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THERMAL PERFORMANCE OF POWER TRANSFORMERS : THERMAL CALCULATION TOOLS FOCUSED ON NEW OPERATING REQUIREMENTS

by

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SUMMARY

For a generator transformer or sub-station unit, the operating conditions are very different. They lead to specific thermal performance requirements as regards to either ageing aspect or overload. The evolutions of the electricity market have introduced new needs for technical and economic optimisation generally leading to operate the equipment in a different way or for a longer period of time.

At the same time the manufacturers have made progress in thermal design control. They have developed new calculation tools based either on simple analytical methods or thermal modelling.

This report illustrates with several examples the new needs of users and the calculation tool progress made by manufacturers enabling them to master all these evolutions.

Transformer - Overload - Ageing - Modelling - Specification - Design - Optic fibre

1. ISSUES OF THERMAL PERFORMANCE CONTROL FOR SYSTEM AND POWER COMPANIES

1.1. Sub-station Transformers on RTE's Transmission Network

The power transformers and auto-transformers account for approximately 10% of the permanent assets of RTE. It is thus significant to optimise their use in order to differ purchase and installation from additional transformers or to avoid the replacement of existing transformers by more powerful equipment. Two types of events are taken into account to decide to increase the capacity of transformation :

- **technical event** : It corresponds for example to the unavailability of one transformer, which may result in transmitting the maximum power flow of the substation through a reduced number of transformers. Severe climatic conditions are not taken into account in this case. In such a situation one authorizes the transformers to be overloaded for a long duration with a current limited to Ild, or for a short duration, limited to Is. This degraded mode is generally noted "N-1 situation".
- **climatic event** : It corresponds to the supply of the maximum power, which may be called during a cold spell of winter, all the network being available. In this mode, noted "N situation", one considers that each apparatus forwards only its rated current Ir.

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The choice of Ild and Ir values is essential to optimise the park of transformers. The definition of the loading limits for substation transformers used currently within RTE today, was carried out in the Sixties. Indeed several normative evolutions came at that time: in 1962 French standard NFC 52-100 brought to 75 K (against 70 K before) the maximum temperature rise of the hottest spot in steady state operation at rated current. In addition the IEC loading guide published in 1968 limited the hot spot temperature during exceptional transient overloads at 140°C.

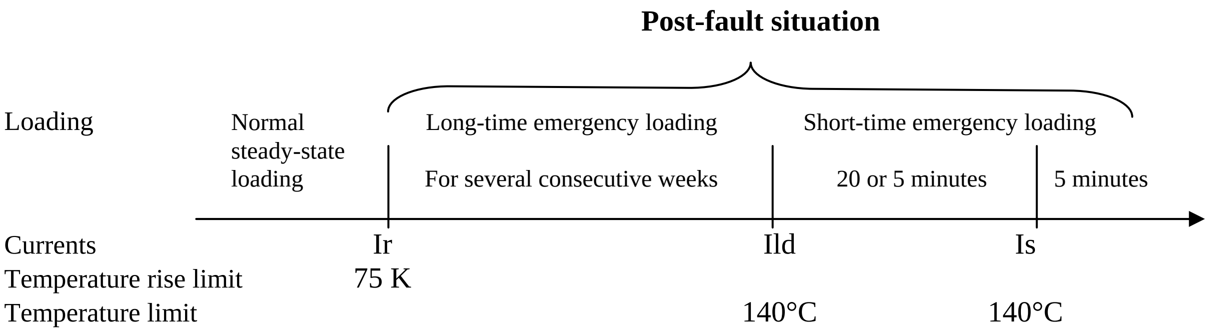

Figure 1 : Limitations for sub-station transformers overloads

From this maximum hot spot temperature of 140° C, new operating rules **[1]** were defined for the overloads of the substation transformers. These rules summarized in Figure 1 consider two types of overload :

