BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
BUDAPEST, HUNGARY
23 April 2015

CURRENT ISSUES REGARDING TO THE INSPECTION OF CONDUCTIVE CLOTHING

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KEY WORDS: conductive, clothing, live, line, maintenance, high, voltage

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SUMMARY

There are different standards and regulations to inspect the efficiency of conductive clothing. IEC's 60895 is widely used and has a complete set of tests including resistance measurement, screening and shielding efficiency inspection, etc. In some cases arrangement of the measurements is not strict enough. In the High Voltage Laboratory of Budapest University of Technology and Economics a suggested modification of the current arrangement of screening efficiency measurement has been developed. Application of new techniques as a part of the next version of the standard is under consideration by IEC's committee. Based on our laboratory measurements during high voltage live-line maintenance high electric fields – often above the current limits defined by International Commission on Non-Ionizing Radiation Protection (ICNIRP) – may occur.

Without any face mesh, face of the worker might be endangered by their harmful effects and critical strength of them often cannot been determined by the current ways of inspection. Suggested arrangement is safer, more efficient and demonstrates real circumstances better than the actual one. During the approach of the conductor or working at the potential of the phase conductor electric field distribution has been calculated and simulated on a 3D model. Critical size of the "Faraday-holes" as a function of voltage level has also been determined. Suggested modifications are expected to increase the safety of the inspection, so the live-line work. To protect the workers and to guarantee their maximal level of safety always has to be a first priority during any kind of live-line related regulation. The aim of this paper is to prove that suggested inspections are more realistic and effective than the actual set of test – based on the results of simulations and measurements.

Introduction

Live-line maintenance is widely applied nowadays because of its technical and economic benefits. At high voltage levels barehand method is a common way of working in a special conductive clothing acting as a Faraday cage to shield extra-low frequency electric field around the workers.

Without any face protection electric field may exceed the current exposure limits (defined by ICNIRP as 10 kV/m [1], [2]) during high voltage live-line maintenance inside the conductive clothing. It have to be guaranteed that electric field strength remains below the applicable limits at any point inside the clothing and at any time during the work.

Electric field distribution on the face without any face mesh: approach of phase conductor

During the approach of the phase conductor, potential of the conductive clothing floats. In this case, electric field strength increases in front of the face of the worker as the distance between the clothing and the phase conductor decreases. Figure 1 shows the values of electric field strength inside the clothing. Each value is an average of calculated electric field evaluated in 10 000 points by finite element method on a 3D CAD model and each curve is approximated by a 3rd degree polynomial function. As it can be seen from Figure 1, above 110 kV electric field strength becomes higher than the limit, even in the distance of 60 cm (23.62”).

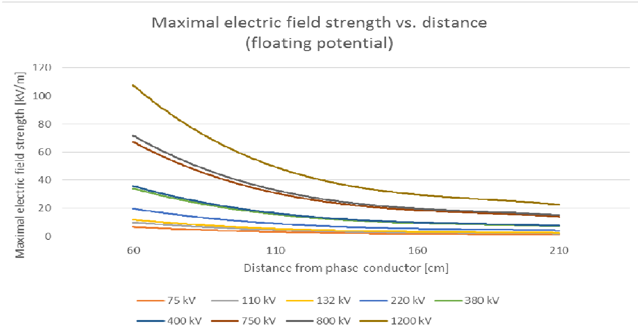

Fig. 1. Maximal electric field strength as a function of distance from phase conductor.

Electric field distribution on the face without any face mesh: energized clothing

After the connection of the potential clamp to the phase conductor, the conductive clothing becomes energized; the electric potential of the clothing and the phase conductor will be equal. In this case, electric field strength decreases in front of the face of the worker as the distance between the clothing and the phase conductor decreases: the root cause is a basic physical law: between same potentials electric field is “shielded” by the conductive parts as electrodes. As in case of Figure 1, electric field was evaluated in 10 000 points by finite element method on a 3D CAD model and each curve is approximated by a 3rd degree polynomial function. Figure 2 shows the values of electric field strength inside the clothing. As it can be seen from Figure 2, electric field strength is higher than the limit in all cases - even in the minimum distance and at the lowest voltage level applied.

