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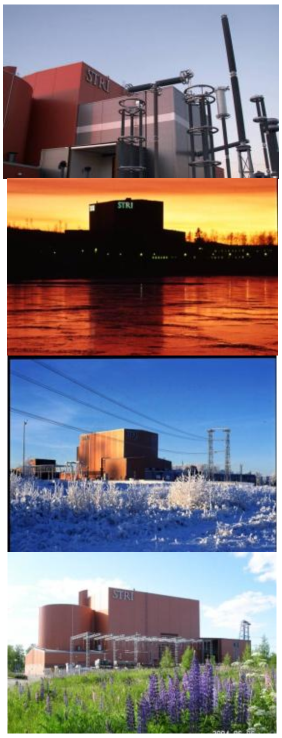

EMF issues for Nordic TSO's

by

Joacim Törnqvist

and

Göran Olsson

Consulting, Software and Testing

Box 707, SE-77180 LUDVIKA, Sweden Telephone +46 240 795 00 Telefax +46 240 150 29 www.stri.se stri@stri.se

Author/-s	Joacim Törnqvist, Göran Olsson
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Summary

This report summarizes literature on primarily acute health effects due to ELF electric and magnetic field exposure. Most of the literature herein is either authored or financed by Nordic TSO's: Fingrid, Svenska kraftnät and Statnett.

The articles and reports covered date back to 1976 and up to modern day. The main subject over the years has been the effects of ELF electric and magnetic field exposure on the human body. Public and worker field exposure close to transmission lines and substations have been investigated.

For electric fields, the lower action level of E = 10 kV/m is hard to meet considering how some maintenance work assignments are performed today. The higher action level at 20 kV/m is less critical, and it should be possible to perform most work assignments up to 130 kV, including work inside the live zone using electrically insulated equipment. Electric shielding, personal protective equipment and proper tools will help to reduce the exposure. Spark discharges between a charged object and a person might result in unpleasant sensations and indirect injuries (e.g. dropping equipment or falling). To help reduce the potential build up a conductive suit together with semi-conductive shoes could be an alternative.

Magnetic fields originating from large structures are often impractical and expensive to shield since necessary joints and holes in the shielding material will have a large impact on the final result. Early planning and awareness in the design phase is probably the easiest and cheapest solution to reduce the magnetic field exposure. For example, a trefoil configuration for cables may reduce the field provided that the load is symmetrical.

Measurements of electric and magnetic fields have often been made to verify the theoretical results which show that the theoretical and measured values show good agreement. In other words, the theoretical results are reasonable and can be used as estimations for most applications.

No adverse acute or long term health effects have been found due to electric or magnetic field exposure under low action levels, but caution is advised nevertheless. Risk groups, including for example children and people with pacemakers, were not included in the studies.

To continue the work in this field it is important to understand what the situation is like today. This can be done in a number of ways, most commonly via measurements and both numerical and analytical calculations with the method chosen as applicable depending on the complexity of the issue. The following topics need further investigation:

- Overview of the current situation
- Tools and work routines in both existing installations and for changes in design of existing and new installations.
- Field exposure and mitigation in the live working zone
- Information and transfer of knowledge

Contents

Revision description

| Rev 0 |

Rev. 0 was submitted 2017-05-23.

| Rev 1 |

Article: A. Ahlbom et al., ”A pooled analysis of magnetic fields and childhood leukaemia”, British Journal of Cancer (2000) 83(5), pp. 692-698, 2000, was moved from section ”Article summary: Norwegian literature” to section ”Article summary: Nordic joint papers” since it was authored by both Swedish and Norwegian authors. Changes are marked by a vertical line in the right margin.

Revision author: J. Törnqvist

2 Introduction

2.1 Background

The EU Directive 2013/35/EU [1] regarding the exposure of workers to electromagnetic fields, together with the national regulations that will be transposed from it [2] will have an impact on mostly all work in "electrical environments". The Directive states exposure limit values and related action levels for exposure together with obligations of employers. Employers shall assess all risks for workers arising from electromagnetic fields and, if necessary, measure or calculate the level of exposure. Furthermore, the employers shall take the necessary actions to ensure that risks arising from exposure at the workplace are eliminated or reduced to a minimum. Workers who are likely to be exposed to risks from electromagnetic fields shall be informed about the outcome of the risks assessment, including the principles of the Directive, measured and/or calculated exposure conditions, related adverse health effects and about safe working procedures to minimize the risks arising from exposure.

2.2 Purpose

The overall goal of this collaboration project is to:

- Summarize the work done up to now regarding workers exposure to electric and magnetic fields (EMF) in each participating TSO.
- Based on this summary, propose areas in which further information and measures are needed in order to comply with the new EU Directive 2013/35/EU and national regulations.

2.3 Method and scope of study

This is a Nordic literature study with focus on acute health effects of ELF EMF exposure. Each main chapter is composed of summaries and comments to available literature divided by country (Finland, Sweden and Norway respectively). Most of the articlea, publicationa or reporta in this review was authored wholly or in part, or financially sponsored, by the country TSO. The results are discussed in ”Discussions and conclusions” at the end of the report.

The literature in this review has been collected over a number of years.

3 Article summary: Finnish literature

3.1 Bioelectromagnetics

3.1.1 Evaluation of Current Densities and Total Contact Currents in Occupational Exposure at 400 kV Substations and Power Lines

Reference 2009, type: Acute

Korpinen, Leena H., Elovaara, Jarmo A and Kuisti, Harri A.: Evaluation of Current Densities and Total Contact Currents in Occupational Exposure at 400 kV Substations and Power Lines. Bioelectromagnetics Vol 30, 2009, pp 231-240

Article summary

Abstract: "*This investigation studied the current densities in the neck and total contact currents in occupational exposure at 400 kV substations and power lines. Eight voluntary workers simulated their normal work tasks using the helmet-mask measuring system*. In all, 151 work tasks with induced current measurements were made. Work situations were: tasks in 400 kV substations, tasks in 400-110 kV towers and the cutting of vegetation under 400 kV power lines. The average current density was estimated from the current induced in the helmet. [...]** The study shows that the maximum average current densities and the total contact currents (caused by electric field) in occupational exposure at 400 kV substations and power lines does not exceed the limit and action values (10 mA/m^2 and 1mA) of the new EU-directive 2004/40/EC (live-line bare-hand works excluded). [...]*"

*)

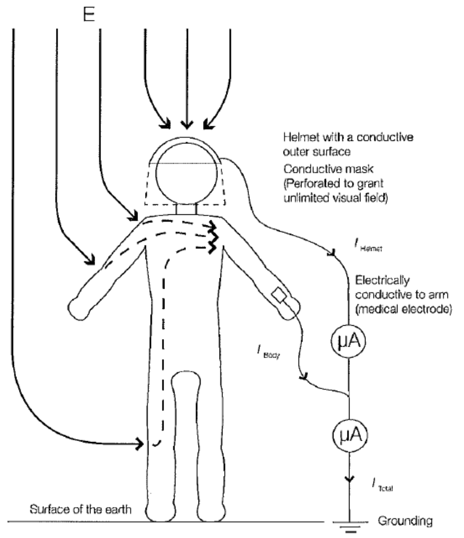


Figure 3-1 Schematics of the measuring system with the worker standing on ground.

