21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

A2-208

CIGRE 2012

Electromagnetic simulations supporting the development of dry-type transformers for subtransmission voltage levels

R. MURILLO*	J. SMAJIC	J. TEPPER	A. NOGUÉS	T. STEINMETZ
ABB	HSR	ABB	ABB	ABB
Spain	Switzerland	Germany	Spain	Switzerland

SUMMARY

Dry-type transformers are widely available up to 36 kV. Dry-type transformers for the 52 kV voltage class were introduced in 2004, which are used in a number of utility and industrial installations proving their high reliability. Several customer requirements, like safety and increased environmental awareness, and market trends in the subtransmission voltage level, motivated the development of the dry-type transformer technology one step further and to introduce a product for the 72.5 kV voltage class, with ratings up to 63 MVA.

Compared to distribution transformers, the transformers for subtransmission voltage levels are much more demanding and require higher voltages, higher rated power, and an increased regulating range, which lead to several technical challenges that had to be solved. These challenges were related with the insulating configuration of the active part, the eddy losses mitigation and distribution and the hot spot calculation. The development tasks were carried out by intensively using FEM simulation tools. Those numerical tools were used in order to evaluate and optimize the performance of a wide set of new technical solutions for dry-type transformers.

The dielectric performance for these new concepts was evaluated by applying electrostatic simulation on very detailed 3-D models. First, the electric field was computed, then the discharge mechanisms in air were included in the simulation tool in order to predict the withstand voltage. Discharge mechanisms, as streamer inception, streamer propagation and leader inception were considered. Finally, two prototypes were manufactured and tested for the 72.5 kV level: a 10 MVA unit with vacuum cast technology coils and a 2 MVA unit with glass-fiber-reinforced epoxy resin under atmospheric pressure coils. Both passed all routine and type tests, (325 kV impulse and 140 kV r.m.s. 1 minute applied voltage).

Apart from the dielectric aspects, the design had to take into account the magnetic aspects, derived from the leakage flux. On one hand, the power ratings for subtransmission are significantly larger than distribution. On the other hand, a subtransmission transformer must be suitable to be connected to an on-load tap changer with up to +-18% regulating range.

rafael.murillo@es.abb.com

Depending on the tap changer position, parts of the winding are disconnected and the stray fields may considerably change and induce locally high eddy currents. The uneven distribution of the eddy losses must be mitigated in order to avoid hot spots. The ampere turns unbalance leads to short circuit forces that must be calculated and withstood.

Several technical solutions were considered in order to meet the aspects related to losses and temperatures. These solutions, since they avoid using a regulating winding apart from the main high voltage winding, are new for dry-type transformers and quite different from the liquid transformers technology.

The way to evaluate the performance of these concepts was by applying electromagnetic simulations. For every considered solution, a 2-D quasistatic magnetic simulation allows to obtain the eddy losses distribution in the windings, at different tapping positions. The 3-D electromagnetic simulations were used to obtain the losses in the metallic structural parts of the transformer and in the low voltage bus bars. In order to obtain the temperatures in the windings, a thermal simulation tool was used including the conduction inside the winding, for a non-homogeneous and non-isotropic material, and the convection and radiation equations from the windings to the ambient. The final solution has been validated by several heating tests, with a full scale coil of 25 MVA with a +-18% tapping range tested at different load conditions.

KEYWORDS

Discharge mechanism - Eddy current loss - Dry-type transformer - 72.5 kV voltage class - Fire risk.

FEATURES OF 72.5 kV DRY-TYPE TRANSFORMERS

Dry-type transformers for the 72.5 kV voltage class are available with the following characteristics:

Table I. Characteristics of 72.5 kV voltage class dry-type transformers.

Rated power	up to 63 MVA
Primary voltage	up to 72.5 kV
Lightning impulse voltage	325 kV for IEC 350 kV for ANSI/IEEE
Short duration AC withstand voltage	140 kV r.m.s.
Connection group	Y or D
Secondary voltage	up to 36 kV
Partial discharge	<10 pC
Insulation class	F (155°C) or H (180°C)
Environmental class	E2
Climate class	C2
Fire class	F1
Cooling	AN or AF

No IEC or ANSI/IEEE standard exists for dry-type transformers with voltage classes above 36 kV. Therefore the respective standards for dry-type and oil-immersed transformers were applied, whenever relevant [1].

Partial discharge measurements at transformers of the 72.5 kV voltage class yielded very small values, much below the limit of 10 pC for dry-type transformers. The transformer is quasi partial discharge free, which is necessary to obtain insulation lifetimes of several tens of years.

