Sweep Frequency Response Analysis of Voltage Transformer for Medium Voltage Applications

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Abstract
This paper presents a computational approach to characterize the impedance of the voltage transformers as a function of frequency in the medium voltage distribution networks and evaluate a potential risk of higher harmonics induced inner resonant overvoltage, The study utilizes a 2D finite element model of a voltage transformer developed in COMSOL Multiphysics (AC/DC Module). The model simplifies the transformer high voltage winding by grouping conductors which enables faster simulations while maintaining accurate and reliable results. Key winding parameters used in the computational model are carefully matched to a real-world object. By simulating the transformer's response across a frequency range, the model calculates the admittance, and subsequently impedance, of the transformer primary winding. The resulting frequency response is compared to a set of measurements obtained using Sweep Frequency Response Analysis (SFRA), a common technique for transformer health assessment.

Keywords: Voltage transformer, SFRA, Internal resonances

Introduction
In the medium voltage distribution network, voltage transformer (VT) plays unique and critical role to monitor the power line voltage and thus controlling the flow and distribution of the electrical energy in the grid. During their service time, the VTs are relatively often exposed to transient overvoltage events, power surges, switching and harmonics frequencies. Due to inherent construction of voltage transformers, they offer varying impedance of their primary winding, dependent on higher harmonics content in the power line voltage. This can lead to excessive currents drawn by primary winding and further causing the thermal failure of a VT.
Identifying internal resonances within the transformer winding and verification of their potential match with the high frequency harmonics presents in the network requires modelling of a complex internal structure of the primary winding of the VT. There is a broad literature addressing analysis of internal high frequency (HF) potential distribution within the windings of power and distribution transformers of various construction (e.g. [1], [2], [3], [4]). The non-linear internal potential distribution has been as well a subject of experimental investigation (e.g. [2], [5]). In the studies, both analytical approaches based on creating an equivalent RLC model or a finite element analysis (FEA) based model can be found. A FEA based model can be further categorized in a finite element method (FEM) or a boundary element method (BEM).
A typical medium voltage VT is a very special type of a transformer, which is designed to generate a secondary voltage proportional to primary voltage with minimum possible phase angle to primary voltage. The primary winding of VT is of typical diameter between 100-200 mm. It comprises of several to tens of thousands of turns of a thin copper conductor of diameter of fraction of millimeter. These small details indicate towards a substantial modelling and simulation challenges as FEM modelling of such a structure is not realistic.
There is a lack of articles addressing this very special type of transformers. Recently Trkulja et al. has attempted to address this issue [6]. In this paper, the authors present and evaluate a methodology for acquiring voltage distribution over the primary winding of inductive voltage transformers under the lightning impulse (LI). The approach is based on discretization of layers, which leads to the reduction of the model size.
In a detailed FEM approach, each individual turn of a layer is modelled. Such approach can be applied to the cases where modelling of a few numbers of outermost layers of primary winding is required. This approach can be justified when applied to analysis of very high du/dt transients, such as transients of risetimes of 1μs order of magnitude. As the distribution of very high du/dt transients affects only the top layers of primary winding.
As in present case, the primary winding is studied under the exposure of lower frequencies, starting from power frequencies or even lower, to the hundreds of kHz. The distribution of these various frequency voltages in the primary winding and their potential impact at any location is to be studied. So, the method cannot be used in this case.

Therefore, the authors developed a different approach leading to a simplification of the winding model by grouping of primary winding conductors in one layer.

Medium Voltage VT: Case study description

In the present study a typical medium voltage VT has been considered. The VTs are commonly epoxy encapsulated units for outdoor application. These VTs comprises of a magnetic core made of standard laminated transformer steel. The secondary winding and the primary winding are located coaxially on the magnetic core. The complete internals prior to epoxy casting are shown in Figure 1.

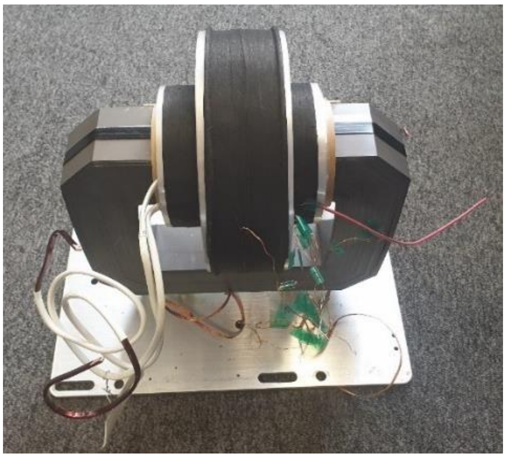


Figure 1. Complete internals of a medium voltage VTs

The primary winding of the VT analyzed, is manufactured using 77 layers of 280 turns of very thin 0.23mm (AWG31) copper wire. The primary coil inner diameter is 67mm. The winding layers are separated by a thin (0.127mm) sheet of a dielectric material. The total number of primary turns is 21560. There is three order of magnitude difference between physical dimensions of individual wire and complete winding. This presents significant challenge to the modelling and simulation process, aiming at identification of internal field distribution within the winding structure.

