ANALYSIS OF THE IMPACT OF THERMAL EXCHANGES IN HV/LV PREFABRICATED SUBSTATIONS WITHIN A GLOBAL ECO-DESIGN APPROACH

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ABSTRACT

The purpose of this paper is to show how the AREVA T&D group deals with the problems posed by the different thermal exchanges affecting HV/LV transformer substations, using tests and simulation tools. In addition, an eco-assessment will enable an understanding of the environmental impact of the final choice, depending on the materials used.

INTRODUCTION

The design trends for HV/LV transformer substations have already been presented [1]. They are not keeping pace with international concern about sustainable development. This concern is reflected in standard IEC 62271-202, which introduces modifications with respect to IEC 61330. The first thermal exchange is the temperature rise of the transformer which is of great interest to customers and manufacturers wishing for greater product reliability. Their qualification, enabling demonstration of their performance, is defined within a precise standard framework. But these performance levels, which are challenged by the environment in which the transformer substations will be installed, require the greatest attention if they are to achieve this maximum lifetime.

An overview of the standard and functional framework will be followed by temperature readings of the different materials with respect to outside temperatures. An enclosure class definition aid tool, corresponding to the temperature rise of the oil in the distribution transformer will then be presented, enabling definition of the input data of another tool, which fully complies with IEC 60076-7 for assessing transformer ageing. On this basis, an eco-analysis will provide a better understanding of certain materials used in the transformer substation enclosure.

The measurements and simulations presented were compared with the results provided by the "Pléiade" and "Comfie" software packages which incorporate 30 years of climatological data, including solar radiation, and can simulate the thermal behaviour of complex buildings.

TEMPERATURE RISE IN HV/LV TRANSFORMER SUBSTATIONS

Standardization

The service temperatures of transformer substations are described in the conditions of service [2], which are those given in IEC 60694, 40 °C max. over 24 hours, except for extreme climates, where the range is from -50 °C/40 °C for cold climates and -5 °C/+50 °C for very hot climates. Solar radiation of 1000W/m² can be taken into consideration. More details concerning solar radiation conditions and temperatures can be found in standard IEC 60721-2-4 and the test methods are in IEC guide 60068-2-9. These climatic conditions affect the ambient temperature of the enclosure. This is also linked to the calories given off by the transformer and the low-voltage distribution board, as well as the enclosure temperature rise class defined in IEC 62271-202, which goes from 5 to 30K in steps of 5K. This class of enclosure affects the transformer temperature rises defined in IEC 60076-2 for dielectric fluid transformers and in IEC 60076-11 for dry type transformers. The final temperature rise is involved in the ageing assessment of oil transformers defined in IEC 60076-7.

Functional aspect

The functional diagram in Figure 1 illustrates the different interfaces of a transformer substation and highlights the advantages of taking thermal exchanges into account.

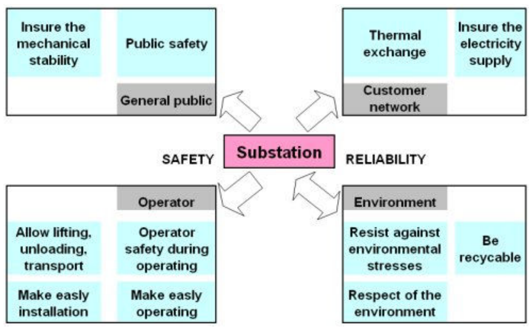


Figure 1. Functional diagram of HV/LV substation

The safety aspect having been dealt with in [1], reliability and sustainable development are then described with an initial presentation of outside temperature readings made on transformer substations.

Analysis of enclosure behaviour

The temperature readings below were taken in the south of France between August and September 2006 on enclosures without electrical switchgear. The aim was to learn more about the behaviour of the enclosures to check the consistency of equations used in simulating inside and outside enclosure temperatures. The readings were taken from the same model of enclosure made of different materials, one from Glassfibre Reinforced Concrete (GRC) and the other from metal. This enabled temperature peaks to be displayed in °C with a moving average over 30 values to smooth the measurements made every minute for each of the enclosures in Figure 2.

