ACCELERATED AGEING FOR A MV/LV DISTRIBUTION TRANSFORMER EQUIPPED WITH OPTIC FIBERS

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ABSTRACT

This paper aims to demonstrate the distribution transformer lifetime consumption under the outdoor service conditions and under variable load. During this test, all the data have been recorded in real time. The link between the transformer ageing and chemical indicators in oil has also been analyzed.

INTRODUCTION

Temperature takes a key role in the initiation and/or the activation of the ageing mechanisms of transformer insulation. This study consists on an experimental and a simulation analysis of the thermal behaviour of a 160 kVA MV/LV transformer. The hot spot temperatures of the windings are measured by optical fibers sensors; the different values of load rate and ambient conditions throughout the experiment are also continuously recorded. The study continues with the analysis of the deterioration of winding insulation and the oil. The properties of mineral oil are characterized by samples taken throughout the test. The correlation between the degradation of the oil and the cellulose insulation is used to estimate the loss of the physicochemical properties of paper in the transformer, which is generally regarded as a key indicator of transformer ageing.

EXPERIMENTAL TECHNIQUES

AREVA T&D has provided a MV/LV transformer, a PSS substation and all data mining equipment (Figure 1). The transformer supplies an adjustable tri-phase load and it is equipped with sensors to measure different temperatures. Data from a meteorological station, which is dedicated to temperature measurements surrounding the substation, is collected by a communication system allowing the weekly data broadcast.

AREVA 160 kVA MV/LV transformer

The principal characteristics of the transformer are resumed in the Table 1.

Rated voltage MV/LV (V)	20000 / 410
No-load losses/load losses (W)	381 / 2923
LV winding	Foil of aluminium
MV winding	Wire of copper
Weigh and type of oil (kg)	168 kg / Taurus Nynas
Cooling mode	ONAN

Table 1 Principal charactheristics of the transformer

Figure 1: Transformer and load in the substations

Data measurement and transmission

Measurements of weather conditions, such as wind, solar radiation, ambient temperature, humidity, are carried out by the meteorological station and the load's current is controlled by current transformers. In order to measure directly the temperature in a such "real scale" experiment, 12 optic fiber sensors were installed in the transformer core (see Figure 2). The transformer is equipped with sensors to measure temperature both outside and inside the tank.

The PSS substation is equipped with PT 100 sensors measuring the temperatures at different places, for example, the fresh air and the outgoing air at the ventilation gates.
The measurements are performed each minute and the programmable automate makes an average arithmetic at the last fifteen minutes. The system allows two months of data storage and each week 16,800 data are transmitted. The TCPIP communication protocol allows the dataset transfer via a mobile device to an email address and/or could be then directly accessed by a web page. This last option allows instantly data consultation, averaged and not averaged.

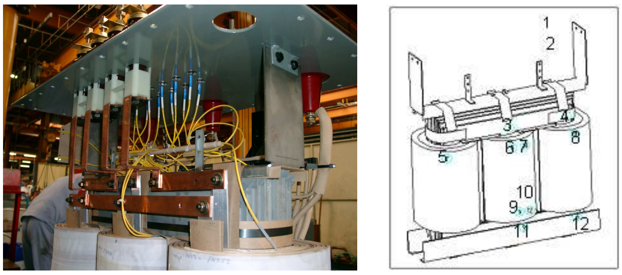

Figure 2: Location of the optic fiber sensors

INFLUENCE OF THE SUBSTATION TO THE TRANSFORMER THERMAL BEHAVIOUR

Due to its installation in the substation, the heating and the winding temperature of the transformer, which is of ONAN cooling mode, increase from 5K to 30K. These increases, depending on the load (and the overload) and the external environment conditions, have significant impact on the transformer's lifetime. In our experiment, the 160 kVA transformer is installed in a class 10K enclosure.

