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Decreasing the Extremely Low-Frequency Electric Field Exposure with a Faraday Cage during Work Tasks from a Man Hoist at a 400 kV Substation

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Abstract—Earlier studies have shown that the occupational exposure of electric fields at 400 kV substations can be higher than the low action level of 10 kV/m set by the Directive 2013/35/EU. One possibility for decreasing the occupational exposure is to surround the worker with a Faraday cage. The objective of the study was to investigate how effective a Faraday cage is in decreasing the ELF electric field exposure during work tasks from a man hoist at a 400 kV substation. First, we measured the electric field exposure while performing maintenance tasks from a man hoist. We then constructed a Faraday cage around the man hoist and measured the exposure again, with hopes that the exposure would be sufficiently reduced to create a safe working environment. The Faraday cage was constructed from a steel net 0.5 m in width with 19-mm meshes. The net was made of hotdip galvanized steel wire, 1.0 mm in diameter. The net and the man hoist were then grounded. The maximum electric field without the cage was 28.8 kV/m, and with the cage, it was 0.5 kV/m. The electric field, therefore, was decreased by 96.8–99.9%, validating the efficacy of Faraday cages.

1. INTRODUCTION

Electric and magnetic fields and workers' exposure to them at substations have been studied in many countries, for example in Greece [1], Belgium [2], Romania [3, 4], Switzerland [5], Colombia [6, 7], Cuba [6, 8], Japan [6, 8], Indonesia [6, 9], Mexico [6,10], Thailand [6,11], and the U.S. [6,12]. For example, Tanaka et al. [6] summarized the EMF measurement results of activities carried out inside and around 500-, 400-, 275-, 230-, 220-, 115-, and 110-kV power facilities in seven countries: Colombia [7], Cuba [8], Japan [8], Indonesia [9], Mexico [10], Thailand [11], and the U.S. [12]. They concluded that most values observed were found to be lower than the existing reference level indicated in ICNIRP Guidelines 1998 [13]. Moreover, the researchers also uncovered that in a limited area inside the substations, electric field values were slightly higher than the ICNIRP reference level [13]. Usually, the maintenance workers do not stay in these high electric field areas for a long time [6].

In the European Union, the occupational exposure to electric fields is governed by the Directive 2013/35/EU of the European Parliament and of the Council on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) [14]. It states that with a frequency of 50 Hz, the action levels (ALs, workers) of the directive regarding electric fields are as follows: low ALs 10 kV/m (*rms*) and high ALs 20 kV/m (*rms*) [14]. Korpinen et al. [15] previously presented an investigation concerning the current densities in the neck of a worker and the total contact currents in occupational exposure at 400-kV substations in Finland. In the study, the workers simulated 15 of their normal work tasks. During the tasks from a man hoist at 400-kV substations, the maximum electric fields were the following: (a) maintenance of contacts

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of reach disconnect or from a man hoist: 8.5 kV/ m; (b) 4 inspection of primary terminals of current transformer from a man hoist: 19.2 kV/m; (c) breaker head maintenance from a man hoist: 44.3 kV/m, which is higher than high ALs 20 kV/m [15].

One possibility to decrease the electric field exposure is to use a Faraday cage. In a Faraday cage, an external electrical field redistributes the electric charges within the cage's conducting material in a manner that cancels the field's effect in the cage's interior. Faraday cages cannot block static or slowly varying magnetic fields. The cage can shield the interior from external electromagnetic radiation if the conductor is thick enough and any holes are significantly smaller than the wavelength of the radiation. A Faraday cage cannot provide full blockage of electromagnetic fields. For example, Cameron et al. [16] studied the incomplete Faraday cage effect of helicopters used in platform live-line maintenance, and Zakaria et al. [17] built a basic human size Faraday cage for decreasing electromagnetic interference in electrocardiogram signals. Zakaria et al. [17], based on the results, concluded that a Faraday cage can eliminate the 50 Hz power line noise in ECG signals.

