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A simplified tool to assess transformer behavior to GIC and other DC disturbances

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SUMMARY

Power transformers can be disturbed by DC or quasi-DC currents flowing through their windings. The performance of transformers regarding such disturbances is increasingly specified by transformer customers and consequently increasingly discussed during the design review process. These can lead to the following issues: additional reactive power, harmonic current and additional losses. Consequently, temperature increase in the windings, the magnetic circuit and the clamping system as well as mechanical vibrations and the resulting noise reach higher levels. Geomagnetic Disturbances (GMD) may lead to the highest values of DC but are also very difficult to predict. Therefore, it can be useful for the transformer end-user to have a simplified approach to quickly estimate the hotspots in the windings and the structural parts of the equipment. Most manufacturers are now able to carry out calculations to evaluate the electrical and thermal values of a given transformer subjected to DC. However, these calculations rely on complex models which usually require a lot of data about the device, namely most dimensions and detailed material characteristics and are consequently barely achievable by transformer users. The challenge they have to face is how to evaluate their fleet with an efficient tool in order to help the operator in case of GIC crisis, knowing the operating limits of its equipment.

This is the reason why EDF has developed tools and methods making possible to easily estimate the behavior of transformers subject to DC, without requiring any exhaustive set of data nor complex simulation tool. This enables to quickly yet accurately rate an entire fleet of transformers. The paper will underline the necessary preliminary investigations, using advanced tools as electromagnetic field finite-element (FEM), Computational Fluid Dynamic (CFD) and Electro-Magnetic Transients (EMT) programs. Reactive power, current harmonics, thermal losses and temperature rises of the windings have been precisely computed with those software programs. This has enabled to include simplified but still representative models in a simple spreadsheet. The proposed tool and its related methods will be discussed in the paper, as well as further improvements that could be considered, especially for the clamping system, which is also a critical aspect with respect to DC disturbances. This tool can be used tool by transformer customers namely at the specification and design review stages, to quickly and easily assess the risk of given levels of DC currents.

KEYWORDS

GIC, temperature, hot-spot, simplified tool

INTRODUCTION

Power transformers performances are disturbed when DC or quasi-DC currents flow through their windings. Thus, additional reactive power, harmonic currents and losses may lead to higher temperatures in the windings, the magnetic circuit and the clamping system. In addition, mechanical vibrations and the resulting noise may also increase.

It has been observed that those DC may result of difference sources, such as neighboring HVDC equipment or Geomagnetic Disturbances (GMD) which unfortunately lead to the highest values and are very difficult to predict. Most manufacturers are now able to carry out calculations to evaluate the electrical and thermal values of a given transformer subjected to DC. However, these calculations rely on complex models requiring a lot of data about the device, namely most geometrical and material characteristics which are barely accessible by transformer users. Therefore, it would be useful to have available a simplified approach to quickly estimate the hotspots in the windings and the structural parts of the equipment. This is the reason why EDF has developed a simplified tool to estimate the temperature of the windings of transformers subject to DC, without requiring any exhaustive set of data nor complex simulation tool. This approach makes it possible to quickly rate an entire fleet of transformers with an acceptable accuracy. The theoretical background and the validation process will be disclosed as well as the feasibility to apply the same principles to the magnetic circuit and the structural parts.

Mitigation measures could then be implemented. One of them is to specify transformers less susceptible to DC currents thanks to appropriate designs.

BRIEF REMINDER OF DC CURRENT EFFECTS ON TRANSFORMERS

DC currents have many detrimental effects on power transformers, since they offset the linkage flux inside the magnetic circuit, leading to significant increase in magnetising currents due to the non-linear B(H) characteristics of the ferromagnetic material (Fig. 1 and 2) This phenomenon is well known and has been often investigated in the last decades [1].

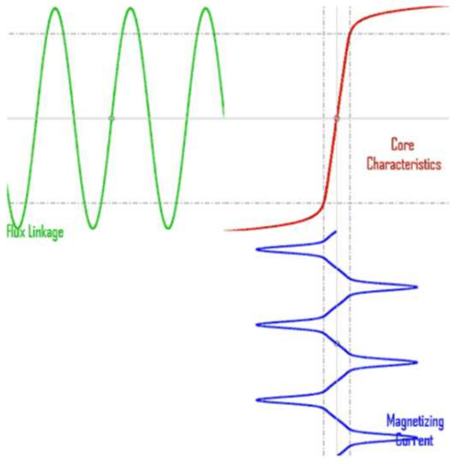

Figure 1 : Flux and currents waveshapes when a transformer is regularly operated (i.e. no flux offset)

