High Frequency FEM-based Power Transformer Modeling: Investigation of Internal Stresses due to Network-Initiated Overvoltages

E. Bjerkan, H. K. Høidalen

Abstract-- This paper presents a method of how to obtain both terminal and internal high frequency models of power transformers using FEM. The model is established from construction information and the approach implements frequency-dependent phenomena on a physical basis. Eddy current effects are represented accurately even with a relatively coarse mesh by using a frequency-dependent complex permeability representation for the core and windings. The model can be employed in EMTP-like programs for a variety of applications, such as analysis for FRA, internal/terminal stresses and transformer network interaction. Analyses of internal stresses are elucidated in this paper.

Keywords: ATP, EMTP, Detailed internal model, FRA, FEM, Frequency dependent phenomena, High frequency transformer model, Internal stresses, Terminal model, Vectfit.

I. Nomenclature

FEM - Finite Element Method
FRA - Frequency Response Analysis

II. Introduction

POWER transformer modeling has been a subject of investigation and research for a century [1]-[7]. Several proposed methods use simplified examples/cases in the elaboration process, and in many cases the methods are not very well suited for real transformers. Using FEM to establish the elementary parameters of a lumped parameter model (Fig. 1) for real transformers is in principle easy assuming constructional details of the transformer are available. However to avoid a huge, unsolvable problem, equivalent materials must be obtained based on analytical calculations.

All parameters such as losses (dielectric, proximity and iron losses), self and mutual inductance and capacitance are calculated from the geometry and material parameters, making this method effective for real transformer geometries (including constructional details). All frequency-dependent effects are included using complex parameters for permeability and permittivity. Frequency-dependent losses due eddy currents are accurately represented by means of a frequency-dependent complex permeability representation, both in core laminates [8] and winding strands [9]. A proper representation of the iron core influence has shown to be very important [10], [11].

The test-object used in this article to exemplify the method was manufactured in 1969 and is a typical power transformer for the Norwegian distribution network. It is a 20MVA 66/6,6kV, YNyn0 and it incorporates a double-start helical LV-winding, a continuously wound HV disc-winding and an interleaved layer-winding as regulation winding. This transformer was scrapped due to its age and a voltage upgrade in the secondary network.

III. Modeling the Geometry

The method described is based on a linear lumped parameter-description using self- and mutual inductances as shown in Fig. 1 (all mutual couplings not shown).

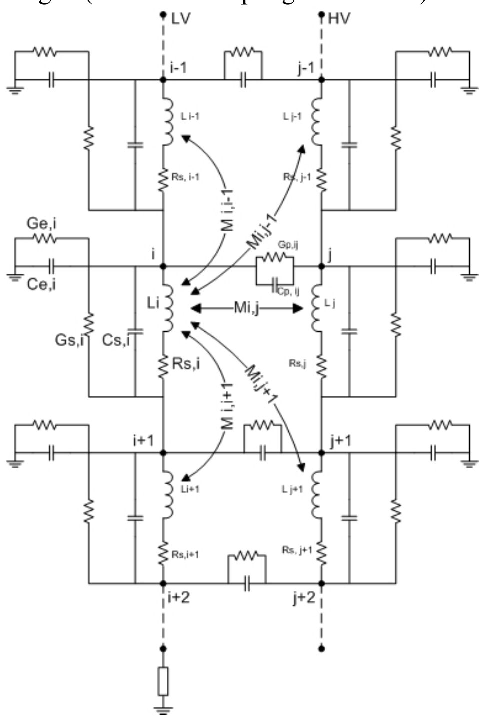

Fig. 1: Equivalent lumped parameter circuit

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Since a lumped equivalent circuit is being established, a certain division of the winding is chosen so that the upper frequency of interest is represented (equivalent to a pi-division of a transmission line equivalent).

A common division for such a model is to use one or two discs as one electrical element (lumped element), since it is easily related to the geometry of the winding. The next step is to model the geometry of the transformer winding. This can be done in any FEM-based software. The software used in this work is called SUMER [12], ref. Fig. 2. This is a FEM-software developed by EdF (Electricité de France) to establish high frequency models of power transformers. Models established with this method has a wide variety of applications; Transferred overvoltages and transformer-network interaction [13], analysis of internal stresses (this article) and resonant overvoltages, and finally sensitivity-analysis of FRA [14], [15].

