THERMAL BEHAVIOR OF DISTRIBUTION TRANSFORMERS IN SUMMERTIME AND SEVERE LOADING CONDITIONS

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ABSTRACT

This report refers to the results of a study performed to individuate some appropriate thermal models to supervise the performance of oil-immersed distribution transformers of the European Standard series, installed in the basement of residential buildings, during summertime when temporary severe overload conditions can occur.

INTRODUCTION

In the hottest weeks of the year, distribution power transformers installed in the basements of residential buildings may be submitted to temporary overloads when the ambient temperature reaches the highest values.

The overload conditions are mainly related to the strong increase in the use of air conditioners, while the highest ambient temperatures occur because of the difficulties encountered in dissipating the heat produced by the losses by means of air circulation.

These temporary operating conditions are limited to no more than two or three weeks per year and therefore the substitution of the transformers with other units of greater size may be not economically justified. Moreover, in large cities some difficulties may occur in programming a complete transformer rotation in a short time.

A situation as described above was encountered in Milan during the summer of 2005, when several emergency conditions occurred because of the particularly warm season. In the metropolitan area more than 5000 MV/LV transformers substations are located in residential buildings and emergency conditions interested, last year, some tens of units.

With the aim to give a rational answer to the problem, a study has been promoted to individuate the best criterion for the transformers operation, admitting, if the case, an abnormal thermal life consumption but avoiding environmental risks of fire and oil spreading.

APPROACH TO THE PROBLEM

As the thermal life of a transformer depends on the temperature of the winding hot-spots, special attention was paid to individuate an appropriate thermal model of the windings that allow a sufficient accurate evaluation of such hot-spots for any possible loading conditions.

In principle, the temperature of the hot-spots can directly measured by means of adequate thermal sensors installed inside the tank, in particular on the windings, but these devices are too expensive for justifying their regular installation.

The problem can be solved in a more simply way controlling the load and/or the top oil after having individuated a transformer thermal model that allows to relate these quantities to the hot-spot.

For each transformer series, the model can be defined starting from knowledge of the losses dissipated in the transformer, how these losses are distributed inside the windings and how the produced heat is transmitted to the ambient.

Temperature-rise tests carried out according to the standard procedure are also useful to determine some basic thermal characteristics of the transformers.

An accurate evaluation of the ambient temperature variations in each installation site is also necessary.

THERMAL MODEL FOR DISTRIBUTION TRANSFORMERS

The thermal model for distribution transformers can be derived from that proposed by the IEC loading guide for oil-immersed transformers for ONAN cooling system.

Considering the transformer at rated power in steady state conditions, the relation that gives the hot-spot temperature-rise is the following:

$$\Delta\theta_{HS} = \Delta\theta_{OT} + H \cdot G$$

where:

- $\Delta\theta_{HS}$: hot-spot temperature-rise [K]
- $\Delta\theta_{OT}$: top oil temperature-rise [K]
- G : thermal gradient between winding and oil average temperatures [K]
- H : hot-spot factor

The graphical model of the function is given in figure 1. The construction of the model can be obtained from the results of a temperature-rise test during which the measurements of top and bottom oil temperature-rise, as well as of the average winding temperature-rise, are performed. The hot-spot factor may be obtained experimentally by means of thermal sensors mounted in the windings where the maximum temperature is expected, or indirectly studying the leakage flux field.