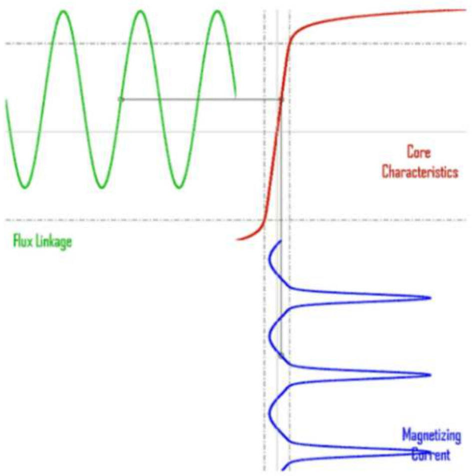

Figure 2 : Flux and currents waveshapes when a transformer is subjected to a DC current

These magnetising currents cause the following issues:

- High consumption of reactive power by the transformer;
- Additional losses in the windings;
- Potential misfunction of protection relays, as the magnetising current frequency content is extremely rich in even harmonics.

This asymmetric saturation of the magnetic core also causes issues:

- Additional losses in the core and the structural parts;
- Increased vibrations, which can rise the noise as well as the mechanical aging of the active parts.

CONTEXT AND PURPOSE OF THE WORK

As mentioned hereabove, transformer users which have transformers eventually subjected to DC current need to rate their fleet in order to identify the most critical ones and take the preventive or corrective actions. This should be possible without requiring any complex, and most of the time barely available, data about the transformers. This has been achieved by developing a simple tool which calculates:

- The magnetizing currents harmonics
- The additional reactive power consumed by the transformer
- The additional losses within the windings
- The hot-spot temperature increase within the windings

The tool and the hypothesis on which it relies will be more precisely described in the following paragraph. All the simple models make it possible to implement these methods in a simple spreadsheet.

The performance of transformers regarding GIC and other DC disturbances is increasingly specified by transformer customers and consequently increasingly discussed during the design review process.

This tool can be used tool by transformer customers at several stages:

- At the specification stage, to check the feasibility of specifying a given value of DC current for a given transformer, depending on its main characteristics;
- During the design review, to easily and quickly assess the transformer manufacturer design file devoted to these topics;
- During the operation, to estimate the particular risks of:
  - overheating the transformer windings;
  - spurious operation of relays.
  -

MAGNETISING CURRENTS AND REACTIVE POWER CALCULATION

It can be shown [2] that a single-phase transformer at no-load and exposed to a DC current I_{DC} produces a magnetising current whose first harmonic I_1 could be simply calculated by:

$$I_1 = \sqrt{2}.I_{DC}$$

The saturations of the transformers are different depending on their core topology [2]. A commonly accepted approximation is that three-phase three-limb core type transformers do not significantly saturate when exposed to DC currents, whereas single-phase transformers are most at risk. In between, three-phase five-limb transformers do saturate but at different levels on each phase, as the central limb tends to less saturate.

The idea of the developed tool is to provide the worst-case scenario to its user; Therefore, the hypothesis will be made that all transformers do saturate at the same level, (except the 3-phase 3-limb, that will be considered to be perfectly immune to DC currents).

Consequently, as the losses due to the saturation of a transformer under DC are negligible compared to the reactive power consumed because of this DC current, the latter can be easily determined by the following equation:

$$Q_{DC} = \sqrt{3}.U.I_1$$

Where U is the phase-to-phase applied voltage.

Without any advanced tool (electromagnetic transient program or finite elements), it is difficult to precisely estimate the right harmonic spectrum of the magnetising current as many factors are involved:

- No-load current vs. voltage profile of the transformer
- Level of saturation of the magnetic circuit
- Connections of the transformer with the rest of the networks, and namely the short-circuit power of the network

Nevertheless, literature describes the following aspects regarding such magnetising currents [1] [2] [3]:

- 2^{nd} harmonics are always a little bit lower than the 1^{st} harmonics
- They generally tend to be very weak and almost negligible, from more or less the 10^{th} harmonic but there are very few cases where it is not the case
- The harmonic profile usually shows a linear decrease on the first harmonics

In the same idea of providing a worst-case scenario, the choice has been made to adopt a linearly decreasing harmonic profile, assuming harmonic 41 be equal to zero, as most standards historically consider harmonics up to 40 (i.e. 2 kHz for 50 Hz systems) (Fig. 3).

For most cases, this spectrum clearly overestimates the high harmonics (i.e. from around 10^{th}).

