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PUSHING THE BOUNDARIES OF INDUCTIVE VOLTAGE TRANSFORMER DESIGN

SUMMARY

Designing inductive voltage transformers for the highest voltage levels (550 kV and above) is a true challenge indeed. The main reason for this is their complex internal R-L-C structure, including an insulating system which needs to be resistant to all types of overvoltages and consequent dielectric stress it can encounter during its lifetime. This is why it is necessary to verify behavior of such transformers during the design process, and under four sets of standard test overvoltage types; the Power Frequency Withstand Voltage (PFWV), the Lightning Impulse Withstand Voltage (LIWV, i.e. BIL), Chopped Impulse Withstand Voltage (CIWV) and the Switching Impulse Withstand Voltage (SIWV).

The main idea of the paper is to demonstrate that by understanding the influence of crucial parameters of the appropriate equivalent diagram on the voltage distribution across the active part of the transformer, it is possible to define the overall design of inductive voltage transformers so that they can satisfy even the most rigorous insulation requirements, thus pushing the boundaries of design even further.

1. INTRODUCTORY CONSIDERATIONS

The inductive voltage transformer is a complex unit by nature. The main reason for this is the fact that it encompasses design features of transformer bushings and a conventional transformer winding outline in a single enclosure [1]. Insulation requirements for such units are strict in general, because it is expected for these units to function with no insulation breakdown for an approximate lifetime of 40 years, essentially without maintenance or any other user intervention during that period [2]. These requirements, as well as prescribed tests which accompany them, are more rigorous than tests required for their power transformer counterparts and vary from standard to standard [3] - [6].

In contrast to IEC-oriented European countries, Canadian standard CAN/CSA C60044-2:07 defines higher test voltages for 550 kV transformers. Test voltages appointed to that standard position are shown in table I [3].

Table I - Standard requirements for 550 kV transformers according to CAN/CSA C60044-2:07

Voltage type	Voltage Magnitude [kV]
Maximum system voltage	550
Power Frequency Withstand Voltage (PFWV)	830
Lightning Impulse Withstand Voltage (BIL)	1800
Chopped Impulse Withstand Voltage (CIWV)	2070
Switching Impulse Withstand Voltage (SIWV)	1300

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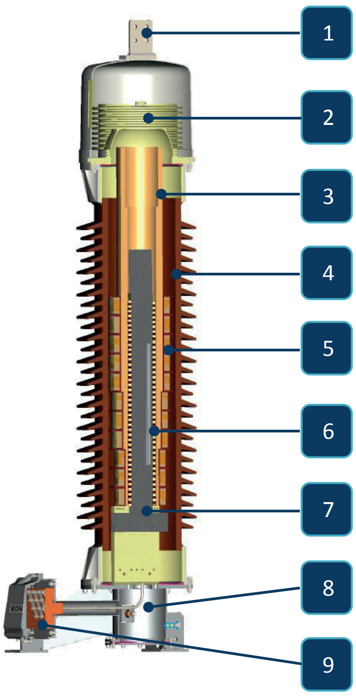
For voltages that high, instrument transformer manufacturers usually resort to capacitive voltage transformers or sometimes even SF_6 insulated inductive voltage transformers instead of using paper-oil insulated inductive transformers. General belief is that with either of these principles it is easier to satisfy insulation requirements specified in Table I, while keeping the transformer dimensions (and consequently the cost as well) within reasonable margins.

However, as far as paper-oil insulated transformers are concerned, the open-core concept adds several advantages insulation and weight wise (and especially cost wise), when higher voltages are considered. This is explained in references [1], [2], [7] and [8].

Figure 1 shows the cross-section of an open-core voltage transformer. As it can be seen from the figure, the active part and most notably the primary winding are distributed along the transformer height, which favorably influences the voltage distribution on the insulator surface. The main insulation cylinder is capacitively graded, meaning that a number of semi-conductive capacitive screens is inserted in-between layers of paper insulation. Screens from the insulation are galvanically connected to the coils of the primary winding, thus adding to the longitudinal capacitance of the primary winding. This makes the transformer much more resistant to lightning impulse and quick high-frequency overvoltages [7]. Finally, because the entire transformer is essentially its own bushing, in contrast to tank and bushing principle utilized by closed core inductive voltage transformers, the dimensions and the resulting weight of the transformer are significantly decreased.



1. Primary (HV) terminal
2. Stainless steel bellows
3. Capacitively graded main insulation
4. Insulator
5. Primary (HV) winding
6. Secondary (LV) winding
7. Open-type magnetic core
8. Base assembly
9. Secondary terminal box

Figure 1 - Open-core inductive voltage transformer cross-section

The ensuing chapters of the paper will deal with the design challenges and principles of the insulation system for open-core voltage transformers, the influence of important parameters on the voltage distribution across the active part of the transformer and the final design, which led to successful type testing of 550 kV open-core paper-oil insulated inductive voltage transformers with insulation requirements from table I.

