ADVANCED FINITE ELEMENT CALCULATION OF LOSSES DUE TO THE HARMONIC CONTENT OF CURRENT AND DESIGN OPTIMIZATION OF HIGH VOLTAGE DISTRIBUTION TRANSFORMERS

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ABSTRACT

Transformer manufacturers are committed to meeting the demands of more efficient and safe equipment. When the generated energy comes from a renewable source such as wind or solar plants, the inverters and other high frequency producing devices can increase the harmonic distortion of the load signal. This paper develops and presents the procedure based on the Finite Element (FE) method to precisely calculate losses in both primary and secondary windings of a three-phase power transformer due to local effects such as skin and proximity effects, and the contribution of the harmonic content of the current.

INTRODUCTION

The integration of renewable generation sources such as solar and wind to the grid involves the use of inverters and other high frequency noise producing devices which increase the load signal harmonic distortion for transformers. This distortion leads to a non-uniform loss distribution along the LV and MV windings. Traditional analytical methods described in the standards, such as IEC60076, lead to oversized winding designs because they consider a uniform distribution of losses.

FINITE ELEMENT MODEL

This paper develops and presents the procedure based on the Finite Element (FE) method to precisely calculate losses in both primary and secondary windings of a three-phase power transformer due to local effects such as skin and proximity effects, and the contribution of the harmonic content of the current.

One possible approach would be to launch a transient 3D simulation of the problem to calculate the influence of the harmonics in losses. This would require a detailed definition and calculation of the windings which is not feasible with the current hardware capabilities. The transient 2D simulation of the problem could be affordable in terms of computational cost but not fully efficient as it would require to have more than 12.000 time steps per period to consider the full harmonic range (up to 304th harmonic). Due to the complexity of the technical challenge and the limitations of computational power, different authors [1-4] propose several simplifications in order to allow the resolution of the proposed transformer model. Geometry was simplified from 3D to 2D, and from 3 phases to a 1 phase axisymmetric model. In addition, the excitation regimen was changed from transitory to stationary for each studied frequency in order to calculate the effect of each harmonic over winding losses.

MAGNETIC ANALYSIS SETTINGS AND PRE-PROCESSING

Considering the topology of the LV and MV windings around each column of the magnetic core (fig.1), two different cases with different gaps between conductors were generated corresponding to the curved or the straight section of the winding (fig. 2).

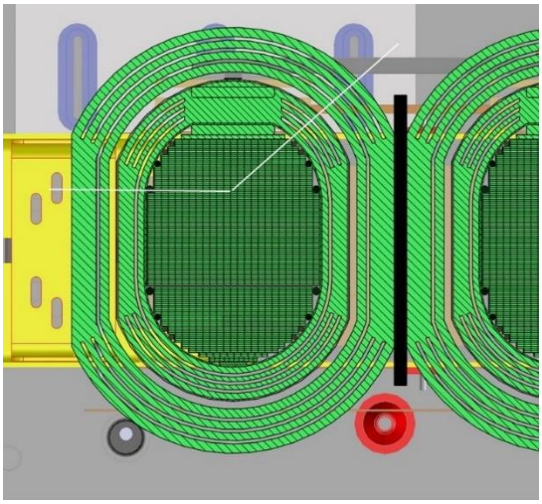
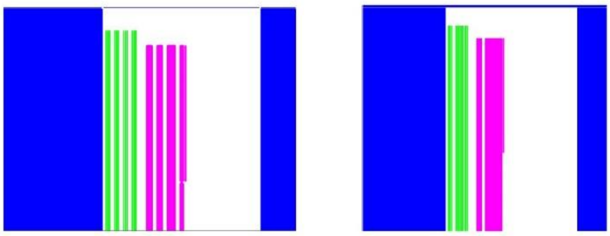


Figure 1: Geometry of one winding.

Also a reduction of the regions' surface is considered due to the flattening of the MV conductors.