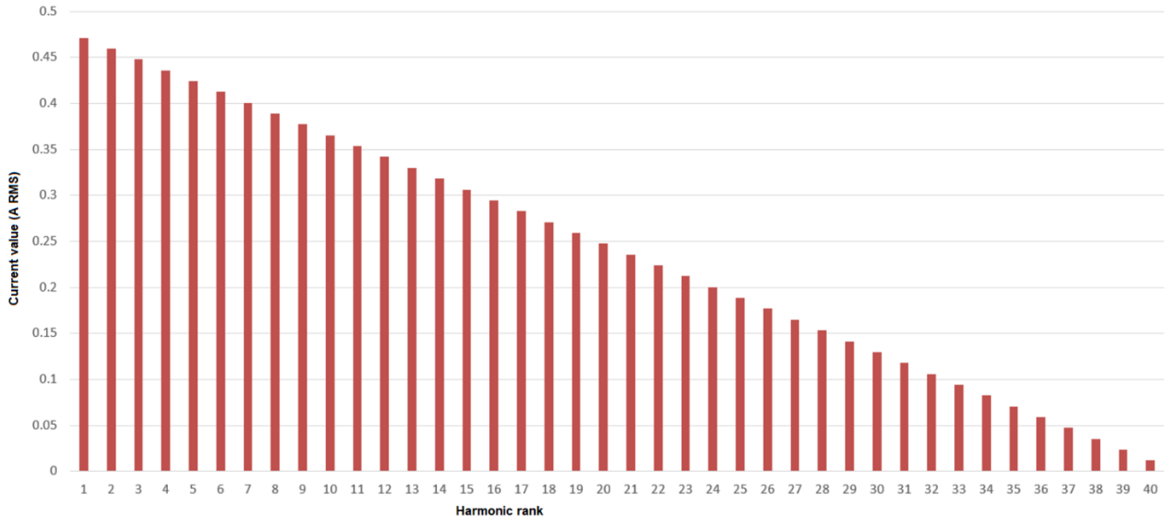

Figure 3 : Harmonic spectrum considered for each phase

In figure 3, the value of $\frac{\sqrt{2}}{3} \approx 0.4714\ A$ can be found for harmonic 1. It is worth noticing that the division by 3 is due to the fact that the neutral DC current is considered (sum of the 3 phases). This will always be the case thereafter.

All these calculations refer to transformers at no-load. The following paragraph will cover the general case of loaded transformers.

The general equivalent single-phase model of the system for the positive and negative sequence harmonics (i.e. harmonics which are not multiple of 3) and its neighbouring network is depicted in Figure 4, where L_d is the positive sequence impedance of the network, L_M is the magnetizing inductance of the transformer, L_{CC} is the short-circuit impedance of the transformer and X_H is the equivalent harmonic inductance of the load connected to the transformer.

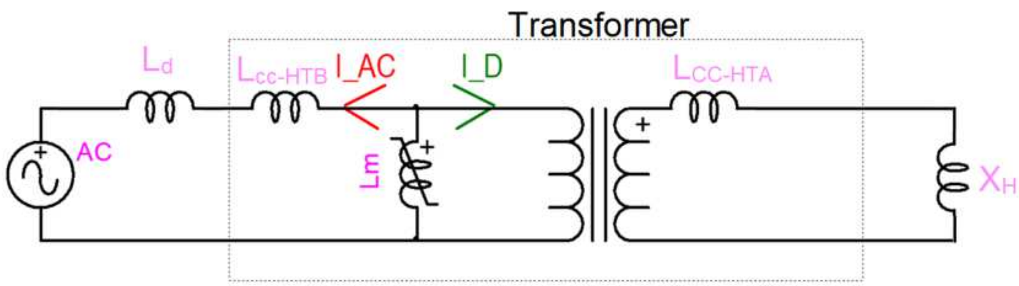

Figure 4 : General model of the transformer and its neighbouring network for positive and negative-sequence harmonics

This model relies on the following approximations:

- The network is modelled as a simple inductance;
- The short-circuit impedance is equally shared between both voltage levels, i.e. both are equals in p.u. and equal to half the total short circuit impedance;
- The magnetizing inductance is approximated as a constant harmonic current source (cf. Fig. 3) and is only proportional to the applied DC current.

In the case of zero-sequence harmonics (i.e. harmonics multiple of 3), the same diagram applies with L_0 instead of L_d.

In the common case of Yd transformers, the short-circuit can be explained by the fact that delta windings act as a short-circuit for such harmonics (Fig. 5).

The harmonic inductance depends on the nature of the load/generation connected to the transformer and can be approximated as follows for typical cases:

- For synchronous generator, as the mean of the sub transient reactances on d and q axis [4];

- For asynchronous motors, as its negative-sequence impedance, which can be approximated in p.u. as the inverse of its starting current.

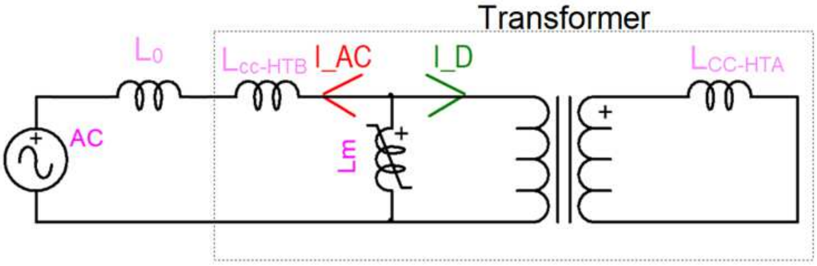

Figure 5 : General model of the transformer and its neighbouring network for positive and negative-sequence harmonics

Using Kirchhoff laws, the repartition of the currents can be easily determined. Similar models can be used for transformers with more windings.

