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Qualification test for power transformers GIC capability

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SUMMARY

Among the climatic aggressions that could jeopardize the transformer performances, Geomagnetic Disturbances (GMD) are environmental events that could affect the electrical power equipment integrity by creating Geomagnetically Induced Currents (GIC). Therefore, the consequently arising constraints must be considered at early stage of the design review.
The utilities are more and more questioned on the transformer robustness regarding the thermal and mechanical stresses that the equipment would experience when a solar storm interacts with the earth. Most of the transformer operators have always in mind the consequences of the 1989 GIC crisis that affected the North American electrical system.

A significant step ahead has been done by the manufacturers to simulate the transformers behavior under the effect of GICs to evaluate their active part thermal limits. The consequences of a Direct Current (DC) component circulation representing the GIC are nowadays discussed during the design review, but usually with more and less satisfactory answers. The technical discussion tends to address the questions about:

- the temperature rises in the active part and particularly clamping system,
- the generated exciting current harmonics due to core saturation,
- the mechanical behavior (noise and vibration),
- the additional reactive power consumption.

However, the simulations undertaken provide some useful and relevant indications, but they remain to be consolidated and validated by tests achieved on site or during the Factory Acceptance Test (FAT). E.g. the re-simulation of tested DC levels in the FAT leads to a validated manufacturer calculation model which also allows a reliable simulation of higher DC levels which cannot be tested in the manufacturer's test bay due to power limitations.
Thus, regarding the power transformers GIC qualification, a great normative lack has been persisting for some decades regarding a standard test to be carried out in the manufacturers high-voltage (HV) laboratories. Conceptually, it might be possible to think that this kind of test is costly and heavy to achieve, but the utilities try to put in perspective the risk of deploying a vulnerable design with regards

to GIC and their consequences on the availability and the security of the electrical system and its equipment.

This paper aims to present some details on the method and the procedure for testing the transformer capability to withstand the GIC in the factory. We will discuss the test sequence to be applied (amplitude, duration…), data to be collected and suitable locations for temperature sensors to measure the thermal behavior of DC affected locations in the transformer. In addition, the paper will describe the test circuit set up challenges and constraints. Especially the consideration of the occurring distorted voltage during a factory DC test will be discussed. The presented paper will also share EDF and Siemens Energy collaborative experience to develop a factory special test to determine the thermal limits of a GSU transformer in service, to evaluate the harmonics and other electromagnetic characteristics under a DC current component. This includes the determination of transformer exciting current with DC out of measurement results from a factory test or the evaluation of the measured temperatures. An analysis of the gaps of such a special test will be discussed to open some improvement tracks and/or to explore new testing alternatives.

KEYWORDS

GIC, back-to-back test, magnetic core, structural steel parts, DC component, simulations.

BACKGROUND

The transformers withstand against GIC is a question which is increasingly asked by the utilities to the manufacturers. Those GIC which are a consequence of solar storms have more significant effects in the countries at high latitudes, but sometimes national security authorities ask utilities from regions less concerned by GIC, about the risk of vulnerability of their electrical installations.
As reported in many articles [1,2,3,4], the effects of GIC consist mainly in the saturation of the magnetic circuits. The half cycle saturation of the transformers magnetic core due to DC component has been described in those publications [5,6].
Since the transformers reliability and the security of the electrical power plants and the network are of great importance, EDF asked Siemens Energy power transformers for a special test to characterize the limits and the capability of a 570MVA GSU design to withstand such DC current components.
It is of course possible to use simulations only, but several difficulties should be overcome to carry out a fully validated computational process:

- A calculation file justifying the thermal capacity of a transformer to withstand a level of GIC requires the use of a model validated by representative tests of the design to be qualified.
- A simulation done according to the rules of the art to consider the treatment of harmonics and therefore the accuracy of the model to be used (e.g. skin effect for the highest harmonics).
- The non-linear characteristics of ferromagnetic materials combining AC+DC excitations are part of the manufacturer's know-how. Acceptability limit criteria are not readily available and accessible.
- Beyond the thermal aspect, mechanical performance (vibrations and noise) must be investigated, but this seems complex to study by simulation knowing the current state of the art.

➢ Normative aspect and recommendations for power transformer design:

Among the useful standards, the IEEE [6] provides a normative frame regarding the GIC to be considered when designing transformers. The IEC [7] gives recommendations regarding the transformers subjected to DC bias.
But, in terms of standardized tests on transformers GIC capability, there is a lack of normative references and there are only few relevant publications to handle the test challenges [8,9]. However, the acceptability criteria are missing and a representative test as close as possible to the operating conditions are the main issues related to this subject.

THERMAL MODELLING OF THE TRANSFORMER UNDER GIC

Although GICs are generally defined by a frequency in the range [0.001Hz-1Hz] according to the literature, equating them with a DC component is a conservative hypothesis that allows to approach the effects of magnetic saturation on the transformer performances.
The simulations carried out by EDF and Siemens Energy allowed to compare the results and to focus on the most constrained components of the active part to optimize the instrumentation for the transformer GIC capability test in the manufacturer high-voltage lab.
The assumptions and data from the simulation works are described in the following sections.

➢ Design parameters of the 570MVA GSU transformer:

The main characteristics are given in the Table 1:

Design characteristics	
Type	Single-phase, oil immersed power transformer
Rated power/ voltage HV	570 MVA/405/√3 kV ± 2.47%
Frequency	50 Hz
Core type	4-leg core
Number of wounded legs	2

Table 1: Design characteristics

➢ Simulation process:

➔ ***Geometrical data***

As it can be seen in Figure 1, the magnetic core, the tie bar, clamping plates, upper yoke shunts and tank shunts have been modelled by an internal Siemens Energy model as well as an in inhouse EDF model with the real geometrical dimensions.