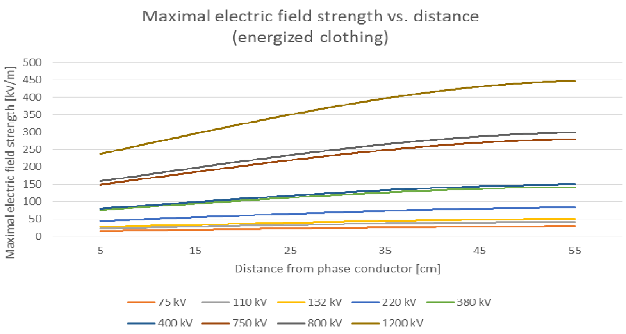

Fig. 2. Maximal electric field strength as a function of distance from phase conductor.

Inspection of different face mesh designs

Electric field strength as a function of the radius of the openings on the face mesh (approximated as circles) can be seen in Figure 3. Results are obtained from finite element calculations and are validated by laboratory measurements at the voltage range of 75-220 kV.

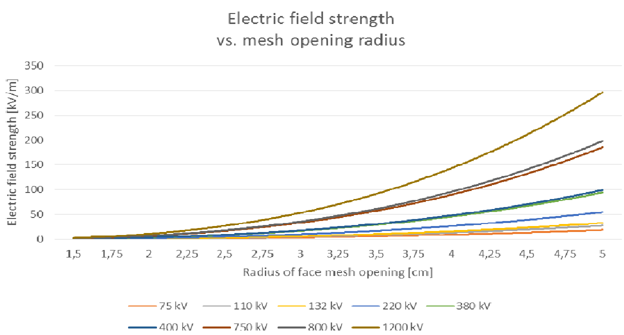

Fig. 3. Electric field strength as a function of mesh opening radius.

As it can be seen at the voltage level of 1200 kV above a Faraday-hole radius of 1.75 cm (0,69”) electric field strength becomes higher than the current limit. In case of the minimal inspected voltage (75 kV) above a hole radius of 4 cm (1.57”) electric field strength exceeds the critical value (10 kV/m).

Inspection of screening efficiency

Current arrangement of IEC 60895 ed2.0 does not demonstrate the highest electric field which can be occurred during real working conditions. A new arrangement based on the Hungarian “Csikós” test method - which was widely used between 1970 and 2000 in the territory of the Hungarian TSO - is suggested to:

- make the process of the inspection safer: it is neither safe nor easy to handle measuring devices which are energized
- simulate real (even worst-case) conditions: in the current arrangement critical electric field is mostly shielded by the same electric potential of the protective parts and the phase conductor; in real working environment much worse conditions may occur (e.g. around the towers or insulators, where grounded structures are relatively close to the energized parts - including the conductive clothing worn by the worker - or between the conductors of different phases)
- increase the accuracy of the test: in the current arrangement it is not easy to recognize the difference between the different types of conductive clothing.

Electric field and capacitive currents have been measured in different arrangements to validate the results of calculations and simulations [3]-[7]. The current procedure shall be carried out at the phase-to-earth voltage corresponding to the maximum nominal AC voltage at which the clothing can be used. The screening efficiency shall be determined by (1).

$$V = \frac{I_1}{I_1 + I_2} \tag{1}$$

The conductive suit pass the test, if the screening efficiency (V) is above 99%. By measuring this way, conductive clothing without any face protection can pass the test (value of current I_1 is high). As it can be seen from the direct electric field strength measurement results, during normal working conditions without any face mesh electric field strength might be higher than the limits, so this arrangement is not suitable to inspect the screening efficiency of a conductive clothing effectively.

Laboratory measurements

The current regulations do not contain any exact details about the placement of the energized conductor; during the test a high voltage wire has been placed to the height of the head in a distance of 30 cm (11.81") from the face of the mannequin. The test voltage level was 111.5 kV and the distance between the ground and the live parts was 1.12 meters (44.09"). During the first experiment the face screen of the suit was folded, so the whole surface of the face was protected by the face mesh. With a leakage current I_1 of 1412 µA and I_2 of 13 µA, efficiency "V" is 99.08% in this case, which is above 99 percent, so the suit has passed the test. In the second case leakage current without face mesh has been measured, so the face was completely unprotected. In this case current I_1 was 1445 µA and I_2 was 14 µA, so the efficiency "V" is 99.04%. As it can be seen from the results, the leakage current was almost the same with and without the face mesh. Arrangement of measurement is shown in Figure 4.

Fig. 4. Electric field measurement in laboratory environment.

Simulation results

The arrangement of this test has been simulated by finite element method (FEM) on a 3D model with a standardized human body by IEC 62233 [8]. Figure 4 shows the results of the simulation for the electric field distribution in the current arrangement for screening efficiency inspection of IEC 60895 (7.2. paragraph) [9]: an energized conductor is placed in front of the mannequin at the same potential than the conductor, isolated from the ground. Leakage currents to be measured are induced by electric field between the energized electrodes and the ground, so distribution has a significant effect on the results. As it can be seen in Figure 5, the electric field is very low near the face; it is "shielded" by the same potential of the conductor and the mannequin inside the conductive clothing. This arrangement simulates the best case from the aspect of electric field distribution instead of the worst-case scenario.