**)

Table 3-1 Results.

Description	Value	Unit
Calculated maximum average current densities in the neck	1,5 – 6,4	mA/m^2
Maximum total contact currents	66,8 – 458,4	µA

3.1.2 Occupational Exposure to Electric Fields and Induced Currents Associated with 400 kV Substation Tasks from Different Service Platforms

Reference 2011, type: Acute

Korpinen, Leena H., Elovaara, Jarmo A and Kuisti, Harri A.: Occupational Exposure to Electric Fields and Induced Currents Associated With 400 kV Substation Tasks From Different Service Platforms, Bioelectromagnetics Vol 32, 2011, pp 79-83.

Article summary

Abstract:”*The aim of the study was to investigate the occupational exposure to electric fields, average current densities and average total contact current at 400 kV substation tasks from different service platforms (main transformer inspection, maintenance of operating device of disconnector, maintenance of operating device of circuit breaker). The average values are calculated over measured periods (about 2,5 min). In many work tasks, the maximum electric field strengths exceeded the action values proposed in the EU Directive 2004/40/EC, but the average electric fields […]* were at least 40% lower than the maximum values. The average current densities […]* and the total contact currents […]* [are] clearly less than than the limit values of the EU Directive. The average values of the currents in head and contact currents were 16-68% lower than the maximum values when we compared the average value from all cases in the same substation. It is also important to take into account that generally the workers' exposure […] are obviously lower if we use the average values from a certain measured time period (e.g., 2,5 min) than in the case where exposure is defined with only the help of maximum values.”*

*) See Table 3-2.

Maximum values in Table 3-2 generally pertain to maintenance of the operating device on the circuit breaker while minimum values were measured for the main transformer. The values generally increase with increased height of the service platform. The correlation between current density and the electric field as well as the total contact current and the electric field can be seen in Figure 3-2.

Table 3-2 Maintenance from service platforms with average values calculated over a measured time period of about 2,5 min.

Description	Value	Unit
Average electric field	0,2 – 24,5	kV/m
Average current density	0,1 – 2,3	mA/m^2
Total contact currents	2,0 – 143,2	µA

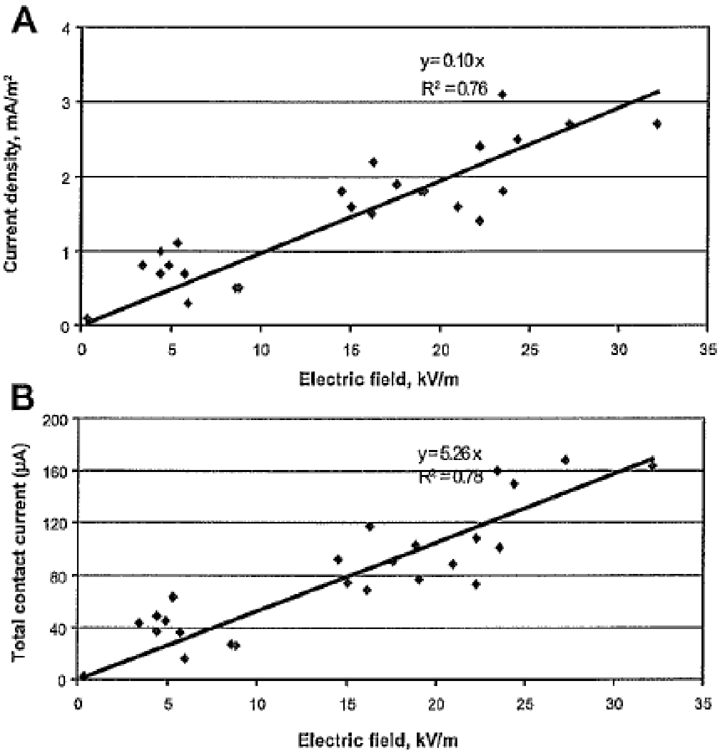


Figure 3-2 **(A)** Correlation between average current densities in the neck and average values of electric fields and **(B)** correlation between average contact currents and average values of electric fields, at a height of 1,7 m.

3.1.3 Occupational Exposure to Electric Fields and Currents Associated with 110 kV Substation Tasks

Reference 2012, type: Acute

Korpinen, Leena H, Kuisti, Harri A, Tarao, Hiroo and Elovaara, Jarmo A: Occupational exposure to electric fields and currents associated with 110 kV substation tasks, Bioelectromagnetics, 33 July 2012, Issue 5, pp 438-442.

Article summary

Abstract: *"The main aim of this study was to investigate occupational exposure to electric fields, and current densities and contact currents associated with tasks at air-insulated 110 kV substations and analyze if the action value of EU Directive 2004/40/EC was exceeded. Four workers volunteered to simulate the following tasks: Task (A) maintenance of an operating device of a disconnector at ground or floor level, Task (B) maintenance of an operating device of a circuit breaker at ground or floor level, Task (C) breaker head maintenance from a man hoist, and Task (D) maintenance of an operating device of a circuit breaker from a service platform. The highest maximum average current density in the neck was 1.8 mA/m2 (calculated internal electric field 9.0–18.0 mV/m) and the highest contact current was 79.4 µA. All measured values at substations were lower than the limit value (10 mA/m2) of the EU Directive 2004/40/EC and the 2010 basic restrictions (0.1 and 0.8 V/m for central nervous system tissues of the head, and all tissues of the head and body, respectively) of the International Commission on Non-Ionizing Radiation Protection (ICNIRP)."*

3.1.4 Numerical Evaluation of Currents Induced in a Worker by ELF Non-Uniform Electric Fields in High Voltage Substations and Comparison With Experimental Results