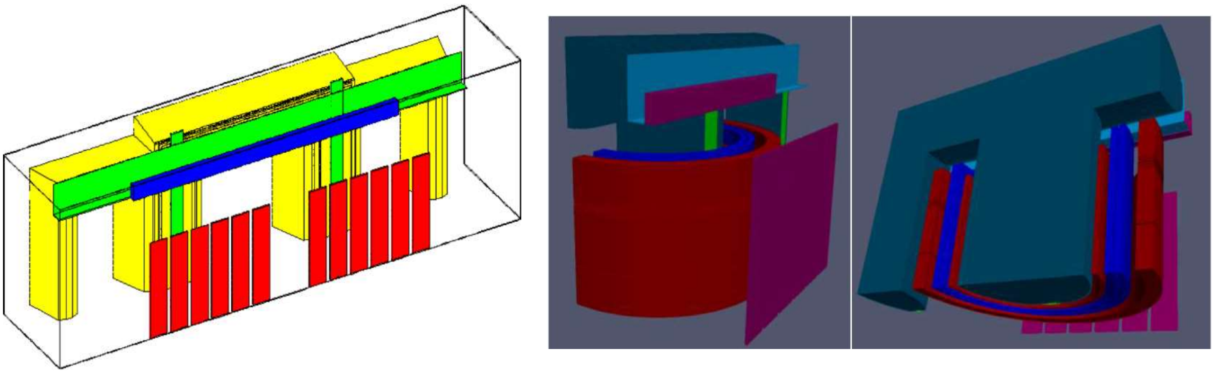

Figure 1 : Models of the magnetic components - Siemens Energy (left), EDF (right)

The model meshing should be dense enough to consider the skin effect penetration thickness for eddy currents. Using in-house tools, EDF model (Figure 1, right) has been sufficiently meshed to investigate the effects up to the 9th harmonics.

➢ Simulation results:

➔ ***Losses evaluation***

For the losses evaluation, the FE calculation provides either the volume loss density distribution directly [Figure 2 (right)], or either the flux density distribution [Figure 2 (left)] combined to magnetic steel specific losses as well as the eddy current losses to calculate the complete loss distribution. The white gaps in the left graphic are caused because in the shielding elements where the flux density exceeds the visualized scaling range.

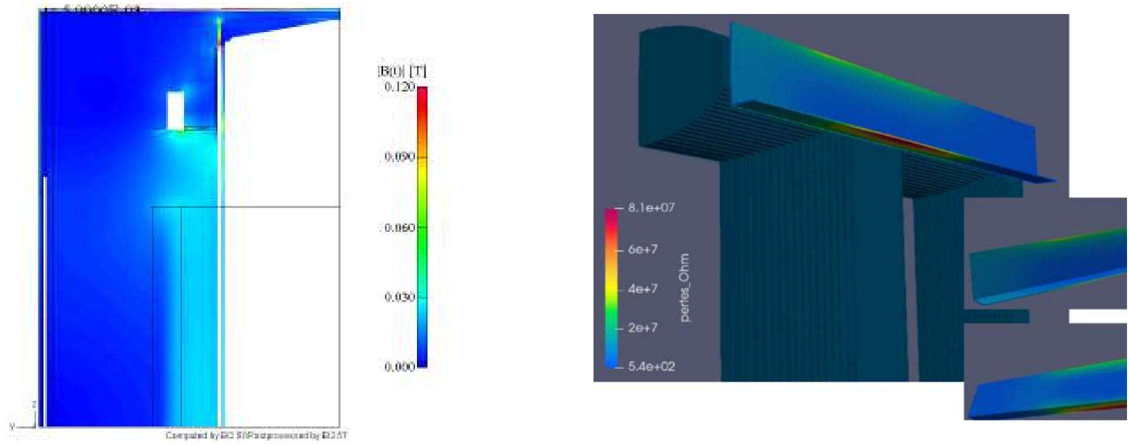

Figure 2 : Flux density distribution by Siemens Energy FE simulation (left), volume loss density distribution by EDF in house tool simulation (right)

The losses variation as a function of the superposed DC component calculated by the FE simulations is given in Figure *3*.

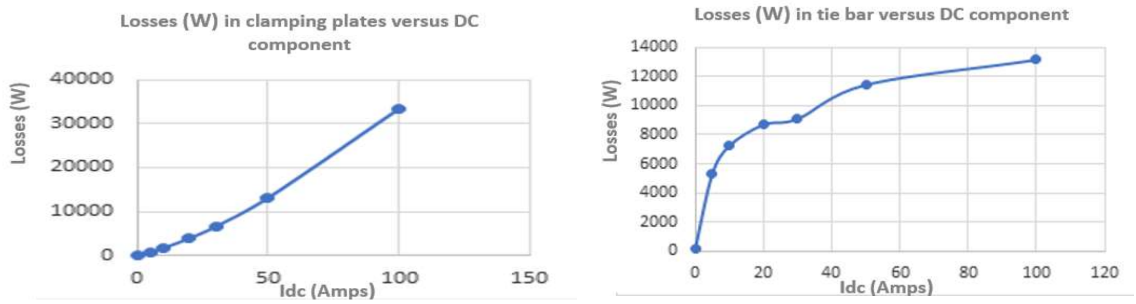

Figure 3 : Losses variations in the clamping plates (left) and tie bar (right) under dc component in no-load conditions

➔ ***Temperature rise evaluation***

For the calculation of the temperature rise, data of the cooling system and the ambient temperature are factors to be considered in the analysis of the results. Heat exchange coefficients are used to calculate the temperature field in the metal structures holding the magnetic circuit. Thus, the oil-metal thermic gradient is the relevant characteristic to be considered.