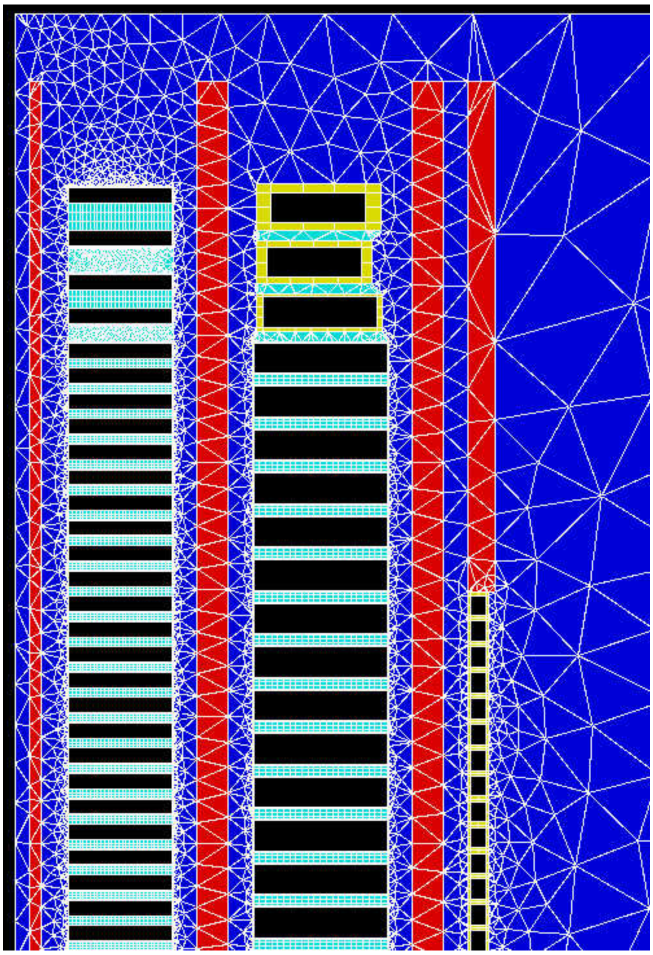

Fig. 2: Upper part of dielectric FEM-model after meshing

The axisymmetric core-representation is shaped to give the same reluctance as the original core as explained in [10]. The core is very important since it contributes severely to the damping/losses of the model. The losses are particularly important at internal resonant overvoltages.

When the geometry is established and meshed properly (ref. Fig. 2) for the two models (magnetic and dielectric), solutions are computed at a few discrete frequencies distributed within the frequency-range of interest, forming the elementary parameters of the lumped parameter model. Interpreting constructional information and establishing the geometry requires most of the time during the modeling.

IV. Parameter Calculation

The basis for the representation of the frequency-dependent phenomena is the principle of complex permeability [9], [11]. The penetration of magnetic field into iron laminates and winding strands are highly frequency-dependent. Field-equations are solved analytically in order to determine the averaged field reaction and bulk losses. The iron core and copper winding is then replaced by an equivalent, isotropic material with a complex frequency-dependent permeability as shown in Fig. 3. This equivalent material has the same external/global behavior as the original material. Wilcox et al. [5] presented measurements of inductance from a coil mounted on a transformer core. The frequency-dependency of this inductance can be closely related to the core influence and the relation described by Fig. 3.