Reference 2013, type: Acute

Tarao, Hiroo; Korpinen, Leena H; Kuisti, Harri A; Hayashi, Noriyuki, Elovaara, Jarmo A and Isaka, Katsuo: Numerical evaluation of currents induced in a worker by ELF non-uniform electric fields in high voltage substations and comparison with experimental results, Bioelectromagnetics, Vol 34, Issue 1, Jan 2013, pp 61-73

Article summary

Abstract: *"An ungrounded human, such as a substation worker, receives contact currents when touching a grounded object in electric fields. In this article, contact currents and internal electric fields induced in the human when exposed to non-uniform electric fields at 50 Hz are numerically calculated. This is done using a realistic human model standing at a distance of 0,1-0,5 m. from the grounded conductive object. We found that the relationship between the external electric field strength and the contact current obtained by calculation is in good agreement with previous measurements. Calculated results show that the contact currents largely depend on the distance, and that the induced electric fields in the tissues are proportional to the contact current regardless on the non-uniformity of the external electric field. Therefore, it is concluded that the contact current, rather than the spatial average of the external electric field, is more suitable for evaluating electric field dosimetry of tissues. The maximum electric field appears in the spinal cord approaching the basic restriction (100 mV/m) of the new 2010 International Commission on Non-Ionizing Radiation Protection guidelines for occupational exposure, if the contact current is 0,5 mA."*

Figure 3-3 describes the model setup while Figure 3-4 and Figure 3-5 provides more information on the results of current and electric field distribution in the human body. Figure 3-6 shows the neck current and total current as a function of the external electric field strength and distance *d* as described in Figure 3-3.

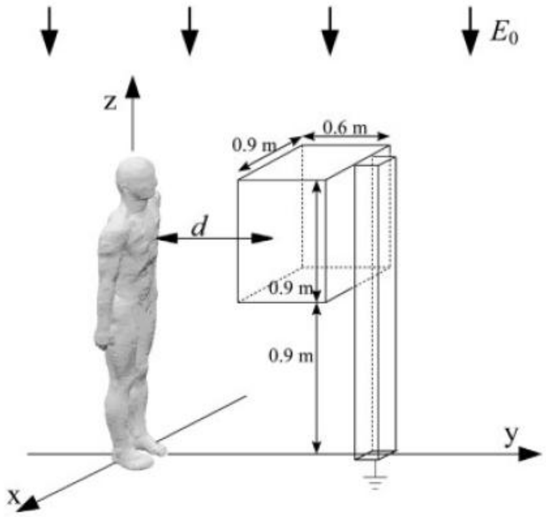


Figure 3-3 Configuration of a grounded conductive object (operating device) and a human model ("Duke"); d is the distance between the surfaces of the human and the conductive object. An ambient electric field (E_0 = 10 kV/m, 50 Hz) is vertically applied, which is the reference level of the ICNIRP guidelines for occupational exposure.

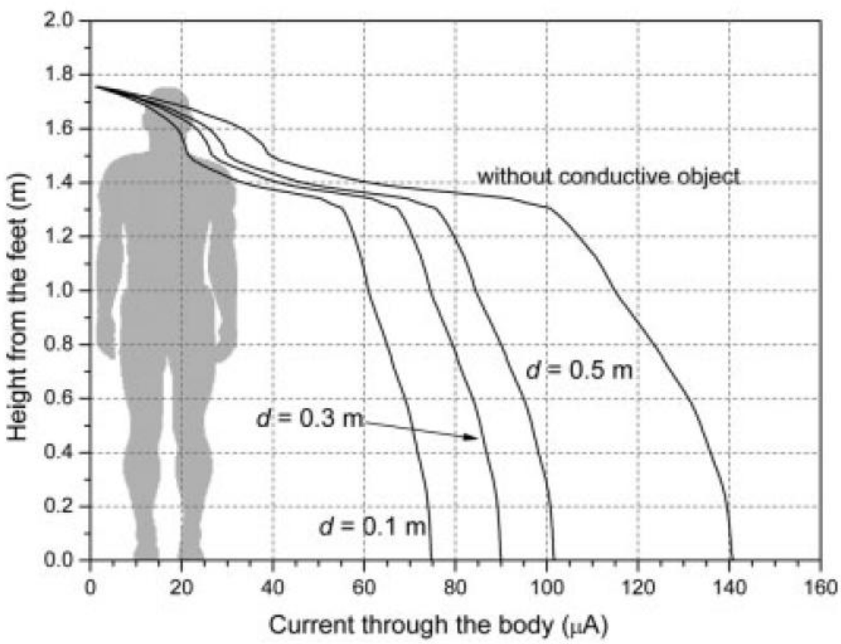


Figure 3-4 Currents through the horizontal layer along the human body for the different distances for the short circuit current (SCC) scenario. The current flowing through the arm is not included. The current at height = 0 correspond to the total current.

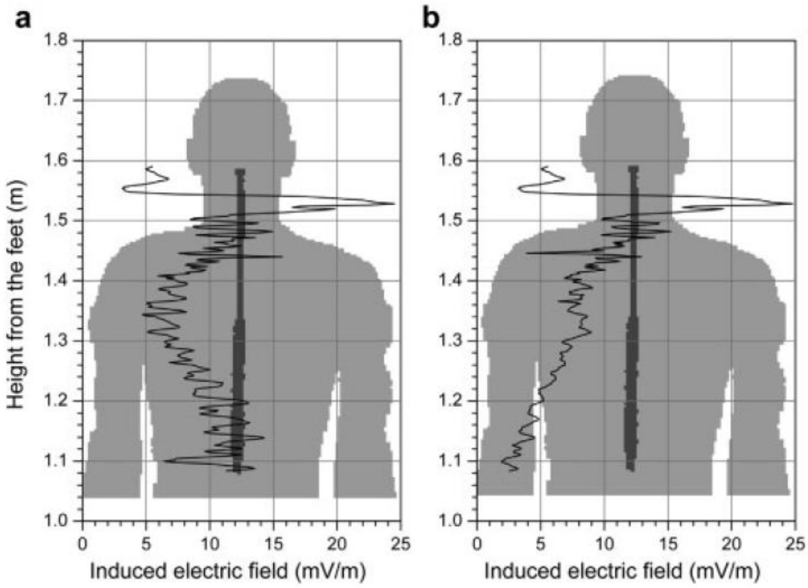


Figure 3-5 Average induced electric fields on each horizontal layer of the spinal cord in the body in the case of d = 0,5 m for (a) the SCC (short circuit current) scenario and (b) the CC (contact current) scenario. The human model is superimposed in the background.