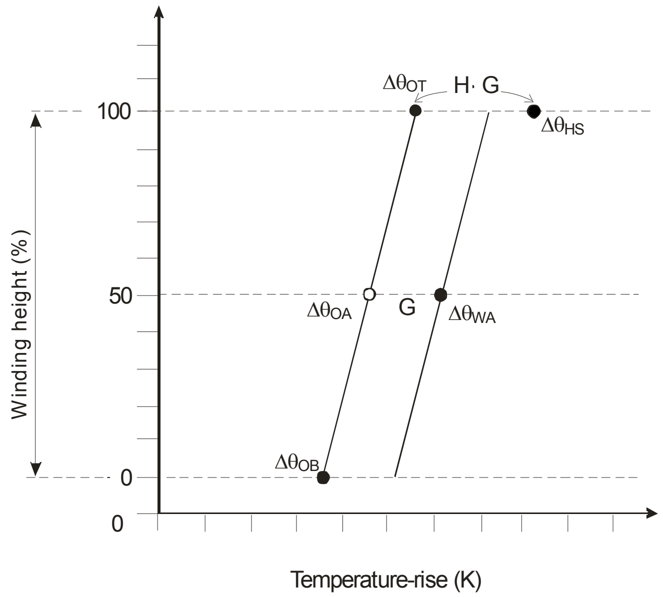

Figure 1 - Temperature-rise distribution model for ONAN cooling systems

$\Delta\theta_{HS}$: hot-spot temperature-rise; $\Delta\theta_{OT}$: top oil temperature-rise; $\Delta\theta_{OA}$: average oil temperature-rise; $\Delta\theta_{OB}$: oil temperature-rise at the bottom; $\Delta\theta_{WA}$: average winding temperature-rise; G: thermal gradient between winding and oil average temperatures; H : hot-spot factor.

Determination of the model parameters

The main parameters can be obtained from a conventional temperature-rise test performed with the modalities stated by the IEC standard in force. [1]

The top oil temperature (θ_{OT}) is directly measured by means of thermal sensors placed in the pocket and the average temperature of the windings (θ_W) is obtained by resistance variation.

The average oil temperature (θ_{OA}) can be conventionally evaluated with the relation:

$$\theta_{OA} = \frac{\theta_{OT} + \theta_{OB}}{2}$$

where:

- θ_{OT} : top oil temperature (pocket)
- θ_{OB} : bottom oil temperature measured on the tank.

The average thermal gradients between windings and oil are the difference between the winding average temperature (θ_W) and oil average temperatures (θ_{OA}).

The different temperature-rises are then obtained subtracting the ambient temperature from the measured temperatures.

The parameter that asks for special considerations is factor H. It was estimated by a special temperature-rise test with some thermal sensors placed inside the windings to allow the direct measurement of the hot-spot temperatures.

The leakage flux field was preliminarily investigated to individuate the regions where the highest specific losses were expected and to limit the number of sensors to be used.

Ambient temperature

The transformer overloading capability also depends on the ambient temperature that in the basement of residential buildings is difficult to maintain in summertime within reasonable limits because of the difficulties to dissipate the heat produced by the losses.

Knowledge of the ambient temperature trend in the critical periods as a function of the time and possibly of the transformer load, should be estimated.

Hot-spot temperature as function of load and ambient temperature

According to the rules proposed by the IEC loading guide, for distribution transformers the following exponents should be used for reporting the temperature-rises to different load conditions [1]:

- top oil exponent: 0,8
- gradient exponent: 1,3

Therefore the complete formula for steady state conditions that gives the hot-spot temperature as a function of the load and ambient temperature is the following:

$$\theta_{HS} = \Delta\theta_{OT} \cdot \left(\frac{P}{P_R}\right)^{0,8} + H \cdot G \cdot \left(\frac{I}{I_N}\right)^{1,3} + \theta_A$$

where:

- θ_{HS} : winding hot-spot temperature [°C]
- P : total losses for the considered load condition [W]
- P_R : total losses at rated current [W]
- I : current at the considered load condition [A]
- I_R : rated current [A]
- θ_A : ambient temperature [°C]

TEMPORARY SEVERE OVERLOADS IN SUMMERTIME

The aspects to be considered are: environmental risks and thermal life consumption.

As far as the risks of fire and oil spreading are concerned, it is sufficient that the hot-spot temperature never exceeds that of the oil flash point. According to the standard on insulating mineral oil, this temperature is not lower than 145°C, so that a limit of 135°C may be reasonably admitted. [2].

Regarding thermal ageing of the insulation systems, the

following basic rules were considered:
- a conventional thermal life of 25 years when operating continuously at 98°C;
- a temperature increase of 6 K halves the thermal life duration (Montsinger law);
- thermal transients disregarded as the overload durations is normally greater than the transformer thermal constants.

Therefore the thermal life consumption associated to each operation in overload conditions can be easily estimated by the following simplified relation:

$$V = \frac{A_\theta}{A_{98}} = 2^{(\theta-98)/6}$$

where:
- V : relative thermal ageing for a generic temperature θ
- A_θ : ageing rate for a generic temperature θ
- A_{98} : ageing rate at 98 °C (reference value).

The above function is also shown in figure 2.