2. CHALLENGES AND APPROACH

Despite the advantages described in the introductory chapter, insulation design for very high voltages is not a trivial task.

The main reason is that the voltage distribution is drastically different for fast, lightning or switching impulse overvoltages, than for power frequency (over)voltages, meaning that the behavior of the main insulation system is different as well [1] [9].

Under power frequency overvoltages, the voltage distribution is mainly inductive and dependent on turn distribution of primary winding sections, meaning that the primary winding essentially determines how the main insulation is dielectrically stressed. However, it has been proven that even at low frequencies (50 - 200 Hz), the influence of capacitance from the main insulation system is not negligible [1].

On the other hand, under lightning impulse, chopped impulse or very fast overvoltages, the voltage distribution is highly capacitive by nature, meaning that the capacitances of insulation cylinder screens dictate voltage and dielectric stress distribution both across the insulation cylinder itself and across the primary winding [8] [9].

Switching impulse overvoltages are somewhere in-between the latter two. Their front time is relatively fast, meaning that the distribution is predominantly capacitive, while their tail is relatively slow, meaning that both primary winding inductances and capacitances come into play [1].

With that in mind, it is obvious that the voltage distribution under these three types of overvoltages has to be as linear and as uniform as possible. Every deviation from this can mean excessive stress on a part of the insulation and/or primary winding, which can lead to partial discharge inception, insulation ageing or insulation breakdown [1] [9].

Dielectric stress across the main insulation is not the only thing we need to worry about. Historically, it has been proven that outside insulation (i.e. air-porcelain or air-silicone boundary on the insulator surface) can become overly stressed, leading to flashovers and/or insulation breakdowns. This is especially problematic during type testing with switching impulse voltage, as this test is performed under artificial rain conditions, which worsen the electric field distribution on the insulator surface [10] [11]. This, combined with the fact that the voltage distribution varies during the waveform, is the reason why switching impulse voltage is considered critical for open-core voltage transformers [1].

Surface flashover under artificial rain conditions is an extremely complex issue on its own, notwithstanding the effect of the active part on the voltage distribution, and would require an extensive research and calculation breakthroughs which surely surpass the scope of this paper [10] - [13]. This is why this paper will disregard this issue entirely.

The proposed way of dealing with the above-mentioned issue is to ensure as uniform and as linear voltage distribution as possible, and to distribute the stress in an axial direction by ensuring a sufficient number of primary winding sections.

The approach of this paper slightly differs than previously published work on this topic. The emphasis in those papers was to verify the calculation methodology, and to observe the influence of discrete iterations (i.e. changing of primary winding turns distribution and/or capacitive screen parameters) [1] [9] [14]. Here we wished to observe the influence of total primary winding turn number and capacitance values on the voltage distribution as it has been noticed that changing of these parameters has a different effect under various types of applied voltage. This is why it was necessary to determine the optimal values of these parameters before fine-tuning the voltage distribution of the actual prototype transformer using the guidelines given in previously published work. All relevant measurements performed on the prototype are included in this paper.

3. METHODOLOGY

The proposed methodology of this paper was successfully tested thoroughly on combined instrument transformers, whose active part concept is almost identical to the one utilized by open-core voltage transformers [1] [14]. This is why the methodology is applicable in this case as well.

A simplified outline of the main insulation system (i.e. interconnected screens form the main insulation and primary winding sections) can be seen in figure 2 (a). The proposed equivalent diagram, which uses lumped parameters, can be seen in Figure 2 (b) [1].

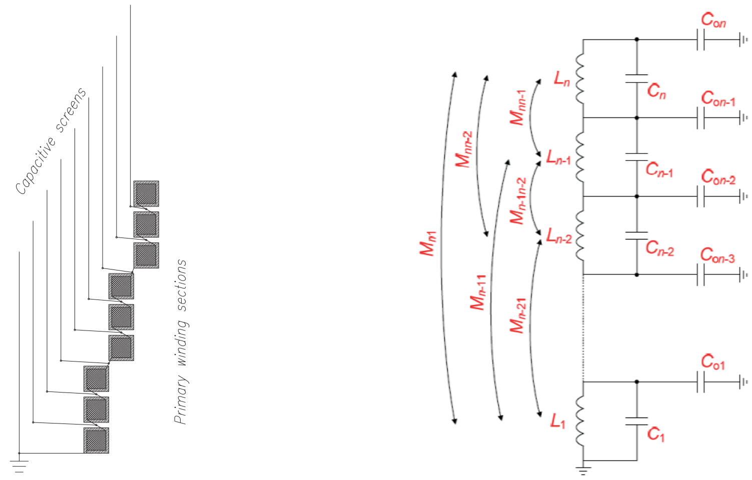


Figure 2 - (a) Simplified active part representation (b) Equivalent diagram used in the calculations

To correctly represent the active part of the transformer, we need three sets of parameters; the inductance matrix of the primary winding, the capacitance matrix of the primary winding screens and the capacitance to ground vector [1] [9]. Winding and leads resistance is neglected in this paper. As it can be seen, the secondary winding is excluded from the diagram in figure 2b. The influence of the secondary winding is however present in the magnetic flux distribution and is reflected on the values in the inductance matrix [1].