The aim of the study was to investigate how effective a Faraday cage is in decreasing the ELF electric field exposure during work tasks from a man hoist at a 400 kV substation. The following chapters describe the study at a 400 kV substation in Finland. First, we tested the electric field meter to see if it operated correctly. Then, we attached the meter to the man hoist platform and took measurements, shown in Table 1, from varying heights in locations where electricians sometimes have to conduct maintenance operations, the main location being a circuit breaker. Subsequently, we constructed the Faraday cage around the man hoist platform and took the measurements, shown in Table 2, again. Lastly, we assessed the effect of the Faraday cage by comparing the measurement results, as can be seen in Table 3.

2. MEASUREMENTS WITHOUT A FARADAY CAGE

2.1. Measurements at Ground Level

The first measurements were performed in front of a feeder (1.14.0) circuit breaker. The electric field strength was measured from the surface of a passageway, approximately halfway between phases S and T (at a height of 1.7 m), using two different meters: (1) Narda EFA-300 (accuracy ±3%, *rms*) and (2) Maschek ESM-100 (accuracy ±5%, *rms*). Figure 1 shows a worker preparing to measure the electric field strength using a Maschek meter on the passageway. Figure 2 shows the view to the southeast from the measurement position.

The results obtained were 1.1 kV/m (Narda) and 0.79 kV/m (Maschek). The temperature at the time of the measurements was 13°C, and the relative humidity was rather high at 88%. The difference in the measurement results could not be explained, but it might be due to the high humidity and a different sensor type. As the people performing the measurements were more experienced in using a Narda, this meter was chosen for further measurements.

2.2. Measurements Using a Man Hoist

The next measurements were performed using a man hoist close to phase R of the circuit breaker (between two phases). First, the man hoist was positioned in line with the middle breaker pole approximately halfway between phases R and S. The center of the man hoist, or the probe, was at a horizontal distance of approximately 2 m from the nearest R-phase breaker frame. The phase conductor lines suspended above were approximately 17 m–18 m from the ground level, depending on how close to the support pylon the measurement site was.

The arrangements for measuring the electric field strength from the man hoist at 5.3 m (and the probe at $(5.3 - 0.17 + 1.7)\,\text{m} = 6.83\,\text{m}$) from the ground are shown in Figure 3(a). Figure 3(b) shows a closer view of the probe and the man hoist.

The measurement results varied between 13.8–15.2 kV/m. Thus, the electric field strength did not remain completely constant in spite of the fact that neither the man hoist nor the probe was moved during the measurement.

Next, the man hoist was moved closer to phase R (support frame distance to man hoist center/probe 1 m), and the measurement was repeated with the man hoist at the same height as earlier (see

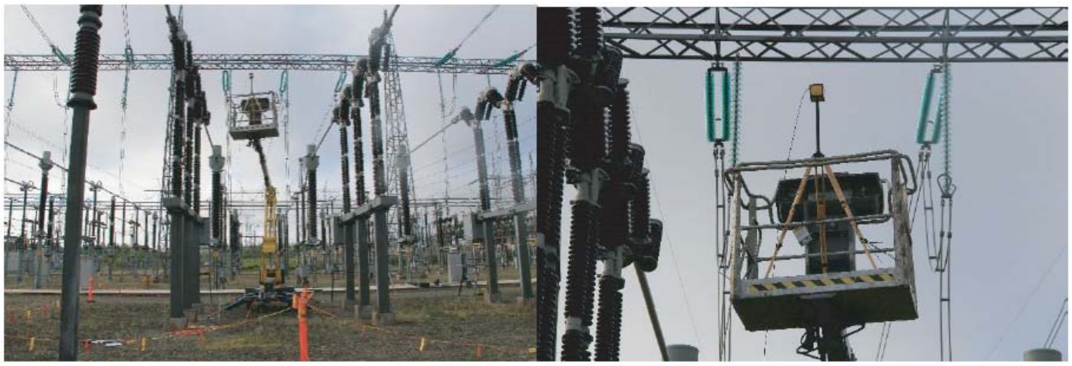
Figure 1. Preparing to measure the field strength using a Maschek meter on the passageway. On the right of the meter, there is a one-phase circuit breaker with three poles and six breaker heads. The breaker poles run approximately from northwest to southeast.