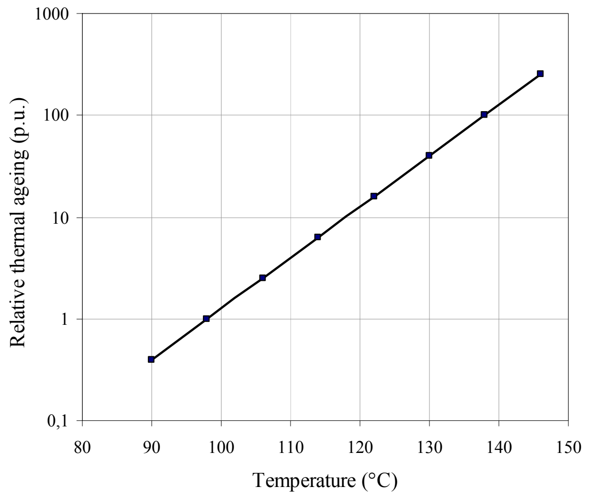

Figure 2 - Relative thermal ageing as a function of temperature

EXAMPLE OF APPLICATION

For the example, reference was made to distribution transformers with the low voltage winding in copper foil for 24 kV systems. In table 1 some characteristics are given for transformers largely used in Italy and installed in the basements of residential buildings. The attention was concentrated on a 630 kVA transformer that, in principle, for the same operation conditions, should suffer the most severe thermal stresses.

Leakage flux field study

The leakage flux field was investigated by means of a two-dimensional finite element program that allows to estimate the maximum punctual current density in the conductors and therefore to individuate where the highest specific losses are located. The leakage flux map given in figure 3 shows that the deviations of the leakage flux pattern are located at the winding extremities.

Table 1 – Characteristics of the transformers

Rated power [kVA]	Load loss at 75 °C [W]	No-load loss [W]	Short-circuit impedance [%]
250	2750	530	4
400	3850	750	4
630	5600	940	6

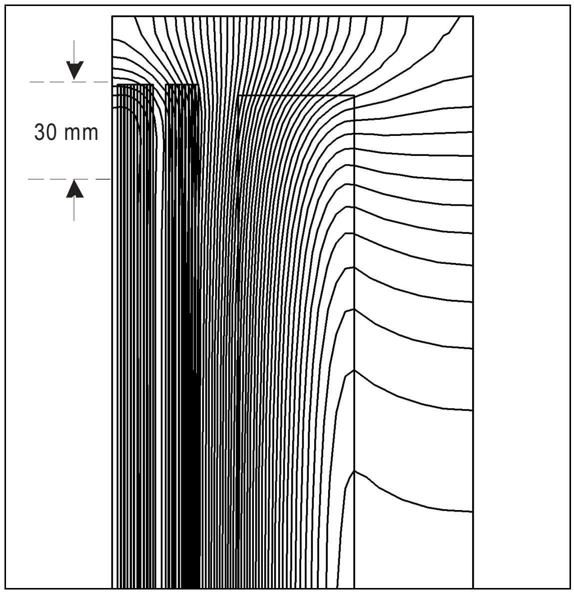

Figure 3 - Leakage flux map of the 630 kVA transformer

The additional loss is of secondary importance for the high voltage winding that is made with small circular conductors, while a different situation occurs on the low voltage winding made with foil conductor. According to the results of the field study, the highest specific losses are located in the first 30 mm and they have been estimated in about 2 times the $I^2{\cdot}R$ loss. Consequently, the winding top area is supposed to be affected by the highest temperature. Some explorations made on smaller transformer sizes confirmed practically the same field distribution, but the specific losses resulted a little lower (for a 250 kVA unit, the specific losses at the winding top was about 1,6 times $I^2{\cdot}R$ loss).
It is noted that the method does not take into account the eventual effects of the winding connections.

Temperature-rise test

The test was performed on a transformer on which an average winding temperature-rises around 65 K was expected (limit prescribed by the standard in force) as this criterion is useful when of the installed transformers only the rated power is known and it can be admitted that the temperature-rise does not exceed that value. [3]

During the construction, in the upper of the windings a number of optical thermal sensors were mounted taking into account the results of the leakage flux field calculations (figure 4).