The inductance matrix itself is obtained by a numerical calculation, which takes into account the actual geometry of the transformer and properties of the magnetic core. The self-inductance of each coil is calculated according to expression (1), while the mutual inductance is calculated according to expression (2) [15] [16]. Numerical parameters necessary for the calculation were obtained using FEMM 2D solver [17].

$$L = \frac{\psi_{ii}}{I_i} \tag{1}$$

$$M_{ij} = \frac{\psi_{ij}}{I_i} \tag{2}$$

In the above equation, ψ is the flux-linkage of a designated coil, while I is the source current through the i-th coil, always set at a value of 1 A. This way the resulting flux linkage value corresponds to the appropriate inductance value.

Capacitance matrix consists only of off-diagonal elements (capacitances between main insulation screens), as each screen has a solid capacitance only towards the next screen. As the main insulation is a cylindrical system, analytical formulation given in expression (3) will suffice for an accurate capacitance calculation [9].

$$C_{ij} = 2\pi\varepsilon_0\varepsilon_r \cdot \frac{l}{\ln\left(\frac{R_j}{R_i}\right)} \tag{3}$$

In the above equation, l is the length of the screen, R_i and R_j are the radii of the i-th and j-th screen, respectively.

In comparison to combined transformers, the ground capacitance of voltage transformers is much smaller, because the screens in the insulation do not have a solid capacitance towards the grounded screen. The magnitude of ground capacitance was determined numerically using the formulation (4).

$$C_{i0} = 2\frac{W}{U^2} \tag{4}$$

In the above equation U is the voltage between two electrodes, and W is the stored electric field energy.

Once all lumped parameters are determined, they are imported into EMTP solver, where an appropriate voltage shape is assigned. Power frequency withstand voltage is assigned using expression (5), while impulse and switching overvoltages are assigned using expression (6).

$$u(t) = A\cos\lfloor \omega t + \phi_0 \rfloor \tag{5}$$

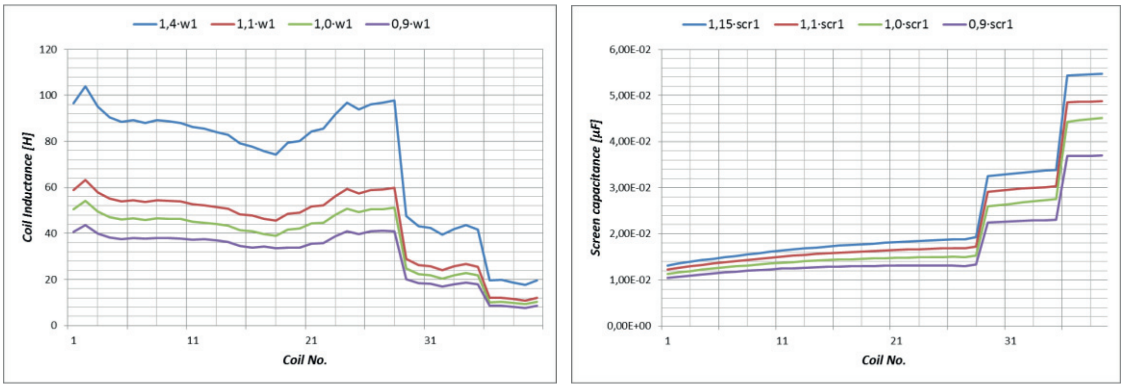
$$u(t) = A\left(e^{-\alpha t} - e^{-\beta t}\right) \tag{6}$$

In equation (5), A is the voltage amplitude, ω is the angular frequency and $\varnothing_0$ is zero. In order to obtain percentage values, A is set to a value of 141. Similar principle is used for equation (6), so that the total amplitude is set at 100 V. Parameters for lightning impulse voltage are as follows: A=103,74 V, α=14598 s^{-1} and β=2457002 s^{-1}. Parameters for switching impulse voltage are as follows: A=110,36 V, α=318 s^{-1} and β=16207 s^{-1}. These values are similar to those used by other researchers [18] [19].