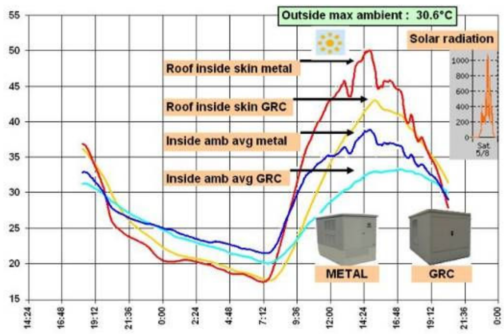


Figure 2. Measurements of temperatures for the same enclosure with two different materials

The solar radiation indication is taken from the same geographical area for the same period, from a meteorological site. The peak difference of less than 2 °C over 24 hours can be eliminated by giving both materials the same thermal stability, for example by producing a fine air current between the two metal skins, thereby avoiding the use of another insulating material that might interfere with eco-design analysis. The GRC station has a 10 cm thick roof and 4.5 cm thick walls. The metal station is made from 15/10mm sheets. As a reminder, the thermal conductivity coefficients λ at a temperature of 20 °C are 1 to 1.2 W/mK for the GRC, 0.4 to 1.8 W/mK for concrete of and between 47 to 58 W/mK for steel. The two transformer substations are exactly the same colour due to measurements on metal surfaces which give 10°C as a highest difference between dark colour (RAL 6013) and light colour (RAL 1015).

Additional measurements using a pyranometer were made on the same GRC enclosure to validate the correlation of temperatures and radiation. This is shown in Figure 3. The solar radiation signal is affected by noise interference due to cloud movements. This noise is completely eliminated on sunny days.

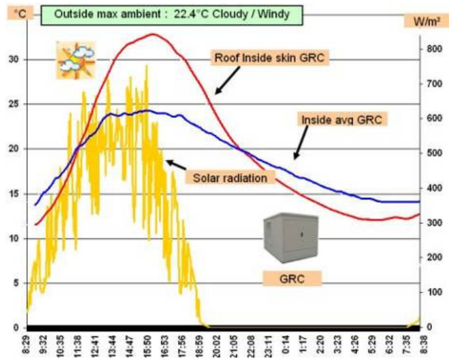
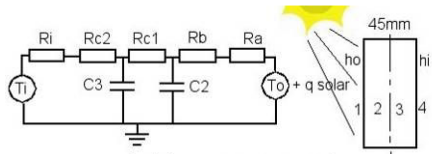


Figure 3. Measurements of solar radiation on GRC

It was therefore possible to verify the findings using a mathematical model. The model used was a standard thermal conduction model, the equivalent electrical diagram of which is shown in Figure 4. Surface resistances hi and ho as a function of surface orientation, the density, specific heat, coefficient of absorption, and thermal conductivity as a function of the material, were integrated into the model.



$$T(i,p+1) = \left(\frac{\Delta t}{C_i}\right)\cdot\left(q_i + \sum_j \frac{T(j,p) - T(i,p)}{R(i,j)}\right) + T(i,p)$$

Figure 4. Equivalent mathematical model

The initial assumptions made were based solely on the effect of heat from outside on a room with no opening. In this example, the outside temperatures in the shade correlated with those measured on the meteorological site were 13.3 °C min and 22.4°C max for the first day. The simulation tool enabled instantaneous modification of the dimensional, thermal and temporal parameters, whereas the stability coefficients for solving the equation above were evaluated automatically. The result of behaviour simulation on the same enclosure is shown in Figure 5. The model produced can be associated with another enclosure class simulation tool.

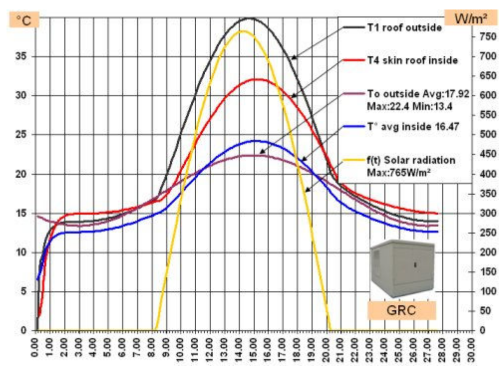


Figure 5. Results of the simulation

Transformer substation ventilation computing tool

Principle

The temperature rise tests required to determine the class of the enclosure of a transformer substation is a mandatory stage in the IEC qualification process. However, this class is determined at constant temperature in a laboratory where the thermal exchanges by conduction varies with the type of materials used, the behaviour of which may be reversed in the event of outside use. In addition, the use of the same enclosure for different calorific losses, different load factors and different climates around the world, requires a simulation tool capable of providing the best possible solution to the different problems facing customers and manufacturers.