LOSSES CALCULATION

Knowing the current in each winding of the transformers, the additional losses can be computed using the following approximation:

- Load-losses share between Joule losses (usually around 80%) and Eddy losses (usually around 20%)
- The Joule losses are equally shared between both windings
- The load current is purely resistive (cos(Φ) = 1), which consequently gives the total first harmonic currents flowing in the windings as follows, considering the first harmonics magnetising current is purely inductive (cos(Φ) = 0):

$$I_{RMS-50Hz\ with\ DC} = \sqrt{(I_{rated}.k)^2 + I_{DC@50Hz}{}^2}$$

Finally, the total RMS current can be computed as follows:

$$I_{RMS\ with\ DC-TOTAL} = \sqrt{I_{RMS-50Hz\ with\ DC}{}^2 + \sum_{harmonics} I_{h-GIC}{}^2}$$

The Joule losses can be finally computed as follows for the winding subjected to DC (WDC):

$$P_{Joules-WDC} = R_{elec\ WDC} \cdot I_{RMS\ with\ DC-TOTAL}{}^2 + R_{elec\ WDC} \cdot I_{DC}{}^2$$

And for the other windings (OW):

$$P_{Joules-OW} = R_{elec\ OW} \cdot I_{RMS\ with\ DC-TOTAL}{}^2$$

The eddy losses are computed as follows [5],[6]:

$$P_{Eddy\ with\ DC} = P_{Eddy} \cdot \sum_{h} h^2 . \left(\frac{I_{h\ with\ DC}}{I_{rated}}\right)^2 . Coefh$$

With h being the harmonic rank, I_h the RMS value of harmonic current of rank h, P_{Eddy} the nominal Eddy losses and Coefh a coefficient taking into account the geometric configuration of the windings. It can range from 0 to around 1.2.

THERMAL CALCULATION

Knowing the losses, the temperature rise of the top oil and the hotspot can be computed, considering that they are only due to load and no-load losses in the windings.
First, the top oil temperature is corrected, considering the new load losses (total Eddy+Joule losses).

$$\Delta\theta_{Top\ oil} = \frac{P_{load}}{(P_{load} + P_{no-load})}\Delta\theta_{Top\ oil\ rated}.k^2 + \frac{P_{no-load}}{(P_{load} + P_{no-load})}\Delta\theta_{Top\ oil\ rated}$$

Similarly, the hotspot temperature is adjusted depending on the load factor k of the transformer:

$$\Delta\theta_{Hotspot\_winding} = \Delta\theta_{Top\ oil} + (\Delta\theta_{Hotspot\_winding\_nom} - \Delta\theta_{Top\ oil\_nom}).k^2$$

Where $\Delta\theta_{Hotspot\_winding\_nom}$ is the winding hotspot relative temperature under nominal conditions (i.e. no DC).

The thermal resistance of each winding is then calculated, again assuming the load losses are equally shared between each winding:

$$R_{therm-eq} = \frac{(\Delta\theta_{Hotspot\_winding} - \Delta\theta_{Top\ oil})}{\frac{P_{load}}{2}.k^2}$$

For each winding, the steady-state hotspot of each winding is then computed, taking into account the additional losses due to the DC current. This assumes that the DC event is short enough to neglect the additional heating of the top oil due to these additional losses and that the location of the hotspot remains the same for nominal conditions during the DC event.

$$\Delta\theta_{Hotspot\_winding\_total\_steady-state} = \Delta\theta_{Top\ oil} + \left(P_{Joules-total-winding} + P_{Eddy-total-winding}\right).R_{therm-eq}$$

If needed, the hotspot rise can then be calculated in time-domain as follows, considering a constant DC current appearing at t=0:

$$\Delta\theta_{Hotspot}(t) = \Delta\theta_{Hotspot\_winding\_nom} + (\Delta\theta_{Hotspot\_winding\_total\_steady-state} - \Delta\theta_{Hotspot\_winding\_nom}).\left(1 - e^{\frac{-t}{\tau_{Winding}}}\right)$$

Where $\tau_{winding}$ is the thermal time constant of the winding, which has been measured during the Factory Acceptance Test (FAT).

VALIDATION OF THESE SIMPLIFIED APPROACHES

For the current calculations, the method has been validated:

- Using comparisons with finite-elements, EMT simulations and manufacturer modelling (Figure 6);
- EMT simulations have been themselves validated by back-to-back tests (Figure 7).