Figure 2. View to southeast (or south) from the measurement position.

Figure 4(a)). Now, the result was 11.6 kV/m. The lower value can probably be explained by a "shadowing effect" caused by the close vicinity of a breaker head. When the probe was raised by 0.8 m from 6.83 m to 7.63 m (Figure 4(b)), the field strength increased to 20.2 kV/m.

Next, the man hoist was lowered to the height and position where it could be moved to another location (probe height $1.13+1.7 = 2.83$ m from the ground), thereby increasing the distance between the man hoist and the breaker frame. The man hoist was not moved in any other way. With the man hoist lower, the measurement of the *rms* value of the electric field strength produced a reading of 9.35 kV/m (range of variation: 9.0–10.3 kV/m).

The next measurements were performed at identical measurement spots on the other side of the



(a) (b)

Figure 3. (a) Measurement between two phases with the probe at 6.83 m from the ground. (b) A closer view of the probe and the man hoist.

(a) (b)

Figure 4. Measurements close to a breaker pole with the probe at (a) 6.83 m and (b) 7.63 m (horizontal distance from pole to man hoist center approx. 1 m). Note: The presence of capacitors and the fact that man hoist movements could not be controlled with extreme precision placed limitations on how close the man hoist could be moved to the circuit breaker.

breaker phase, on the assumption that the shorter distance to the overhead 400-kV conductor would result in higher field strengths. The only difference in the arrangements, compared with those shown in Figure 4, was that the center of the man hoist was now at a distance of 0.75 m from the nearest vertical surface of the breaker frame. (A shorter distance to the circuit breaker was possible because the breaker heads were not accompanied by capacitors on this side.). Figure 5 shows the man hoist at the new location, still in the down position, allowing transfer. At this point, a decision was made to record field strength components in the direction of axes x, y, and z to gain a more detailed figure of the non-uniformity of the electric field.

Figures 6(a) and 6(b) show the arrangements for measurements with the probe at 6.83 m and 7.63 m from the ground.

At the measurement site depicted in Figure 6, the highest *rms* values obtained for the electric field strength were 16.4 kV/m (range of variation: 16.0–18.2 kV/m) and 23.5 kV/m (range of variation: 22.7–23.2 kV/m). With the probe at 8.53 m, the component with the greatest magnitude — 28.9 kV/m — was in the direction of the y axis, i.e., vertically towards the ground. The z component, in the direction of the circuit breaker, was only 5.2 kV/m, while the x component was just over a half of this value. A repeated measurement with the probe at 7.63 m produced a 3-phase *rms* value of 20.8 kV/m and a vertical component value of 18.0 kV/m.

When the man hoist was lowered to a height where the probe was at 6.83 m, the 3-phase *rms*

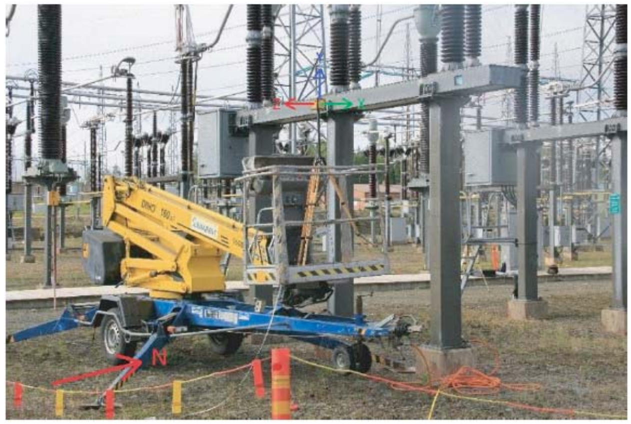
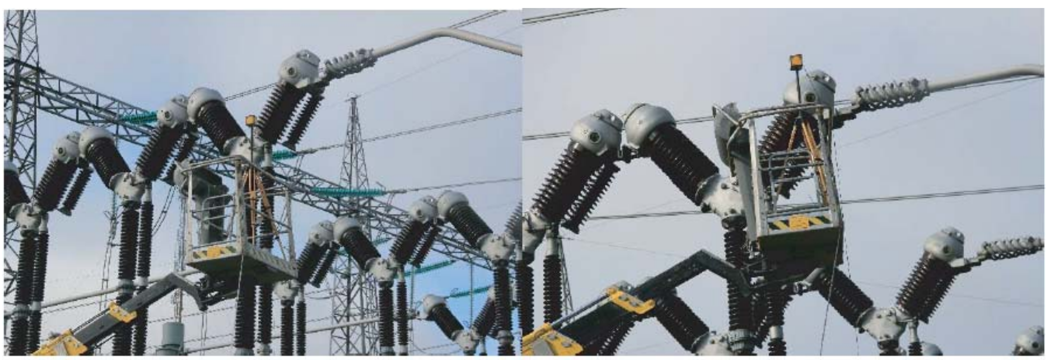