- **No-Load conditions:**

Considering the boundary conditions (ambient temperature, tank top oil), both FE simulations of the manufacturer and the transformer user show similar results. The simulation results on the left side are based on an oil temperature of about 44 °C whereas the results on the right side are based on an oil temperature of 80 °C. One can note that without DC component the boundaries conditions are not the same for both simulations. However, the field temperature gradient (Figure 4) is similar at least for the tie bar. It is more relevant to consider the thermic gradient between the oil and steel part for the comparison purpose.

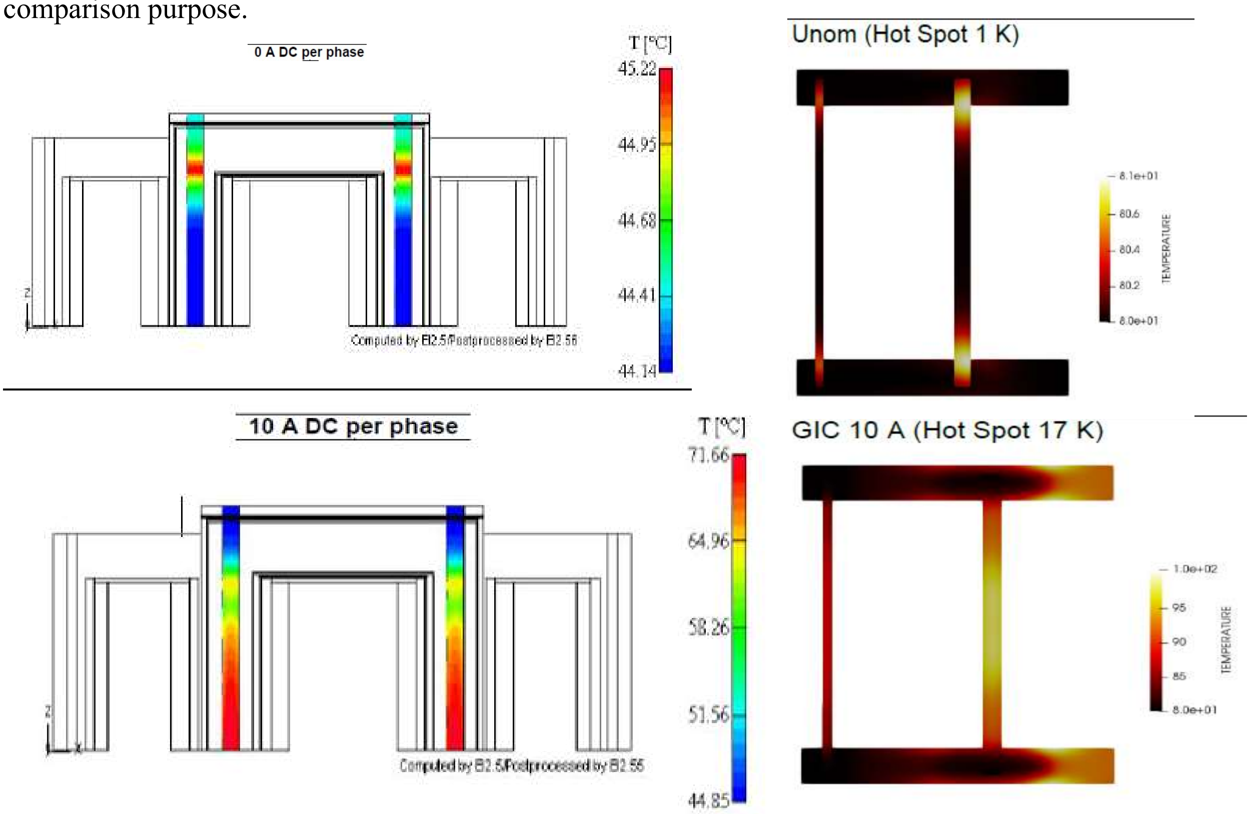

Figure 4 : Tie bar temperature distribution of Siemens Energy(left) and EDF (right) simulations with and without DC component.

- **Full load conditions:**

Figure 5 below summarizes the simulations results of the transformer manufacturer over a wide DC range. It shows the calculated steady-state temperatures of different transformer components when DC currents are present in the high-voltage winding of the transformer in addition to its nominal AC loading. Under full load and at no-load the highest temperatures under DC occur in tie bars.
The maximum hotspot is located in the axial center in the area over the winding height. For this transformer design, the temperature on the top of the tie bar (upper end of the winding height) is low, especially for high DC levels.
For the tie bar, under full load and with 20 A DC per phase the simulated hotspot rise above the tank top oil temperature is about 37 K. Based on the thermal steady-state temperatures above, the permissible operating time of the transformer can be determined when DC current occurs in the high-voltage winding. For that reason, the transient thermal behavior of the components must be taken into account, considering the permissible duration of different DC levels to avoid hotspot temperatures above 160 °C in the tie bar or 140°C as EDF specify.