The tool performs a dynamic simulation that provides an overall assessment of conduction-related heat balances and calculates the class of enclosure on the basis of the convection model. It is also capable of optimizing surfaces according to a fixed maximum temperature or class constraint.

Calculation principle

The principle is based on the theories of thermodynamics where, according to Bernoulli's Law:

$P_{TS} - P_{TE} = P_M - P_R$ where P_T is total pressure, P_M is driving pressure, P_R is resistive pressure, S is the outlet and E the inlet. The total pressure P_T, expressed in Pa, is composed of: $P_T = P_S + \rho.V^2/2 + \rho.g.z$, where P_S is static pressure, $P_D = \rho.V^2/2 = \rho.Q_V^2/(2.S_R^2)$ is dynamic pressure, which gives the kinetic energy, and $P_G = \rho.g.z$ is the gravitational pressure, which gives the potential gravitational energy. Taken together, this gives the final equation :$(P_S+\rho(T_S).V_S^2/2+\rho(T_S).g.z_S) - (P_E+\rho(T_E).V_E^2/2+\rho(T_E).g.z_E) = P_M - P_R$

The draft pressure corresponds to the weight difference between two columns of air of unit section. For example, for two columns of air of height H, one being at temperature T_C and the other at temperature T_F with $T_C > T_F$, the draft pressure between these two air columns will be: $P_M = (\rho(T_F)-\rho(T_C)).g.H$. Based on this, a definition of the temperatures and gauge heights required for the calculations is shown in Figure 6 and a diagram of the variations in pressure for each zone of the transformer substation is shown in Figure 7.

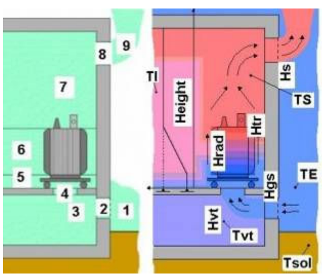


Figure 6. Temperature distribution.

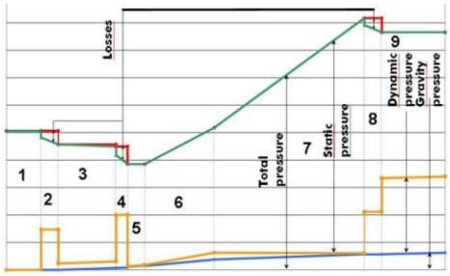


Figure 7. Substation pressure analysis.

This gives a looped calculation model that stabilizes when:

_The mass air flow at the inlet is equal to the mass air flow at the outlet, as there is neither production nor accumulation of air inside the transformer substation.

_There is a balance between the losses waiting to be discharged by convection after the heat balance by conduction and the sum of the losses of the transformer and other components dissipating heat in the transformer substation. The transfer function is shown in Figure 8.

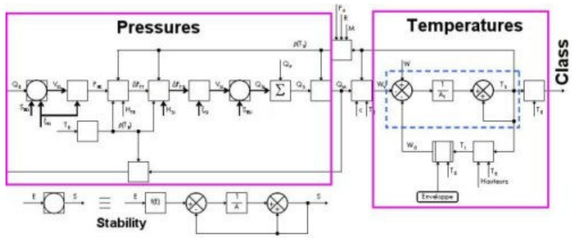


Figure 8. Transfer function

Additional tests

Additional tests were required to check the tool described above, in particular the temperature rise of the air in the enclosures and changes in class depending on the material selected for an equivalent perimeter. Figure 9 shows the temperature readings during investigation tests carried out on a transformer substation with an area of 5.4 m² and height of 2.3m, 1.5m of which was above the ground, with a 2m² metal opening roof and a transformer of 9400 W losses associated with a low-voltage installation of 1700 W of additional losses.

