Shielding efficiency of conductive clothing during live-line maintenance

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Abstract -- **Nowadays live-line maintenance (LLM) is one of the most common methods to repair and maintain energized elements of the power grid. The main advantage of this technique that it represents a balance between technical and economic factors: no consumer disturbance is needed, there is not any service outage caused and losses can be kept as low as possible. Because of these reasons different live-line methods are becoming more and more popular on all voltage levels. Special techniques are available for low, middle and high voltage grids. On high voltage levels "barehand method" is widely applied worldwide. The main principle of this method is an enclosed metal surface around the worker acting as a Faraday cage. Inside an ideal Faraday-cage electric field is zero from outer source. The efficiency of a clothing mainly depends on the size of holes (so called "Faraday-holes") on the surface. A proper face mesh can guarantee the safety of the live-line worker. Calculations, simulations and measurements in the High Voltage Laboratory of Budapest University of Technology and Economics have proved that poor, coarse or missing face shield decreases the efficiency by the increase of body current.**

Keywords: electric field, live-line maintenance, barehand method, conductive clothing, face mesh

I. Introduction

In case of high voltage LLM conductive clothing is used as a Faraday-cage: the elementary cotton threads of the clothing are combined with metal threads which guarantee the electrical conductivity of the suit. Conductive clothing connected to the high voltage conductor guarantees safe and comfortable circumstances to execute even difficult tasks on energized power lines of the high voltage grid. Although the principle is well-known and there are strict regulations, standards and detailed instructions for all the steps of a given kind of work, health effects of high electric field are often neglected. This paper investigates both the strength of this field and its possible effects on live-line workers.

II. Extra low frequency electric field

In case of common power grids with a frequency of 50 Hz or 60 Hz electric and magnetic fields have to be investigated separately from each other. The length of even the longest power lines is much shorter than the wavelength of a sinusoidal wave with the frequencies above. In the territory of ENTSO-E 50 Hz is the common frequency in all the member countries, so calculations, simulations and measurements have been executed on this frequency.

This range of frequencies is in the range of extra low frequency (ELF) electric and magnetic fields. There are many opened questions about the health effects of these fields. The limits of them are mostly based on the inspection of stimulation caused. The exact relation between the strength of electric field and its long-term effect on human body is still unknown. It can be clearly seen that the aim has to be to minimize the electric field strength on the surface of the whole human body – especially during live-line maintenance when the strength – and also the effects – of this field can be much higher than usual.

Current limits for electric fields are defined by International Commission on Non-Ionizing Radiation Protection (ICNIRP). Values for 50 Hz ELF electric and magnetic fields from the Directive 2013/35/EC of the European Parliament and of the Council based on ICNIRP guidelines are shown in Table 1.

	Limits for electric field strength before 2010 [kV/m]	Current limits for electric field strength [kV/m]	Limits for magnetic induction before 2010 [μT]	Current limits for magnetic induction [μT]
Public	5	5	100	200
Occupational (max. 8 hours/day)	10	10	500	1000

Table 1: current and previous limits for 50 Hz electric and magnetic fields based on ICNIRP guidelines

III. Simulation results

Electric field distribution on the face of the worker has been calculated by using finite element method (FEM). Conductive clothing was modeled as an enclosed metal surface with "Faraday-holes" on it. The size of these openings must be a balance between the proper electric shielding properties, good visibility and proper ventilation. Two different cases have been investigated: in the first case the worker approaches the phase conductor of a 400 kV high voltage power line, but in the distance of 50 cm (19.69 inches) the potential clamp of the clothing has not been connected to the phase conductor yet. In the second case the conductive clothing is connected to the conductor and the distance between the face of the worker is only 10 cm (3.94 inches). The voltage level of the conductor has been chosen as the peak value of the phase voltage of a 400 kV power line in both cases.