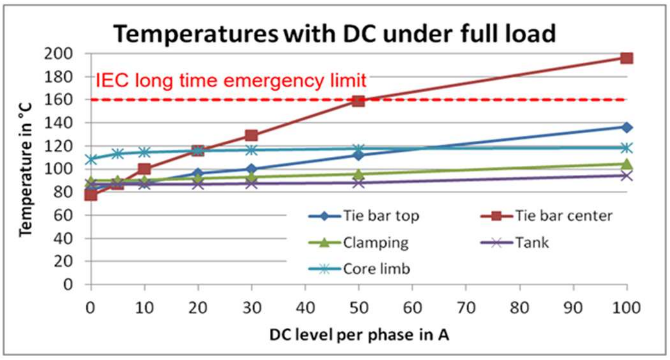

Figure 5 : Thermal steady-state values of affected components under DC (full load condition, Top oil temperature of 80°C)

- **Mechanical impact on core structural parts of the tie bar temperature rise increase:**

The results of Figure 5 show that a DC current in the HV winding of a transformer can lead to a significant increase of the tie bar temperature and consequently a length expansion of the tie bar. Therefore, it is important to check that the active part is still sufficiently clamped, and such length variations are acceptable for its mechanical stability. The calculations indeed show that a DC component of 100A, could induce by its thermal effect, a variation of the tie bar length about 3 mm under load conditions. The length extension of 3 mm impacts the clamping force with a decrease of 20% to 30% which should be discussed with the transformer manufacturer.

GIC TEST CIRCUIT

The test circuit is designed in a way to subject the transformer to a superposition of AC and DC current. In this back-to-back configuration test set-up, both transformers are magnetized by the DC current but the instrumentation for the measurement can be installed only in one unit.
The test in no-load condition allows to characterize the thermal behavior of the structural steel parts and of the magnetic core. In addition, the measured harmonics is a data which helps to reasonably characterize the transformer behavior under GIC. It must be noted that a test at no-load condition is not completely representative of the operation conditions in the grid, but it is an essential basis for having a validated calculation models to be used then for load conditions simulations.
The combination of a load condition and GIC is indeed much more complicated to reproduce in the factory test facilities, if not impossible. Thus, the harmonics spectrum measurement is useful to reconsider the windings and active part structural components losses that could affect the thermal performance of the unit. The impact of the harmonics on the protection devices is out of our study scope.

- **Test circuit construction:**

As mentioned above, for power transformers, there is no standardized special test, nor criteria indicating how to check the acceptability of the transformer's performances under DC.

To achieve the proposed test, Siemens Energy used two single-phase units manufactured in Weiz factory in Austria. One challenging point was the availability of both units in the manufacturer test bay at the same time, because the test is a back-to-back configuration that allows to circulate DC current in both HV windings to perform the magnetic core DC magnetisation. The polarity of the DC current defines the shift of the AC flux cycle to reach saturation. The test circuit principle is illustrated in Figure 6. The polarized saturation effect produces a flux dispersion through the core clamping metallic structure, resulting in rising temperatures which can be instrumented by pre-installed temperature sensors.

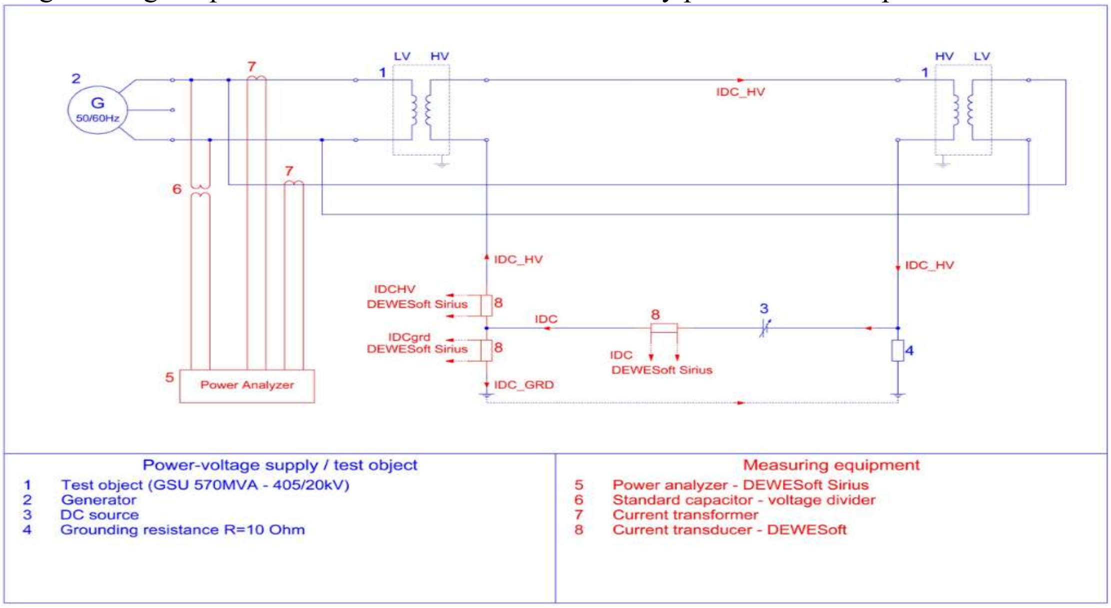

Figure 6 : GIC back-to-back test circuit for the 570 MVA single-phase design

For information purposes, by agreement with the manufacturers, the following illustration Figure 7, shows a possible back-to-back test circuit that could be used for 3-phase transformers where only one unit is available. The principle is the same, here a DC source is used injecting a DC current between the HV neutrals of both transformers. It is beneficial that the step-up transformer is a 3-phase, 3-limb transformer, therefore only the test object will reach the saturation as shown in [2]. With a suitable step-up transformer, the testing of 3-phase transformers with 3-leged cores and 5-leged cores is possible.