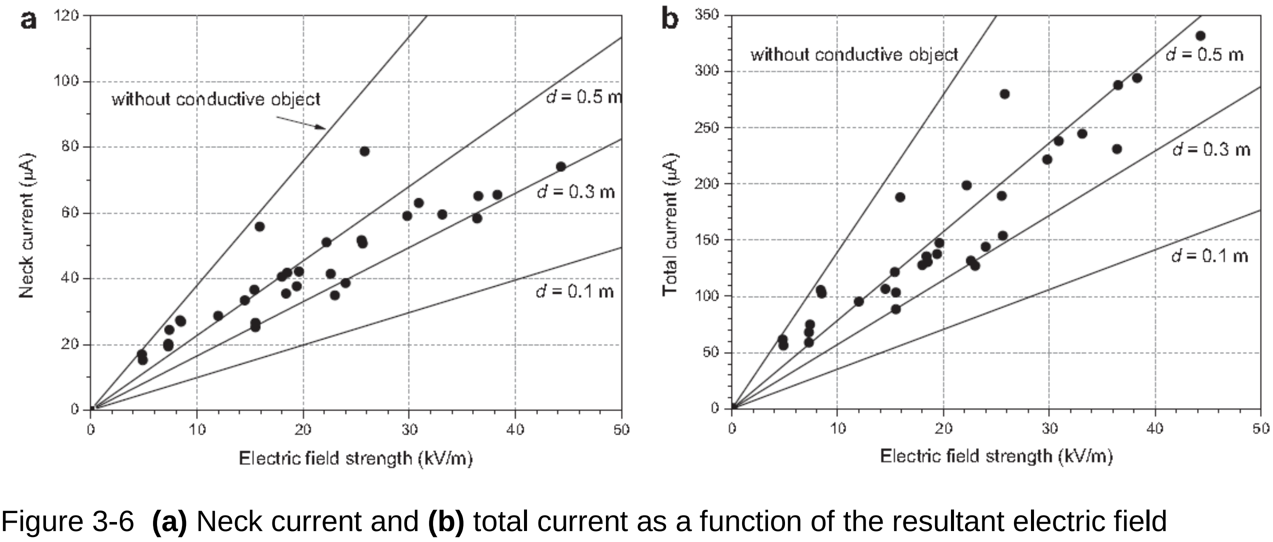


Figure 3-6 **(a)** Neck current and **(b)** total current as a function of the resultant electric field strength at 1,7 m height for the CC scenario. Solid lines are obtained in the calculated study and dot symbols represent the measured data that are quoted from the tasks reported by Korpinen et al. [2009] (maintenance of operational circuit breaker or disconnector).

3.1.5 Current Densities and Total Contact Currents Associated With 400 kV Power Line Tasks

Reference 2013, type: Acute

Korpinen, Leena, Kuisti, Harri and Elovaara, Jarmo: Current Densities and Total Contact Currents Associated With 400 kV Power Line Tasks. Bioelectromagnetics 34:641-644 (2013)

Article summary

Abstract: *“The aim of the study was to analyze all current values from measured periods while performing tasks on 400 kV power lines. Our aim was also to study the average current densities and average total contact currents caused by electric fields in 400 kV power line tasks. Two workers simulated the following tasks: (A) climbing up a portal tower, (B) climbing up a portal transposing tower, (C) working on the cross-arm of a portal tower, (D) climbing up a portal tube tower, (E) climbing up a Tannenbaum tower on the side of the energized circuit with the other circuit unenergized, (F) climbing up a Tannenbaum tower with both circuits energized, and (G) climbing up a Donau tower. […]*. All measured values at 400 kV towers were lower than the limit value of 10 mA/m^2 in the first version of the EU Directive 2004/40/EC and the basic restrictions (0,1 and 0,8 V/m) of the International Commission on Non-Ionizing Radiation Protection.”*

*) Results, see Table 3-3.

The results were measured using the helmet/mask system described in Korpinen et al., 2009 (see Figure 3-1). In each case the measured time periods were over 12 min while the longest measurement was close to 49 min. The exposure was highest in Task (B), climbing up a portal transposing tower. Figure 3-7 shows the measured change in total contact current and current in the head while the worker is climbing the tower.

Table 3-3 Results. In each case the measured time periods were over 12 min. The longest measurement was close to 49 min.

Description	Value	Unit
Maximum average current density in the neck	2,5	mA/m^2
Calculated internal electric field Maximum with average current density in the neck	31,5 – 63,0	mV/m
Highest average contact current	240,0	µA