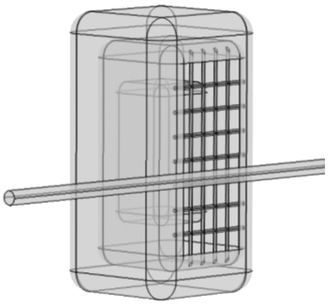

Figure 1: model for finite element calculations

COMSOL Multiphysics 4.3a has been used for the simulations. Calculations were executed for three different types of conductive clothing. "Type A" had a normal face mesh with an average opening size of 2.96 cm (1.17 inches) – applied on the Hungarian conductive clothing since 1980s. "Type B" had a coarse face mesh and the average opening size was 7.13 cm (2.81 inches). "Type C" was a conductive clothing to be simulated without any face screening. Many conductive clothing is produced without any face mesh, so all the conductive clothing types used for the simulations were based on real constructions.

Figure 2 shows the results for Type A, B and C in case of approaching the conductor on a floating potential.

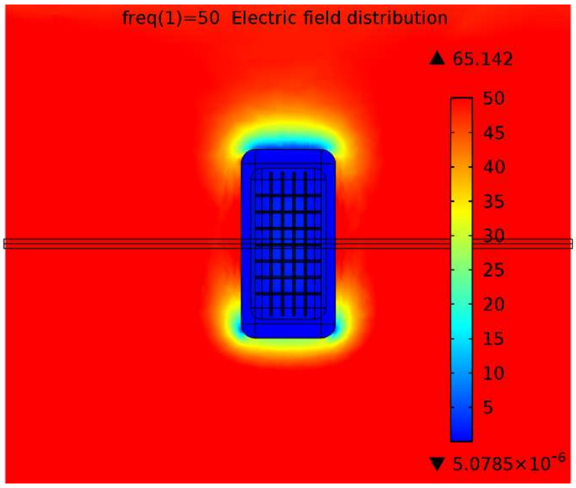

Figure 2.a: electric field distribution in front of the face of the worker – normal (Hungarian) face mesh (Type A)

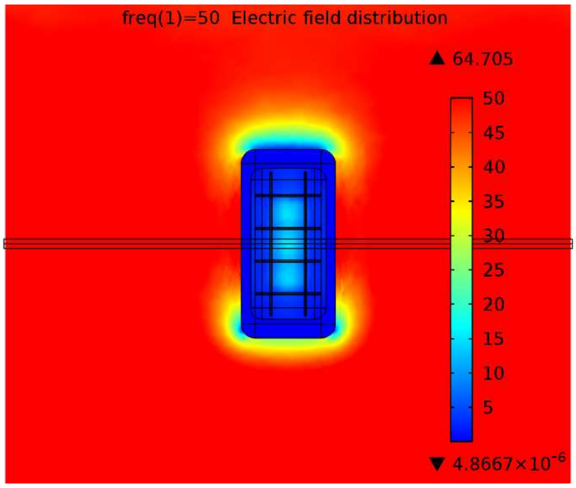

Figure 2.b: electric field distribution in front of the face of the worker – coarse face mesh (Type B)

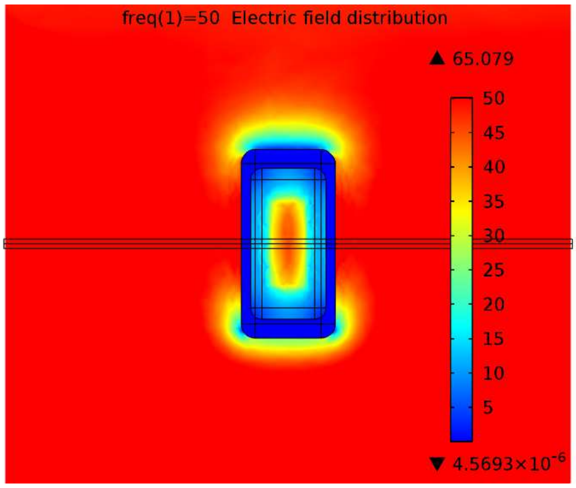

Figure 2.c: electric field distribution in front of the face of the worker – no face mesh (Type C)