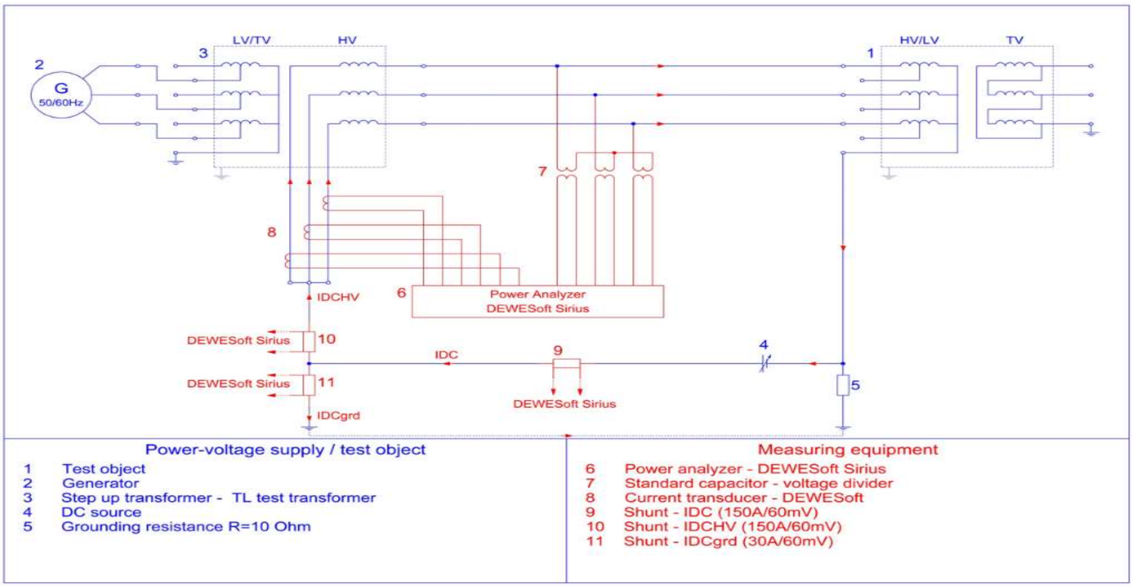

Figure 7 : Potential GIC back-to-back test circuit for 3-phases transformers.

- **Temperature sensors positioning for GIC capability test:**

For the test of the 570 MVA design, the instrumentation consists mainly of thermocouples installed on one transformer only. Thanks to carried out FEM-3D simulation results before the experiment, considering the no-load condition combined to additional DC currents of different intensities per phase in the high-voltage winding, thermocouples have been placed in the transformer to measure the hottest temperature areas during the DC test. Figure 8 shows an example for the determination of suitable sensor positions based on FEM-3D results and Figure 9 the exact positions of the sensors in the 570MVA design.

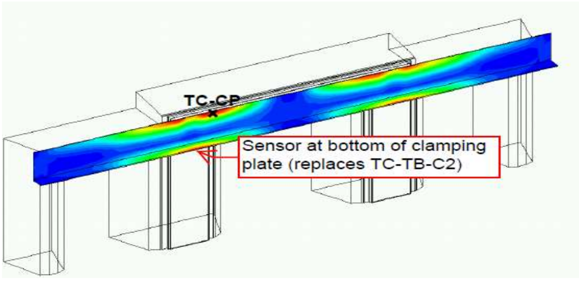

Figure 8 : Sensor locations on clamping plate

The sensor locations in the 570 MVA transformer are as follows:

- The tie bar surface in the axial center
- The tie bar surface in the height of upper core limb end
- The clamping plate/beam
- The smallest core package in axial center
- The smallest core package on top
- The top of the smallest core package oil duct

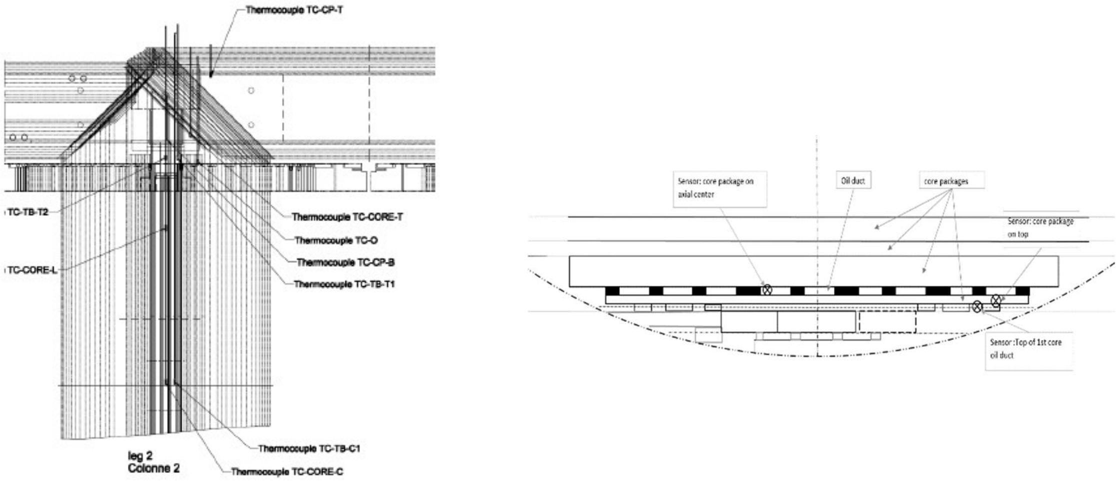

Figure 9 : Sensor locations in the 570MVA design

➢ GIC test sequences:

In order to reach a representative core temperature level, it has been agreed to keep the instrumented unit operating at no-load condition during the night. The unit was operated before GIC test at no-load conditions according Table 2 to heat up the magnetic core:

Time sequence	Voltage supply (p.u.)
07:15pm-03:00am	1.1
03:00am-08:00am	1.0

Table 2 : No Load conditions cycles before GIC test

The unit was cooled by a special hydrocooler with reduced oil circulation flow rate. Afterwards different DC levels were injected through the HV windings with the back-to-back test configuration. The duration of each cycle of DC component is determined to reach the thermal steady-state hotspot rise of the tie bar above the oil temperature.