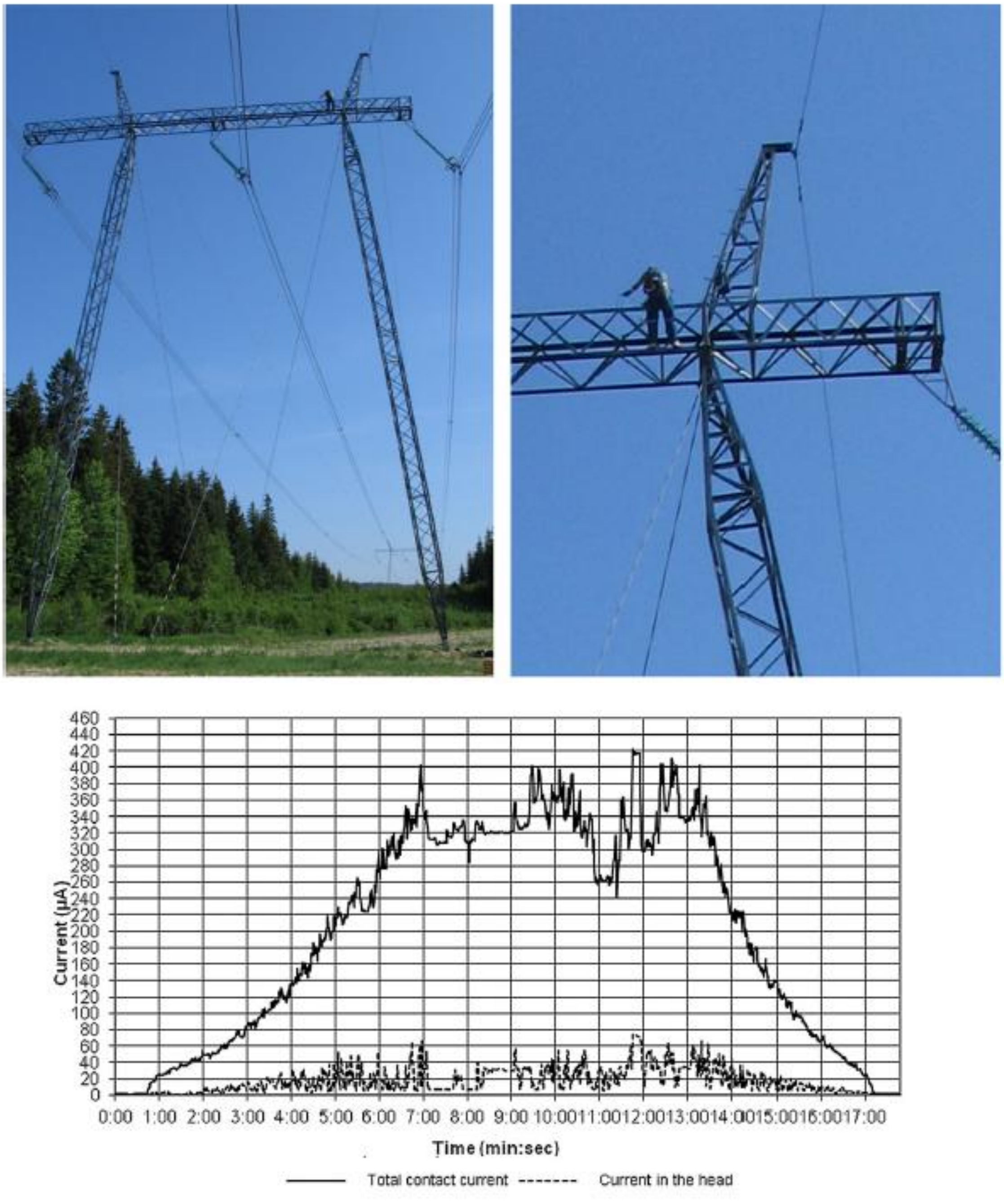


Figure 3-7 **Top:** Worker climbs up the 400 kV portal tower. **Bottom:** Measured currents in the head and total contact currents during climbing.

3.1.6 Current Densities and Total Contact Currents for 110 and 220 kV Power Line Tasks

Reference 2014, type: Acute

Korpinen, Leena, Kuisti, Harri and Elovaara, Jarmo: "Current densities and total contact currents for 110 and 220 kV power line tasks", Bioelectromagnetics, Vol 35, Issue 7, Oct 2014, pp 531-535.

Article summary

"The aim of this study was to analyze all values of electric current from measured periods while performing tasks on 110 and 220 kV power lines. Additionally, the objective was to study the average current densities and the average total contact currents caused by electric fields in 110 and 220 kV power line tasks. One worker simulated the following tasks: (A) tested insulation voltage at a 110 kV portal tower, (B) checked the wooden towers for rot at a 110 kV portal tower, (C) tested insulation voltage at a 220 kV portal tower, and (D) checked the wooden towers for rot at a 220 kV portal tower. The highest average current density in the neck was 2.0 mA/m^2 (calculated internal electric field was 19.0-38.0 mV/m), and the highest average contact current was 234 μA. All measured values at 110 and 220 kV towers were lower than the basic restrictions (0.1 and 0.8 V/m) of the International Commission on Non-Ionizing Radiation Protection."

3.1.7 Current Densities and Total Contact Currents During Forest Clearing Tasks Under 400 kV Power Lines

Reference 2016, type: Acute

Korpinen, Leena, Kuisti, Harri and Elovaara, Jarmo: Current densities and total contact currents during forest clearing tasks under 400 kV power lines, Bioelectromagnetics, Vol 37, Issue 6, Sep 2016, pp 423-428.

Article summary

Abstract: *"The aim of the study was to analyze all values of electric currents from measured periods while performing tasks in forest clearing. The objective was also to choose and analyze measurement cases, where current measurements successfully lasted the entire work period (about 30 min). Two forestry workers volunteered to perform four forest clearing tasks under 400 kV power lines. The sampling frequency of the current measurements was 1 sample/s. [...]*. All measured values during forest clearing tasks were lower than basic restrictions (0,1 V/m and 0,8 V/m) of the International Commission on Non-Ionizing Radiation."*

*) See results in Table 3-4.

Table 3-4 Measurement values of current density and contact current for forestry workers under a 400 kV power line.

Description	Value	Unit
Maximum current density Calculated internal electric field	1,0-1,2 5,0-12,0	mA/m^2 mV/m
Average current density	0,2-0,4	mA/m^2
Highest contact current	167,4	μA

3.2 CIRED

3.2.1 Occupational Magnetic Field Exposure in Working nearby Low Voltage Switchgears

Reference 2005, type: Acute

Keikko, Tommi; Sessvuori, Reino; Kalliomäki, Pentti and Pihlajamaa: Occupational magnetic field exposure in working nearby low voltage switchgears, CIRED, 6-9 June 2005

Article summary

Introduction: *"[…] The magnetic fields of electric distribution substations and low voltage (LV) switchgears are indistinct, and further there are only a few investigations concerning occupational exposure to magnetic fields in working nearby LV switchgears. […]. The aim of this study is to investigate magnetic fields in operations of the low voltage systems. This paper describes critical locations in power distribution systems considering the exposure guidelines and directive (ICNIRP 1998 and EU-Directive 2004/40/EC)."*

Work tasks included; detection of dead bus bars, replacement of a fuse and measurement of the load current. An analytical calculation was also made for comparison.

Results show that there is a large variation in the measured magnetic field. The occupational exposure limit was exceeded twice while the public limits were exceeded three times even though the load current was low compared with the rated current 630 A.

The analytical results indicate that the magnetic field levels may exceed the occupational reference value for workers even at a distance of 0,5 m and at a distance of 1 m for the public. See Figure 3-8.

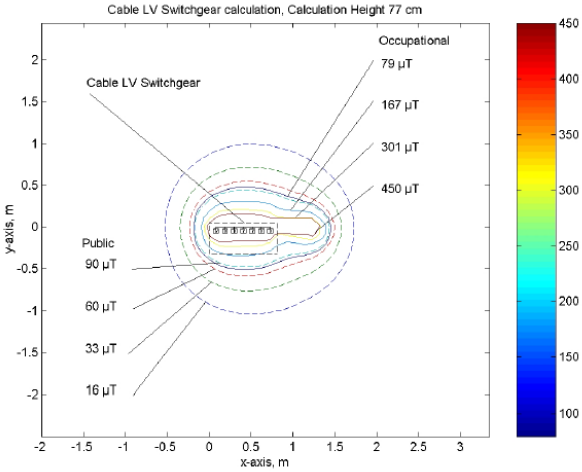


Figure 3-8 Magnetic field calculation results for cable LV switchgear.