- **long-time emergency overloads** (Ild): Under the degraded operation of the system, transformers can be submitted to overloads of limited magnitude over long durations. As the highest loaded periods of the network in France are in winter-time two levels of long-time overloads were defined according to the ambient temperature : Ild = 1.15 Ir for an ambient temperature lower than 30°C and Ild = 1.25 Ir for ambient temperature lower than 15°C. Later on, a third threshold of 1.35 Ir was introduced for ambient temperature lower than 5°C following the periods of great cold met during winter 86-87.
- **Short-time emergency overloads** (Is): Sudden failure of a system element leads to larger overloads in transformers, that is to say up to Is=1.5 Ir. The transformer is not designed to withstand such a level of overload without damage over a long period, but over the time needed for the network to be operated (topology, generation, loads). A 20 minutes duration was defined for the 220/90 kV or 220/63 kV transformers for which the occurrence of high overloads are low, since the 63 and 90 kV networks are usually not meshed. Furthermore, the operation of the 400 kV transformers between Ild and Is is authorized during 20 minutes only if the top oil temperature does not exceed a predetermined value “TL” when the current reaches Ild. Beyond Is, tripping of the transformer occurs automatically after 5mn. This temporisation used to be fixed at 20 seconds before the Eighties.

1.2. Generator step-up transformers at EDF’s nuclear power stations

This equipment is made up of single-phase unit banks, the rated powers of which are in respect of generator power, namely either 360MVA for 1120MVA generators of 900MW power stations or respectively 550 and 570MVA for 1650 and 1710MVA generators of 1300 and 1400MW power stations. These transformers produce on 400kV interconnection network and their low voltage level is either 24 or 20kV on the generator side.

For this equipment, the slightest failure during production periods, means costs incurred as a consequence of loss of production. These costs are much greater than the replacement cost of the failed unit. The impact would be significant in the event of established generic default. Therefore, these transformers are required a high level of reliability. The first manufacturing generations were specified with acceptance tests in seventies, in particular a full temperature-rise test. The later equipment was still constructed with the same design as the first generation power transformers.

One of the design features for the total of 174 single-phase transformers is to operate most of the time at higher loads, close to their specifications duty. Another feature of all these transformers is that their commissioning spread over a period of 20 years (1975 –1995), which is, a short period when compared to the usual transformer life expectancy.

As regards the technology, this equipment is specified with ODAF type cooling and will comply with the same requirements, such as average temperature rise and hot-spot temperature rise, as for the sub-station transformers. These performances have to be respected with reference to rated power and for each of 3 de-energized type taps, at 30°C ambient temperature. The minimum cumulative lifetime of operation is set to 200 000 hours, for reference hotspot temperature value of 105°C. Some exceptional duties are also specified, which correspond to a maximum cumulative duration of 5 hours, but which will lead to hotspots lower than 120°C.

Supplying of new spare transformers is subjected to identical specifications, except for life expectancy, which is extended to 40 years.

2. ISSUES FOR THE MANUFACTURERS

The technical and economic issues of the optimisation of the thermal design for transformers and particularly for large power transformers are well known. This has given scope for a large number of theoretical and experimental research by the manufacturers and by the users **[2]**. Regarding the use, we are beginning to accumulate a large amount of data on apparatus which have been in service for many years. In the frame of a partnership between manufacturers and users, this may allow the confrontation between the life durations as estimated theoretically and the field observations.

In any case, the accurate knowledge of the temperatures reached within the transformer, and particularly, the knowledge of the temperature reached by the hottest spot within the windings enables the manufacturers to come up with the most reliable design, regarding a given assigned life duration of the insulations.

Such a knowledge requires a good understanding of the principles of the generation and of the dissipation of the heat in transformers. That is translated into thermal software with varying levels of detail.

2.1. Control of the heat sources

Today, the manufacturers are equipped with powerful calculation tools to determine the losses, and in particular, the winding stray losses with a good accuracy. Furthermore, some solutions allow to treat and to reduce the losses. The following examples can illustrate this point :

- to reduce the no-load losses : elaborate techniques for the magnetic steel sheet cutting and stacking (step lap core)
- for the load losses : use of continuously transposed cables (CTC) or permutation techniques, use of magnetic shielding or conducting plate shielding.

Thus, all the heat sources are under control.