In one hand, this test allows the verification of the transformer behaviour and, in the other hand, to check the ability to predict the thermal behaviour. The simulation tools presented at the CIRED 2009 [1] have been used in the test for this goal. In this case, we compute the behaviour of the enclosure by using the dynamic simulation tool "Pléiade + Comfie", the input data being outdoor temperatures and solar radiation. The outgoing temperature of this thermal calculation is injected into the ageing simulation. With this tool, the time constant of the enclosure has been defined using this previous tool and the temperature data of the hottest week as shown in Figure 3.

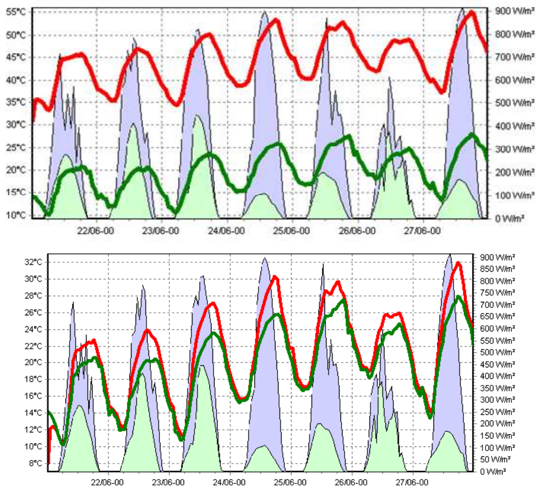

Figure 3: Dynamic thermal simulation with and without transformer losses

To determine the impact of the irradiance, we use the simulation tool in order to compare the difference between the fresh air temperature (in green) and the ambient temperature in the enclosure (in red), with and without solar radiation. Figure 4 shows that 4K are brought by irradiance in June.

To take into account this effect, the impact of the class of the enclosure has been added to the ageing simulation tool. It allows to obtain a dynamic ageing simulation as shown on **Figure 4**.

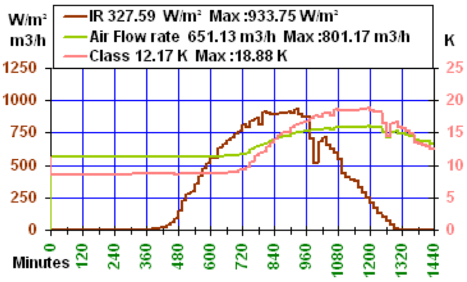

Figure 4: Dynamic enclosure temperature rise class

Figure 5 shows the result obtained by comparing the measurement and the simulation of the temperatures of incoming air and those of the oil and the windings. The blue curves are the results of this simulation, the measurement ones are in brown. In order to improve the obtained results, we should take into account the real aspect of the substation (S-E for example) and the wind.

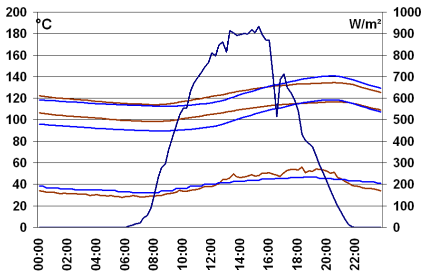

Figure 5: Measurements and simulations comparison

THERMAL BEHAVIOUR OF THE TRANSFORMER

First, temperature-rise tests, according IEC 60076-2, were performed on the alone transformer, then on the transformer inside the PSS substation. For both, the applied loads were of 80%, 100% and 120% of the rated power.

The results show that in the MV/LV transformer, the exponent coefficients of top-oil (x) and winding (y) are different from those given in the IEC 60076-2 and IEC 60076-7. For example, the top-oil exponent was found with a value of 0.72 instead of 0.80. Fortunately, for the ageing simulation, these values have no influence because we use the measured temperatures for the ageing calculations.

The repeated simulation of the same load, for various environmental conditions, showed that under given conditions of sunshine and wind, the thermal response of the transformer is putting back due to the different time constants of the substation and of the transformer.