Minimum, maximum and average values of electric field has been calculated in front of worker's face. In case of normal face mesh, even the maximal values of electric field strength remains below the limits in front of the worker's face. Average values of electric field strength are acceptable with coarse face mesh, but maximal values can be above the limits. No face mesh is the most dangerous case from the aspect of the harmful health effects of high electric field. In this case both average and maximal values are above the limits during the approach of the conductor. Exact values are shown in Table 2 and are marked with red if they are above the limits.

	Normal face mesh	Coarse face mesh	No face mesh
Minimum	0,62	1,49	6,38
Maximum	2,47	**16,73**	**45,68**
Average	1,59	6,75	**24,89**

Table 2: values of electric field in front of worker's face during approaching the conductor [kV/m]

Values of Table 2 are shown in Figure 3 (current limits for electric field for workers is 10 kV/m).

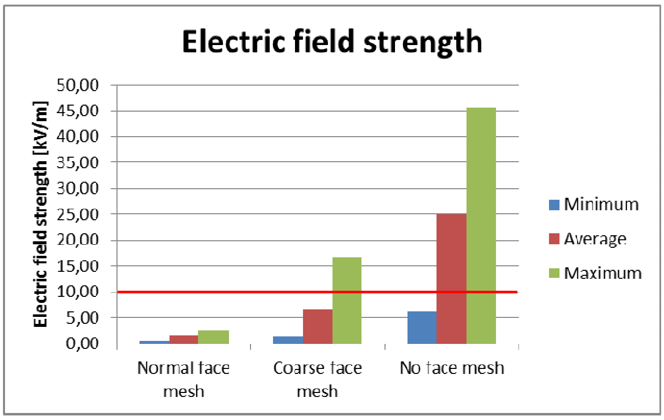

Figure 3: trend of electric field in front of worker's face during the approach of the conductor [kV/m]

The same kind of simulation has been executed for the second case as well. Now the worker's clothing were connected to the phase conductor with the potential clamp, so their electric potential became the same.

Electric field strength has been evaluated in front of the worker's face. In case of normal face mesh all the values of electric field strength were below the limits. Both in case of coarse face mesh and no face mesh average and maximal values were above the limits. It can be seen that conductive clothing without face mesh endanger the health of the worker extremely; all the electric field strength values are above the limits - even the minimum values.

Electric field distribution for conductive clothing Type A, B and C is shown in Figure 4. Minimum, maximum and average results are summarized in Table 3. Trends of values in Table 3 are shown in Figure 5.

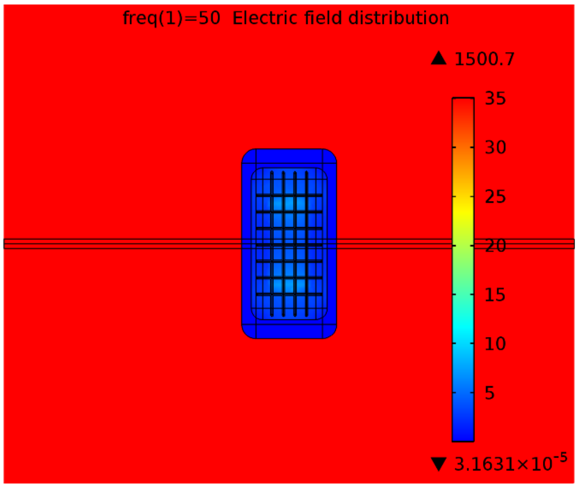

Figure 4.a: electric field distribution in front of the face of the worker – normal (Hungarian) face mesh (Type A)