Oil-filled transformers are mostly built in accordance to an A-class temperature rise of 65°C. For the present dry transformer solution F-class or H-class insulation material are used, which allows an average winding temperature rise of 100°C and 125°C, respectively.

The E2 environmental class allows for heavy pollution and frequent condensation on the transformer. Operation and storage for temperature down to -25°C is possible for C2 climatic class transformers. F1 class transformers offer restricted flammability and the emission of toxic substances and opaque smoke is minimized.

INSTALLATION ASPECTS

72.5 kV dry-type transformers require a similar footprint as oil transformers. Cooling equipment and radiators of oil transformers are quite spacious, especially for larger ratings. In contrast to this, dry-type transformer coils are directly cooled by air and heat does not need to be transmitted first to the radiators by the oil. Further, the higher temperature rise of the dry-type transformer makes the cooling more efficient due to a higher temperature gradient between cooling air and coil surfaces and the corresponding increased heat transfer. In addition the radiative cooling is also increased at higher temperature.

However, since the dry technology requires larger dielectric clearance distances, the core and therefore also the mass of the transformer is slightly larger. This also results in a somewhat increased no-load loss. The load loss is comparable to the load loss of an oil transformer, so that total losses are only slightly larger with a dry transformer.

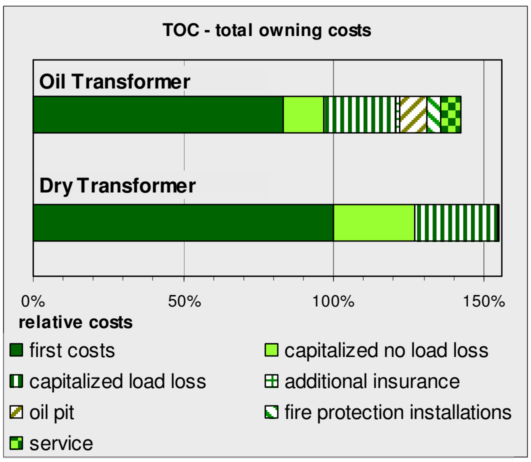


Fig. 1: comparison of total ownership costs for a 66 kV / 16 MVA Oil and Dry Transformer with OLTC.

Figure 1 shows a comparison of the total ownership cost of a dry transformer compared with an oil transformer of the 72.5 kV voltage class (66 kV/11 kV 16 MVA) with On Load Tap Changer (OLTC), considering also the evaluated costs of the no load losses and load losses, at 5 €/W and 1 €/W respectively [2]. The costs purely based on the transformer costs and the loss evaluation, are approximately 30% larger for a 72.5 kV dry transformer compared to an oil transformer. If costs related to the use of oil are also taken into account, like the expensive oil pit, oil related fire extinguisher installations and more expensive insurances, and that dry transformers have much less need for service, as a conclusion it can be seen that the total cost difference of a 72.5 kV dry transformer to an oil transformer is rather small.

If system considerations are taken into account, the application of dry technology may also allow the achievement of substantial energy savings. Taking the example with power supplied from a subtransmission line (see Fig. 2), it is now possible to connect customers using a 69 kV cable and to transform the power directly at the customer site or in its building to the required voltage. Traditionally the power is transformed to a medium voltage level in a substation close to the transmission line. Due to the lower current, the cable losses are substantially reduced. For a 5 km long cable this results in annual energy savings of 280 MWh, which corresponds to a reduction of 140 t/yr of CO2 emissions (for EU electricity mix).

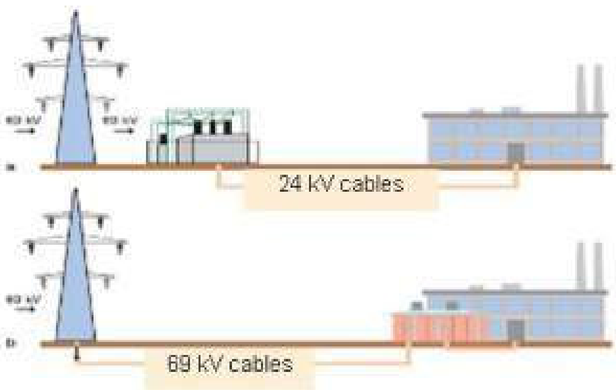


Fig. 2: substantial energy savings due to reduced cable losses can be achieved by transforming directly at the customer site.

ANALYSIS OF THE DIELECTRIC DESIGN

A technical challenge was to develop an insulating configuration made of a combination of air and solid materials which is able to fulfil the 72.5 kV voltage class requirements without using an insulating liquid, in a competitive way, that is to say, with small enough clearances in the active part. In order to reduce the clearances of the active part a new set of concepts for dry-type transformers were taken into account: shielding rings in the windings, conductive shielding pieces for the clamps and magnetic yokes, rounded corners in windings and shields, and an optimized number of barriers and barrier arrangement criteria to control the electric field in the insulating air.