Therefore, the authors developed a methodology of reducing the model size by clustering (grouping) the turns so that a good compromise can be achieved with respect to both the model size and model behavior for frequency range. The study aims to identify resonances within the frequency up to 100kHz. In the present approach only, the primary winding is modelled, and the impact of the magnetic core is neglected at which is a common practice reported in literature addressing HF modelling and simulations of transformers.

Modelling approach based on turns clustering

In order to simplify the winding modelling and design step, a dedicated tool has been developed. Usually, the step which may require several iterations, can be done in few simple steps. The tool allows to automatically generate a 2D simplified simulation model of the axial symmetry based on the key design parameters. The tool utilizes the 2D Axisymmetric model of COMSOL Multiphysics to generate the model. The complete process of analysis of the transformer winding is shown in Figure 2.

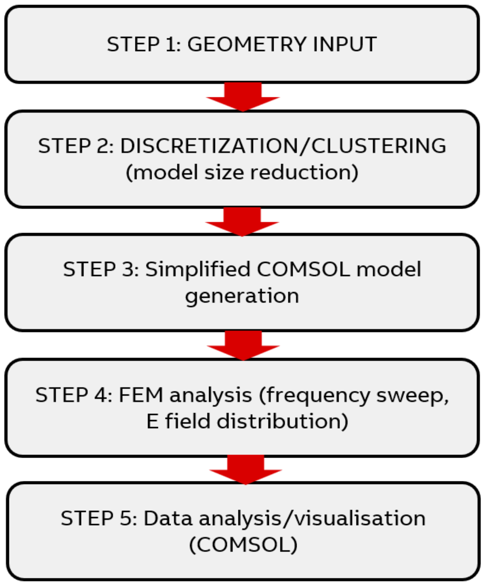
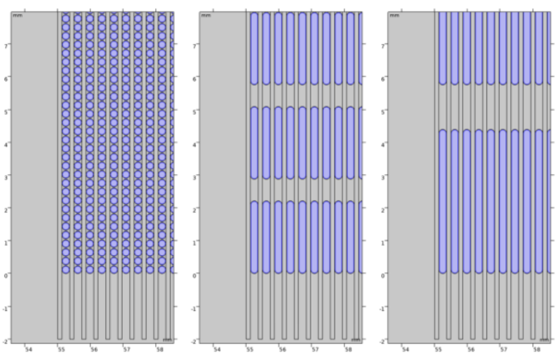


Figure 2. Flowchart showing the step-by-step approach of the winding analysis

The process starts from entering the key design parameters of the winding such as the winding inner diameter, number of layers, number of turns in a layer, wire thickness and layer-layer insulation thickness and its dielectric constant. Specifying the number of groups of turns in a layer result in generating a simulation model as shown in Figure 3. The larger the turns cluster the smaller the model but also the lower becomes the boundary frequency of the internal resonances which could be identified. In practice for the winding of a complexity and size as the presently analyzed one, the groping of 10-20 turns within a single cluster is sufficient for identification of resonant frequencies up to 100kHz.



a) b) c)

Figure 3. Automatically generated 2D simulation models with a different grouping/clustering parameter: a) full model; b) 20 groups per layer; c) 10 groups per layer

It must be pointed out that the clustering approach described results in a reduction of key parameters of the winding, including the total number of grouped turns, winding inductance and the turn-to-turn capacitance distribution within the layer.
Therefore, the application of the clustering approach requires certain modification of the model parameters so that the 'RLC Coil Group' in AC/DC module provides correct values of the winding inductance and the capacitance distribution along the layer.

A. Modification of magnetic properties to compensate the turns number reduction.

Grouping multiple turns into groups, results in a reduction of winding inductance. To obtain correct results, an approach involving the modification of the magnetic parameters of the materials surrounding the winding is required. In all materials, except conductor, the magnetic permeability was altered in such a way that the inductance of the simplified winding corresponded to the inductance of the real winding without simplifications. This was achieved by setting the magnetic relative permeability value to the square of the number of turns per group times original relative permeability. Additionally, conductivity of conductors was reduced, by dividing its value by the number of turns in the group.