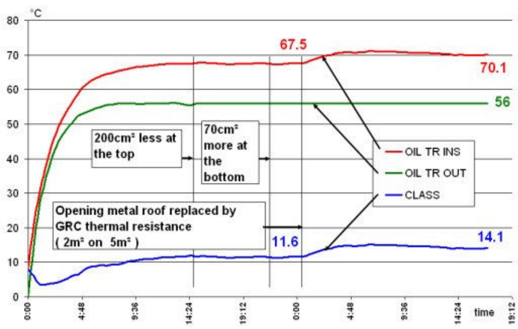


Figure 9. Metal roof effect

It is to be noted that there is a class loss of 2.5 K simply by cancelling the effect of the metal roof, of which 1 K results from the alignment of the thermal resistance of the metal roof with that of the GRC. Now, let us try to understand by simulation what happens with outside use compared to laboratory conditions.

Example

A complete simulation of the supplied transformer substation subjected to solar radiation was carried out for a 630 kVA transformer, with an 85% load, i.e. 5636 W losses with 800 W provided by the low-voltage board. The enclosures were class 10 according to IEC. The ventilation computing tool estimated the classes at 6.6 K for the steel substation and 7.1 K for the GRC substation, which would give a temperature rise of the air of approximately the double of the class, so 14 °C according to IEC 60076-7 subclause 8.3.2. With solar radiation the temperature rise goes from 14° to 17 °C/18°C, as shown in Figure 10.

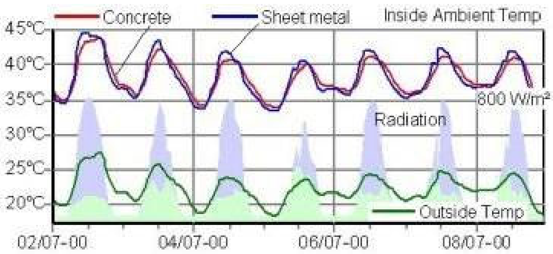


Figure 10. Pleiade simulation

The temperature difference between the two enclosures, when convection is taken into consideration, goes to 1.5 °C max. over the week and to 1 °C over the year, or a min. of 0.5 K of oil temperature rise in continuous service. This shows that a minimum variation of 1 K can be found between behaviour of an enclosure in the laboratory and its actual behaviour according to design.

Calculation of transformer ageing

The above-mentioned tools were essential for an understanding of what has been demonstrated in this chapter. A complete simulation tool of IEC 60076-7 shows how important it is to learn the load factors of the distribution network and pass them on to manufacturers. All the simulations were carried out using the coefficients and calculation methods defined for distribution transformers (<2500 kVA) and not for power transformers.

Let us consider the 630 kVA transformer with 6500 W + 1300 W losses, a 0.85 In load and an average outside temperature of 22 °C to resume the previous simulation, with all this equipment in a class 10 enclosure. Ageing would be 0.21 day/day without an enclosure, rising to 2.1 days/day with a class 10 enclosure, and to 2.2 days with sinusoidal temperature. A combination of load factors in which the pre-load is 0.85 and the average is also 0.85, reveals different ageing. Ageing is 6.2 days/day at constant temperature, 6.8 days/day for a sinusoidal temperature and 7.1 days if this is phase-shifted to coincide with the load peak shown in Figure 11, which rises to 8.9 days/day if we take an additional 1 K on the class of enclosure compared to what has been demonstrated previously.

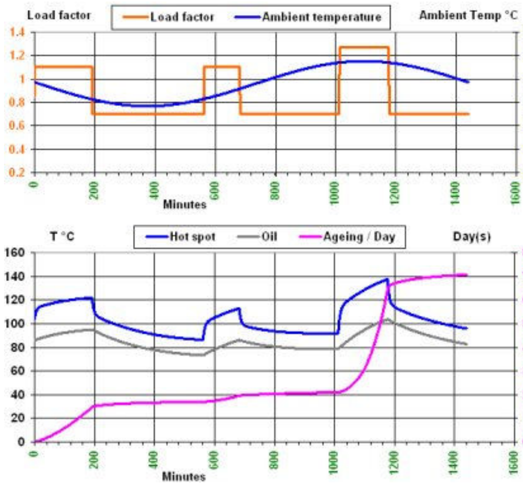


Figure 11. IEC 60076-7 simulation tool

This is why it is useful to have modified the step of enclosure classes in IEC 62271-202 to improve adaptation to ambient temperatures and fine tune the ageing assessment. An example of an enclosure in service since 2003, which corresponds to a new class of 5 K type, is shown in Figure 12, in which 1.2 kw/m² was allowed for in the customer specification [3].