Electrostatic simulations were performed to analyze the dielectric design of the 72kV dry-type transformer. The simulations were done in 3-D to take into account the realistic geometry of the unit including the structural components.

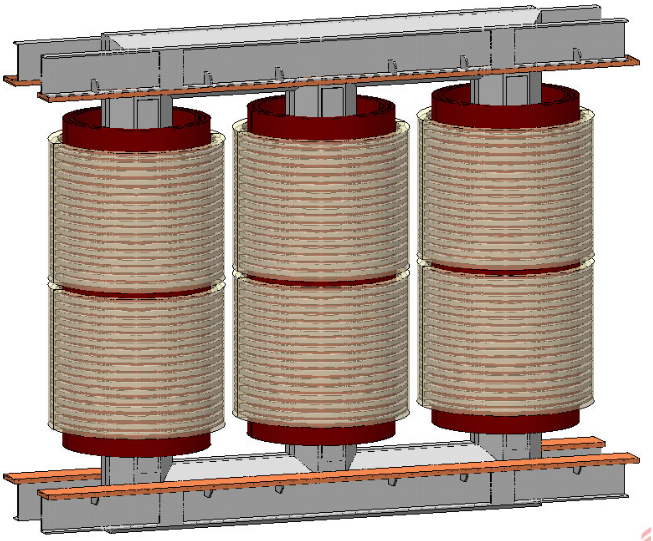


Fig. 3 : geometry of the 72kV dry-type transformer unit showing core, core-clamps, clamp-shields and windings.

The symmetry of geometry and boundary conditions allowed considering a reduced computational model in the simulations, which saves both simulation time and the computer memory. The reduced model, shown in Fig. 4 (left), consists of ¼ of the full transformer geometry. It is obtained by intersecting the full geometry with two perpendicular cutting planes and it considers the magnetic core, core clamps, clamp shields and the windings of the three phases. The windings consist of a LV foil winding and HV foil-disc winding which both are cast individually in epoxy. To improve the dielectric performance of this unit, three barriers are positioned in the main duct between LV and HV windings and field grading rings are used above the uppermost and below the lowermost HV disc.

The boundary conditions chosen for the simulations were based on the potential specifications of the AC one-minute test according to IEC 60076-3. Thus, all components except the HV discs are grounded, whereas the HV discs are set to an electric potential of 198kV, which resembles the peak voltage required in test of the 72kV transformer.

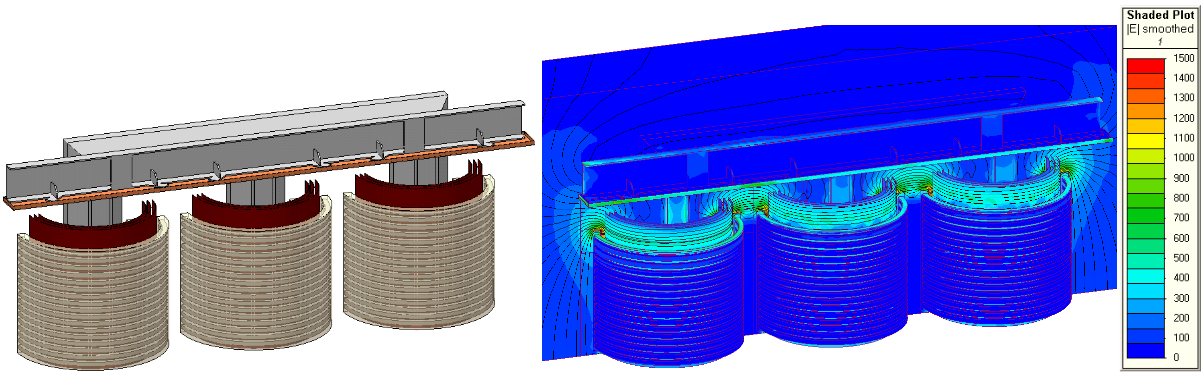


Fig. 4 : Left: reduced geometry which is considered in the simulations, ¼ of the full transformer. Right: distribution of the electric field magnitude in kV/m and the equipotential lines of the scalar potential of the 72kV transformer.

Fig. 4 shows the reduced geometry and the corresponding simulated distribution of the electric field magnitude. Simulations of this type can be used to support the assessment of the robustness of the dielectric design. However, physics of electric discharges is very complex. Thus, only phenomenological criteria can be used currently to assess the dielectric design.