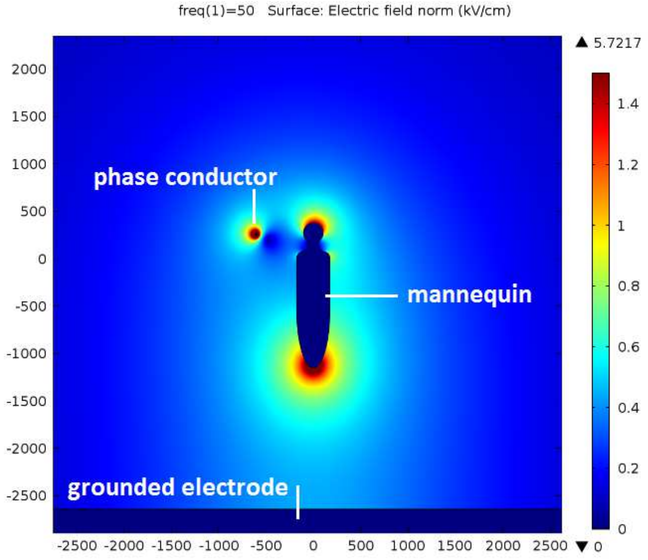

Fig. 5. Electric field distribution in the current arrangement.

Another issue with this arrangement is that the strength of the electric field strongly depends on the distance from the grounded parts in the surroundings of the arrangement, so the measurement cannot be repeated easily. The measurement has been repeated with a different electrode arrangement (a few, and after that significantly more grounded structures in the vicinity of the arrangement, further than the minimal distance calculated from the standard). Figure 6 shows the difference between the results of the two experimental measurements. As it can be seen from the results of the simulation, grounded parts in the surroundings of the measurement have significant effects on the strength and distribution of electric field. The standard only determines the minimal distance from the nearest grounded part as a function of applied voltage. Electric field distribution - and value of leakage currents – might be easily modified by some grounded structures in the vicinity of the arrangement. This makes this way of measurement hard to repeat.

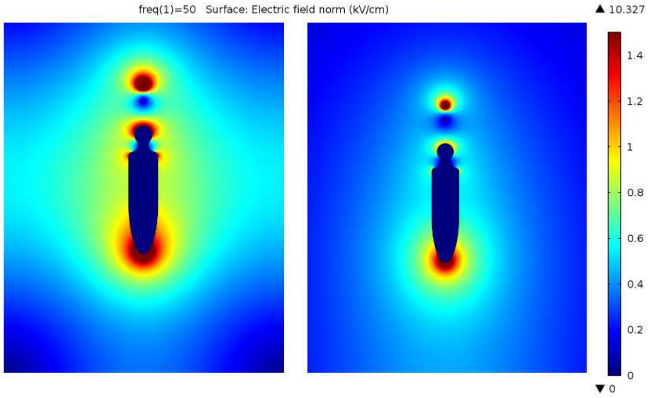

Fig. 6. Effect on the results of surroundings in the current arrangement.

Suggested way of measurement

Both theoretical (FEM simulations) and practical (laboratory measurements) investigations have proved that the current arrangement of IEC 60895 for the inspection of screening efficiency is not effective enough. Based on the results the High Voltage Laboratory of Budapest University of Technology and Economics suggests some modifications in the way of this measurement.

The main disadvantages of current way of measurement:

- there is no significant difference in the results between "acceptable" and "not acceptable" clothing (even not acceptable clothing may pass the test because of the shielded area by the arrangement in front of the face, which is critical from the aspect of "Faraday-holes")
- instruments are energized; it is not safe and not easy to read them correctly
- the position of the energized conductor is not determined clearly
- it is hard to repeat the measurement because of the significant effect of grounded structures on the results in the vicinity of the arrangement.