3.2.2 Validation and Analysis of a Magnetic Field Measurement Method to be Utilized in Indoor MV/LV Substations

Reference 2007, type: Long term

Keikko, Tommie; Kettunen, Kati; Hyvönen, Marti; Seesvuori, Reino; Valkealahti, Seppo: Validation and analysed measurement method to be utilized in indoor MV/LV substations, CIRED, Paper No 0183, Vienna, 21-24 May, 2007.

Article summary

Abstract: *"This paper describes validation and analysis of a magnetic field measurement method to be utilized in studies of indoor MV/LV substations. Synchronous magnetic field and load current measurements were performed inside 8 indoor MV/LV substations. The magnetic field measurement point nearby the LV connection was determined by considering public exposure in the residence above the indoor distribution station. Based on the results and the analysis of the substation structures we will present simple methods to define magnetic fields in the vicinity of indoor MV/LV substations applicable for regular use in power distribution network companies."*

The study presents a breakdown of typical indoor MV/LV substation types. A method for calculating the magnetic field using extrapolation is then introduced for the most common substation types. Error margins in terms of stochastic inaccuracy are discussed.

Based on the results the authors claim the method to be fit for utilization when defining exposure, although further studies seem to be required.

3.2.3 Magnetic Field Categorization in Indoor MV/LV Substations by the Structure of the Low Voltage Connection

Reference 2007, type: Long term

Kettunen, Kati; Keikko, Tommi; Hyvönen, Martti; Valkealahti, Seppo: Magnetic field categorization in indoor MV/LV substations by the structure of the low-voltage connection, CIRED, Paper No 0331, Vienna, 21-24 May, 2007.

Article summary

Abstract: *"Indoor MV/LV substation may cause higher magnetic field around it than the usual background field. LV connection is often the most important source of magnetic field in a substation. By knowing the structure and route of the connection it is possible to estimate the magnetic field level in rooms around the substation. The aim of the study was to categorize indoor MV/LV distribution substations by LV connection in Finland."*

The categorization is based on the evaluation of 53 "typical" substation layouts and is primarily based on the distance between the LV connection and the roof of the substation and if there is shielding (e.g. metal wires or plexi glass) present or not. See the results in Figure 3-9.

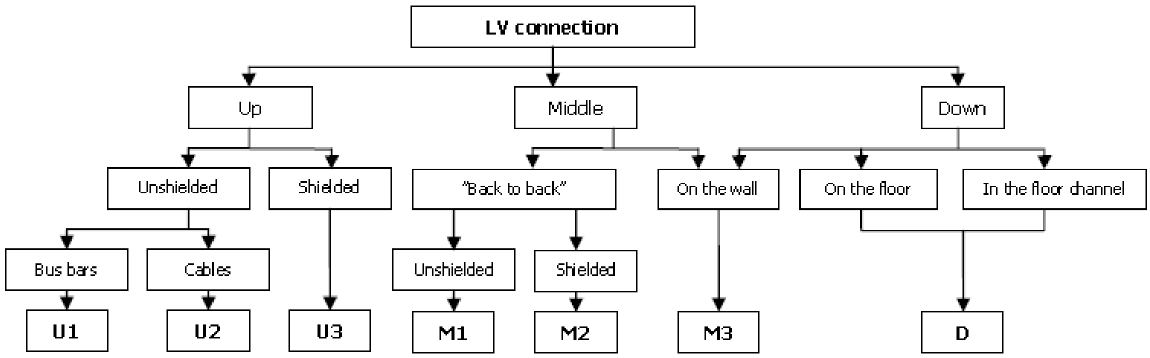


Figure 3-9 The categorization of the indoor MV/LV substations according to the low voltage connection.

3.3 Health Physics

3.3.1 Assessment of Complex EMF Exposure Situations including Inhomogeneous Field Distribution

Reference 2007, type: Acute

Jokela, Kari: Assessment of complex EMF exposure situations including inhomogeneous field distribution, Health Physics 92 (6), 2007, pp 531-540.

Article summary

Abstract: *"Assessment of exposure to time varying electric and magnetic fields is difficult when the fields are non-uniform or very localized. Restriction of the local spatial peak value below the reference level may be too restrictive. Additional problems arise when the fields are not sinusoidal. The objective of this review is to present practical measurement procedures for realistic and not too conservative exposure assessment for verification of compliance with the exposure guidelines of ICNIRP. In most exposure situations above 10 MHz the electric field (E) is more important than the magnetic field (B).At frequencies above 500 MHz the equivalent electric field power density averaged over the body is the most relevant indicator of exposure.[…]. Below 50 MHz down to 50 Hz the electric field induces currents flowing along the limbs and torso. The current is roughly directly proportional to the electric field strength averaged over the body. A convenient way to restrict current concentration and hot spots in the neck, ankle and wrist, is to measure the current induced in the body. This is not possible for magnetic fields. Instead, for a non-uniform magnetic field below 100 kHz the average magnetic flux density over the whole body and head are valid exposure indicators to protect the central nervous system. The first alternative to analyze exposure to non-sinusoidal magnetic fields below 100 kHz is based on the spectral comparison of each component to the corresponding reference level. In the second alternative the waveform of B or dB/dt is filtered in the time domain with a simple filter, where the attenuation varies proportionally to the reference level as a function of frequency, and the filtered peak value is compared to the reference level derived from the ICNIRP reference levels."*

The first part of the review focuses on radio frequencies and the second topic on non-uniform exposure from various low-frequency electric and magnetic field sources. In the third part of the review, non-sinusoidal broadband magnetic fields are considered.

In non-uniform RF electric and magnetic fields the maximal field strength may considerably exceed the ICNIRP reference level without the exposure exceeding the basic restrictions for SAR (specific absorption rate). Below 100 kHz the average electric field exposure and current induced in the neck are the critical exposure factors. Below 10 MHz low impedance sources such as loops and coils produce predominantly magnetic fields which should be averaged over the body and head when the source is 20-30 cm away.

3.4 IEEE

3.4.1 Electric Fields in 400 kV Transmission Lines

Reference 1999, type: Acute

Keikko, T; Isokorpi, J and Korpinen, L: Electric Fields in 400 kV Transmission Lines. IEEE International Conference on Electrical Power Engineering, 1999, p 57.