Figure12. Substation Class 5 12kW as losses /24kV IAC 16kA1s.

ECO-ASSESSMENT

The different types of materials used in the enclosure, together with their thickness and coatings, contribute to the safety and lifetime of the transformer substation. These are the criteria examined here.

Safety

Before going into the details of the eco-assessment, it is important to note that the criteria governing fire reaction were modified in the new standard IEC 62271-202 to improve adaptation to construction materials and to limit the impact of proximity in case of fault.

Sustainable development

The following simulations were carried out using the SIMAPRO software package, which is better suited to transformer substations as it enabled complete modelling of the concrete and GRC composition as well as the working of the sheet metal used in the metal station. The cases covered only concerned the enclosures of the transformer substations examined in this article, because the impact of the switchgear used will be the same for each case. Recycling and the type of transport used were taken into account. The method used by SIMPAPRO is "CML 2 baseline 2000/World" with the assumption that the energy resources are those used for a product made in the European zone. Obviously, the relevance of this type of study is determined by the accuracy of the software data and the particular attention paid to the units. The materials used were reinforced concrete (m = 8.9Tonnes), metal fiber-reinforced concrete (7.2T), Glassfibre Reinforced Concrete (6.2T) and steel sheet (1.5T) for equal function. It emerges from the study that as eco-toxicity criteria are proportional to weight, concrete is penalized with respect to its strength and the distance of road transport involved. However, without recycling, metal transformer substations will always be the least preferred, regardless of the mode of transport and the distance involved. However, if recycling is taken into account, and with more than 6000 km of road transport, they become more efficient when assessed on the basis of most of the criteria in Figure 13. Road transport replaced by sea transport of 10,000 km is shown in Figure 14. In conclusion, GRC remains more cost-effective than other materials, in spite of the penalty of the cement content.

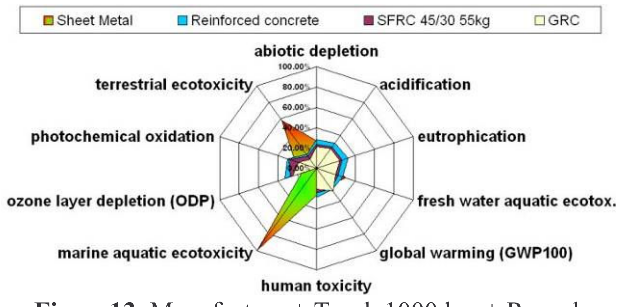


Figure13. Manufacture + Truck 1000 km + Recycl.

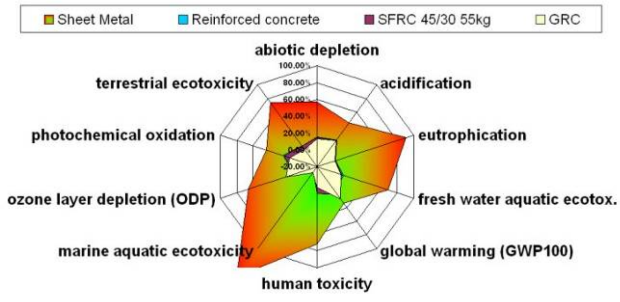


Figure14. Manufacture + Ship 10000 km + Recycl.

CONLUSION

When complying with the IEC qualification descriptions of HV/LV transformer substations, the two main materials used for the construction of the enclosures produce efficient substations. Sinusoidal temperatures and load factor cycles must be taken into consideration to understand ageing behaviour. Classifying enclosures in 5 K rather than 10 K steps makes more allowance for load factors and mean ambient temperature, while ignoring minor variations. Finally, eco-assessment has become an obligatory part of the choices to be made during the development of a transformer substation with respect to attainable markets.

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