B. Modification of dielectric properties to compensate the turns number reduction.

The application of the clustering approach also results in deviations in determining the values of interlayer and inter-turn capacitance due to changes in the model geometry. Grouping multiple turns into a solid, conductive element causes an increase in interlayer capacitance. Additionally, there is a difficulty concerning the assumption of appropriate distances between groups of turns within one layer to account for the series connected inter-turn capacitances within a single group of turns. The solution to this problem is to appropriately modify the dielectric constant of the interlayer and inter-turn insulation materials, allowing for the correct matching of capacitance values. Besides this, the distances between groups in layers should contain accumulated gaps between turns of a given group (Fig. 3b, Fig. 3c).

Simulation Results

For meshing of geometry, normal mesh setting of COMSOL with physics generated mesh option, has been used. For the case study, turn cluster is selected as 20 group per layer as shown in Figure 4. Conductor groups for simplification of study can be seen in zoomed view of plot. The right-hand side of arranged conductors in 2D geometry is the top layer of high voltage winding. Similarly, the left side arranged conductor geometry represent bottom most layer of high voltage winding. Farthest left side of geometry represent the start of core region.

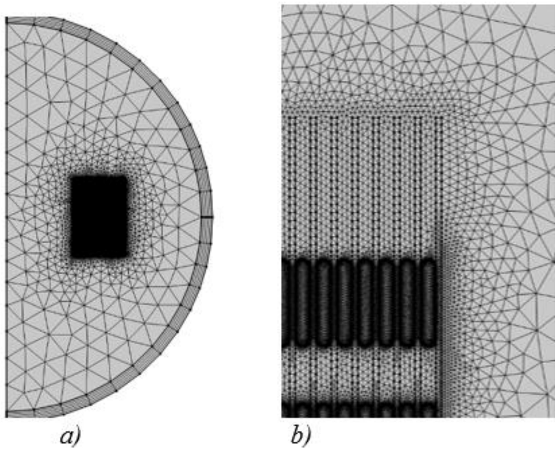


Figure 4. Mesh: a) Complete model; b) Zoomed view

The simulation study is completed for 2D model. The electric potential and equipotential lines are plotted for the geometry at frequency of 100 Hz, which is lower than winding resonance frequencies calculated in simulation study. Applied voltage is used as 1.0 unit to normalize all cases and to show the relative distribution of electric potential across the winding layers and conductor groups in Figure 5.

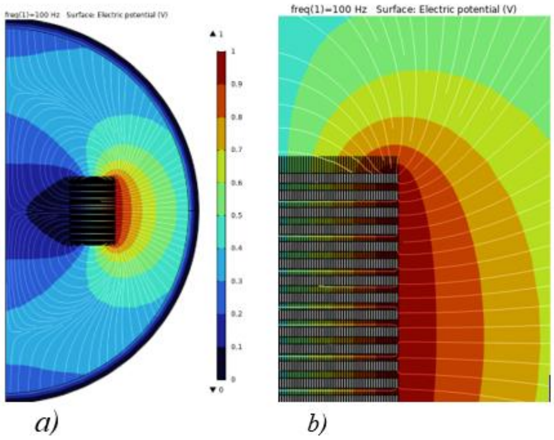


Figure 5. Electric potential plot at 100 Hz: a) Complete model; b) Zoomed view

The Electric potential and Electric field can be plotted for all frequencies for the range of simulation. Electric field distribution at resonant frequency provides us magnitude of high electric field stress and distribution in high voltage winding. The high voltage winding admittance is calculated for the frequency range from 100 Hz to 100 kHz and plotted on logarithmic scale in Figure 6. Winding admittance is plotted on Y-axis and X-axis represents the frequency range of simulation study.

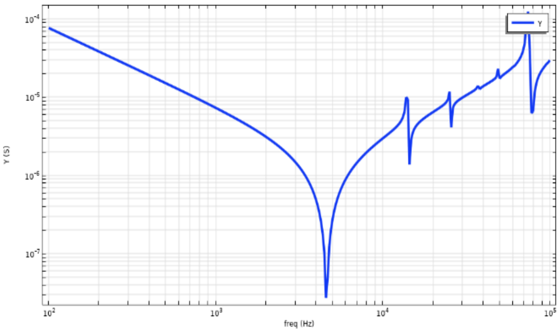


Figure 6. Simulated frequency characteristic of the winding admittance

It is observed that winding admittance initially decreases with increase of frequency when approaching the main resonance. The main winding resonance can be explained by a simple, lumped inductance and lumped capacitance values. When passing the main resonance, the winding admittance increases as its capacitive character dominates, with local resonances seen at certain higher frequencies. Identification of those internal resonances and their frequencies may play important role during design phase of VTs. In order to minimize the potential internal overvoltage when the VT wining is subjected to very high order harmonics in the system An example of a non-uniform internal electric field distribution at 4.57kHz, at which a resonance is identified at the admittance characteristics (Figure 6) is shown in Figure 7.