Intensity and duration of the DC component was defined and agreed between EDF and Siemens Energy according to the Figure 10. The highest level of DC component to be tested depends on the manufacturer test facilities capabilities (depending on the reactive power provided by the generators to compensate the one absorbed by both units).

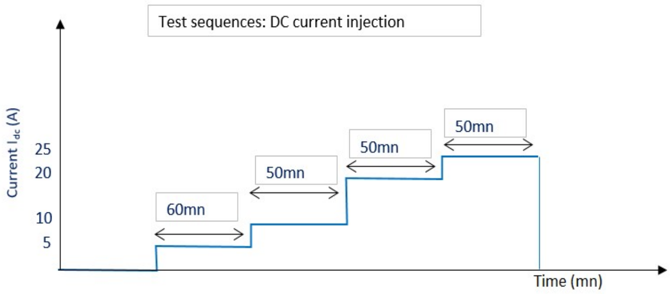

Figure 10: Sequences of injected DC current

It is worth noticing that the level of DC current to be tested is a matter of transformer specification. The GIC capability should be defined at early stage of the commercial tender. In the present case, Siemens Energy had been asked to check the GIC withstand of the 570 MVA GSU design.

GIC TEST RESULTS

This section presents the measurement results carried out during this special test. The purpose of the instrumentation put in place was to thoroughly characterize the thermal behavior of the magnetic circuit and its structural parts. In addition, sensors have been set up to obtain information on the trend of vibration behavior via the tank wall, as well as on the generated noise. The purpose of these latter measures is to verify their relevance to determine decisional/acceptance criteria on the mechanical capability of transformers to properly operate under GIC crisis.

- **Reactive power evolution versus the DC component:**

One of the characteristics we wanted to analyze is the reactive power consumption of one unit in (Figure 11) and its variations depending on the DC component injected into the HV circuit. The more or less linear increase of the reactive power consumption, which is caused by the increased exciting current due to the part-cycle core saturation, starts at the tested single-phase transformer already at a very low DC level of about 1 A DC per phase. The reason is low magnetic reluctance path for the DC flux by the return limb of the core.

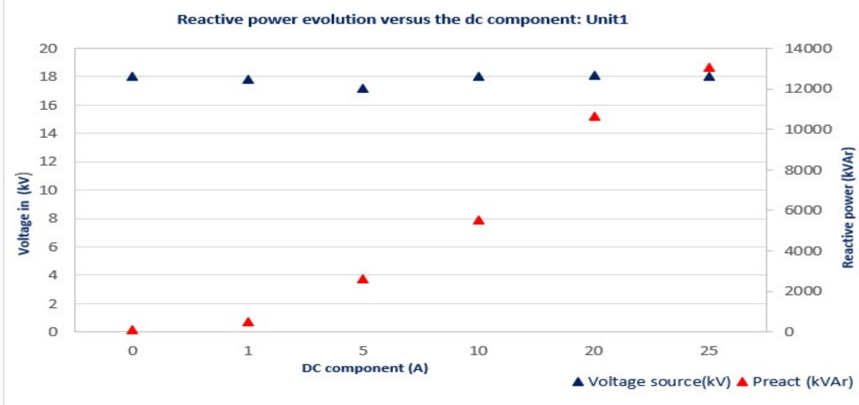

Figure 11 : Reactive power consumption versus injected GIC dc component.

- **Characterization of the excitation current harmonics:**

Another characteristic that shall be analysed during a GIC test are the harmonics in the measured currents where also the pure exciting current can be determined out of it. Figure 12 shows a screenshot of the power analyser where the spectrum of the low voltage winding current in one of the transformers is shown. The left graphic captures the spectrum for the nominal AC voltage condition without a DC current in the transformer and the right side the current when in addition 1 A DC current flows in the high voltage winding of the transformer. It can be seen that a DC current in the transformer winding, and the resulting part cycle core saturation, lead to a significant increase of the even harmonics in the current spectrum.

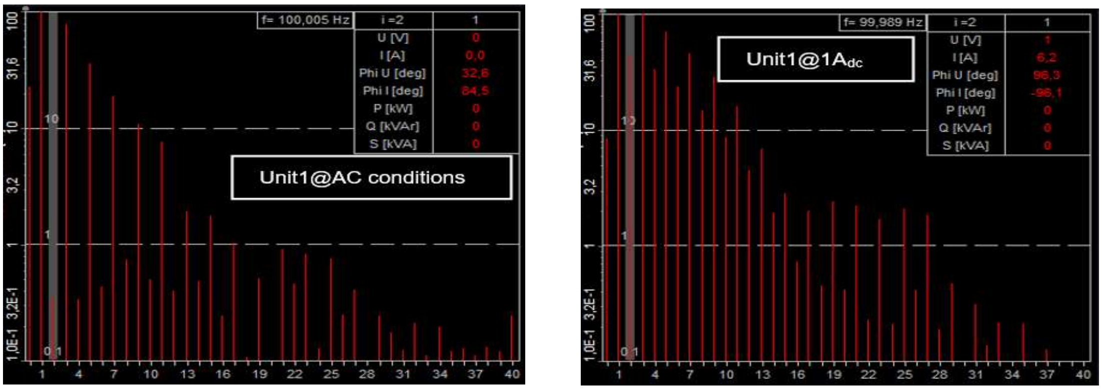

Figure 12 : Recorded current spectrums by a power analyzer at different DC levels (without DC (left), with 1 Amp DC (right)

- **Core and structural part Thermal behaviour under GIC:**

The test allows also to have a vision on the temperature evolution of different steel components during the injected DC profile as shown in Figure 13 and Figure 14. It can be seen from the measurement results, that the tie bars experience a significant higher temperature increase compared to other components. With 25 A DC the tie bar temperature rise above the cooler-outlet oil is about 30 K. The temperatures of all other components show a lower increase.