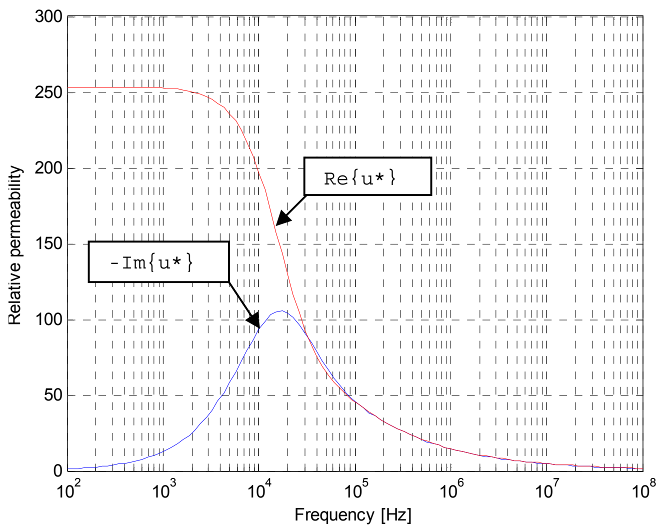

Fig. 3: Complex permeability of iron laminate as a function of frequency

The complex permeability is the most important material parameter in the magnetic part of the model since it determines the flux penetration and losses both for the iron core laminates and the winding structure. The example in Fig. 3 shows a complex permeability computed with an initial permeability of 300 (found from datasheets, Epstein-measurements [16] or measurements on the core directly), a stacking-factor of 0.96, a cooling-duct-factor of 5% and a resistivity of $4.8 \cdot 10^{-7}$.

The elements of the system matrices **RLCG** are calculated by FEM for each frequency-point. Calculation based on vector potential and complex flux [9] results in a fast computation but a poor accuracy since solution is a result of an integral across very few finite elements. A better approach for the computation of these elements is based on the energy as shown below. The domain of integration in the energy approach is based on the complete geometry rather than across the element considered, and thus more time-consuming.

Self inductance and resistance is calculated applying current in the element considered.

$$L_{ii} = \frac{2 \cdot n_i^2 \cdot \mathrm{Re}\{W_{mag}\}}{I_i} \quad (1)$$

$$R_{ii} = \frac{2 \cdot n_i^2 \cdot \omega \cdot \mathrm{Im}\{W_{mag}\}}{I_i} \quad (2)$$

Mutual effects are calculated by applying current in both elements i and j:

$$M_{ij} = \frac{n_i \cdot n_j \cdot \mathrm{Re}\{W_{mag}\} - \frac{1}{2} \cdot L_{ii} \cdot I_i^2 - \frac{1}{2} \cdot L_{jj} \cdot I_j^2}{I_i \cdot I_j} \quad (3)$$

$$R_{ij} = \frac{n_i \cdot n_j \cdot \omega \cdot \mathrm{Im}\{W_{mag}\} - \frac{1}{2} \cdot R_{ii} \cdot I_i^2 - \frac{1}{2} \cdot R_{jj} \cdot I_j^2}{I_i \cdot I_j} \quad (4)$$

This shows that the matrix diagonal must be calculated first applying (1) and (2), then the off-diagonal elements using (3) and (4).

Dielectric parameters (C & G) are calculated in generally the same manner as the magnetic parameters, using the electrostatic energy.

Since the R- & L-elements have a predictable frequency-dependency, it is possible to interpolate between as low as 5-10 different frequencies across 4 decades, depending on the type of interpolation (linear interpolation requires larger number of samples). C- & G-elements can be interpolated using 2-3 different frequency-samples.

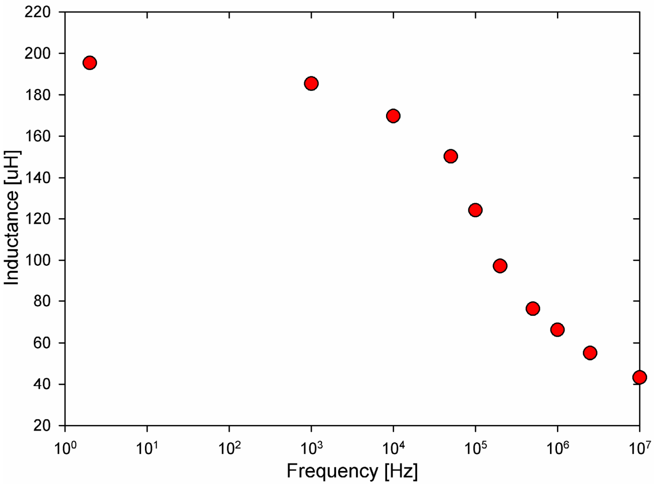

Fig. 4: FEM-results for inductive element L_{11}

As seen from Fig. 4, the inductance is reduced at increasing frequencies due to the displacement of magnetic field from the core laminates. It is however interesting to observe that there is still a considerable inductance above 1MHz, opposed to the traditional assumptions where magnetic field is believed to be displaced completely from the core laminates above 10 kHz [17]. The resistive losses consist of several different contributions:

- Ohmic/DC-losses
- Skin-effect losses
- Proximity-effect losses
- Iron core losses

The three last contributions are eddy-current losses. Proximity- and core-losses are represented by the complex permeability, while skin-effect is handled analytically by modifying the diagonal elements of the R and L matrices. Resistive losses are mainly dominated by the core losses, and Fig. 5 shows the total losses computed for the first element for the chosen frequency-distribution:

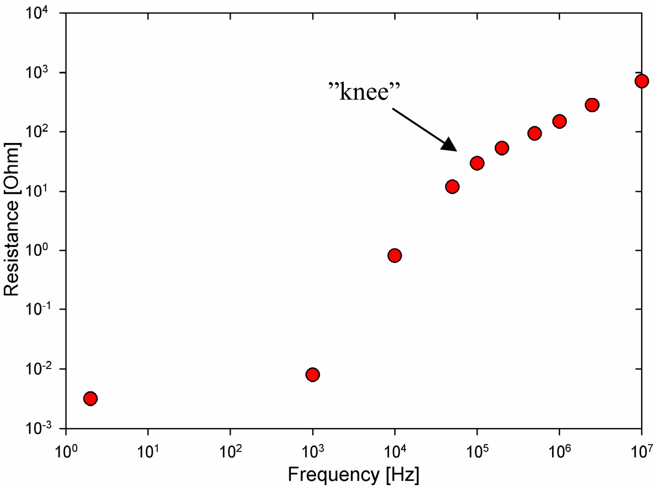

Fig. 5: FEM-result for resistive element R_{11}

As seen from Fig. 5 the characteristic ”knee” can be observed just below 100 kHz. This is the area where the skin-depth is equal to the dimensions of the laminate. The slope beneath the “knee” is proportional to the square of the frequency while the slope above the “knee” is proportional to the square-root of the frequency. The transition to DC-losses is observed at 1 kHz.

V. System Description

The next step is to establish a system description by means of an admittance matrix. This system description can be used to investigate internal resonances of the transformer winding, or to establish transfer-functions between terminals.

A nodal transformation is applied to branch-elements (resistance and inductance) before added to the system description.

$$\mathbf{Z}_B(j\omega) = \mathbf{R}(\omega) + j\omega \cdot \mathbf{L}(\omega) \quad (5)$$

$$\mathbf{Y}_N(j\omega) = \mathbf{G}(\omega) + j\omega \cdot \mathbf{C}(\omega) \quad (6)$$

The branch-matrix $\mathbf{Z}_B(j\omega)$ is then transformed to a nodal form by means of a transformation matrix:

$$\mathbf{Y}_B(j\omega) = \mathbf{A} \cdot \mathbf{Z}_B(j\omega)^{-1} \cdot \mathbf{A}^T \quad (7)$$

The transformation-matrix $\mathbf{A}$, describes the relation between nodal currents and branch currents. The system description is then given as:

$$\mathbf{Y}_{SYS}(j\omega) = \mathbf{Y}_{N}(j\omega) + \mathbf{Y}_{B}(j\omega) \tag{8}$$

When including terminal conditions, the internal amplitude-frequency spectrum can be visualized as in Fig. 6.

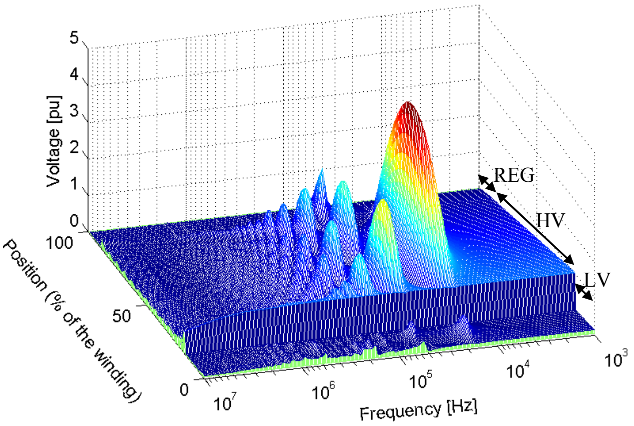

Fig. 6: Internal frequency response derived from $\mathbf{Y}_{\mathbf{SYS}}(j\omega)$

For the example shown in Fig. 6, both neutrals are grounded, and the regulating winding is floating/unloaded. The source is connected to the HV-terminal. The transfer function from HV to LV-terminal can be seen at front edge of the plot.