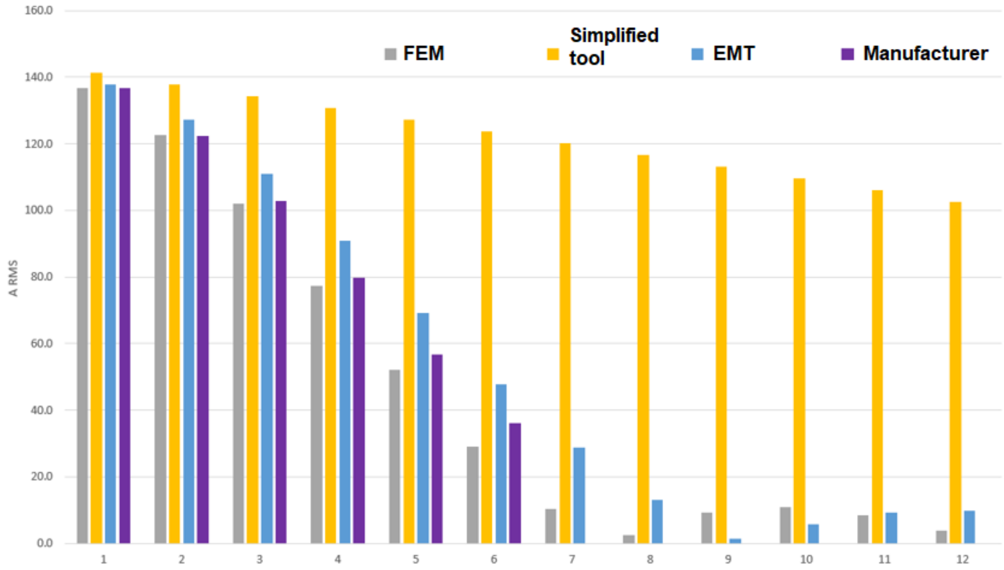

Figure 6 : comparisons between the simplified approach, finite-element modelling (FEM), EMT simulations and manufacturer model

As it has been stated before, the model gives a reasonable approximation for the first harmonics but the bigger the harmonics are, the bigger the overestimation is.

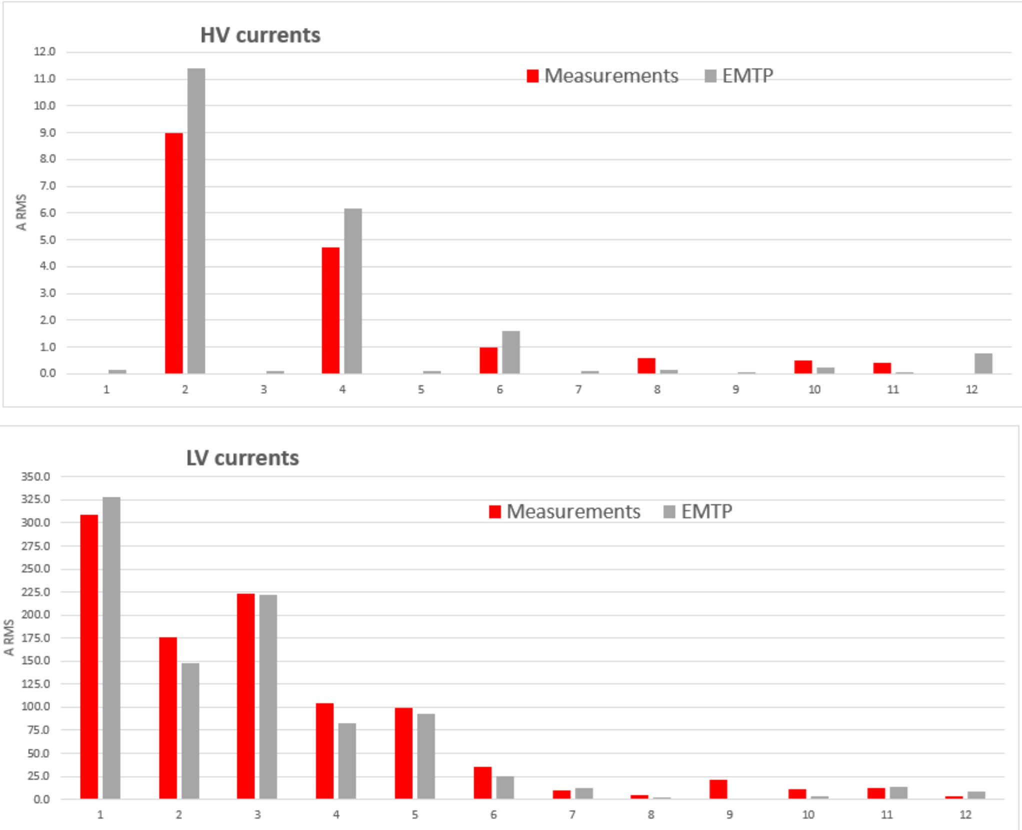

Figure 7 : comparisons between measurements and EMT simulations

The losses computation has been validated using a single-phase core-type simplified fictive transformer of 57 kVA (Figure 8).