The visualization of the streamlines of the electric field can enhance this assessment further on by indicating areas with high probability of dielectric breakdown. However, it must be noted that the streamlines can serve only as first indication of these critical areas, because discharges do not necessarily follow the streamlines of the electric field.

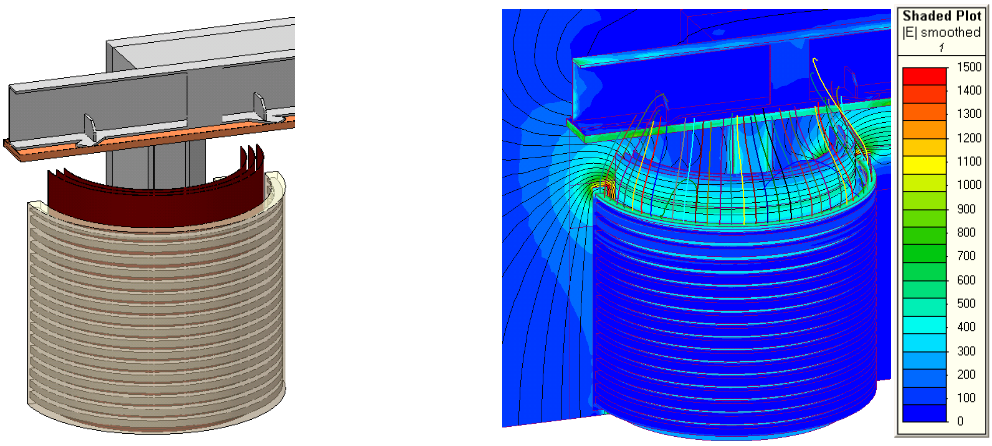


Fig. 5 : Left: geometry of the left outer winding. Right: distribution of the electric field magnitude in kV/m and the equipotential lines of the scalar potential. Additionally, streamlines of the electric field starting at the grading ring are visualized.

Fig. 5 and Fig. 6 show streamlines in addition to the distribution of the electric field magnitude for the windings of one outer phase of the reduced model. Fig. 5 shows this winding phase in the same perspective view as Fig. 4. One can see in Fig. 5 (right) that almost all streamlines starting at the top surface of the grading ring end at the upper core clamp or its copper shield. Please recall that the grading ring is positioned at the upper end of the HV winding. Thus, the external clearance from the grading ring to the core clamps has to be determined carefully.

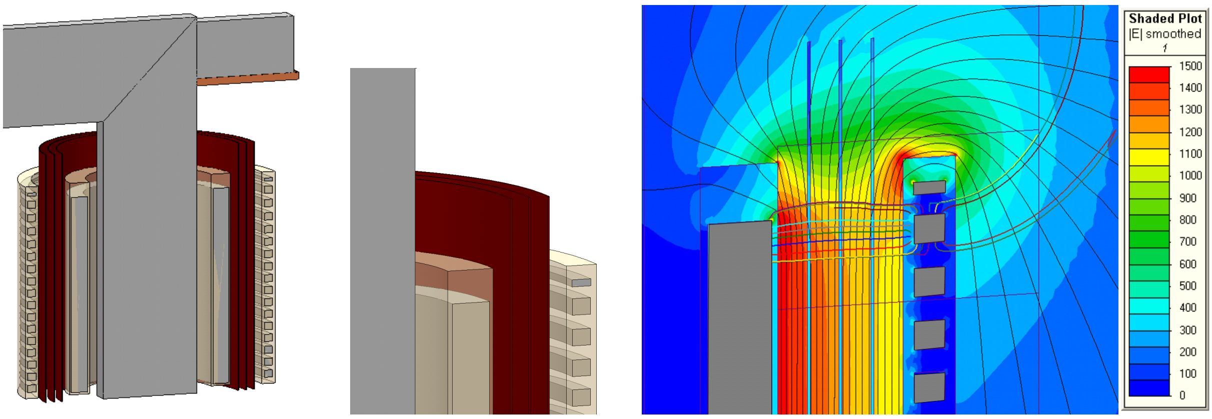


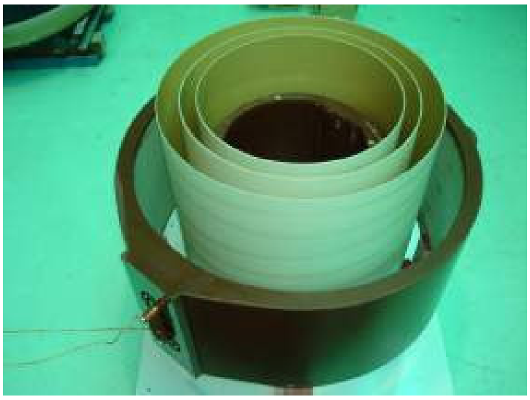
Fig. 6 : Left: geometry of the model seen from the cutting plane. Center: zoom to the upper end of the windings. Right: distribution of the electric field magnitude in kV/m, equipotential lines of the scalar potential and streamlines starting at the uppermost HV disc.