Figure 5. Man hoist "outside" the circuit breaker in the position where it can be moved to another location (man hoist/probe height 1.13/2.83 m).



(a) (b)

Figure 6. Arrangements for further measurements with the probe at (a) 6.83 m and (b) 7.63 m.

value was significantly lower, at 15.8 kV/m, and the vertical component reached the value of 14.2 kV/m. Moreover, the z component, in the direction of the circuit breaker, was now 8.8 kV/m, compared to 10.7 kV/m of the previous measurement performed at a greater height. The results were as expected, considering that the distance to the live overhead conductor was now greater, and the probe was not "shadowed" by breaker heads in any way. Another measurement was performed with the probe at 3.53 m, the height of the horizontal member of the breaker frame. The results were as follows: $rms = 8.5$ kV/m, $x = 0.2$ kV/m, $y = 7.5$ kV/m, and $z = 4.1$ kV/m.

Finally, the field strength was measured with the man hoist down in the transfer position (probe height 2.88 m, distance to breaker frame 1.80 m), with the following results: $rms = 9.0$ kV/m, $x = 1.1$ kV/m, $y = 8.9$ kV/m, $z = 3.1$ kV/m. In other words, the field strength was slightly higher than in the vicinity of the breaker frame.

Table 1 shows all results of field strength measurements without a Faraday cage.

3. MEASUREMENTS WITH A FARADAY CAGE

The next step was to construct the Faraday cage around the man hoist to see if it would protect the electrician working from there sufficiently. The materials for constructing the cage were purposely purchased from a common hardware store to see how effective a cheap "Do-It-Yourself" solution would be. The materials included two rolls of welded net, four relatively thin ($\varnothing_{\text{in}} = 12$ mm, $\varnothing_{\text{out}} = 14$ mm) aluminum tubes 2.0 m in length and copper wire ($\varnothing = 1$ mm). The net, 0.5 m in width and with 19-mm

Table 1. Results of field strength measurements performed in the vicinity of a substation circuit breaker (most resultant values E_{res} as well as component values E_x, E_y, and E_z in the x, y, and z directions are given in kV/m). The height of the measurement spot h is given as the probe distance from ground level. N = a number of measurement, F = a figure number, Mh = man hoist center.

N	E_{res} /kV/m	E_x	E_y	E_z	h (m)	Notes	Figure
1a	0.79	-	-	-	1.7	**Passageway**, between S and T	1a
1b	1.1	-	-	-		–”–, view to the south	1b
2	13.8	-	-	-	6.83	**Halfway between phases S and T**	2
						Northernmost pole of phase R, between phases	
3a	11.6	-	-	-	6.83	Mh distance to vertical R-phase pole: 1 m	3a
3b	17.5–20.2	-	-	-	7.63	Mh distance to vertical R-phase pole: 1 m	3b
3c	9.0–13.3	-	-	-	2.83		
						Outside breaker bay between 1.16.0 (T) and 1.14.0 (R)	
4a	16.0–18.2	-	-	-	6.83	Probe distance to breaker pole surface: 0.75 m	4a
4b	24.0–28.0	2.7	28.9	5.2	7.63	Probe distance to breaker pole surface: 0.75 m	4b
5a	20.8	0.2	18.0	10.7	7.63	Measurement repeated, probe distance to vertical pole: 0.8 m	6b
5b	15.8	0.3	14.2	8.8	6.83	– ” – –”–	6a
5c	8.5	0.2	7.5	4.1	3.53	–”–, probe at horizontal beam height	
6	9.0	1.1	8.9	3.1	2.83	Man hoist down in transfer position	5