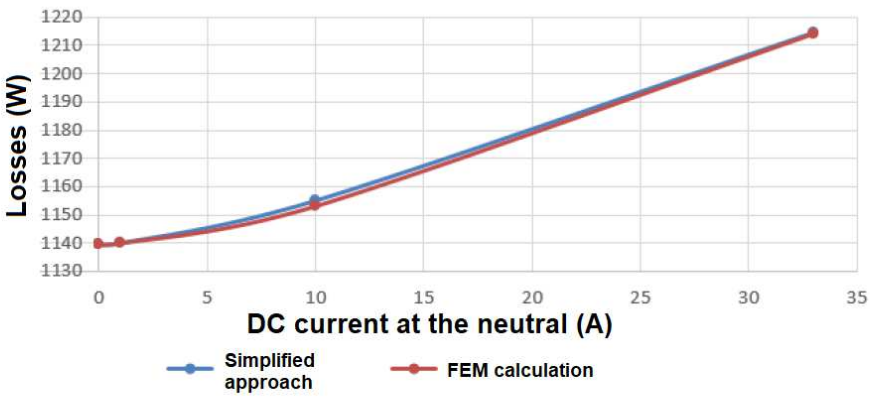

Figure 8 : losses comparison on a simple transformer between the simplified approach and a FEM calculation

For the temperature computation, different levels of losses have been simulated using CFD and compared with the simplified approach on a single-phase core-type 550 MVA transformer (Fig. 9). The CFD calculation assumes that the increase in losses is homogeneous for each conductor.

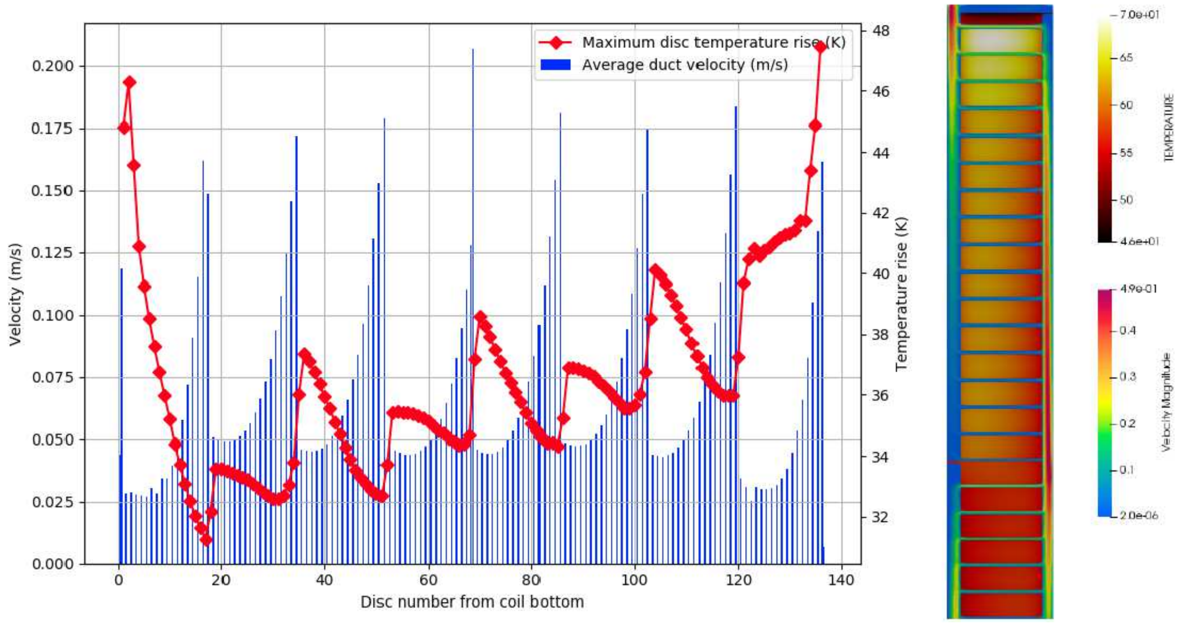

Figure 9 : CFD results of oil velocity and temperature at each coil of the windings for 100% losses

