XXIV Seminarium

ZASTOSOWANIE KOMPUTERÓW W NAUCE I TECHNICE 2014

Oddział Gdański PTETiS

THE MODELLING OF ELECTRIC FIELD DISTRIBUTION FOR MULTI-SEGMENT ELECTRODES OF HV TEST EQUIPMENT

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Abstract: Electric field grading or stress control, refers to the technique of reducing local enhancements of the electric field in various devices. This problem for laboratory testing equipment is considered when multi-segment electrodes – also known under the name “polycon electrodes” are applied. Such symmetrical electrodes were designed on the basis of a polyedrical framework and modified for practical applications. They must be carefully designed with respect to the reliable operation and the cost of the equipment. The multi-segment electrodes can be characterized by so called segment factor, which is defined as the relation between maximum field strength of a curved multi-segment electrode and its envelopment. This covers not only the shape and arrangement of the plate electrodes but also the angle between them in space. The segment factor is influenced also by the dimensions and parameters of each single plate.
The aim of the simulations is analysis of the maximum field strength at smooth and multi-segment electrodes. These aspects, referring to the real configuration of the two-stage laboratory cascade transformer system 250 kV, are presented in the paper.

Keywords: multi-segment electrodes, electric field, FEM simulations.

1. INTRODUCTION

Equipment of high voltage (HV) laboratories usually consists of: testing transformers, dividers and DC generators, located in laboratory hall or in fenced positions. Parts of electrical apparatuses on the HV potential must be carefully designed and shielded to avoid high field strength leading to local ionization and inception of streamers.

The maximum field strength in the vicinity of the element under high voltage depends on the shape of the element, the configuration of the surrounding space and the distance from the earthed elements. It is a problem of so called "safe spaces" and the conditions for generating streamer forms of discharges. Therefore the elements of sharp edges must be eliminated in construction of HV equipment.

The multi-segment electrodes, also known as “polycon electrodes” are well introduced for HV objects in HV Laboratories [1]. Multi-segment electrodes are subdivided into a fixed number of single plates, which substitute a smooth plane representing the shape of the HV electrode. The main reasons of the introduction of the segmented electrodes to the HV objects were of practical and economical nature. For many applications making of the HV electrodes from many small segmented plates is cheaper and easier than manufacturing of large aluminum electrodes as a single element.

For assessment of such designs, not only the maximum field strength but also the total stressed area of the electrode should be considered.

This problem is presented in the paper, based on the example of testing transformers in High Voltage Laboratory at AGH University of Science and Technology (AGH-UST) in Kraków. It refers to the 2-stage cascade transformers rated for a voltage 250 kV, containing multi-segment electrodes on a top of each stage of the cascade.

2. FEATURES OF MULTI-SEGMENT ELECTRODE

The exemplary multi-segment electrode of 18 plates is presented in the Figure 1. The following set of parameters describes the multi-segment electrode:

- R - the radius R of the envelopment,
- n - the number of plates,
- d - the diameter of the single plate,
- r - radius of the ledge,
- d_0 – the diameter of air gap between adjacent plates.

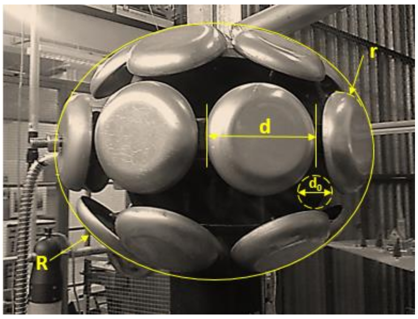

Fig. 1. Multi-segment electrode of 18 plates and its parameters

The relation between the maximum field strength of a curved multi-segment electrode and its envelopment (representing a smooth electrode surface) is determined by the segment factor k_s (1):

$$k_s = \frac{E_{ms}}{E_{se}} \tag{1}$$

where: E_{ms} – the maximum field strength of a curve multi-segment electrode, E_{se} – the maximum field strength of a smooth electrode.