The situation in the main duct can be analyzed best looking at the cutting plane intersecting the winding. Fig. 6. shows the geometry of this view (left), a zoom to the upper end of the windings (center) and the corresponding simulation results. Streamlines of the electric field which start at the uppermost disc are visualized in this figure. These streamlines end either at the opposing LV winding, or at the upper core clamp or its conductive shield.

Once the electric field magnitude is calculated and the streamlines are obtained, it is necessary to evaluate the breakdown voltages of the possible discharge paths shown by the streamlines. Discharge mechanisms, as streamer inception, streamer propagation and leader inception are considered in the breakdown voltage calculation. The discharge lengths in air for dry transformers for the 72.5 kV voltage class are typically below the meter range, so that from that perspective a leader transition should not occur [3]. Anyhow, due to the presence of dielectric barriers and insulation material, respectively, a leader transition could occur even at smaller discharge length. This has to be avoided, since the voltage drop along a leader becomes significantly small and an immediate breakdown is then expected [3].

The evaluation of the breakdown voltages along the streamlines are preliminarily based in the theoretical values of the literature, but validated and tuned by testing real models in the laboratory. These real models cover from very simple configurations to complex ones that include the new features to be introduced: multiple barriers in the main duct, shielding rings at the end of the coils, and shielded core clamps. Figure 7 shows a model example. In this way it is obtained a safe dielectric design criteria.

.



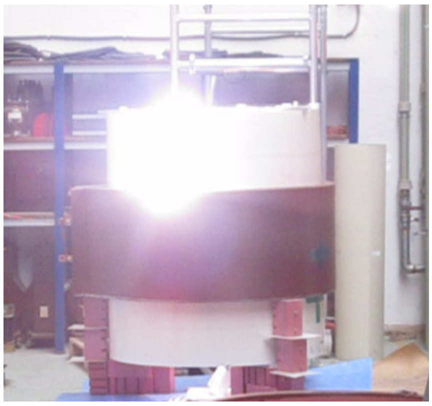


Fig. 7: Left: configuration for real model test including high voltage winding, low voltage winding and insulating barriers. Right: discharge during impulse test between the high voltage and the low voltage test coil.

FULL PROTOTYPING

After all these simulations were performed, the optimum insulating configuration was defined and ready for full transformer prototyping. Finally, two prototypes were simulated, manufactured and tested: a 10 MVA unit in vacuum cast technology and a 2 MVA unit with glass-fiber-reinforced epoxy resin under atmospheric pressure coils. Both passed all routine and type tests, (325 kV impulse and 140 kV r.m.s. applied voltage for 1 minute). Both prototypes were tested to the limits by increasing the test voltage beyond the values required by the standards, until a flashover occurred (Fig. 8). The results validated the forecasted theoretical breakdown voltage and confirmed that adequate safety margins exist.

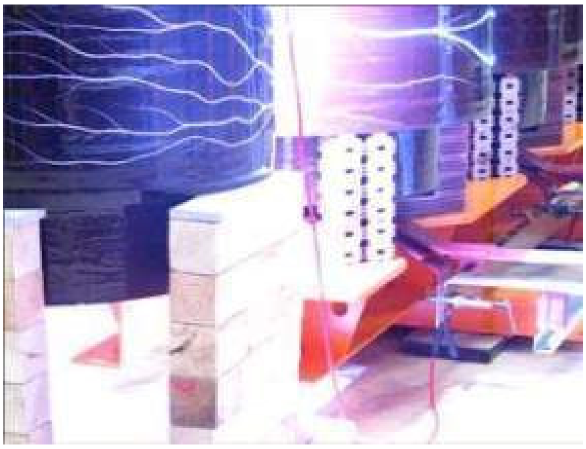
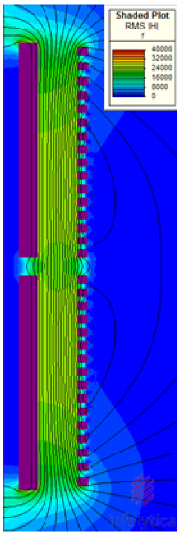
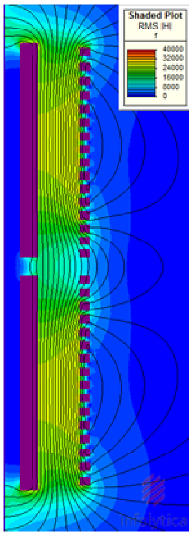
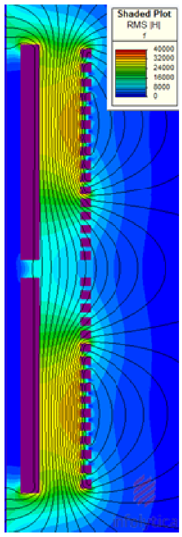
 

Fig. 8: Left: 72.5 kV 2 MVA dry-type prototype being tested to the limit. Right: 72.5 kV 10 MVA dry-type prototype.