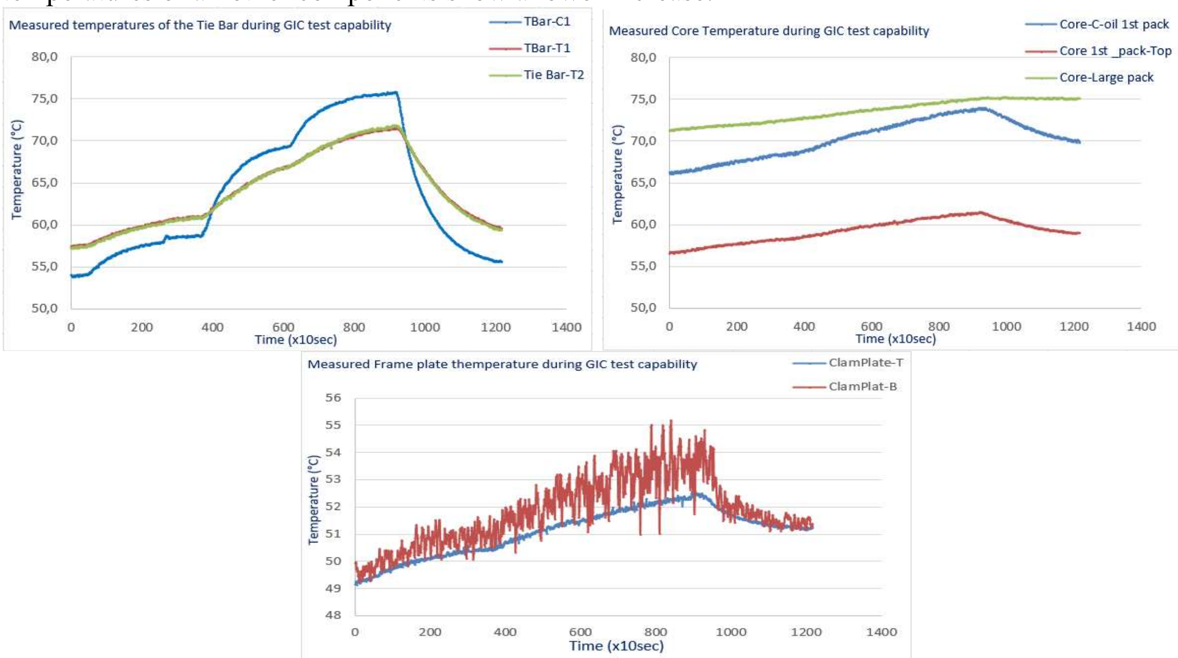

Figure 13 : Measured temperatures during the GIC test for the Tie bar, the shunt tank and oil close to the first core step.

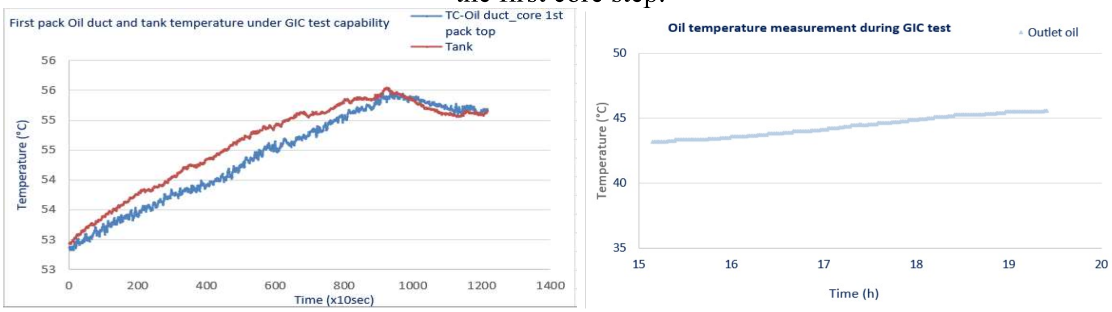

Figure 14 : Measured temperatures during the GIC test for the Tie bar, the shunt tank and oil close the first core step.

In the no-load conditions, the comparison between the measured and the calculated temperatures for different components is possible. A comparison of the measured and simulated tie bar temperature is illustrated in Figure 15 below.

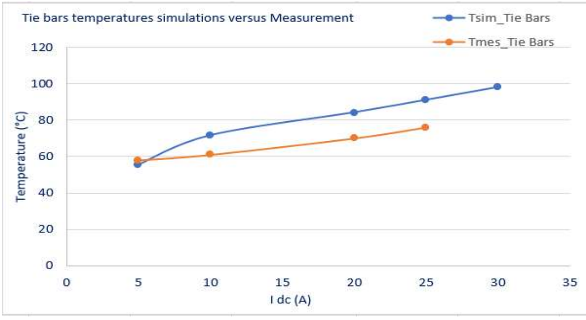

Figure 15 : Measurement and simulations comparison for tie bar

By comparing the measured and simulated temperatures of the different magnetic circuit components, the similar thermal behavior is confirmed. Thus, on this basis, we can note that the tie bars are the components that have the highest thermal stress compared to other components of metal structures in the 570 MVA design.

Nevertheless, an evident difference between measurements and simulations of 10 to 15K can be seen in Figure 15 depending on the applied DC component value.