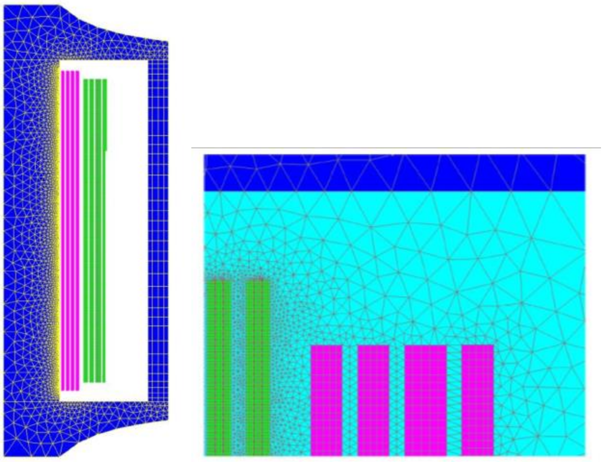


a) Curved section b) Straight section

Figure 2: Different sections of the transformer winding.

Once the geometry of the model is defined, the next step is to build the FE mesh in whose nodes, the Maxwell equations will be solved. The precision of the results depends on the mesh quality. Therefore, all the aspects related with energy conversion must be foreseen, especially in the conductors, where the current density distribution loses its uniformity as the section increases.

To achieve the maximum precision with the lowest number of nodes, instead of triangular elements, a rectangular element based mesh is constructed. In the next figure, figure 3, the combination and the transition between both types of elements is shown.



Complete model Detail of the mesh in the winding

Figure 3: FE mesh.

The magnetic field simulations were carried out applying 2D sinusoidal permanent magnetic to the electric circuits using the FE software FLUX®.

Magnetic core

Considered as a non-conductive magnetic surface region, whose magnetic characteristic is shown in figure 4. The material used is a Fe-Si Steel plate with grain orientation designated as Powercore® C 130-30.

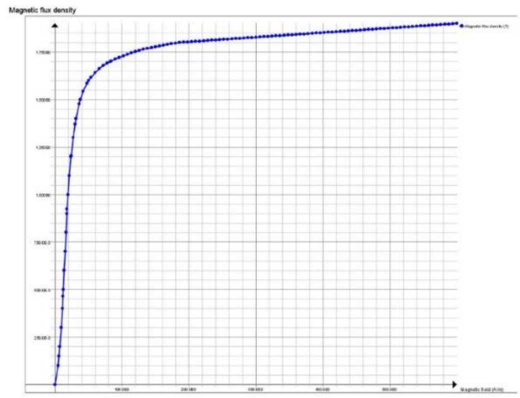


Figure 4: Magnetic flux density Vs Magnetic field of C 130-30 steel plate.

LV windings

Represented by 12 solid conductor type regions. One for each turn of the LV winding. In this kind of regions, the current density is not obliged to be uniform.

MV windings

2 different modelling techniques were studied and compared for these coils.

Homogenization technique:

The windings are represented by 5 surface regions specified as wound conductor with losses and a turn number of 279, 279, 372, 186 y 22 respectively.

This kind of regions enables the automatic homogenization technique described in [2]. Thus permitting the calculation of the losses due to skin and proximity effects without representing every turn but nevertheless considering the dimensions, quantity and gaps between conductors.

Detailed meshing technique:

The windings are represented by the detailed geometry and the mesh of the total number of turns. In this case 1138 turns.

Excitation and electric circuit

In the secondary winding, a current source with harmonics is connected. This harmonic content of the current needs to be specified by its amplitude for each harmonic.

In the case of this study, as it was observed afterwards, the main contribution to losses was that from 102nd harmonic order.

I %	# harmonic
100	1
.	.
3,1	102
.	.

Table 1: Example of harmonic content of the current.

In the primary, the voltage source is set to the transformer feeding tension.

Both conducting regions are connected as shown in the diagram below and solved simultaneously with the Maxwell Equations.

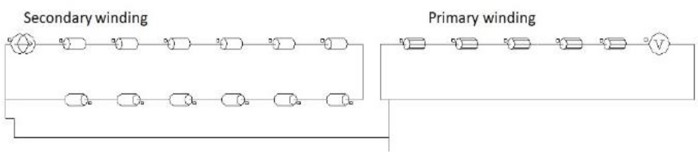


Figure 5: Electric circuit of the system.

RESULTS. HOMOGENIZATION TECHNIQUE

The following figure shows the induction and leakage flux in the upper part of the winding at a constant frequency of 60Hz and a power of 4920kVA. The temperature of the windings was 20ºC.