4. STARTING PARAMETER VARIATION

Two sets of calculations were conducted. The first set is the variation of total number of turns, while keeping the same insulation cylinder (keeping original first screen length value scr_1). The second set is the variation of the insulation cylinder capacitance (while keeping the primary winding turns at a chosen number of turns w_1).

Starting parameters (inductance and capacitances) which were considered are shown in figure 3 (a) and 3 (b). Only self-inductances of the coils are shown, instead of the entire matrix, because they illustrate the point, while keeping the representation digestible.



(a) **(b)**

Figure 3 - (a) Inductance variation (b) Screen capacitance variation

All calculations in this part of the paper were done with the same number of primary winding coils. As it can be seen from the figure 3 (a) and (b), the upper coils have a higher corresponding capacitance and lower corresponding inductance. The reason for this is to obtain a more discrete voltage distribution on the upper portion of the primary winding in order to better control and decrease dielectric stress on the insulator surface during fast overvoltages, as explained in chapter 2.

Before getting into the calculation results, the way they are presented should be discussed. Each set of results is shown in comparison to the ideal (desired) voltage distribution, which is given as a percentage value. For each variation four sets of data are presented: voltage distribution at 60 Hz (rated frequency), voltage distribution at 120 Hz (1-minute power frequency withstand voltage test frequency), distribution of impulse voltage wave front and distribution of switching voltage wave tail. Distributions of lightning impulse front, lightning impulse tail and switching impulse front are essentially the same, so the latter two were excluded from further analysis.

4.1. Primary winding turn number and main insulation screen capacitance variation

Results for total turn number variation can be seen in figure 4 (a) - 4 (d).

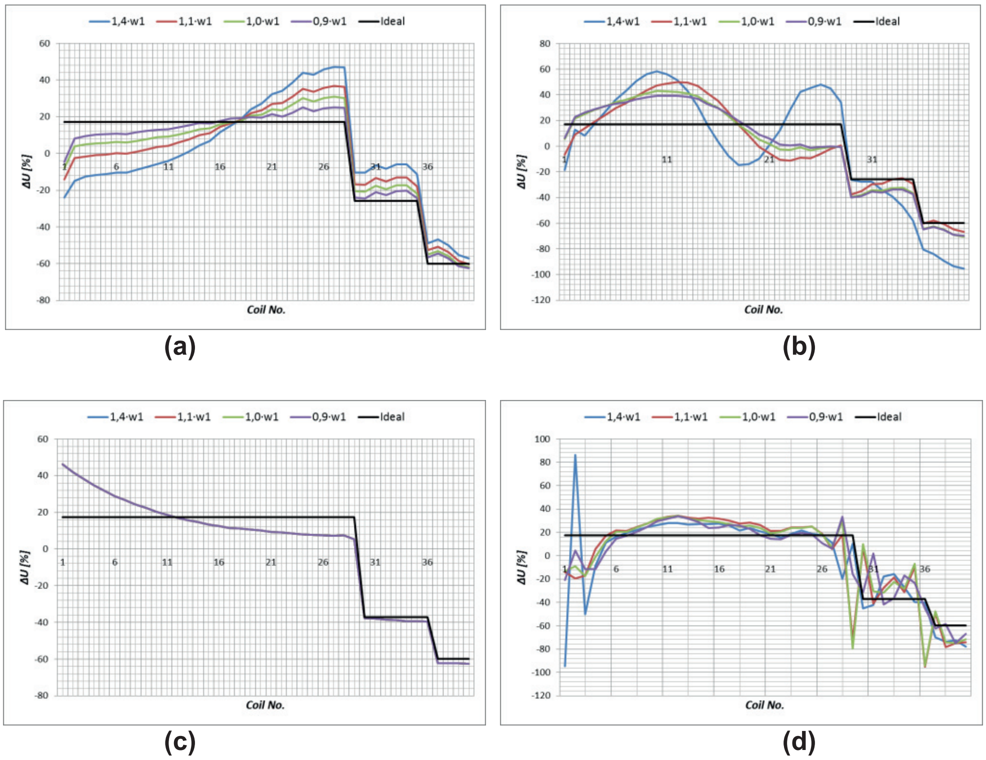


Figure 4 - (a) Voltage distribution at 60 Hz (b) Voltage distribution at 120 Hz (c) Lightning impulse front distribution (d) Switching impulse tail distribution

Results for insulation screen capacitance variation can be seen in figure 5 (a) - 5 (d).