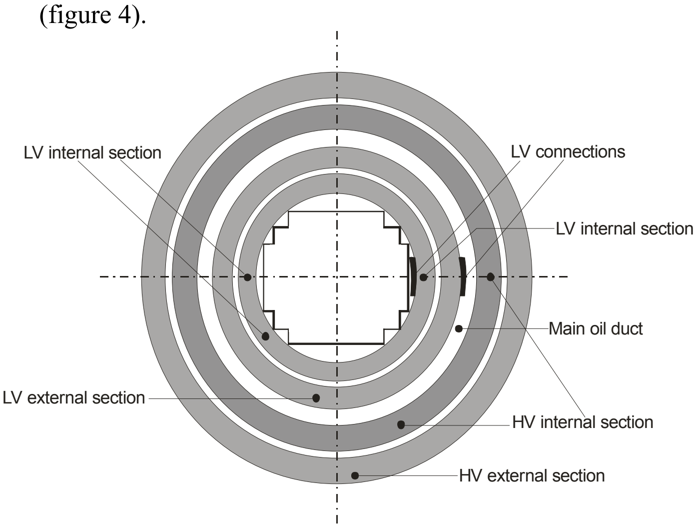

Figure 4 – Position of the optical fiber sensors mounted on the 630 kVA transformer

The measurements of pocket oil, tank waves and ambient temperatures were carried out in accordance with the rules indicated in the standard, by means of other appropriate sensors.

The average temperatures reached by the windings were determined by resistance variation.

The results obtained by the test are summarized in table 2. By these results it was possible to determine the terms $H \cdot G$ of the thermal model that resulted of 19.9 K and the hot-spot factor that resulted of about 1.25.

It was also possible to determine the overload conditions for which the LV winding hot-spot reaches the limit of 135°C (or other conventional value) and, at the same time, the corresponding pocket oil temperature, as functions of ambient temperature (figure 5).

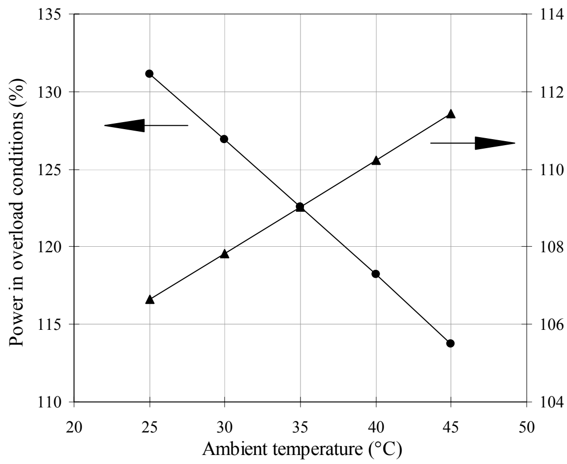

Figure 5 – Admitted overloads and oil temperature as functions of ambient temperature

It is therefore possible to evaluate the admissible overload through the top oil and ambient temperatures, quantities that can be easily detected on site.

The results obtained on the 630 kVA transformer can be practically extended to the other units mentioned in table 1 as it is expected they should operate at a less severe hot-spot temperature.

Table 2 – Results of the temperature-rise test

Quantity	Measuring unit	Results	Admitted limits
Pocket oil temperature-rise	K	55,4	60
LV winding average temperature-rise	K	64,4	65
LV winding hot-spot temperature-rise (1)	K	75,3	78
HV winding average temperature-rise	K	65,0	65
Oil temperature-rise at the top of the main vertical duct	K	67,3	-
Oil temperature-rise at the exit of the tank waves	K	41,5	-
Average oil temperature-rise	K	48,5	-
LV winding average thermal gradient (G)	K	15,9	-
HV winding average thermal gradient	K	16,5	-
H Hot spot factor	-	1,25	
(1) Highest measured value			

Table 3 – Equivalent life consumption as a function of the hot-spot for continuous overload

Hot-spot temperature [°C]	135	130	125	120
Overload duration (days)	Equivalent thermal life consumption (days)			
7 (1 week)	504	287	161	91
14 (2 weeks)	1008	574	322	182
21 (3 weeks)	1512	869	483	273

Thermal life consumption

The evaluation of thermal life consumption during summer overload periods can be made in a simplified way choosing a conventional duration of the periods during which the hot-spot temperature as a constant and defined value.
Using the relation discussed above, some calculations were done considering different period durations and some hot-spot temperature.
The results obtained, expressed in equivalent number of days of normal consumption, are summarized in table 3.
For example, considering a three weeks operation period with a permanent hot-spot of 135°C, the equivalent life consumption results of 21x 72 = 1512 days, that is about 4 years. This period reduces to about 1,3 years if the hot-spot temperature is 125°C.
In the case of daily cycling operation, the life consumption can be evaluated integrating the consumption of any typical time interval.
As the considered exceptional service conditions are expected once per year and for no more than two years, that is the time necessary to undertake the necessary actions (transformer substitution or different load distribution), the problem is if the corresponding life consumption can be accepted or not from an economical point of view.