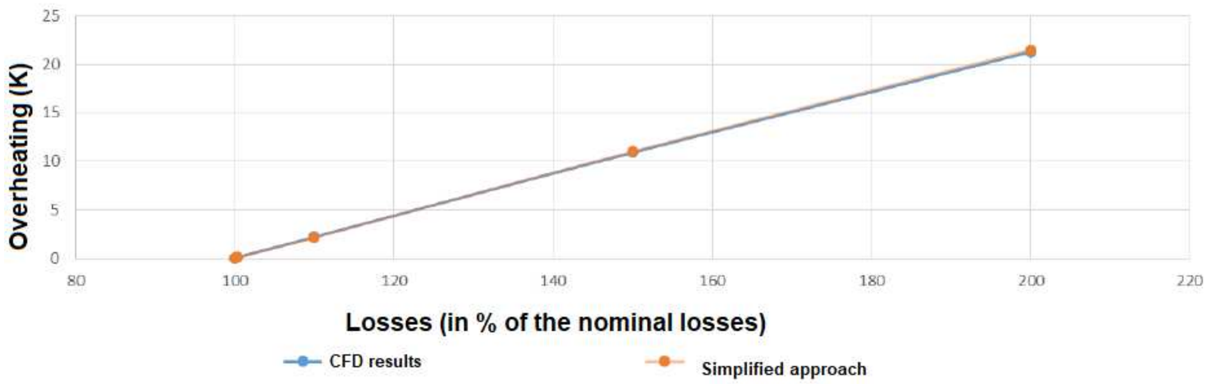

Figure 10 : Comparison between CFD and the simplified approach

INVESTIGATIONS FOR A SIMILAR APPROACH APPLIED TO THE MAGNETIC CORE AND STRUCTURAL PARTS

Investigations have been carried out to extend this approach for the computation of the temperature in the magnetic core and the structural parts. Both of these transformer's parts are known to be the most likely to see high temperature when exposed to GIC.

Two models of the magnetic core and structural parts of the same transformer have been developed, then electromagnetic and thermal 3D simulations have been conducted.

The two models are identical except for the shape of the clamping plate and the addition of a shunt in front of the clamping plate (Fig. 11).

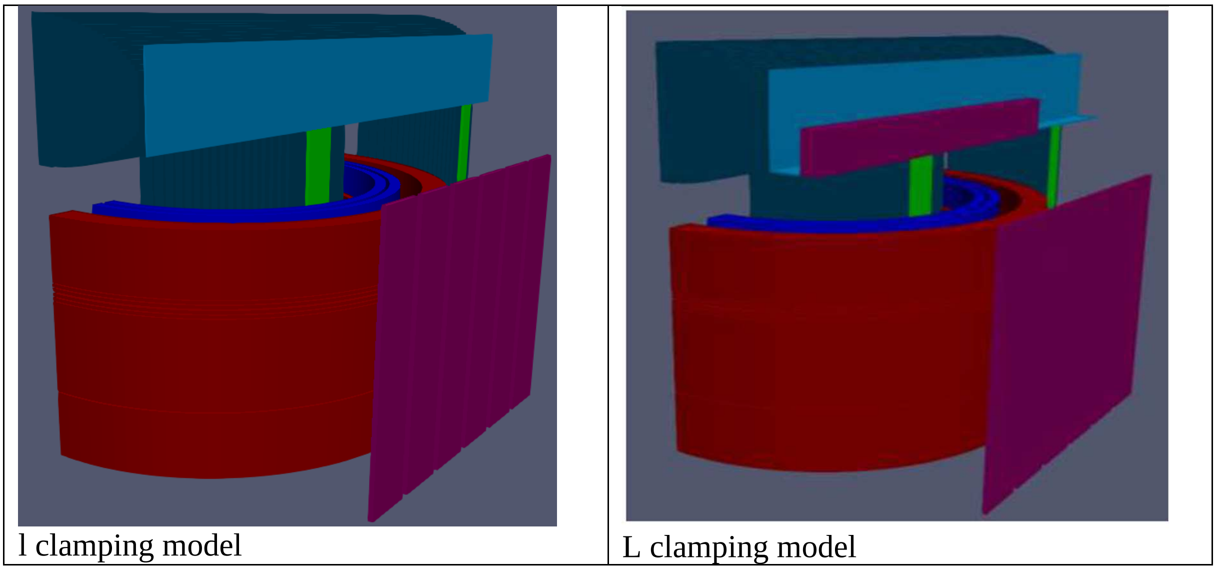

Figure 11 : Geometry of the two models of the transformer

The simulation results show that the losses and the temperatures are significantly different for the two models [Figure 12, Figure 13].