Resonant modes and characteristics of the windings can easily be observed from visualizations like this, and it forms a good basis for further analysis of a specific transformer construction. To elucidate the coherence of the model with measurements up to 1MHz, a comparison is shown in Fig. 7.

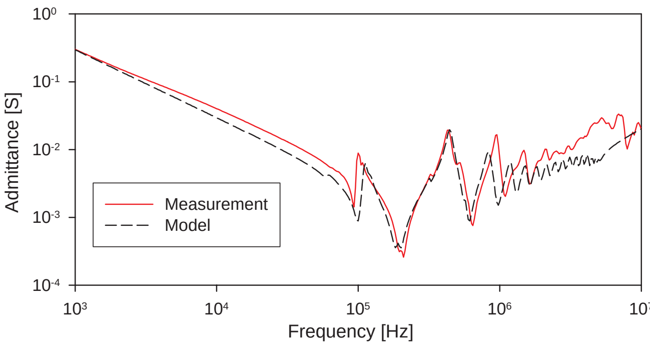

Fig. 7: Comparison: Model vs. measurement of LV-input admittance

VI. Terminal Model

For further analysis, a time-domain model must be established. This can either be done within SUMER applying modal analysis in order to find a terminal equivalent. This terminal equivalent can be directly interfaced with EMTP/EMTP-RV. The other option is to establish a system description/admittance matrix (as in the previous chapter) in Matlab from the system matrices (RLCG) and then use this as input to Vectfit [18]. Vectfit is a robust, public domain software that applies vector fitting/rational approximation in order to find an equivalent terminal description. Vectfit can output this description to a coupled RLC-branch file that can be used directly in ATP/ATPDraw.

VII. Internal Stress-Analysis

In this paper, analysis of internal stresses is emphasized. A typical in-service electrical stress is impulse stresses. Such stresses are usually enforced as either switching- or lightning surges. Resonant overvoltages are also of major concern.

A full lightning impulse is applied to the terminal equivalent developed, in order to study internal oscillations, ref Fig. 8 (Node 1 is the HV-terminal):

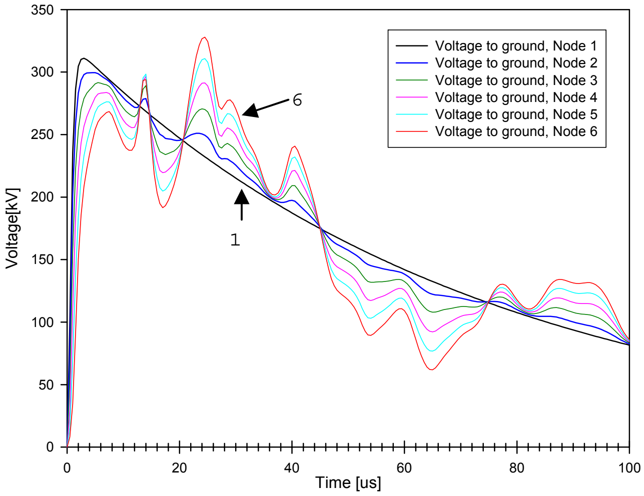

Fig. 8: Nodal voltages to ground at full lightning impulse

In SUMER the resulting oscillations at the terminals are transferred to internal nodes by means of a transfer matrix $\mathbf{H}(t)$. An inter-node voltage spans two discs in the high voltage winding. Since the numbers of turns (see Fig. 12) are reduced in the first discs of the HV-winding, the inter-disc voltage is not largest across the first discs, as shown in Fig. 9:

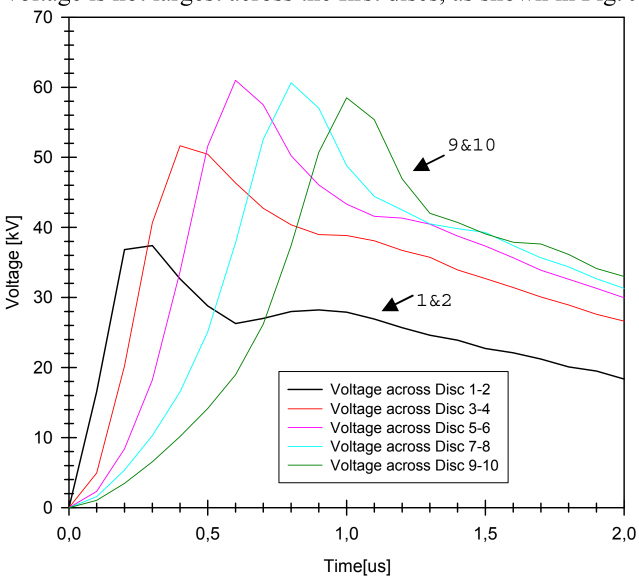

Fig. 9: Interdisc voltages at full lightning impulse

Due to the "low" frequency of a full lightning impulse, the inductances also play a role. This is the reason why the largest stresses occur across disc 5 & 6.

A chopped lightning impulse contain higher frequencies than a standard LI, and this contributes to a higher degree of capacitive voltage-division along the winding. Nodal voltages during such an impulse are shown in Fig. 10.

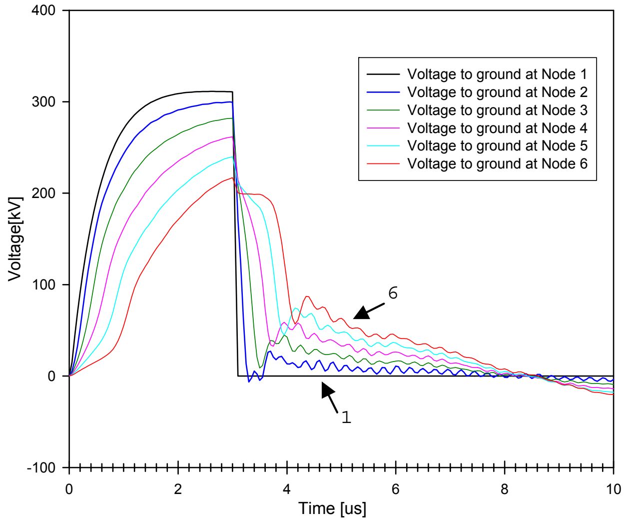

Fig. 10: Nodal voltages to ground at tail-chopped lightning impulse

As seen in Fig. 10, the fall-off-time of the chopping is quite steep (0.1usec.). This is faster than any normal flashover, but in the area of transients occurring in GIS. This fast collapse will normally result in a capacitive voltage-division along the winding. This can clearly be seen from Fig. 11 showing inter-disc voltages along the first discs of the HV-winding:

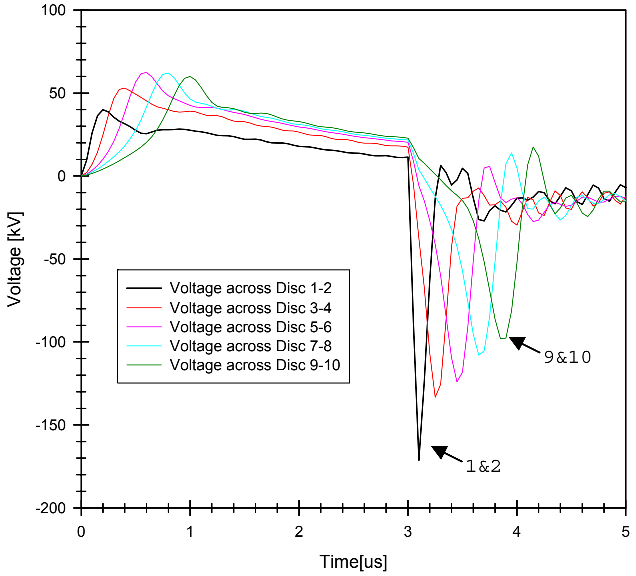

Fig. 11: Inter-disc voltages at tail-chopped lightning impulse

As seen in Fig. 11 the peak voltage occurring across the first two discs are rather high due to the capacitive behavior of the winding. This voltage reaches 171kV at its maximum. The maximum voltage is applied to the two first discs in an electrostatic FEM-calculation (in Femlab [19]) in order to determine the maximum electrical field-strength directly in the geometry of the HV-winding. The solution of this calculation is shown in Fig. 12.