meshes, was made of hot-dip galvanized steel wire, 1.0 mm in diameter.

The aluminum rods were tied to the vertical angled members of the man hoist using copper wire, and the top of the structure was covered with one layer of welded net to form a roof on the man hoist. The net and the man hoist were also grounded. The area below this top net (from the guard rail up to the net) was also wrapped in welded net, with one side left open for the hands of the electrician. First, the opening was on the long side with the man hoist controls. The top net permitted a practically unobstructed view of the work area. There was no net below the guard rails, meaning that no attempt was made to further attenuate the electric field exposure of legs. Another piece of net was used as a top cover of the cage. The cover was tied to the vertical net using copper wire. The structure of the cage is shown in Figures 7(a) and 7(b).

The worker in Figures 7(a) and 7(b) only tested that it was possible to work from within the cage and was not inside the cage during the measurements.

With the protective net ready, more measurements were performed to the side of the breaker bay. The EFA-300 meter, and nothing else, was placed inside the cage, with the probe at the center of the man hoist at a height of 1.7 m from the man hoist floor. With the man hoist in the transfer position, a field strength measurement performed halfway between 1.16.0 (T) and 1.14.0 (R) produced a 3-phase rms value of not more than 0.2 kV/m, showing that the electric field was effectively attenuated (97.8%) by the relatively simple method of protection. Figure 8 shows the man hoist provided with a Faraday cage made of welded net.

Figures 9(a) and 9(b) show the E-field meter EFA-300 inside the protective cage.

Next, measurements were performed at the same spots as before the construction of the cage. With the probe at a height of 2.83 m and at a horizontal distance of 1.8 m from a vertical pole of the breaker frame, the results obtained were $rms = 0.3$ kV/m, $x = 0.1$ kV/m, $y = 0.2$ kV/m, and $z = 0.1$ kV/m.

It should be observed, however, that these results were produced with the net having an opening facing north rather than the circuit breaker (see Figures 8(a) and 10). The significance of these results

(a) (b)

Figure 7. (a) The Faraday cage constructed on site to protect the man hoist, with the top net already in place and the cover being installed. (b) The cage and an opening down in the front.

(a) (b)

Figure 8. The man hoist provided with a Faraday cage made of welded net. (a) Working at the height of the horizontal support beam, with an opening down on a long side of the man hoist (no direct access to the breaker). (b) Working in the vicinity of a breaker head, with an opening down on a short side, facing the breaker.

is further decreased by the fact that, during the measurements, the probe was leaning in relation to the directions agreed upon beforehand (x, y, and z). Therefore, the probe was moved to the position where it had been before the cage was constructed, while also moving the man hoist closer to the circuit breaker (the center of the man hoist at a distance of 0.9 m from the nearest vertical pole surface). The opening could not, however, be moved to face the breaker. Field strength measurements were performed anyway, at probe heights of 6.83 m and 7.63 m, with the following results: $rms = 0.5\,\mathrm{kV/m}$, $x = 0.2\,\mathrm{kV/m}$, $y = 0.4\,\mathrm{kV/m}$, $z = 0.1\,\mathrm{kV/m}$, and $rms = 0.5\,\mathrm{kV/m}$, $x = 0.2\,\mathrm{kV/m}$, $y = 0.5\,\mathrm{kV/m}$, and $z = 0.2\,\mathrm{kV/m}$. The measurement resolution did not allow more accurate readings, but it is nevertheless clear that the cage decreased the electric field strengths significantly.