This segment factor covers not only the shape and arrangement of the plate electrodes but also the angle between them in space. The factor k_s is dependent also on the dimensions and parameters of each single plate [1].

3. CONFIGURATION OF THE 2-STAGE CASCADE TRANSFORMERS IN HV LABORATORY

The picture, scheme as well as nominal parameters of the 2-stage cascade transformers in HV Laboratory at AGH-UST in Kraków are presented in the Figure 2 and the Table 1, respectively.

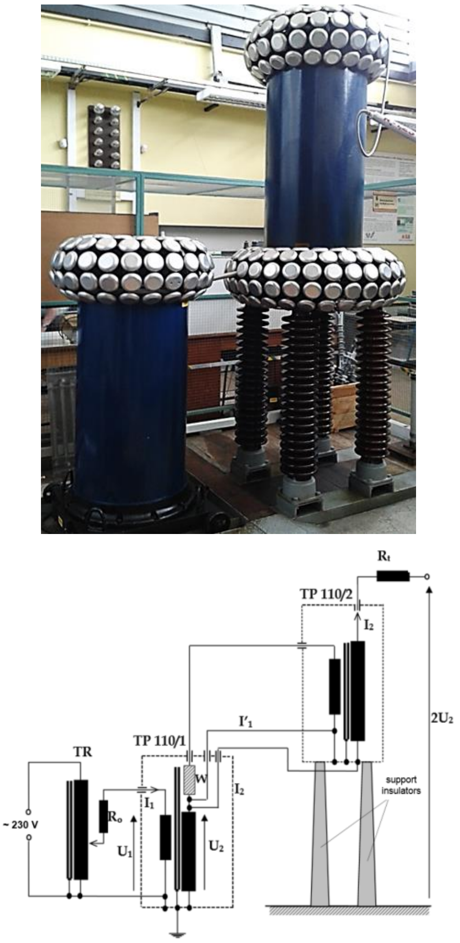

Fig. 2. Photograph (top) and scheme (bottom) of the two-stage cascade transformers in HV Laboratory at AGH-UST, TP110/1 – first stage of the cascade, TP110/2 – second stage of the cascade, TR – regulating transformer, R_0 – short-circuit current limiting resistor, R_t – dumping resistor [2]

Table 1. Nominal parameters of the cascade transformers

Primary voltage	230 V
Secondary voltage	250 kV
Secondary current	90 mA
Nominal power	10 kVA
Nominal frequency	50 Hz

The cascade transformers are located in a fenced test area. The distances of the HV electrodes from grounded fences and walls are calculated so that there is no risk of flashover between these elements at 250 kV AC voltage.

4. SIMULATION MODEL DESCRIPTION

4.1. Scope of simulations

The simulation results of the electric field distribution near the two-stage cascade transformers are presented in this paper. The scope of simulations cover the case when the cascade transformers are “free in space” as well as located in a fenced test field of real dimensions. To show the shielding effect of the multi-segment electrodes arrangement, the results are compared to the equivalent cascade transformers equipped with smooth electrodes with the shape corresponding to the envelopment of the multi-segment electrodes.

4.2. Simulation approach

The simulations have been done by means of the COMSOL Multiphysics v4.4. In this case, the “*AC/DC - Electric Currents*” program interface and *Frequency domain* analysis have been used. In this program interface the following general equation is being solved for the electric potential V in every point in space [3]:

$$-\nabla \cdot (\sigma + j\omega\varepsilon_0)\nabla V = 0 \tag{2}$$

where: σ – electrical conductivity, V – electric potential, ε_0 – vacuum permittivity, ω – angular frequency.

Then, the electric potential that was obtained by solving equation (2) is used to find out the electric field strength:

$$E = -\nabla V \tag{3}$$

4.3. Model details

A full-scale 3D models of the two-stage cascade transformers with smooth and multi-segment electrodes were implemented into the simulation software. The geometry and selected dimensions of the simulation model are presented in the Figure 3. The cascade transformers comprise three electrodes numbered from 1 to 3 according to the picture below.