The main difference from the current way of inspection is that the mannequin (with a conductive surface in conductive clothing) shall be placed into inhomogeneous electric field. The body and the clothing shall be grounded through micro-ammeters. A high voltage conductor shall be placed at height of the horizontal midline of the head, in front of the mannequin. The distance between the conductor and the mannequin shall be determined by the valid standard for the evaluation of minimal arcing distance. The test shall be carried out at the maximal design AC (phase-to-earth) voltage of the clothing. Suggested mannequin-to conductor-distances shall be calculated from IEC 61472 ed3.0 [10]. Efficiency "V" shall be above 99%. FEM simulation results of electric field distribution in the suggested arrangement as a function of grounded structures in the vicinity of the measurement are shown in Figure 7. As it can be seen from the results, in this case the environment does not affect the electric field distribution - neither the value of leakage currents - significantly. The highest electric field strength occurs in front of the face, similarly than during real working conditions during approaching the conductor. After the simulations, results have been validated by laboratory tests: a conductive clothing with and without face mesh at a voltage level of 111.5 kV has been inspected in the suggested arrangement. At this voltage level the minimal arcing distance is 0.5 m (19.69") by IEC 61472 ed3.0. Table 3 summarizes the results in the suggested arrangement.

TABLE I. RESULTS IN THE SUGGESTED ARRANGEMENT

Conductive clothing with face mesh			Conductive clothing without face mesh		
I_{body} [μA]	$I_{clothing}$ [μA]	V [%]	I_{body} [μA]	$I_{clothing}$ [μA]	V [%]
0.5	360	99.86	6.6	350	98.12

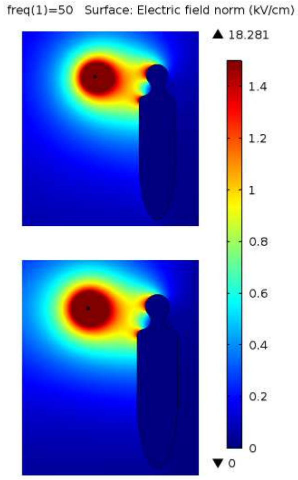

Fig. 7. Effect of surroundings on the results in the suggested arrangement.

As it can be seen from the results of Table 3, efficiency of conductive clothing with face mesh became much higher than the other conductive clothing – without any face protection – which has failed the test. Results are clear and there are significant differences between the values of screening efficiencies both in case of acceptable and not acceptable results.

Validation of new arrangement suggestion in laboratory environment

As a part of a laboratory experiment a mannequin (with a conductive surface) in conductive clothing has been placed in a distance of 30 cm (11.81") from an energized high voltage conductor. The potential of the clothing and the conductor were the same during the test. Electric field has been measured between the face and the face mesh with EPRI/Enertech EMDEX II field measurement system and "free body type" E-probe in x, y and z directions [11] at the voltage levels of 25, 50, 69.3, 75 and 100 kV. Electric field norm is shown in the figures. In the first case the face of the mannequin was unprotected. Figure 8 summarizes the results of electric field strength measurement as a function of voltage. As it can be seen from the chart, values are much above the limits at all voltage levels. In the second case, a face mesh has been folded in the front of the face. Electric field strength has been measured at the same voltage levels than in the first case (Figure 9).

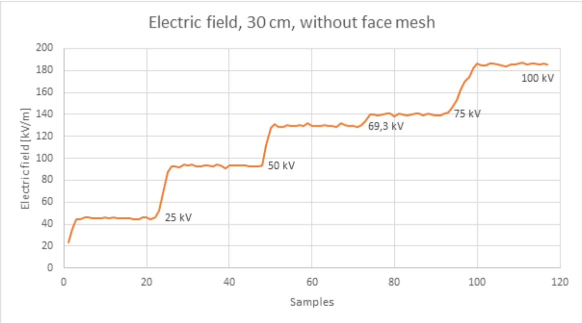

Fig. 8. Electric field strength in a distance of 30 cm from the conductor (without face mesh).

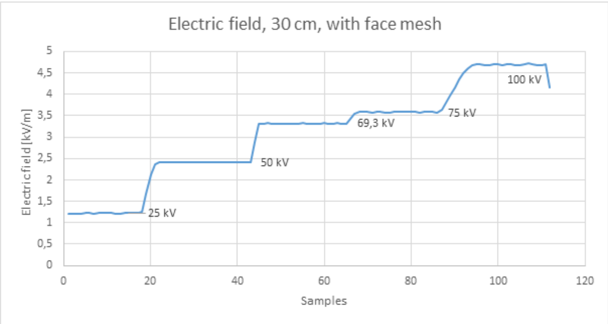

Fig. 9. Electric field strength in a distance of 30 cm from the conductor (with face mesh).

As it can be seen the face mesh has increased the screening efficiency significantly; the electric field remained below the limit at all voltage levels. According to the results, face screen is a very important piece of the conductive clothing, which significantly reduces the electric field in the vicinity of the face; it shall be applied on every class of conductive clothing.

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