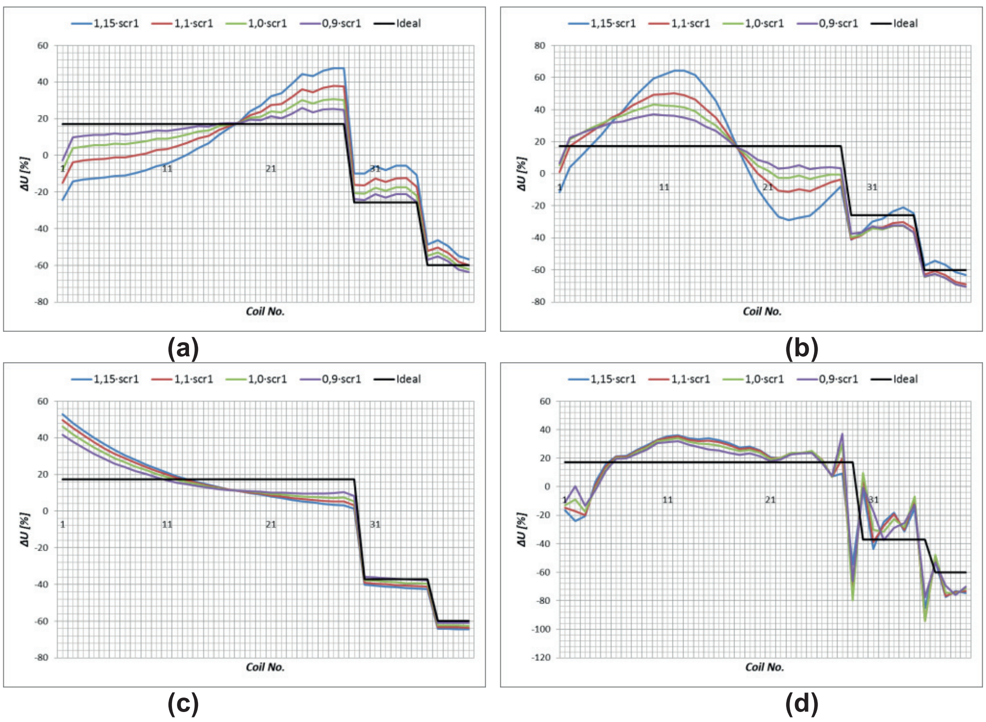


Figure 5 - (a) Voltage distribution at 60 Hz (b) Voltage distribution at 120 Hz (c) Lightning impulse front distribution (d) Switching impulse tail distribution

4.2. Result Analysis

Several trends can be observed by analyzing the charts shown in the previous chapter.

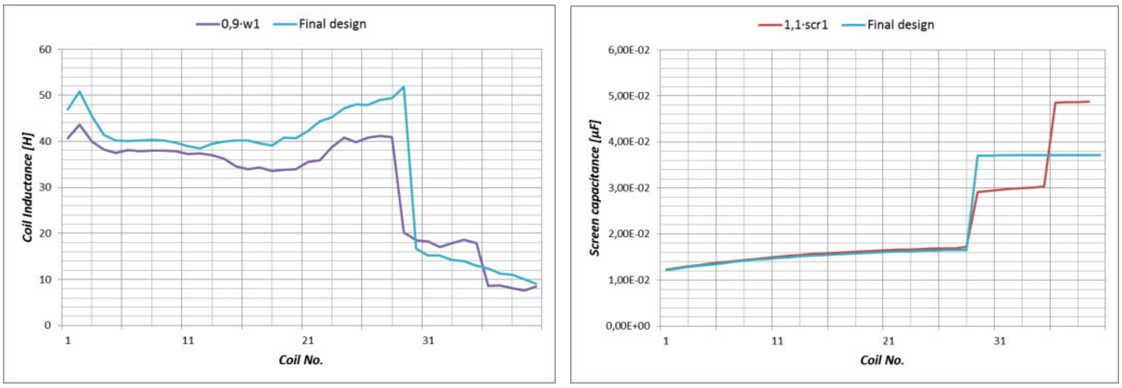
First, it is apparent that a decrease in total number of turns (and a consequent inductance drop) has a very positive effect on distribution of power frequency and switching impulse voltages. With a lower turn number, the voltage distribution becomes more "stable" and closer to the ideal distribution. As expected, lightning impulse voltage distribution is not affected by this variation.

Second, it is generally assumed that an increase in length of main insulation cylinder (and a subsequent increase in capacitance between insulation screens) has a favorable effect on lightning impulse voltage distribution, while a non-favorable effect on power frequency withstand voltage distribution. Increasing the length of capacitive screens is usually done to alleviate the stress on the upper coils. However, in this case this is already achieved by using smaller primary winding coils with less insulation between corresponding screens, thus increasing the capacitance (Figure 3 (b)). This rendered the effect of increasing the cylinder length counterproductive, because the power frequency voltage and switching impulse voltage distributions are considerably worse for a longer cylinder, and the effect on lightning impulse voltage distribution is almost negligible.

The results given in this chapter were used as a guiding beacon for final transformer design.