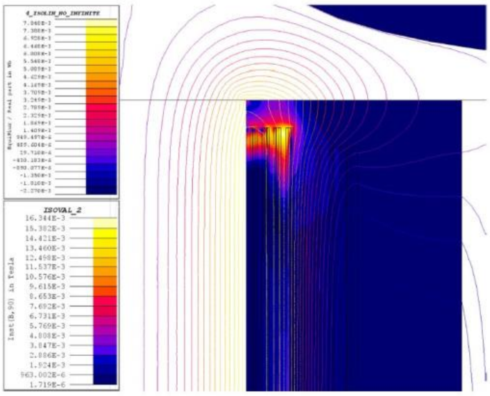


Figure 6: Induction and leakage flux in the upper part of the coils.

The highest loss values are found in the upper part and in the lower part of the windings. The non-uniform losses density distribution for these coils is shown in figure 7 and figure 8.

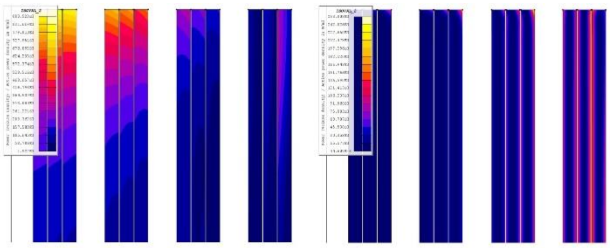


Figure 7: Loss distribution in the LV winding.

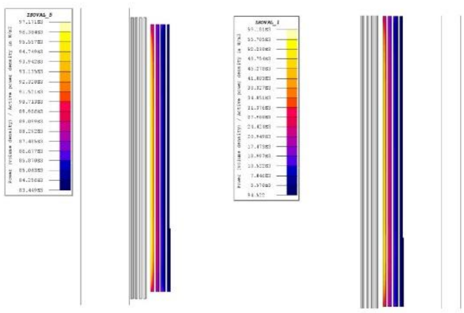


Figure 8: Loss distribution in the MV winding.

In order to identify the highest loss density, an analytic computation is presented:

$$dW_{LV} = \frac{W_{LV}}{V} = \frac{1{,}772.10^{-4}.4508{,}8^2}{0.028645} = 125.758.10^3\ W/m^3$$

$$dW_{MV} = \frac{W_{MV}}{V} = \frac{2.343.47.54^2}{0.053855} = 98.149.10^3\ W/m^3$$

The table 2 shows a comparison between the losses due to the fundamental harmonic obtained by calculation and those obtained by the FE simulation over the conductor length.

	RI^2	simulation
LV	3602.3W	4020.4W
MV	5295.3W	5261.7W

Table 2: Comparison of total losses.

It is possible to obtain the losses for each frequency (table 3), by integration of the loss density along the frequency range and represent it in a 2D plot (figure 9).

#	Loss_LV [W]	Loss_MV [W]
1	**4020,42**	**5261,69**
.	.	.
102	773,36	5,94
.	.	.
Total	**5954,54**	**5276,32**
Pcu	**1934,11**	**14,63**

Table 3: Losses corresponding to one of the most significant harmonics and the summation of losses.

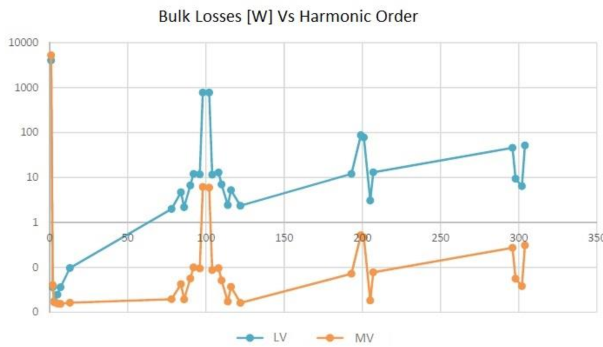


Figure 9: Contribution of the harmonics to the losses in both LV and MV windings.

As commented before, the biggest contribution to the losses is for the 98th and 102nd harmonics.

In the LV winding it is possible to detail the losses per turn and even divide each turn in different areas to have more insight on the losses distribution. An example of the losses representation would be as shown in figure 10.

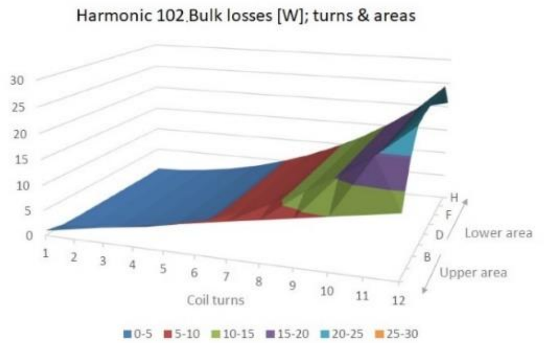


Figure 10: Losses distribution along the coils for a particular harmonic.

