M. Musy, E. Wurtz, F. Winkelman, F. Allard, 2001, "Generation of a zonal model to simulate natural convection in a room with a radiative/convective heater", Building and Environment 36 (2001) 589-596.

[12] J. Stewart, Z. Ren, 2003, "Prediction of indoor gaseous pollutant dispersion by nesting sub-zones within a multizone model", Building and Environment 38 (2003) 635-643.

[13] J. Gastelurrutia, J. C. Ramos, G. S. Larraona, A. Rivas, J. Izagirre, L. del Río, 2011, "Numerical modelling of natural convection of oil inside distribution transformers", Applied Thermal Engineering 31 (2011) 493-505.

[14] J. Gastelurrutia, J. C. Ramos, A. Rivas, G. S. Larraona, J. Izagirre, L. del Río, 2011, "Zonal thermal model of distribution transformer cooling", Applied Thermal Engineering 31 (2011) 4024-4035.

[15] J. R. Otegi, L. Del Río, 2010, "Simulation as an Innovation Trigger – Three Pills for Creativity and Decision Making", International Research Conference. Fachhochschule Dortmund, Jun 2010.

[16] L. Del Río, J. R. Otegi, 2010, "Towards a New Paradigm to Unlock the Potential of Virtual Experimentation. Simulation as the Innovation Vector", XXII NAFEMS North America Conference – 2020 Vision of Engineering Analysis and Simulation, Nov 2010.

[17] L. Del Río, J. R. Otegi, 2011, "How simulation can address product innovation through knowledge. The Simulation-Driven Knowledge Paradigm", XXII ISPIM Conference (The International Society for Professional Innovation). Hamburg, June 12-15, 2011.