The simulation results that are shown above have been carried out considering a generator supply voltage whose waveform is purely sinusoidal, while the test voltage shows significant distortions. This partly explains the difference between simulation and measurements. The simulation results could be considered as a conservative approach in the evaluation of the thermal stresses under GIC. The next illustrations in Figure 16, show the applied voltage to LV windings and the measured current excitation. The LV voltage is indeed quite different from a perfect sinusoid. This shows that it is important to consider the real occurred voltage condition during the measurement in the simulation to evaluate the quality of the calculation model by comparing simulated results with measured ones.

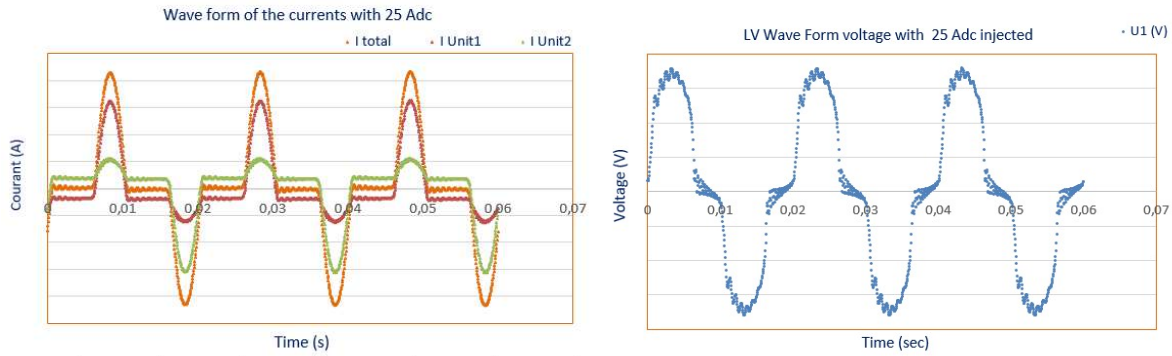

Figure 16 : Test voltage and currents applied under DC component

- **Core and structural part mechanical behaviour under GIC:**

The saturation of the core under DC results in dynamic mechanical stresses such as the core magneto-strictive vibrations transmitted to the structural parts on one hand and to the tank via the oil on the other hand. Thus, the noise of the transformer is obviously affected by the value of intensity of the GIC circulating through the neutral of the unit. The tests carried out in Siemens Energy' HV laboratory allowed to highlight and quantify this behavior. The results are shown in Figure 17.

The tank wall vibration levels up only about 17 µm at 25 A DC per phase. This value is very low and is no issues for the mechanical condition of the tank. To evaluate this value, it can be mentioned that the allowed peak-to-peak displacements of shunt reactors tanks can be much higher up to 200 µm according to the relevant standards [IEC 60076-6]. The measurement results for the noise show, that here the steep increase happens already at very low DC level and no significant further increase occurs with higher DC levels.

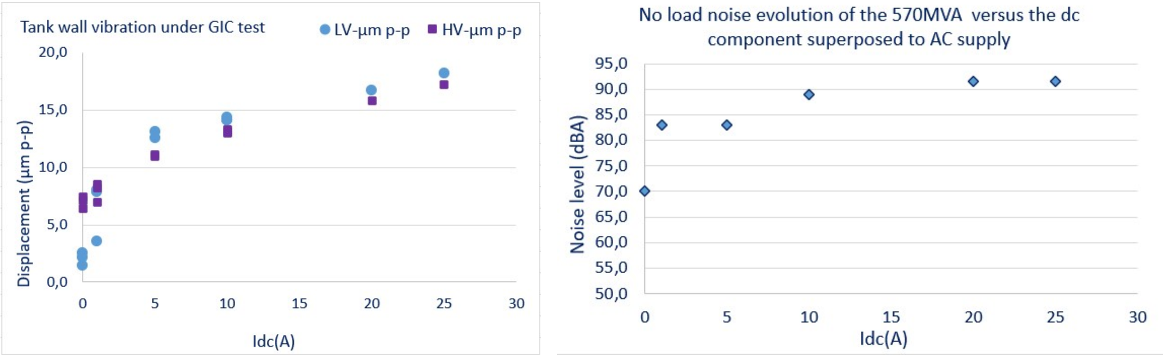

Figure 17 : Displacement of the wall tank by accelerometers (left) and noise measurement (right)

CONCLUSION

The work carried out by EDF and Siemens Energy shows that the transformer GIC capability can be demonstrated by a computational approach supported by a special test at the manufacturer's test bay. The simulation models must be fine enough to also consider the non-linear effects of the core lamination and structural parts due to the saturation of the magnetic circuit. The paper confirms the fact that DC component simulating GIC magnitudes, in the high-voltage winding of the investigated transformer cause a significant peak in the transformer exciting current.

In addition to these current harmonics, the temperatures of the structural steel parts also increase with the applied DC level. Detailed FEM-3D simulation for the 570 MVA GSU design indicates that the tie bars nearby the core are the most stressed components under DC magnetization whereas other components show only a small heating.

The back-to-back test carried out in no-load conditions allows to highlight the differences and limitations compared to the simulations. The characteristics of the materials and the excitation voltage waveform influence significantly the results. Although the back-to-back test is not completely representative of the operating conditions, the obtained test results allow the validation and evaluation of the performed simulations with the used calculation model.

A further interest of such GIC test is to measure the mechanical impact of GICs on transformers like vibrations and noise, which seems currently not feasible using simulations.

The shared experience in this paper highlights the need of standardization regarding the implementation of such test and the technical recommendations supporting both the transformer suppliers and users.

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