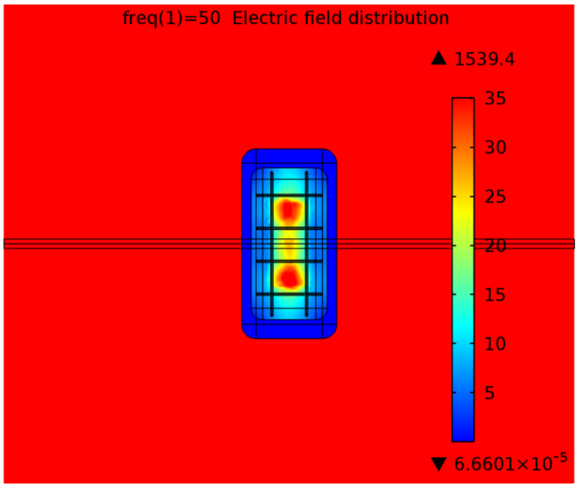

Figure 4.b: electric field distribution in front of the face of the worker – coarse face mesh (Type B)

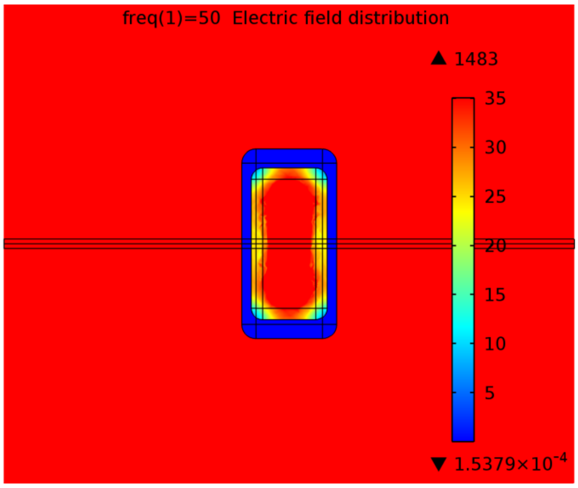

Figure 4.c: electric field distribution in front of the face of the worker – no face mesh (Type C)

	Normal face mesh	Coarse face mesh	No face mesh
Minimum	1,70	4,53	**21,05**
Maximum	8,06	**41,03**	**112,93**
Average	4,17	**16,23**	**60,00**

Table 3: values of electric field in front of worker's face after the conductive clothing has been connected to the conductor [kV/m]

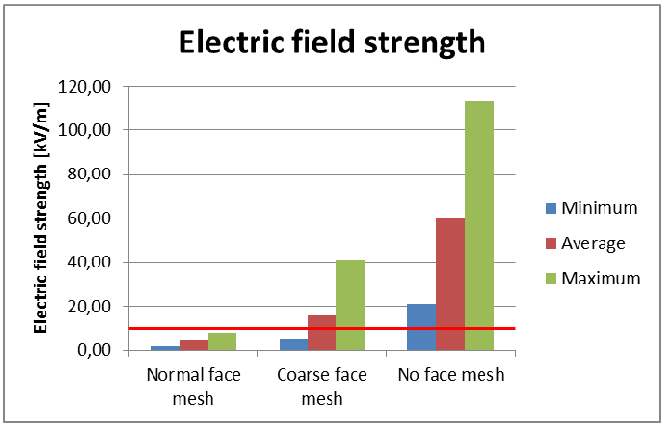

Figure 5: trend of electric field in front of worker's face after the conductive clothing has been connected to the conductor

Figure 6 shows electric field strength on the face of the live-line worker as the function of voltage level in case of no face mesh. It can be seen that even on 120 kV both average and maximal values are above the limit, so on practical nominal high voltage levels it is unacceptable to use conductive clothing without any face mesh. The distance between the face of the worker and the phase conductor has been chosen to 10 cm (3.94 inches).