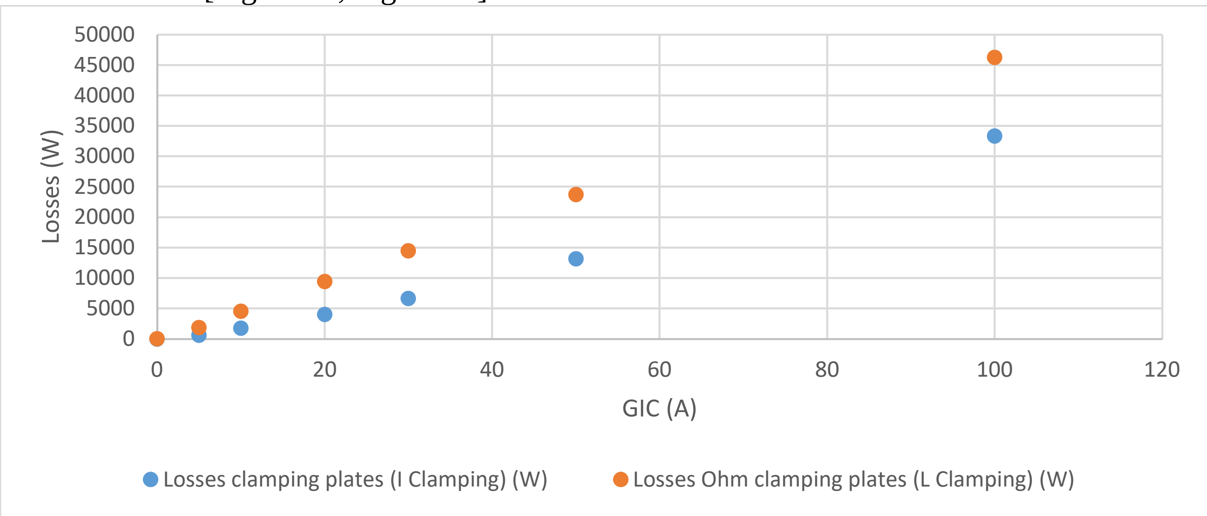

Figure 12 : Losses in the clamping plates as a function of the DC component for the two models

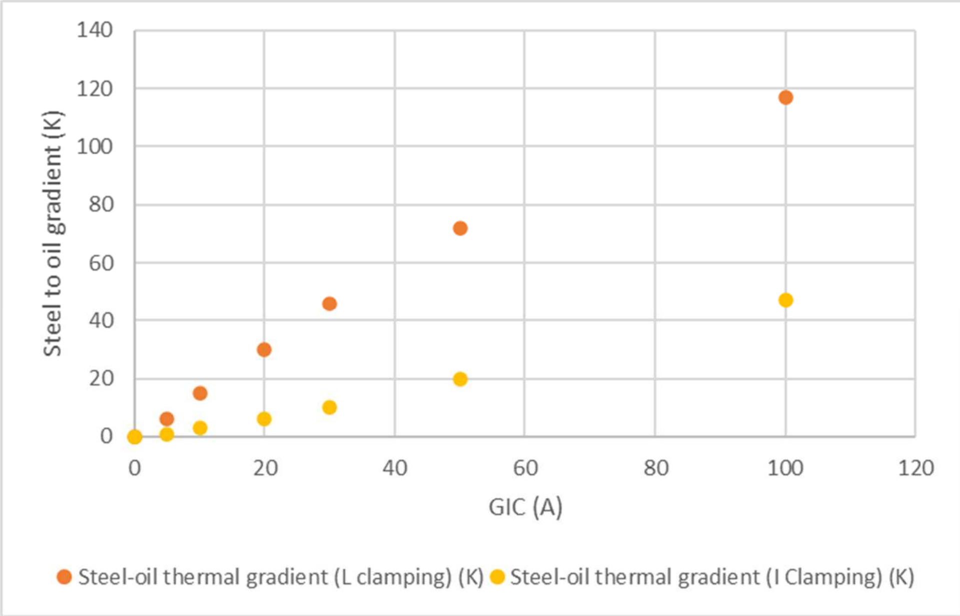

Figure 13 : Steel-oil thermal gradient in the clamping plates as a function of the DC component for the two models

These results indicate that losses and temperatures are strongly dependent on the geometry. A detailed knowledge of the clamping system would then be necessary to obtain a relevant estimate of the temperature rise due to GIC.
In most cases, geometrical data and physical properties of the clamping systems of the transformers are not available. It is therefore quite challenging to develop a simplified tool without taking into account the precise dimensions of the clamping system as input data.

CONCLUSION
EDF has developed tools and methods making possible to easily estimate the behavior of transformers subject to DC, without requiring any exhaustive set of data nor complex simulation tool. This enables to quickly yet accurately rate an entire fleet of transformers.
The paper has underlined the necessary preliminary investigations, using advanced tools as electromagnetic field finite-element (FEM), Computational Fluid Dynamic (CFD) and Electro-Magnetic Transients (EMT) programs. Reactive power, current harmonics, thermal losses and temperature rises of the windings have been precisely computed with those software programs. This has enabled to include simplified but still representative models in a simple spreadsheet.
This tool can be used tool by transformer customers namely at the specification and design review stages, to quickly and easily assess the risk of given levels of DC currents.
If it has been well validated for temperatures in the windings, it would require further studies to extend it to the magnetic circuit and structural parts.

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