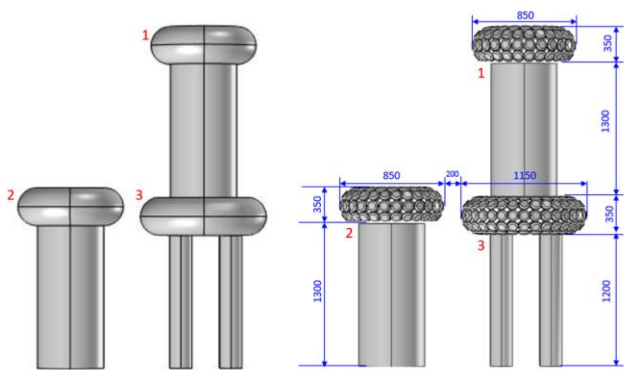

Fig. 3. Geometry and dimensions (in mm) of the analyzed cascade transformers with smooth (left) and multi-segment (right) HV electrodes

In the first case, the cascade transformers have been located in a space representing the real fenced test field in HV Laboratory at AGH-UST (Fig. 4). Red boundaries represent the grounded elements, while green ones are electrically insulated. In the case with the "free in space" transformers, no elements were grounded – all elements surrounding the cascade were electrically insulated. This means that the ground potential was placed infinitely far from the cascade transformers.

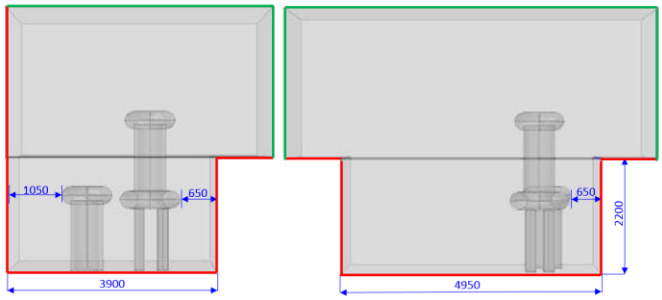

Fig. 4. Selected dimensions of the fenced test field at HV Lab at AGH-UST and location of the cascade transformers (left - front view, right - side view)

Dimensions of the each single plate of the multi-segment electrode are as follows: d = 100 mm, r = 20 mm. The radius of the HV multi-segment electrodes envelopment R=175 mm.

The 50Hz electric potential was applied to the HV electrodes: top electrode (no.1) V_1=250 kV, bottom electrodes (no.2 and 3) V_2=V_3= 125 kV. The properties of materials used in the simulation are presented in the Table 2.

Table 2. Material properties used in simulations

Material / Parameter	Relative permittivity ε_r	Electrical conductivity σ [S/m]
Air	1	10^{-12}
Aluminum electrodes	1	$3{,}7 \cdot 10^{7}$
Cylinders filled with oil	2.2	10^{-12}
Support insulators	5	10^{-12}

5. SIMULATION RESULTS AND DISCUSSION

5.1. Cascade transformers in real lab arrangement

The results of the electric field strength distribution near the laboratory arrangement of the cascade transformers with smooth and multi-segment HV electrodes are presented in the Figure 5 and 6, respectively.

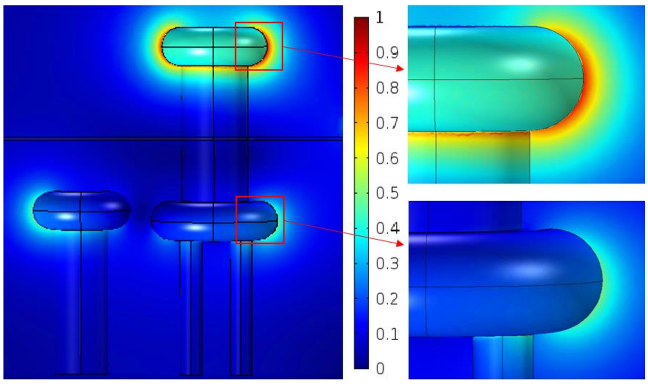

Fig. 5. Electric field distribution near the real lab arrangement of cascade transformers with smooth electrodes