Figure 6: Thermal behaviour of the transformer

Figure 6 shows the evolution of the measured temperatures with load steps from 65% to 100%, during the month of April 2008. Notice that, during a daily temperature cycle, there are also changes according to ambient temperature variations.

The fiber optic sensors showed that the difference between the average heating and the hot spot is very small in case of a LV winding in foil. The temperature vertical distribution is much more uniform in this case than with a LV layer one.

TRANSFORMER AGEING AND ITS CHEMICAL INDICATORS

The loading guide IEC 60076-7 takes an assumption that above 98°C, the ageing doubles for an increase of 6 K, with a Kraft paper of 105°C thermal class. Considering that while the hot spot temperature of windings is 98 °C, it gives an ageing rate equal to unity. The instantaneous ageing rate can be then computed by the following formula:

$$(V = 2^{(\theta_h - 98)/6}). \qquad (1)$$

The lifetime consumption L, within an period from t_1 to t_2 can be thus computed as:

$$L = \int_{t1}^{t2} V(t)dt \qquad (2)$$

This lifetime consumption L is given in normal day (Figure 7).

In our study case, the experiment lasted 21 months of real loading and the transformer insulation has consumed 5,374 days of life which is equivalent to 14.7 years of "normal life at the rated power". To speed up the ageing, many overload cycles were applied giving very high operating temperatures exceeding the maximum limits of IEC 60076-7 and it lasts for much longer periods than the prescribed ones.

The continuous recording of winding temperatures and the mineral oil sampling makes possible the periodic monitoring of the oil ageing and the determination of degradation indicators of the insulation. At the end of the experiment, the active part of the transformer was off-tank and the coils were unwounded. Insulating paper and oil are sampled for the final state analyzing, said "end of life" of the transformer.

The regular mineral oil sampling shows that the oil keeps its good dielectric properties such as breakdown voltage, dissipation factor, resistivity, permittivity and its correct chemical properties such as acidity and corrosiveness. Any anomalous variation of the water content has been shown. It indicates that there is no loss of the hermetic seal of the tank. All these parameters confirm that the transformer is in correct operating state and it is not subjected to any serious fault.

The insulation ageing study has be focused on the variation of the following properties:

- Concentration of dissolved gases in oil: H2, CO2, CO, CH4,
- Concentration of furan compound: 2-FAL.

This choice is based on the recommendations of IEC 60599[2,3].

The Figure 7 presents the variation of theses parameters during the 21 months of experiment. The computed loss of life is also placed on the same figure to show the relation between the ageing and its chemical indicators.

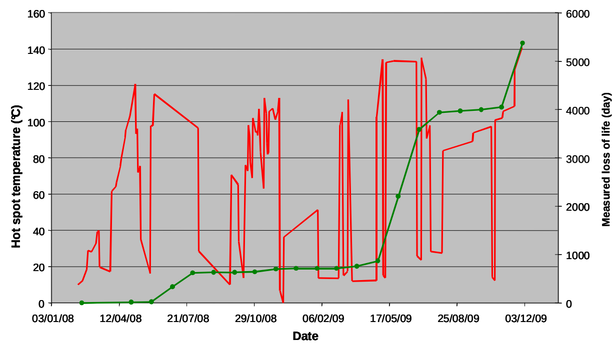

Figure 7: Measured loss of life according to the hot spot temperature

During the experiment, the transformer has been subjected to three periods of overload (summer 2008, summer 2009 and autumn 2009), resulting in three rapid increases in the computed loss of life. The oil samples taken during these periods of high temperatures show a significant increase of dissolved gases and 2-FAL concentration.

Between September 2008 and April 2009, the hot spot temperature and the temperature of the dielectric liquid varied from 65°C to 80°C for 3 months, 98°C to 110°C for 2 months and 1 week from 110 ° C to 122 ° C.