5. CALCULATION AND MESUREMENTS OF THE FINAL DESIGN

The final design was set upon the foundations shown in chapter 4. Some of the parameters were updated in order to achieve a better axial dielectric stress distribution. Final parameters of the prototype design are shown in figure 6 and are contrasted with data given in figure 3.

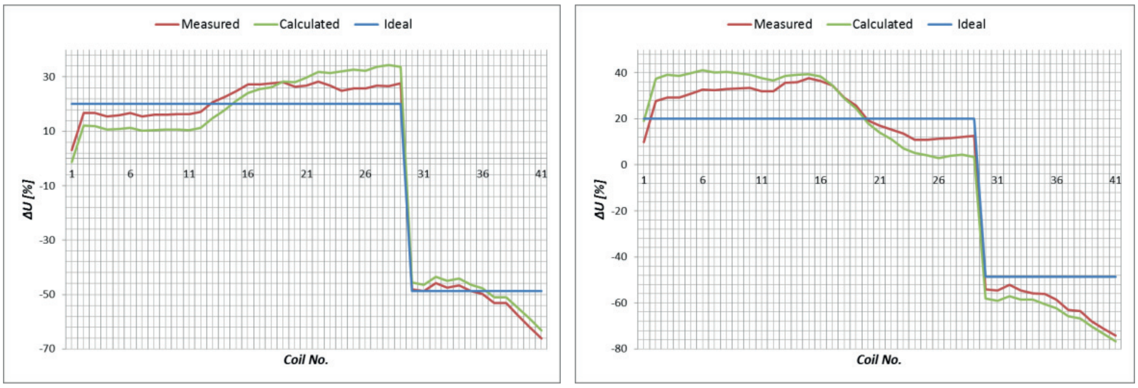


(a) (b)

Figure 6 - (a) Final design coil inductance (b) Final design screen capacitance

The transformers entered the production process with parameters shown in figure 6. As a part of interphase testing, voltage distributions for sinusoidal, lightning impulse and switching impulse waveforms were measured. The results of these measurements were compared with calculation results. It is necessary to note that all measurements were done on an oil-impregnated active part, meaning that the transformer went through the entire drying, vacuuming and oil-impregnation process before the active part was taken out of the enclosure and measurements were performed.

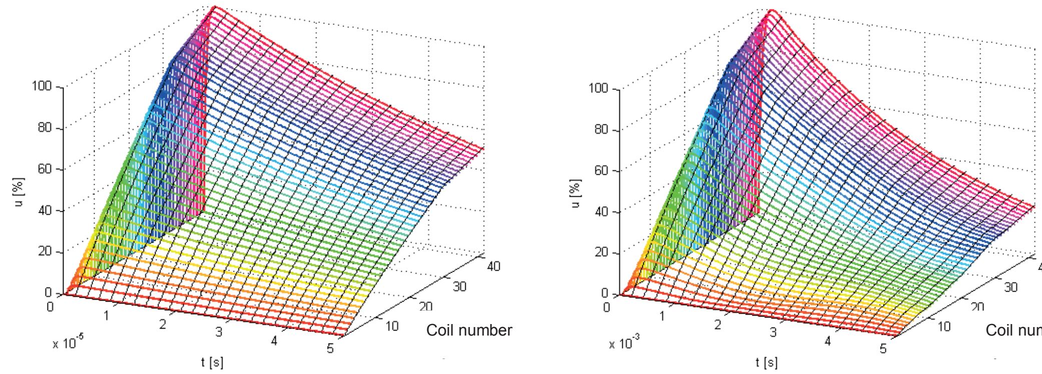
Comparison of results for sinusoidal, power frequency withstand voltage distribution can be seen in figures 7 (a) and 7 (b). As it can be seen from these figures, there is some difference between measured and calculated values, although they display the same trend. The average difference is 4,1% for 60 Hz and 5% for 120 Hz. It is worth noting that, according to measurements, the voltage distribution in both cases is closer to the ideal voltage distribution than the one calculated.



(a) (b)