EDDY CURRENT LOSSES AND HOT SPOTS

Apart from the dielectric aspects, the design had to take into account the magnetic aspects, derived from the leakage flux. On one hand, the power ratings for subtransmission are significantly larger than distribution and, on the other hand, a subtransmission transformer must be suitable to be connected to an on-load tap changer (OLTC) with up to ±18% regulating range. These two causes, higher power and coils designed to be connected to an OLTC, lead to specific issues related to Foucault currents induced in certain parts of the windings, the eddy losses.

Table II. Flux pattern and relative losses of a 10 MVA 66 kV ±18% at different position of the OLTC.

Flux pattern of a 10 MVA 66 kV ±18% at different position of the OLTC		
Tapping at +18%	**Tapping at 0%**	**Tapping at -18%**
		
Relative AC losses at different position of the OLTC		
79.87 %	**100.00 %**	**130.44 %**

To evaluate these eddy losses phenomenons within the windings it has been required the help of 2-D magnetic simulations to derive a loss distribution along the winding section. When the OLTC is connected at the lowest position, parts of the windings are disconnected which produces an uneven distribution of ampere-turns through the axial direction of the coils causing an uncommon leakage flux pattern. Finally the magnetic simulations offered the losses distribution caused by this peculiar leakage flux shape.

The result of the magnetic simulation was coupled with thermal simulations to calculate the thermal behavior of the transformer considering non-isotropic materials and conditions of convection and radiation between different solids. By studying the particular case of transformers with a ±18% OLTC, it was concluded that without a specific design for these conditions the eddy losses calculated previously would cause intolerable hot-spots within the coils.

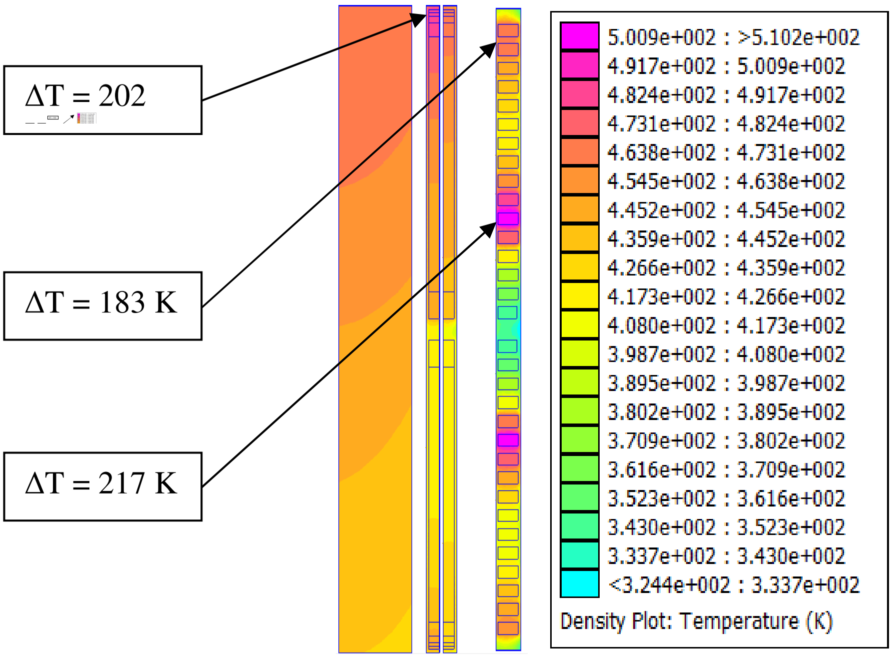


Fig. 9 : temperature distribution in a 25 MVA 66 kV connected at -18% tapping position, without taking any action to mitigate the eddy losses (ambient temperature 293 K).

Different eddy losses mitigation techniques were evaluated with thermo-magnetic simulations in order to solve this problem. One idea very simple and very easy to implement consist on to use smaller copper conductor instead of aluminum only in the tapping disks in order to reduce the gap without ampere-turns, obtaining an important saving of eddy losses and consequently a reduction of the temperature of the hot-spots.