2.2. Control of the temperature rise

For a given technology, each manufacturer has developed theoretical and empirical methods for the determination, not only of the average temperature rise of oil and of copper, but also for the assessment of the hottest spot of the windings (See examples given in §4).

To act on the thermal performance of large power transformers, the aim is to achieve a sufficient oil flow in every part of the magnetic circuit and of the windings. Various well known techniques are being optimised by the manufacturers for a long time :

- cooling ducts for the windings and, if necessary, for the magnetic circuit
- forced and/or directed oil flow to improve the thermal exchange between the windings and the oil
- zigzag oil flow in ONAN (for core type transformers with disk type coils) …etc.

As an illustration, Figure 2, schematically gives an example of oil flow for a shell type transformer with ONAN type cooling.

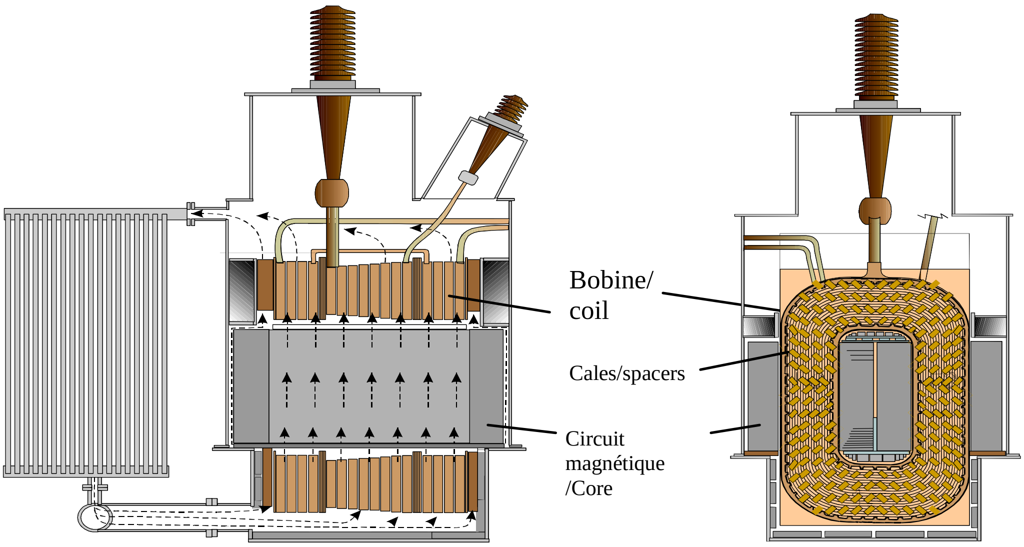

Figure 2 : Schematic cut section of a shell type transformer with the cooling of the active part

2.3. Use of more high-temperature materials

In addition to the solutions mentioned above, some high-temperature electrical insulation materials can be used for the solid insulation and also for the dielectric liquids (full insulation or hybrid insulation). That is the topic of the draft standard IEC 60 076-14. To give three examples :

- Thermo stabilized papers
- Aramide fibres (Nomex) for the turn insulation
- Esters (MIDEL) as dielectric liquid.

Nevertheless, their actual high cost still limits their practical use to low power rating apparatus for which the mass reduction associated with high operating temperatures is an important factor; the most usual application is the case of traction transformers.

3. EVOLUTIONS AND NEW NEEDS

3.1. Sub-station Transformers on RTE's Transmission Network

The main evolutions for RTE result from a growing pressure on the transmission costs which leads to search for new technical and economic optimisation in the use of equipment. Therefore new operating modes, which go further than the existing practices, need to be defined for equipment without decreasing their reliability.

As seen in § 1.1, the substation transformers are, most of the time, loaded under their nameplate rating but they also have to face overloads due to climatic events or to unavailabilities (N-1 situation). It is estimated that the thermal ageing of substation transformers does not exceed a few percent of a transformer ageing running continuously at full load. The limiting factor to decide for a reinforcement is then the hotspot temperature, which can be reached during these overloads.