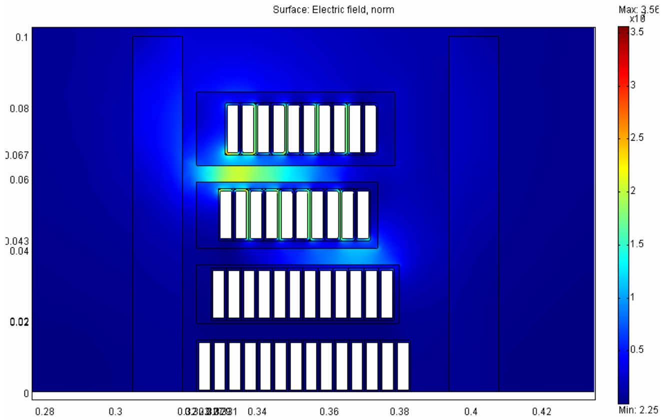

Fig. 12: FEM-computation to determine interdisc stresses (electrical field)

Since two discs are considered as one electrical element in this simulation, the interdisc voltage is assumed distributed linearly within the ten turns of the two first discs. The stresses are then computed as shown in Fig. 12. Increased pressboard and paper insulation is also typical for this kind of transformer. An enlarged section can be seen in Fig. 13.

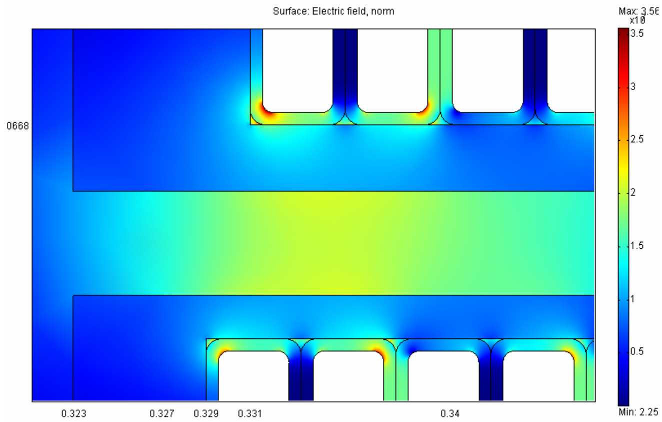

Fig. 13: Enlarged interdisc zone of high stress

The maximum field strength can be read directly out of the solution by point-and-click. It is found to be 19 kV/mm in the oil-gap between the discs. The inter-turn stress is 16 kV/mm. The rise-time of a chopping impulse is so small that the voltage distribution is mainly capacitive (also the internal voltage-distribution in the discs). This will further increase the inter-turn stresses for the first turns. Whether these stresses will lead to a breakdown or not, is depending on several factors. Condition of the oil related to ageing and moisture is one important factor. The critical zone is the main oil-gap, but also the strand-corners (with a maximum of 35 kV/mm) and the oil-filled voids between insulating paper and pressboard.

If a more accurate solution of the internal stresses at very-high frequency transients is wanted, the 5-10 first discs may be modeled on a turn-to-turn basis. This increases the number of finite elements in the model slightly, but still the complex permeability representation keeps mesh size on a reasonable level for the solver.

VIII. CONCLUSIONS

This paper presents a robust and comprehensive method for high frequency modeling of power transformers, resulting in a multi-purpose model (internal/terminal analysis). The model incorporates all frequency-dependent losses such as eddy current effects (core losses and skin-/proximity losses in the winding) and dielectric losses in the insulation structure on a physical basis using complex permeability representation for eddy-current effects and measurement data for dielectric effects. The conclusion is that this procedure is well-suited for modeling real transformer constructions in cases where frequency response measurements are missing. It also constitutes an accurate method for evaluating internal stresses in detail.

All constructional details and variations along the windings can be modeled using the FEM-approach. The major limitation is the use of 2D axisymmetric modeling, which excludes all 3D-effects (coupling between phases). When compared to measurements, this has shown to be important only close to the first resonance of the HV-winding. The model is applicable in the frequency range from the first resonance of the HV-winding at 10 kHz and up to 1MHz.

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XI. BIOGRAPHIES

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