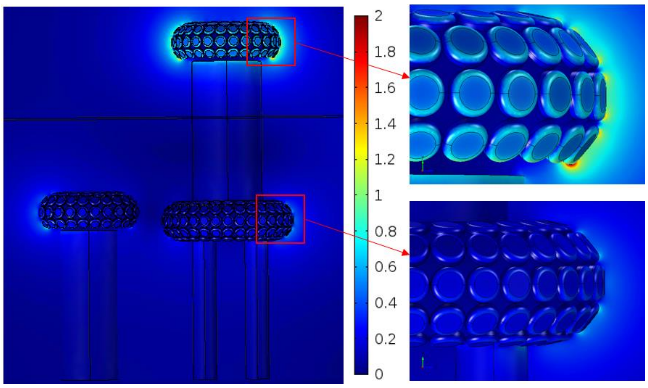

Fig. 6. Electric field distribution near the real lab arrangement of cascade transformers with multi-segment electrodes

In both, the smooth and multi-segment electrode cases, the maximum electric field strength exists near the surface of the top electrode which in on the 250 kV potential, on their curved edges. The maximum field strength is ca. 0,87 kV/mm for the smooth electrode, while for the multi-segment electrode is more than twice higher. This big difference of the maximum values of electric field strength is caused by the curved edges of the small segment plates. The highest electric field strength is observed on the curved edge of the lowermost row of plates, in the place where the distance to the grounded fence is the smallest. However, near the flat surface of each segment plate of the HV electrode, the field strength is comparable to that of smooth electrode case (ca. 0,9 kV/mm). The maximum field strengths near the top electrode and the calculated segment factor k_s for both cases are shown in the Table 3.

Table 3. Comparison of the maximum field strengths near the HV electrodes

Electrode type	Smooth electrode	Multi-segment electrode
E_{max}	0,87 kV/mm	1,95 kV/mm
k_s	2,24	

The electric field strength distribution along the line between the points P1 and G1 (the smallest distance between the top electrode and grounded fence) is presented in the Figure 7.

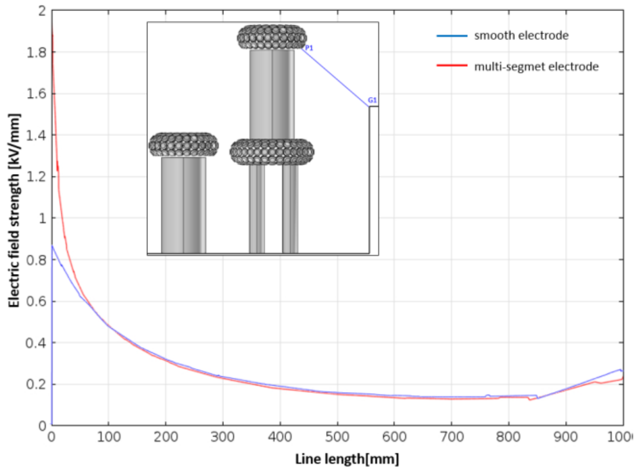

Fig. 7. Plot of electric field strength distribution along the line P1-G1

As can be seen, the difference of electric field strength distribution is observable only in the nearest area of the top electrode (on the curved edge of the lowermost single plate). This must be taken into account during design process of the segmented electrodes and location of the electrode in relation to grounded elements to avoid discharges at lower voltage levels.

5.2. Cascade transformers in "free in space" conditions

The results of the simulations of electric field distribution near the "free in space" cascade transformers with smooth and multi-segment electrodes are of similar character to those presented in the Figure 5 and 6, however the field strengths are much lower due to infinitely long distance to elements on the ground potential. The maximum field strengths near the top, "free in space" electrodes and the calculated segment factor k_s are shown in the Table 4.