SOME OPERATION RULES

The results of the study described above allow to individuate a few simple rules for the management of the transformers when temporary summertime overloads occur. The rules depend on the loads and other economical conditions.
The first condition, is to respect the hot-spot should not be exceeded for safety reasons.
In principle, the hot-spot control can be based on power overload or temperature of top oil.
As far as the ambient temperature is concerned, the simpler approach is to individuate for each interested substation a reference value that could be, for example, the mean value of the hottest two or three hours expected during the considered period.
For the transformers of the considered series (table 1), the limit value of the two functions can be obtained using the diagram of figures 6 and 7, starting from the reference value of the ambient temperature.

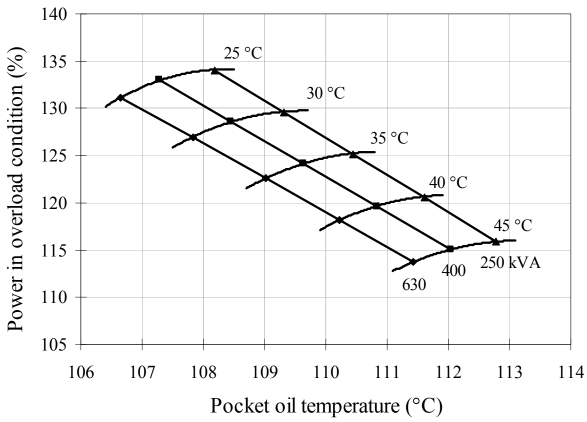

Figure 6 – Relation between overload and pocket temperature for different transformers size at 135 °C hot-spot

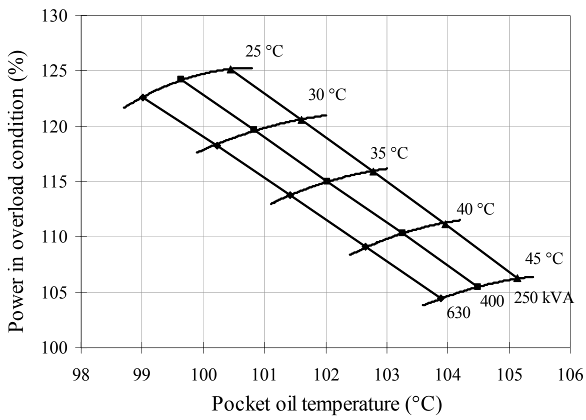

Figure 7 – Relation between overload and pocket temperature for different transformers size at 125 °C hot-spot

CONCLUSIONS

On distribution transformers installed in the basements of residential buildings, some exceptional overload conditions can occur for short periods in summertime, because of the unexpected fast increase of the air conditioner diffusion.
The study at which this report refers to, was aimed to evaluate the overloads that should not be exceeded for maintaining the winding hot-spot within reasonable limits for safety reasons and thermal life consumption.
The work was supported by a study on the leakage flux field and by a special temperature-rise test performed on a typical distribution transformer monitored with optical fiber sensors, that allow to define an acceptable thermal model.
As far as the overload limits, some criteria are given for controlling that the hot-spot temperature does not exceed a pre-established value, not above 135°C.
The control of the hot-spot can be done through the

transformer load or the top oil temperature, quantities that can be easily recorded in service.
The thermal life consumption for any possible operation condition can be evaluated using the well known Montsinger law.
As a hot-spot temperature of 135°C maintained for three weeks may produce an equivalent life consumption of about 4 years, some economical evaluation of the consequences of overload reiteration should be made.
As the distribution transformer conceptions does not differ considerably, with some precaution the reached conclusion could be easily generalized.

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[2] IEC 60296/2003: Fluid for electrotechnical applications – Unused mineral insulating oils for transformers and switchgear
[3] IEC 60076-2/1993: Power transformers – Part 2: Temperature-rise (under revision)