In the same way, to allow an access to the market of electricity to all the actors, it is necessary to be able to connect new producers in a short time as well as to facilitate the exchanges on the interconnections. These new elements require to bring fast answers to solve the local constraints on the network. Among the various solutions to relieve congestion zones with high load flows, one of them consists on taking profit of the existing margins on the network by installing s like phase-shifting transformers. One of the characteristics of the phase-shifting transformers compared to the substation transformers, is to be in series with transmission lines. Therefore their transmission capacities must be compatible with those of the line in steady state operation as well as in overload conditions. However these loading capacities are dependent on the temperature and the thermal behaviour of a line is very different from that of a transformer. Moreover the loading capacity of a line can be reinforced in future.

These two examples illustrate the need to modify the operation rules of transformers. Several possibilities exist :

- to operate at continuous loads and overloads exceeding the nameplate rating by accepting an accelerated thermal ageing rate,
- to assess the margins on the design of the transformers,
- to increase their performances (for example by improvement of the cooling system efficiency).

The implementation of these solutions requires to be able to calculate accurately the temperature rise and to know the laws of thermal ageing.

3.2. Generator step-up transformers at EDF's nuclear power stations

With the operating conditions of these transformers and the life expectancy of power stations where they are installed, particular attention has begun to be focused to thermal ageing of the first-generation equipment, which is presently considered to be, on average, at mid life. In the event of a demonstrated generic thermal problem, a corrective action could be defined and applied to all the identical units.

In case of failure, the equipment is no longer systematically replaced with the original design, but with newly design equipment, paying a particular attention to the thermal performances.

Therefore, the new computing tools and the new measurement device enable the manufacturers to research thoroughly on the two following items :

- extending of life time of the first-generation equipment, with respect to original specifications, from 30 years to at least 40 years
- testing of thermal performances of new designs.

An illustration of this second aspect is developed at § 4.2.

4. DESIGN TOOLS AND THEIR VALIDATIONS

4.1. Examples of calculation tools fitted to new needs

The design tools and their validations have been improved using new calculation means, applicable for any existing transformer technology.

We can illustrate these progresses on a case study concerning a three phase substation transformer of 70 MVA 227/21 kV Yy 50 Hz.

4.1.1. Analytical methods

New methods have been recently developed, from which we can notice a simple one for winding temperature rise calculation **[3]**.

The general formulation of the problem uses the electrical analogy. From analytical tools, we calculate the thermal resistance of the solid insulation. The calculation of the thermal resistance of the oil boundary layer is determined using the correlation of test data from actual transformers, for natural or directed cooling.

The major improvements of this new method are the following :
- the new method dispenses with the gross approximation that the heat transfer is uniform throughout the winding
- the treatment of the solid insulation is more rigorous
- test data from actual transformers is used to calculate the heat transfer coefficient of the oil boundary layer.

This leads to more accurate results, as shown in Table I.

Table I: Average and standard deviation errors between calculations and measurements (in K)

	Layer windings				Disc windings			
	ON		OD		ON		OD	
	average	deviation	average	deviation	average	deviation	average	deviation
Previous methods	between 2.6 and 5.6	between 5.9 and 6.3	1.8	9.5	between -0.4 and 3.5	between 1.2 and 2.2	-4.4	3.5
New method	-0.5	2.6	-0.5	3.7	-0.5	1.3	-2.5	2.2

For the example of three units of 70 MVA, differences between calculation with new method and measurements vary from –0.9 to 1.1 K.

4.1.2. Finite-element methods

Tools using finite-element methods are getting more and more powerful and give, today, possibilities of coupling loss, thermal and hydraulic distributions. But, if they are more and more advanced, their uses require more competencies. For example, oil volumes need to be modelled with sufficient number of meshes, which reduce today the use of these tools to certain parts of the transformer without being able to treat it as global.

We can, for example, examine the oil flow distribution in winding bottom blocks (see Figure 3). This study can help to understand some oil distribution problems or to be a basis for shape optimisation.