Next, the net had an opening on a short side of the man hoist. This opening was facing a breaker pole (see Figure 10). Subsequently, we conducted field strength measurements at different heights on both sides of the pole. Measurements performed "outside" the circuit breaker, at a shorter distance from the phase of the live overhead conductor, were expected to exhibit higher field strengths than measurements performed on the opposite side; on the other hand, the top cover of the cage was expected to have an attenuating effect.

The first measurements were performed outside the circuit breaker at the northernmost breaker pole, using the same three probe heights as before. Here, the field strengths were too low for any kV/m

(a) (b)

Figure 9. The position of the probe on the protected man hoist.

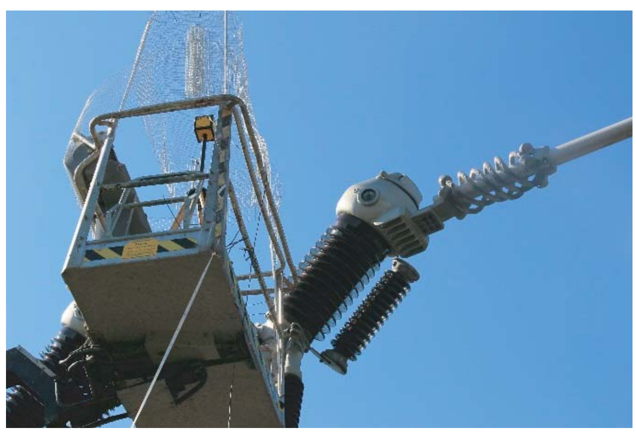


Figure 10. E-field measurements performed with the meter on the protected man hoist, with an opening in the net on a long side of the man hoist.

readings. With the meter switched to the V/m mode, the following *rms* values were obtained for the 3-phase field at different probe heights: 3.53 m/32 V/m, 6.83 m/46 V/m, and 7.63 m/63 V/m. At heights 6.83 m and 7.63 m, the component of the greatest magnitude was in the z (breaker pole) direction, the values being 40 V/m and 44 V/m, respectively. At the lowest spot (3.53 m), the greatest magnitude — 24 V/m — was shown by the y component, i.e., vertically in the direction of the ground, while the z component was only approximately 10% lower.

Measurements performed at almost identical spots on the opposite side of the breaker phase (between two phases), with an opening in the net on a short side of the man hoist (again facing the breaker) and with the center of the man hoist at a horizontal distance of 1.2 m from the surface of a vertical breaker pole, produced, unexpectedly, much lower *rms* values: 3.53 m/17 V/m, 6.83 m/18 V/m, and 7.63 m/52 V/m.

Next, the man hoist was moved even closer to the breaker pole, to a distance where the center of the man hoist was not more than 0.9 m away from the corner of the pole. With the pole this close, it was not possible to raise the probe to the highest measurement spot, at 7.63 m, without causing damage to the porcelain parts of the capacitors. Therefore, measurements were only performed at the two lower heights, with the following results (probe height / *rms* field strength): 3.53 m/20 V/m and 6.63 m/12 V/m. Only the value from the lowest spot, approximately 15% higher than that obtained at the almost identical spot on the opposite side, is comparable with the previous results. At the higher measurement spot, the component of the greatest magnitude was in the direction of the breaker phase ($x = 8$ V/m); however, given an accuracy of 10%, the component perpendicular to the breaker bay was not any weaker ($z = 7$ V/m). At the lower measurement spot, the greatest magnitude, by a considerable margin, was shown by the component in the direction of the ground ($y = 18$ V/m). Most importantly, none of the measured values were higher than a few tens of V/m, which is only a fraction of the values envisaged as maximum permitted levels.

Table 2 shows all results of field strength measurements with the Faraday cage.

Table 2. Results of field strength measurements performed in the vicinity of a substation circuit breaker with the Faraday cage installed (resultant values E_{res} as well as component values E_x, E_y, and E_z in the x, y, and z directions are given in V/m). The height of the measurement spot h is given as the probe distance from ground level. N = a number of measurement, F = a figure number.