Table 4. Comparison of the maximum field strengths near the HV electrodes

Electrode type	Smooth electrode	Multi-segment electrode
E_{max}	0,43 kV/mm	0,79 kV/mm
k_s	1,84	

6. SUMMARY

The electric field strength distribution in the area of shielding electrodes of HV testing equipment is analyzed and presented in this paper. The analyses were based on the real arrangement of the two-stage cascade transformers in the HV Laboratory at AGH-UST in Kraków, rated for a 250 kV voltage. Two types of shielding electrode were taken into consideration: smooth and so called multi-segment electrodes. The analysis consists of two cases – the cascade transformers located in a fenced area of a real dimensions and "free in space". The maximum electric field strengths obtained for these simulation cases have been compared. Segment factor k_s has been calculated for both cases.

The performed analysis showed that multi-segment electrodes can be well introduced as a shielding electrodes of HV equipment, however special attention should be paid to the design of the shape of the electrode. The electric field strength near the surface of such electrodes is affected mainly by the curvature radius of each single plate, its diameter and radius of the envelopment of the complete electrode.

Due to the curved edges of each single plate there is a local enhancement of the electric field strength when compared to the electrode of a smooth shape. In the analyzed cases the field strength enhancement was even more than two times. This might lead to streamers inception at lower voltages what should be taken into consideration during designing and dimensioning of the shielding electrodes.

Despite the fact that electric field strength is enhanced in the case of multi-segment electrodes, they are often used due to practical and economical reasons. For many applications making of the HV electrodes from many small segmented plates is cheaper and easier than manufacturing of large aluminum electrodes as a single element.

The FEM simulations can be used for analysis and optimization of such constructions of HV electrodes, however analysis of equipment of a real dimensions and equipped with many small segmented elements, requires generation of a complicated mesh with large number of elements. The number of elements can be of course reduced, but this leads to quite bigger errors in calculated values of the field strength. A 2D simulation models can be a good alternative, but the proper cross-sections of the equipment must be chosen for the simulations, in order to obtain credible results.

7. REFERENCES

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MODELOWANIE ROZKŁADU POLA ELEKTRYCZNEGO W OTOCZENIU WIELO-SEGMENTOWYCH ELEKTROD WYSOKONAPIĘCIOWYCH UKŁADÓW PROBIERCZYCH

Słowa kluczowe: elektrody wielo-segmentowe, pole elektryczne, modelowanie

Problematyka kształtowania rozkładu pola elektrycznego w wysokonapięciowych urządzeniach elektrycznych dotyczy metod ograniczania maksymalnych wartości natężenia pola elektrycznego w pobliżu elektrod wysokonapięciowych. W laboratoryjnych wysokonapięciowych urządzeniach probierczych, problem ten występuje m.in. w przypadku zastosowania tzw. elektrod wielo-segmentowych. Takie elektrody składają się z wielu jednakowych elementów w kształcie okrągłego dysku o zagiętych krawędziach. Elektrody segmentowe muszą być odpowiednio zaprojektowane i zwymiarowane aby spełnić swoją funkcję. Elektrody segmentowe można scharakteryzować za pomocą parametru k_s określanego jako stosunek maksymalnej wartości natężenia pola elektrycznego na zakrzywionej krawędzi elektrody segmentowej, do maksymalnej wartości natężenia pola przy elektrodzie o łagodnym kształcie, odpowiadającym obwiedni elektrody segmentowej. Współczynnik k_s określa zatem nie tylko kształt ale i układ segmentów elektrody względem siebie oraz względem uziemionych elementów w otoczeniu urządzenia.

Celem symulacji była analiza maksymalnych wartości natężenia pola elektrycznego wokół „gładkich" oraz wielo-segmentowych elektrod wysokonapięciowych. Problem został przedstawiony na przykładzie dwustopniowej kaskady transformatorów o napięciu 250 kV, znajdującej się w Laboratorium Wysokich Napięć Akademii Górniczo-Hutniczej w Krakowie.