Figure 7 - (a) Voltage distribution at 60 Hz (b) Voltage distribution at 120 Hz

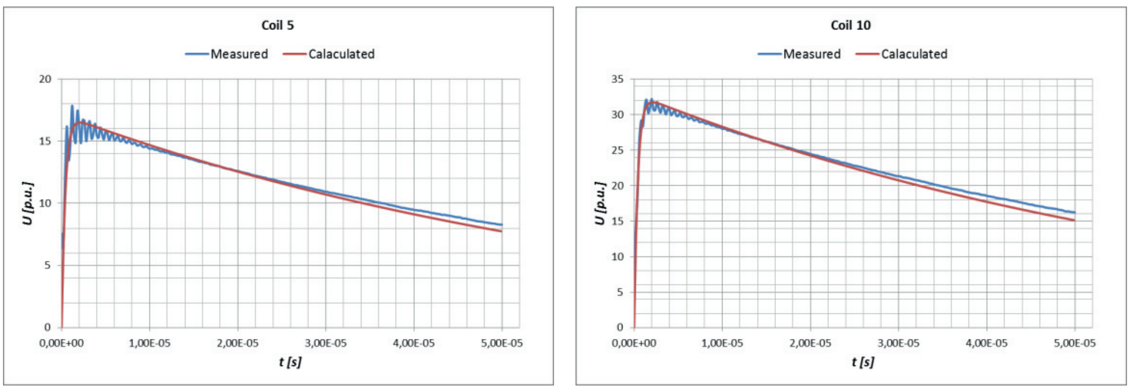
Calculated lightning impulse and switching impulse voltage distributions for the entire waveform are shown in figures 8 (a) - 8 (b).



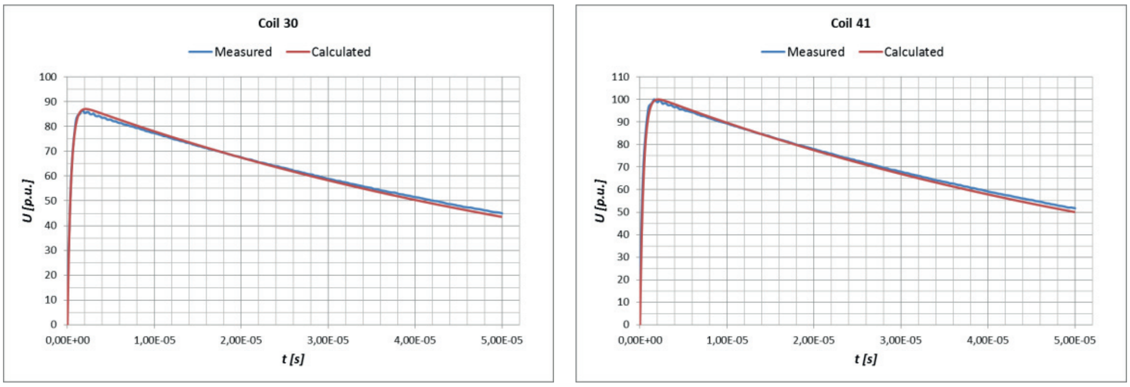
(a) (b)

Figure 8 - (a) Calculated lightning impulse voltage distribution (b) Calculated switching impulse voltage distribution

As it would be impractical to compare the entire waveform for measured and calculated results graphically, the comparison is done on a coil-to-coil basis. Coils 5, 10, 30 and 41 are taken as example coils for voltage distribution comparison. This is done to show the behavior on lower coils and upper coils, as it sometimes differs, especially for switching impulse voltage. Comparison is shown in figures 9 (a) - 9 (d) and 10 (a) - 10 (d).



(a) (b)



(c) (d)

Figure 9 - Comparison of lightning impulse voltage distribution (a) Coil 5 (b) Coil 10 (c) Coil 30 (d) Coil 41