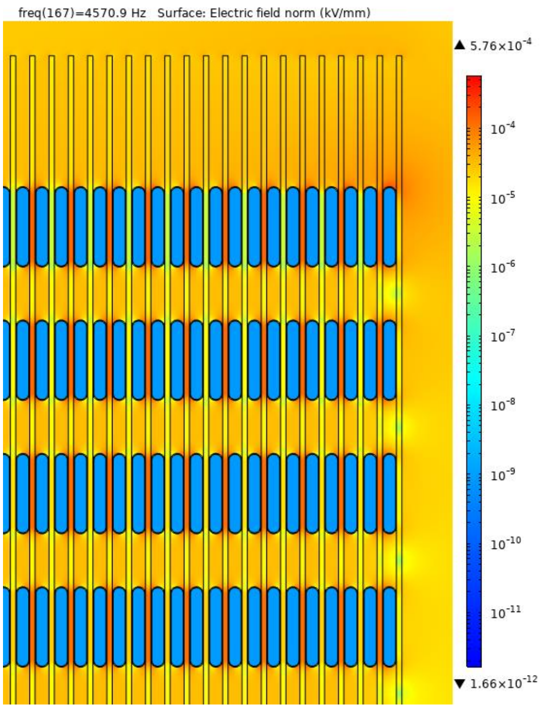


Figure 7. Electric field distribution at 4.57kHz

Experimental results: SFRA measurements

A finished VT unit which is used for simulation study, is tested for Sweep frequency response using a Megger sweep frequency response analyzer (SFRA). The SFRA plot is shown in Figure 8. The SFRA characteristics of tested VT shows similar response as the simulated response. The second and onwards resonant frequencies in SFRA test are not as assertive as compared to simulated plot. The spiked presence of resonances in simulation plot as opposed to more suppressed ones in the measurements may be result of simplification of geometry, use of clusters and neglecting losses other than ohmic losses due to the skin effect in the conductors. Additional losses resulting from e.g. dissipation factors of insulating materials, core losses and from the proximity effect not included in the model and may play important role in lowering the Q-factor of the internal resonant circuits, lowering the resonant peaks magnitudes.

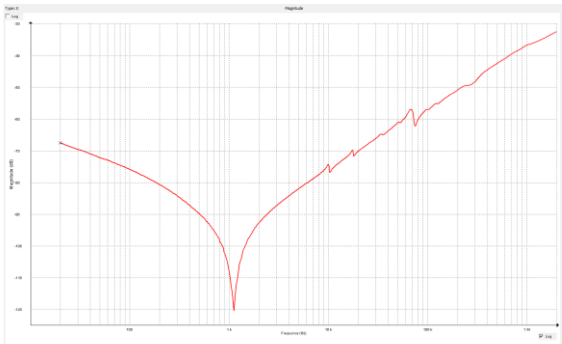


Figure 8. Measured frequency characteristic of VT

Design considerations for VTs

The estimation of SFRA signature for VT is a significant step. Presently SFRA signature is extensively utilized to detect electrical and structural problems. The problems may arise during condition which may cause mechanical or electrical issues. For example, during a short circuit test, which is destructive in nature or during transport. Use of SFRA has been mostly confined to applications to check for integrity of mechanical structure and electrical connections. SFRA signature of a unit also provide valuable information of resonance frequencies. These resonance frequencies become important in modern world grid where signal is polluted by the excessive use of power electronics devices. The devices inject higher frequencies voltage back into the grid, which may cause the failure of VTs operating in field.

In such scenario, the prior estimation of SFRA signature becomes very significant. During design stage of VT, the SFRA signature can be calculated and checked. Then depending on application, the SFRA signature of designed VT can be altered to make it more resilient to higher harmonics present in grid. Alternatively, a VT can be guarded with suitable filters to cover the frequency zones, where it is more susceptible to failures.

Conclusions

The paper provides valuable insights into the resonance behavior of a selected medium voltage VT, identified as the specific Y-axis points in the frequency-impedance plot. The discussed simulation method offers a valuable tool for detailed understanding and optimization of the voltage transformers performance in the medium voltage networks. The winding parameters like interlayer insulation, gap between the conductors, number of conductors in one-layer, total winding dimensions, etc. are defined to exactly represent a real object under the investigation. With frequency variation, admittance of the voltage transformer is calculated, and the resonance frequencies of the voltage transformer are found in the entire frequency spectrum.

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