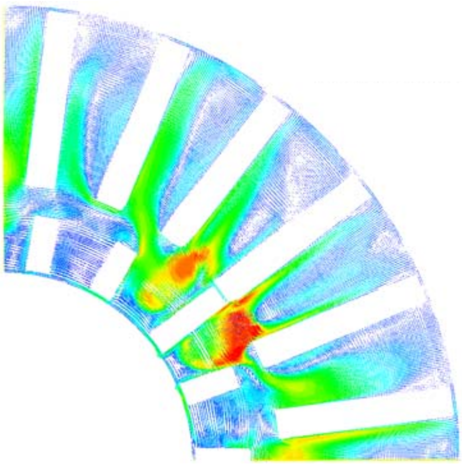

Figure 3 : Oil flow distribution within winding bottom blocks of the 70 MVA

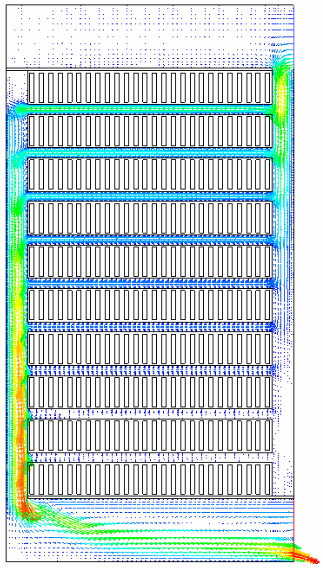

Figure 4 : Oil flow distribution with a group of discs

The example in Figure 4 shows the oil flow distribution calculated in a group of discs separated by two washers.

Even if it is very difficult to get precise experimental validations of such models, these studies can be useful for parametric analyses which can improve, for example, the design of the oil ducts.

4.1.3. System analysis

From methods similar to the analytical ones (electrical analogy), it is possible to represent the transformer behaviour with a system of equations using a loss, thermal and hydraulic coupling. The whole transformer and its cooling devices can be modelled by some systems whose definitions and numbers of elements are chosen to have sufficient information.

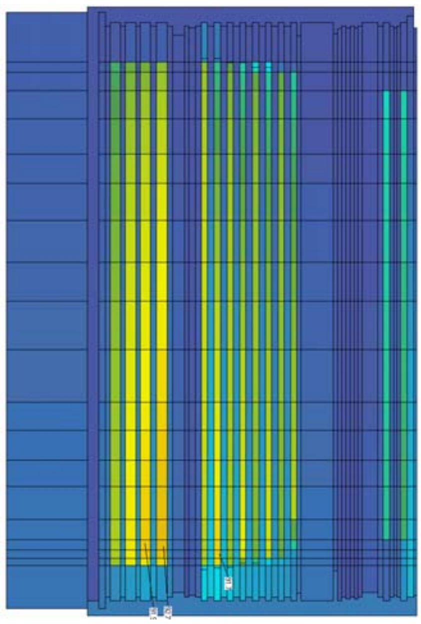

Figure 5 : Thermal model for the 70 MVA

For example, we can get the temperature distribution within the windings, and more particularly the hot spot location and the mean copper temperature rises (see Figure 5 for the case study of the 70 MVA). This last information can be easily compared to the temperature rise test measurements and then validate the calculations. This comparison can made for all windings and for all types of cooling modes (ONAN, ONAF, ODAF).

This thermal hydraulic model can be also used for transient analyses, for example for future applications on overload capabilities. We can note that this transient ability can be validated by the temperature rise test measurements, in which a cooling curve is measured.

Figure 6 represents the calculation results for the 70 MVA thermal model with different hypotheses on the temperature of oil : constant bottom oil temperature, decreasing bottom oil temperature, oil with only tank exchanges.