N	E_{res}/V/m	E_x	E_y	E_z	h (m)		Figure
						Faraday cage, opening on long side	
7	300	100	200	100	2.83	Probe distance to vertical pole: 1 m	8a
8a	200	100	200	100	3.53	Probe distance to vertical pole: 0.9 m	
8b	500	200	400	100	6.83	Man hoist ↑, probe distance 0.9 m	
8c	500	200	500	200	7.63	–”– –”–	
						Opening shifted 90°, to short man hoist side	
9a	32	4	24	22	3.53	Probe distance to vertical pole: 0.8 m	
9b	46	19	11	40	6.83	–”– –”–	
9c	63	18	41	44	7.63	–”– –”–	10a
						Between phases, opening on short side	
10a	17	3	16	5	3.53	Probe distance to vertical pole: 1.2 m	
10b	18	7	16	3	6.83	–”– –”–	
10c	52	10	51	3	7.63	–”– –”–	
						Between phases, closer to breaker	
11a	20	4	18	4	3.53	Probe distance to vertical pole: 0.9 m	
11b	12	8	5	7	6.63	Probe distance to vertical pole: 0.9 m	

4. DISCUSSION AND CONCLUSION

In the scientific literature, electric and magnetic field exposure at substations, near power lines, at residential area medium voltage power lines and at home have also been studied [18–21]. However, in substations of the Finnish transmission system, electric fields are closer to limit values than magnetic fields. Therefore we focused this study to electric field exposure questions.

The highest *rms* electric field strengths measured from a man hoist near a circuit breakers ranged between 20 and 24.5 kV/m. In the immediate vicinity of 400-kV equipment, the electric field tends to be highly non-uniform. The field strength component of the greatest magnitude can be the one perpendicular to the equipment (lateral in relation to the workers), or the one in the direction of the ground (vertical in relation to the workers). At the height of the circuit breaker heads, components can have magnitudes of 14–28 kV/m and exceed the high action level established by the European Union (20 kV/m) [14].

On the ground level, electric field strengths do not usually exceed even the low action level (10 kV/m), while ascending in the man hoist to complete work tasks may expose workers to increased electric field strengths, depending on the type of man hoist and circuit breaker.

Electric field exposure in any man hoist work on circuit breakers and current transformers can be significantly attenuated by constructing a simple Faraday cage on the man hoist, as can be seen in Table 3. The attenuation was very good, varying 96.8–99.9%. This means that it is possible to develop a cage that reduces electric fields enough but does not impede work efficiency. The results are also as expected for this kind of a Faraday cage at 50 Hz.

Table 3. Comparison of the measurements results with and without the Faraday cage (measurement results (EF) are from Tables 1 and 2).

N	E_{res}/kV/m	Attenuation [%]
2	13.8	
10b	0.018	99.9
3b	20.2	
10c	0.052	99.7
5a	20.8	
8c	0.5	97.6
5b	15.8	
8b	0.5	96.8
5c	8.5	
8a	0.2	97.6

The cage can be quickly constructed on site, using common materials found in hardware stores, prior to the commencement of work. The cage can have a completely net-free opening for hands at any appropriate place, extending across the entire length of one side of the man hoist. It is important that the net is unbroken at the level of the worker's head and that the cage has a top cover made of the same net. This study focused on the protection of the head and torso, and therefore lower limbs were not considered so much. However the guard rails on the man hoist form a partial Faraday cage around the legs of the worker, reducing their exposure. In addition we did not test the net during real work tasks. Perhaps the net could negatively impact work efficiency because the worker cannot use as large of a working area as operating without a net. It could be also difficult the use a fall protection harness with the net.

Where EU action levels are likely to be exceeded, an alternative protection method is an outfit specially designed for work on live equipment, covering the body and the head (but not the face) and with a built-in copper net that can be grounded with a conductor. Such outfits are currently in use in some countries, especially for work on potentially live power lines. In Finland, these outfits are familiar, for example, to companies, such as ELTEL Networks, a Norwegian subsidiary operating in the field of live working on overhead lines.

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