Article summary

Abstract: *"The 400 kV transmission line electric field was measured, and these results were compared to the guidelines. Transmission lines were measured in surroundings of Tampere, Helsinki and Paimo for 25 spans with 38 measurements. In the study the measured electric field values did exceed the 5 kV/m guideline for general public exposure by ICNIRP in 10 measured spans. […]."*

In general the exceeded amounts were small (5< value < 6,5 kV/m). Ground height and vegetation was considered to have an influence on the results.

3.4.2 Exposure to Electric and Magnetic Fields at 110 kV Gas Insulated Substation (GIS)

Reference 2002, type: Acute

Sauramäki, T; Keikko, T; Kuusiluoma, S; and Korpinen, L: Exposure to Electric and Magnetic Fields at 110 kV Gas Insulated Substation (GIS). IEEE/PES Transmission and Distribution Conference and Exposition, 2002, Vol 2, pp 1226-1229.

Article summary:

Abstract: *"[…] The aim of this study was to measure and analyze the electric and magnetic fields at a gas insulated substation (GIS) using long-term and instantaneous measurements. In addition to field strength measurements, also the harmonic contents of the fields were examined."*

See the results in Table 3-5. The harmonic content was found to be insignificant and the highest measured values for the magnetic and electric field were both (well) below the ICNIRP guidelines.

Table 3-5 Highest measured electric and magnetic fields (rms).

Description	Value	Unit
Highest magnetic field	173	µT
Highest electric field	0,002	kV/m

3.4.3 Comparison of Electric and Magnetic Fields near 400 kV Electric Substation with Exposure Recommendations of the European Union

Reference 2002, type: Acute

Keikko, T; Kuusiluoma, S; Sauramäki, T and Korpinen, L: Comparison of Electric and Magnetic Fields near 400 kV Electric Substation with Exposure Recommendations of the European Union. IEEE/PES Transmission and Distribution Conference and Exposition, 2002, Vol 2, pp 1230-1234.

Article summary:

Abstract: *"[...] Fields have been measured near 400 kV electric substation along two straight lines. Line 1 on the road away from the fence of the substation* and line 2 on the switchyard of the substation**."*

See the results in Table 3-6. All values were below the occupational exposure guidelines (ICNIRP).

Table 3-6 The highest measured electric and magnetic field along two lines.

Description	Value	Unit
*) Line 1, highest electric and magnetic fields	0,80 1,74	kV/m µT
**) Line 2, highest electric and magnetic fields	7,64 16,5	kV/m µT

3.4.4 Magnetic Field Disturbances of Indoor MV/LV Substations in Finland

Reference 2002, type: Long term

Kuusiluoma, S; Keikko, T; Korpinen, L: Magnetic Field Disturbances of Indoor MV/LV Substations in Finland, IEEE/PES Transmission and Distribution Conference and Exposition, 2002, Vol 2, pp 2348-2351.

Article summary:

Abstract: *"[...] The aim of this study was to find out about the magnetic field problems the electric utilities might have had. Altogether 34 utilities were contacted in connection with this phone questionnaire. Questions about the possible magnetic field interference and different reduction methods were discussed in a telephone conversation. [...]. The questions have included inquiries about possible magnetic field interference, customer complaints, different reduction methods, costs and of course the outcome of magnetic field reductions. Twelve of the utilities reported to have problems caused by the MV/LV substation magnetic fields Most of the utilities that had encountered these problems, had succeded in reducing the magnetic fields."*

3.4.5 Measuring Occupational Exposure to Electric and Magnetic Fields at 400 kV Substations

Reference 2008, type: Acute

Latva-Teikari, Jari; Karjanlahti, Tapani; Kurikka-Oja, Jussi; Langsjo, Toni; Korpinen, Leena; "Measuring occupational exposure to electric and magnetic fields at 400 kV substations", IEEE/PES Transmission and Distribution Conference and Exposition, April 21-24, 2008

Article summary:

Abstract: *"The new European Directive states that if the electric and magnetic field action values of 10 kV/m or 500 μT at the working place are exceeded, the employer has to ensure that the limit value, given as an induced current density in the body, is not exceeded. The aim of this study was to measure field strengths and find out how the new directive will affect working at Finnish 50 Hz, 400 kV substations. Spots where the action value was exceeded could be found at 75% of the selected eight substations. The largest electric field strength, 14.3 kV/m, was measured between two adjacent busbars carrying the voltages having the same phase angle. Over 500 μT magnetic flux density was measured in one substation at the safety fence around a three-phase air-core reactor set. Fields were measured at a height 1 m above the ground. According to simple ellipsoid calculations the exposure limit, 10 mA/m^2 of induced current density in the head or trunk, will not be exceeded. However, many of the maintenance tasks have to be done closer to the conductors and busbars and thus more in-depth study and measurements will be necessary at least in Finland."*

3.5 International Symposium on Electromagnetic Compatibility

3.5.1 Cardiac Pacemakers and Electromagnetic Fields: Comparison of Experimental Results in France and Finland

Reference 2014, type: Acute

Magne, Isabelle; Korpinen, Leena; Souques, Martine: Cardiac pacemakers and electromagnetic fields: comparison of experimental results in France and Finland. Proceedings of the 2014 International Symposium on Electromagnetic Compatibility (EMC Europe 2014.) Sep 1-4, 2014, pp 1149-1154.

Article summary:

Abstract: *"The risk of perturbation of a cardiac pacemaker by an electromagnetic field has been studied for many years. However, the instructions given to the patient remains vague, especially concerning electric and magnetic fields linked to electricity. In the context of Directive 2013/35/EU, this paper discusses the level of risk for 50 Hz electric and magnetic fields. Different studies on pacemaker interferences, with different methodologies are compared. The results are coherent and show the importance of pacemaker parameters for risk of intereference: the type of electrodes (unipolar or bipolar) and the sensitivity threshold. When the magnetic field is lower than the reference level recommended for the general public in Europe, and when the PM is in bipolar mode, no interference with clinical consequences were observed. These results* *may be used for workers exposed to electromagnetic fields, if the magnetic field levels are equivalent."*

For exposure to a 50 Hz magnetic field lower than 100 μT PM interference is rare. Unipolar electrodes are more sensitive. The experimental data partly allows for the conclusion that if the worker has the PM set to bipolar mode, and if the 50 Hz magnetic field is lower than 100 μT, there is no risk of interference.