A complete phase corresponding to a 25 MVA 66 kV ±18% transformer was manufactured with this simple solution, in which 96 temperature sensors where placed inside the coils to measure the temperature distribution within the coil, and then tested in the most critical positions of the tap-changer, being the results shown in the Fig. 11.

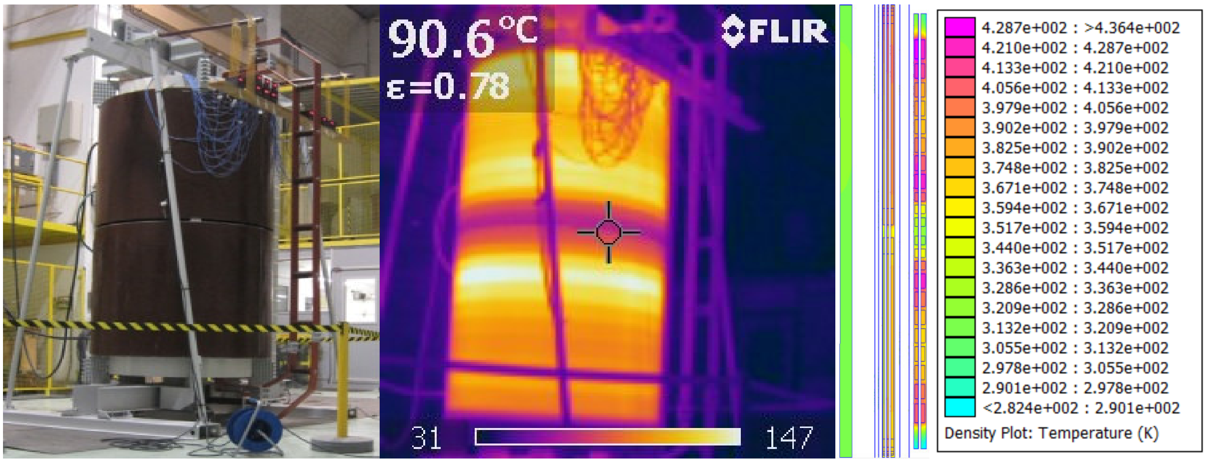


Fig. 10: Left: 25 MVA 66 kV ±18% phase in the laboratory. Center: thermography when it was tested in a heat run test with tapping connected at -18% position. Right: predicted values for this test (ambient temperature 293 K).