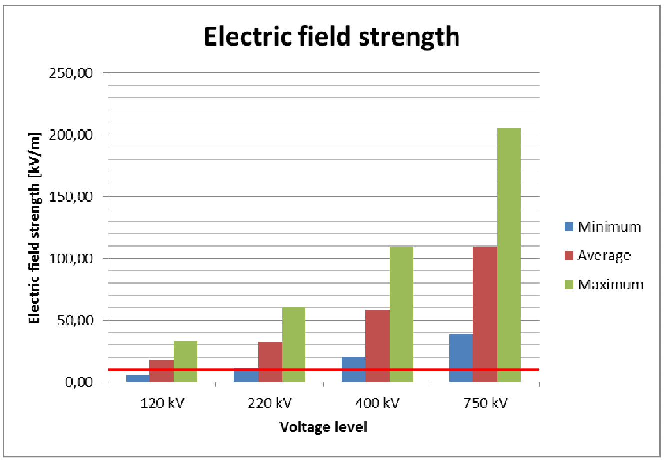

Figure 6: electric field strength on the worker's face without any face mesh

IV. Mesh Openings

As results of FEM simulations show, a "proper" face mesh is required for the proper protection against the harmful health effects of high electric field. The efficiency of a face mesh is mainly characterized by the size of the openings on the mesh. FEM simulations have been executed with a parametric sweep of the radius of the openings.

A worst-case, but still practical arrangement have been investigated: the distance between the conductor and the worker's face has been chosen as 10 cm (3.94 inches). The distance of the face mesh and the face – modeled as the standard human body defined in IEC 62233 – were 5 cm (1.97 inches). A practical example for these distances during high voltage live-line maintenance is shown in Figure 7.

Figure 7: live-line maintenance with conductors close to the worker's head

Electric field strength as the function of the radius of face mesh openings on 400 kV is shown in Figure 8.

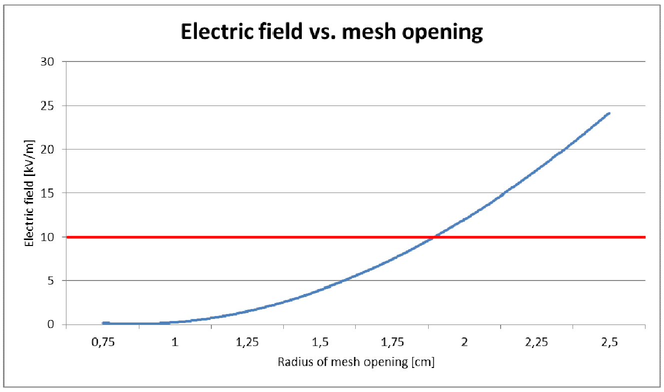

Figure 8: electric field as the function of mesh opening radius

It can be seem that on voltage levels of 400 kV and above, a face mesh with a larger opening radius than 1.75 cm (0.69 inches) can endanger the safety of the worker because of the electric field strength above the limits.

V. Summary

It can be clearly seen from the results of the calculations and simulations above that there are some cases when strength of electric field is much higher than its current limits. Only “Type A” of conductive clothing had the proper shielding properties against ELF electric field. Based on the simulations’ results it is not allowed to execute live-line works in conductive clothing without any face mesh. Even coarse face mesh can be dangerous, so it is always necessary to investigate the construction of the face screen. Electric field values above their limits can be dangerous because of their mostly unknown long-term effects. Conductive clothing produced without proper face meshes have to be modified. An additional face mesh is shown in Figure * in the High Voltage Laboratory of Budapest University of Technology and Economics. Size of openings on this type of mesh has been determined by Dr. Béla Csikós, one of the pioneers of high voltage live-line maintenance in Hungary and worldwide as well.

It is also important to apply additional metal bands on the clothing to ensure proper conductive paths for high currents caused by failures. Although the duration of these failures is short (typically a few μs or ms) the heat generated by their current can be extremely high. Current-carrying threads can guarantee the controlled way of fault currents and can increase the protection of the worker even in case of a failure.

Figure 9: additional face mesh and metal threads on a conductive clothing

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