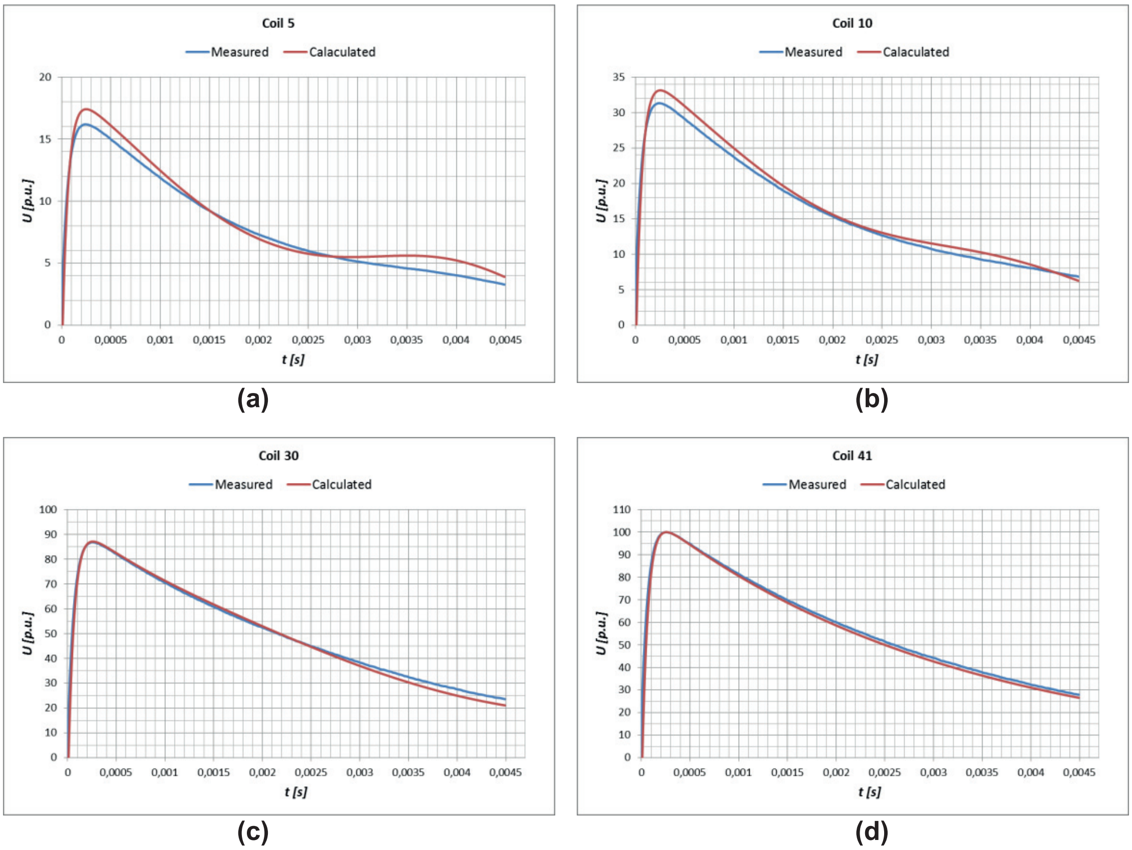


Figure 10 - Comparison of switching impulse voltage distribution (a) Coil 5 (b) Coil 10 (c) Coil 30 (d) Coil 41

As it can be seen from figures 10 and 11, the measured values correspond to the calculated ones very well, with the average difference of 2,1% for lightning impulse and 3,2% for switching impulse voltage distributions, respectively.

6. AFTERMATH

Criterion for insulation breakdown for systems of such complexity is extremely hard to determine. This is why, in some cases, it is easier to perform type testing, see how the transformer does and use this as a reference point for future design.

This was the logic for 550 kV inductive voltage transformer in question. Seeing that all interphase measurement results were satisfactory, as explained in chapter 5, the transformer was submitted to type testing according to IEC 60044-2 and CAN/CSA C60044-2:07 standards (test voltages taken from the latter).

Because of their unique insulation system, explained in chapters 1 and 2, lightning impulse voltage testing generally is not considered critical for open-core inductive voltage transformer. On the other hand, switching voltage under artificial rain conditions is the most perilous test for these transformers. This is why we wanted to emphasize the results of this particular test.

Not only did the transformer pass the type testing according to standard requirements from table I, but also withstood several impulses with higher amplitude, ending with three positive polarity impulses of 1375 kV. Neither insulation breakdown, nor any difference in wave shape was observed.

A subsequent chromatographic analysis of the transformer oil showed no evidence of any gasses appearing as a consequence of type testing. Naturally, the transformer was successfully re-tested routinely, with partial discharge intensity remaining non-existent. A photograph of the transformer during type testing can be seen in figure 11 (a), while the applied voltage magnitude can be seen in figure 11 (b).

(a) **(b)**

Figure 11 - (a) VPU-525 under type testing (b) Maximal applied voltage magnitude

7. CONCLUSION

The aim of this paper is two-fold. The first objective was to demonstrate the influence of starting parameters of every inductive voltage transformer design (i.e. the primary winding turn number and geometry of the screens in the main insulation) on the voltage distribution under typical overvoltages that the transformer can encounter during its lifetime. The second objective was to show that by understanding the effect of these starting parameters and by utilizing the described calculation toolset, it is possible to efficiently and swiftly calculate and assess voltage stress in the main insulation, thus essentially forcing the main insulation to behave the way the designer intended.

It is shown that decreasing the total primary turn number has a positive effect on the voltage distribution overall. Increasing the capacitances of the main insulation generally has a positive effect on voltage distribution during lightning impulse and chopped impulse overvoltages and a negative effect on power frequency voltage distribution. For this particular case, however, the effect of capacitance increase remained relatively negligible.

Transformer design based on these foundations was thoroughly checked during interphase testing, before being succumbed to final type testing. Results of interphase measurements corresponded very well with the calculated values, thus once again confirming the applicability of the proposed calculation methodology. Type testing was completely successful as well, with the transformer withstanding 830 kV PFWV, 1800 kV BIL, 2070 kV CIWV and 1300 kV SIWV without any problem whatsoever.

Such insulation design is enabled by the mentioned galvanic interconnection between primary winding sections and corresponding capacitive screens, unique to the open-core inductive voltage transformer concept. This paper has shown that the entire philosophy and background behind that design are ready to accept the next challenge in line and push the boundaries of design even further.

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