RESULTS. DETAILED MV WINDINGS

In the second case, where the MV windings were represented by the detailed geometry of the coils instead of using the homogenization technique, the highest detail level on the losses distribution was achieved.

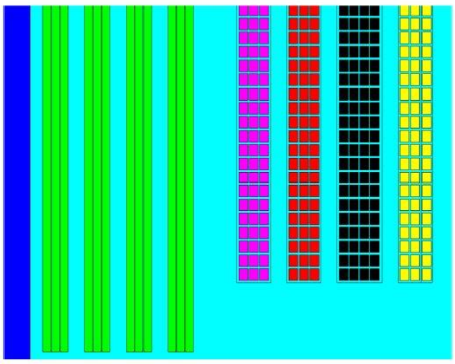


Figure 11: FE mesh of the MV winding.

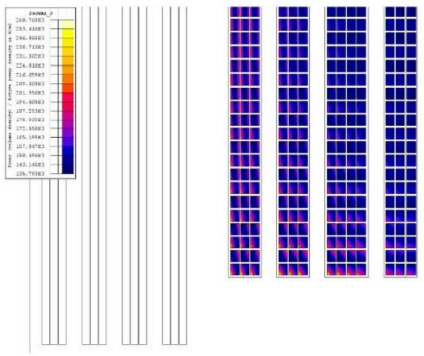


Figure 12: FE mesh of the MV winding.

Similar to the case of the homogenization technique, the comparison between the losses due to the fundamental harmonic obtained by calculation and those obtained by the FE simulation are presented in table 4.

	RI^2	simulation
LV	3602.3W	3937.5W
MV	5295.3W	5495.2W

Table 4: comparison of total losses.

The next figures show the comparison of the losses obtained by both described techniques for 2 selected harmonics of the frequency.

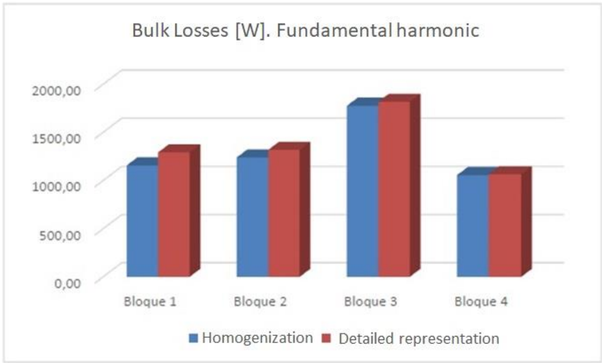


Figure 13: Losses for the fundamental harmonic.

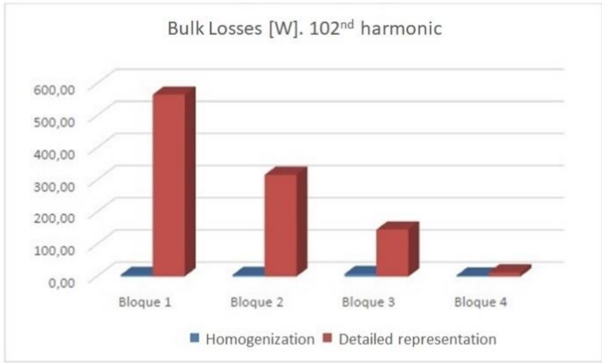


Figure 14: Losses for the 102nd harmonic.

CONCLUSIONS

The 2D approach is valid in order to accurately know the losses distribution within the transformer coils due to skin and proximity effects and due to a set of harmonics in the secondary winding.

The differences between the curved section and the straight section are negligible. Therefore, there is no need to calculate both configurations as long as the total length of the windings is considered.

The skin and proximity effects due to the fundamental harmonic are proportionally higher in the LV side, where an increment of losses of 9.3-11.6% for each technique is observed; than in the MV side (0-3.77%).

When calculating the losses for the whole range of the harmonics, the homogenization technique was shown to be inaccurate and a detailed representation of the winding was required.

The detailed and non-uniform distribution of losses obtained along each turn and section opens the door to efficiently dimensioned transformer designs as stated in [3].

A 3D study of the whole system would give additional information about the losses in connections or in structural parts.

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