The various samplings and tests have shown that the measured insulation degradation has slowed down. The amount of gas produced by the chemical reactions is not enough to compensate the micro leakages or the chemical recombinations. Actually, there is a decrease in the concentration of all observed gases on the Figure 9 (March 2009). These gas losses or loss of information can influence the relevance of the analysis based on the absolute concentration of dissolved gases. In comparison with typical values mentioned in IEC 60076-7, it is noted that the dissolved gas concentrations have all exceeded the recommended standard values but there is no abnormality in the ratios of these concentrations.

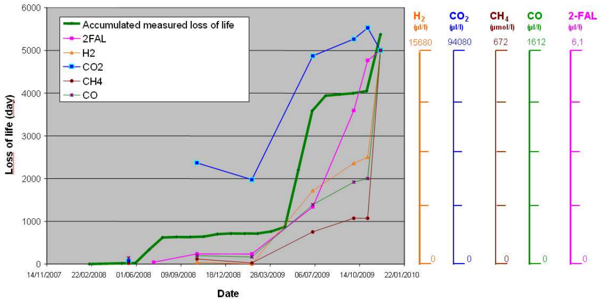

Figure 8: Variation of the oil properties and the measured loss of life

For a more quantitative estimation of the degradation level of cellulose insulation (DPm), we can base on the formula of "Chendong"[4]:

$$DPm = \frac{\log_{10}(2FAL \times 0.88) - 4.51}{-0.0035}$$

The computed results of the DPm by using this formula are presented in Figure 9. In this figure, the computed model consistently described the transformer ageing : DPm varies from 800 to 200 while the cumulative consumption of transformer lifetime goes from 0 to 14.7 years.

DPm of paper		
Phase A	Phase B	Phase C
276	268	242
Oil : non-corrosive, none of dissolved metal		
2-FAL (mg/kg)	H_2O (mg/kg)	Acidity (mg KOH/g)
6.9	17	0.13

The PDm measured on the paper samples, which are collected from the phases A, B, C, are respectively 276, 268 and 242.

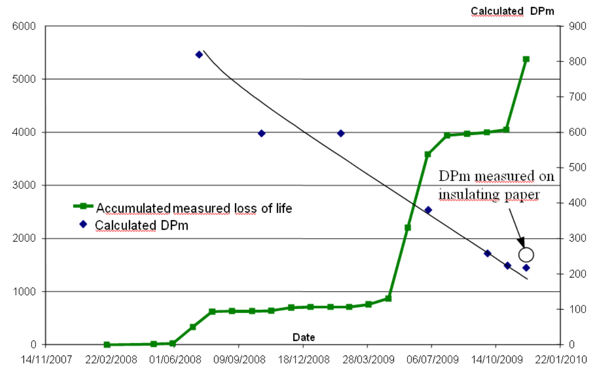

Figure 9: Computed loss of life and DPm

These measurements confirm in a qualitative way the validity of the formula "Chendong" which gives a DPm value of 216 for the transformer end of life. By using this formula, the concentration of 2-FAL dissolved in the transformer oil can be a relevant indicator of the transformer ageing.

CONCLUSIONS

The in-situ temperature measurement made in "real scale" experiment requires significant logistics preparation but it reveals great understanding about specific thermal behaviour of the MV/LV transformer and its involved ageing.

The temperatures of the transformer are not only directly linked to the load and to the ambient conditions but also resulted from environmental phenomena such as solar radiation, which accounts for additional 4-5 K. Also, the wind could temporarily disturb the flow of cooling air.

In this experiment, a regular temperature monitoring has been carried out thanks to the optic fiber sensors. This temperature monitoring, added to the use of a dynamic simulation tool, allow the simulation of the transformer lifetime consumption. It also allows to verify the link between the variation of numerous chemical indicators dissolved in oil and the transformer lifetime consumption.

One of the most important result in this study is the verification of the formula Chendong. A quantitative evaluation of the cellulose DPm can be made from the 2-FAL content dissolved in oil. Actually, the final results show that the 2-FAL could be a pertinent and a very practical indicator to evaluate the MV/LV transformer thermal ageing.

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