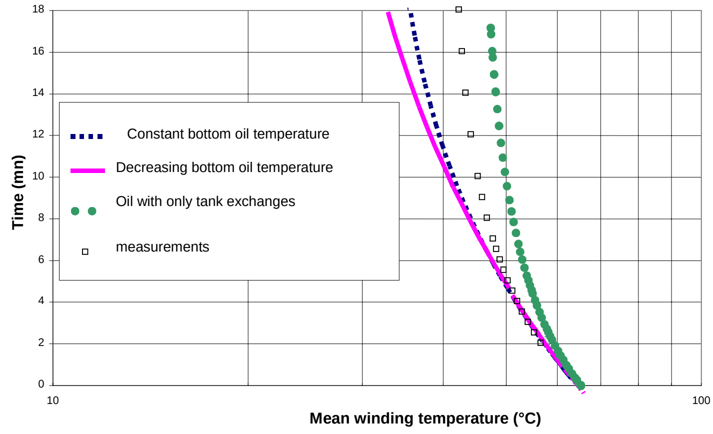

Figure 6 : Cooling curve for the 70 MVA

4.2. Example of instrumentation for a new design

With the occasion of an order, a collaboration was established between the manufacturer and the user in order to equip the windings of a GSU transformer with thermal sensors. This was in order to enable the online reading of the winding temperature evolutions during the factory heat run test and later during operation on site.

- **Electrical characteristics of the transformer :**

The apparatus equipped is a single phase pole which is part of a three phase bank of a 1400 MW nuclear plant step up transformers. These transformers are oil immersed and are of shell type. The main characteristics are as follows :

Number of phases	: 1	Number of windings	: 2
Power rating	: 570 MVA	Voltage rating	: 20/405 kV+/-2.5 % Ynd
Frequency	: 50 Hz	Cooling	: ODAF

- **Arrangement of the windings of the transformer :**

The transformer's windings are laid out symmetrically. In each half of the transformer, the HV winding is composed of two groups located on both sides of the LV winding. Electrically, the HV is composed of two sections in parallel ([coil1-7 + coil16-25]//[coil26-35 + coil44-50]). The LV is composed of four sections in parallel ([coil8-11]//[coil12-15]//[coil36-39]//[coil40-43]). [Figure 7] .

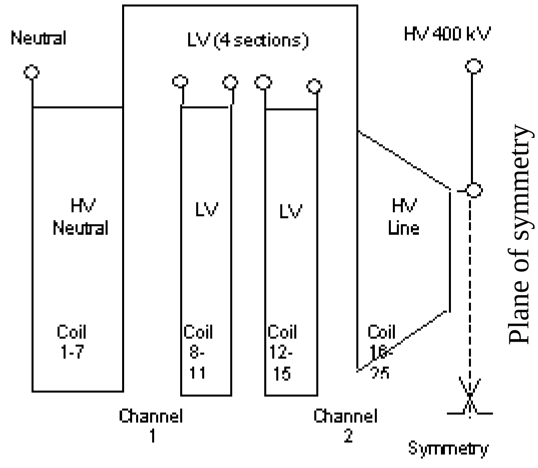

Figure 7 : Winding arrangement of half a 570 MVA transformer

- **Determination of the points to be equipped and instrumentation**

The determination of the hottest spots of the coils is based on the manufacturer's experience, taking into account the local distribution of losses in the coils, the number of heat transfer surfaces, the overheating due to insulated parts (presence of spacers), the average oil flow rate and the overheating due to reduced oil flow rates in some parts of the windings.

The calculations made by the manufacturer were confirmed by a more detailed 2D thermo/hydraulic model performed by the R&D department of the Utility taking into account the local losses and also oil speeds between the spacers [Figure 9]. This modelling allowed to validate and to supplement the instrumentation locations initially defined by the manufacturer.

Thus, during the design review dedicated partly to the thermal aspects, by mutual agreement, it was decided to place 10 optic fibres on the coils of the LV winding :

- 4 optic fibres on coil number 8.
- 4 optic fibres on coil number 43 (coil symmetrical of the 8) .
- 1 optic fibre on coil number 13.
- 1 optic fibre on coil number 15.
- 2 other optic fibres in oil, in the vicinity of coils 8 and 43.

The following Figure 8 and Figure 10 illustrate the implantation technique developed by the manufacturer and the optic fibre locations on coils 8 and 43.