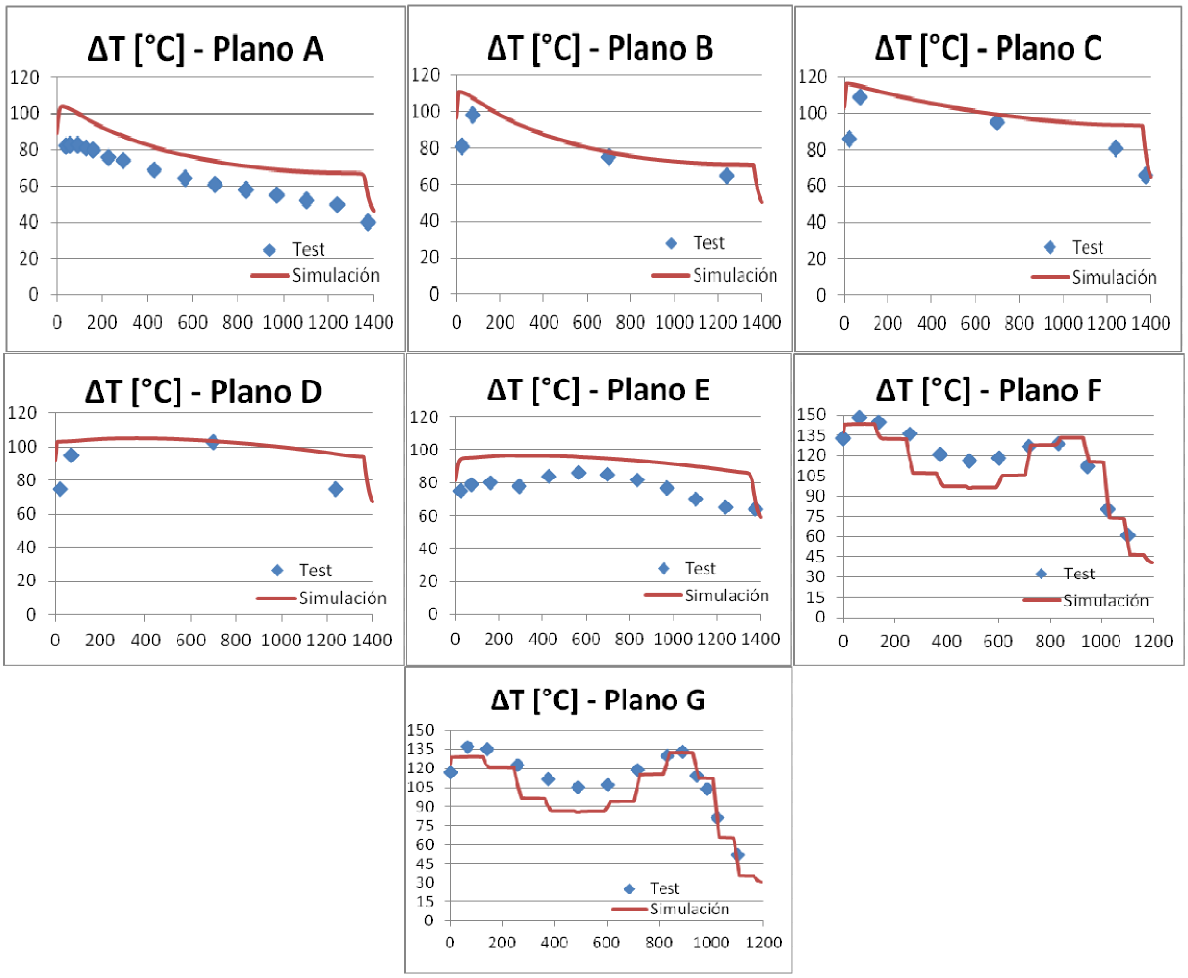


Fig. 11 : measured temperatures with the probes in the laboratory and expected values calculated with simulations. Each graph represents the temperatures at a particular radial position of the coils, from the innermost (A) to the outermost (G). In each graph, the temperatures (ordinates) versus the axial height of the coil from top to bottom (abscisses) are shown.

The 3-D electromagnetic simulations were also used to obtain the losses in the metallic structural part of the transformer and in the low voltage bus bars in order to optimize the design of these elements.

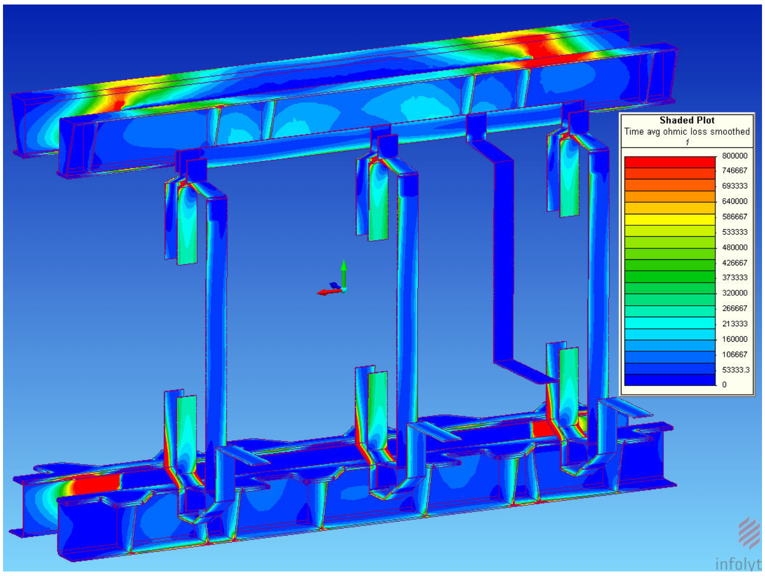


Fig. 12 : stray losses distribution in structural components and busbars.

BIBLIOGRAPHY

[1] IEC 60076 International Standard, series on Power Transformers, and especially IEC 60076-11:2004 “Dry-type transformers”

[2] M.Carlen, S.Schreiber, From the Power Plant to the Customer – Clean, Efficient and Safe; ew 109 (2010) vol. 4, 34-38 .

[3] A. Kuechler, Hochspannungstechnik: Grundlagen – Technologie – Andwendungen, VDI-Verlag 1996. ISBN 3-18-401530-0

[4] A. Pedersen, T. Christen, A. Blaszczyk, H. Boehme, Streamer inception and propagation models for designing air insulated power devices, Proceedings IEEE Conf. on Electrical Insulation and Dielectric Phenomena, Virginia Beach, USA, 19 – 21 Oct 2009

[5] Jasmin Smajic et al., Analysis of near and far stray magnetic fields of dry-type transformers: 3D simulations vs. measurements; 14th biennial IEEE Conference on Electromagnetic Field Computation (CEFC), Chicago, May 2010