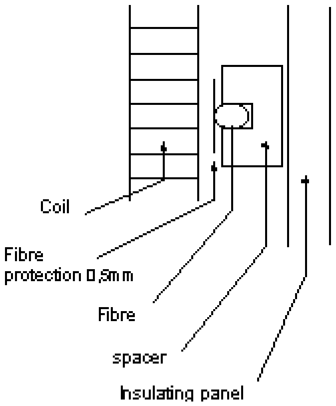

Figure 8 : Method of implantation of the optic fibres

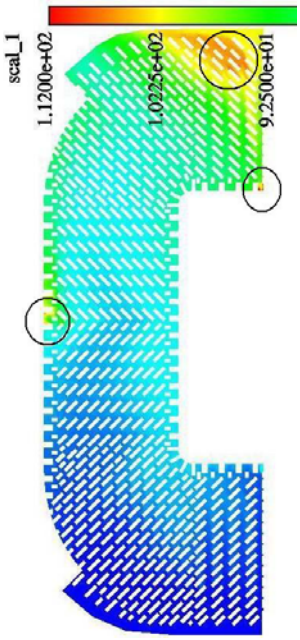

Figure 9 : Typical temperature distribution plot for coils 8 and 43

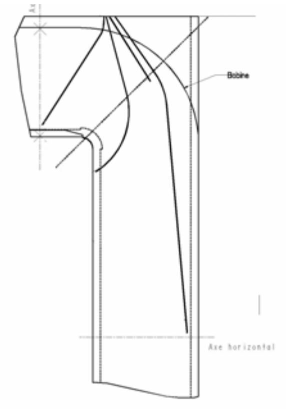

Figure 10 : Locations / paths of the optic fibres on coils 8 and 43

The optic fibres used are point sensors, performing temperature measurements, thanks to a semi-conducting cristal in gallium arsenide (GaAs), using the principle of photoluminescence. This type of optic fibres was qualified by the transformer manufacturer, particularly regarding the dielectric, mechanical and thermal stresses. The instrumentation also comprises two measuring apparatus (transmitter, receiver, reading and information storage), giving access to 2x6 measurement channels.

Thanks to positive feedback already acquired by the manufacturer on some other large power transformers in service, the optic fibres will be kept in the transformer for online measurements of windings temperature in service on line.

- **Measurement results during the factory heat run test :**

The factory heat run test was performed following the short-circuit method as described in the standards (IEC 60076-2). Below are the curves of evolution of the LV winding hottest spot temperature as well as the temperature of the surrounding oil during this test.

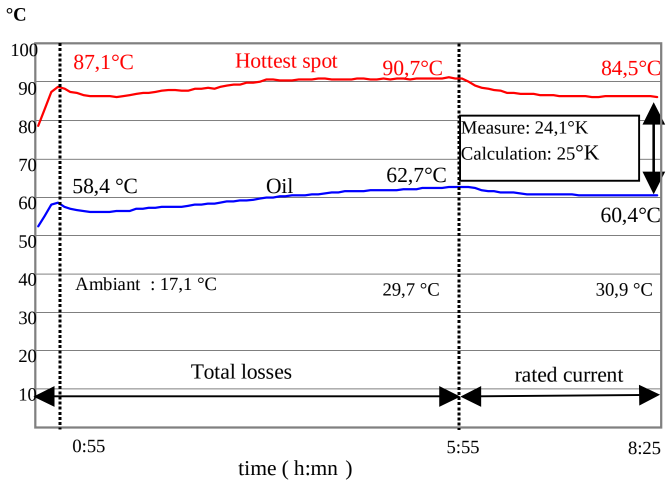

Figure 11 : Evolution of the temperature of the windings hottest spot during the factory heat run test

Note :
- The pumps are started at the beginning of the heat run test.
- The temperatures recordings begins at 0: 40
- 15 fans are started at 0:55

5. CONCLUSIONS

After a presentation of specificities concerning loading of the generator step-up transformer on the one hand and the substation transformer on the other hand, this report has set out the new needs introduced by evolutions of the electricity market. These needs concern the ability of existing equipment to be used in different operation modes or the definition of spare unit supply based on new requirements.

For the two transformers types, the new operating modes require the mastering of temperature rise calculation on the one hand and ageing rules on the other hand.

At the same time the manufacturers have made progress in controlling the generation and the dissipation of the losses as well as using traditional or higher-temperature materials. Thus they have developed new calculation tools based either on simple analytical methods or using thermal modelling.

By their increased know-how, the manufacturers are able to help the users to master the evolution of theirs new needs.

6. REFERENCES

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