3.6 International Symposium on High Voltage Engineering (ISH)

3.6.1 Electric and Magnetic Fields from Electric Power Systems in Living and Work Environment

Reference 1999, type: Acute

Korpinen, L; Isokorpi, J and Keikko, T: Electric and magnetic fields from electric power systems in living and work environment, International Symposium on High Voltage Engineering, 1999, Conf Publ No 467, pp 2.99.P6 - 2.102.P6.

Article summary:

Abstract: *"The aim of this paper is to present the levels of extremely low frequency electric and magnetic field levels from previous studies and to compare them to the new guidelines. Four different power system environments were studied: transmission and distribution lines, substations, distribution substations and indoor mounting in the buildings. Results were gathered together to find out the essential sources of the electric and magnetic fields in living and work environment. Then the results were compared to exposure guidelines by […] ICNIRP. The electric or magnetic field exposure guidelines were exceeded only at 400 kV substation in this study. […]."*

The electric field exceeded 10 kV/m for a 400 kV substation (max 11,2 kV/m). All other values for both the electric and magnetic fields were below the ICNIRP guidelines.

3.6.2 Practical Problems in Calculating Electric Fields of Transmission Lines

Reference 1999, type: Acute

Keikko, T; Isokorpi, J and Korpinen, L: Practical problems in calculating electric fields of transmission lines, International Symposium on High Voltage Engineering, 1999, Conf Publ No 467, pp 2.103.P6 - 2.106.P6.

Article summary:

Abstract: *"The aim of this study was to compare calculated and measured electric fields of transmission lines and to consider possible reasons for differences. The calculation was carried out analytically. The fields were also measured, and these results were used to analyze the problems in calculations. The line voltages and structures were received from the owner of the line. The problems in calculation were caused by uncertainties in line and ground height and by vegetation damping the field."*

The highest measured electric field strength under the span of a 400 kV overhead transmission line was 6,50 kV/m. The analytical calculation yields somewhere between -8,7% to +43% difference between analytical and measured electric field strengths. The conclusion is that the environment must be considered when the analytical values are "close" to the ICNIRP guidelines.

3.6.3 Power Frequency Electric and Magnetic Fields at 110/20 kV Substation

Reference 1999, type: Acute

Isokorpi, J; Keikko, T and Korpinen L: Power frequency electric fields at a 400 kV substation, International Symposium on High Voltage Engineering, 1999, Conf Publ No 467, pp 2.107.P6 - 2.110.P6.

Article summary:

Abstract: *"The aim of this paper is to study electric and magnetic fields at a 110/20 kV substation. The fields were measured on the switchyard of the substation. Magnetic field measurements were carried out at two heights along two straight lines and on a quadrangular area. The currents in the conductors were also recorded during the measurements. [...]* The highest magnetic fields were caused by the crossing of a busbar and an outgoing feeder with the highest load, and by a 20 kV cable from the transformer to a 20 kV switchgear. The highest electric fields were caused by conductors passing below bus bars."*

*) see Table 3-7.

All the values were below EMC level for the industry and the occupational exposure guidelines by ICNIRP, see results in Table 3-7.

Table 3-7 Highest measured magnetic and electric fields.

Description	Value	Unit	Height [m]
Highest magnetic field	18,6	µT	1
	14,8	µT	0,5
Highest electric field	4,6	kV/m	1

3.6.4 Power Frequency Electric Fields at a 400 kV Substation

Reference 1999, type: Acute

Isokorpi, J; Keikko, T and Korpinen L: Power frequency electric fields at a 400 kV substation. International Symposium on High Voltage Engineering, 1999, Conf Publ No 467, pp 2.107.P6 - 2.110.P6.

Article summary:

Abstract: *"[...] The aim of this paper is to study electric fields at a 400 kV substation to find out whether they exceed occupational exposure guidelines, 10 kV/m, by [...] ICNIRP. The 400 kV switchyard of the substation had two power transformer feeders and four outgoing transmission line feeders. The electric fields were measured on the switchyard of the substation. Measurements were carried out at 1 m height along four straight lines (n=251). The voltages in the bus bars were also recorded during the measurements. The highest measured electric field was 9,9 kV/m. This value does not exceed the occupational exposure level for electric fields by ICNIRP."*

Although the measured electric field strength was close to 10 kV/m it never did exceed the ICNIRP guidelines at a height of 1 m above ground level.

3.6.5 Electric Fields Caused by Transmission Lines in Finland

Reference 2001, type: Acute

Sjöblom, Toni; Keikko, Tommi; Halinen, Sami; Kivelä, Tuomas and Korpinen, Lena: Electric fields caused by transmission lines in Finland, International Symposium on High Voltage Engineering, 2001, Publ No 1-19.

Article summary:

Abstract: *"[...] 400 kV transmission lines were measured in the surroundings of Tampere, Helsinki and Paimio (total 25 spans). 110 kV transmission lines were measured in the surroundings of Tampere for 9 spans with 10 measurements. This paper concentrates mainly on the measurements of 110 kV transmission lines. Electric field values did exceed the 5 kV/m guideline for general public exposure by ICNIRP in 10 spans. All these measurements which exceeded the guideline were measured under the 400 kV transmission lines."*

The highest measured value for 400 kV transmission lines was 9,32 kV/m. The electric field strength under 110 kV transmission lines measured consistently below the 5 kV/m guideline for public exposure by ICNIRP.

3.6.6 Calculation of Induced Electric Fields in Human Models Exposed to ELF Magnetic and Electric Fields

Reference 2011, type: Acute

H. Tarao, N. Hayashi, L. Korpinen, T. Matsumoto , and K. Isaka, "Calculation of induced electric fields in human models exposed to ELF magnetic and electric fields". XVII International Symposium on High Voltage Engineering, Hannover, Germany, August 22-26, 2011.

Article summary:

Abstract: *"[...] Recently, the ICNIRP have published new guidelines for LF-EMF's, which physical quantity of the basic restrictions has been changed into internal electric fields from current densities. The aim of this paper is to demonstrate induced electric fields in real human models of whole body exposed to electric or magnetic fields at 60 Hz, and is to compare those results with the basic restrictions. Calculations of the induced fields in the models were carried out using the SPFD method for magnetic field exposure. And a hybrid two-stage approach with a finite difference method for electric field exposure. As a result, calculated internal electric fields in the human models for all scenarios* are sufficiently lower than the basic restrictions."*

*) By "all scenarios" the authors probably mean the scenarios covered in the article. In this case: a calculation of the internal electric field strengths in mV/m for different parts of the body as a result from the exposure to a uniform 60 Hz, 4,2 kV/m electric and 200 μT magnetic field (first separately and then both fields at the same time).

Three numerical models of a human body were used;

1. **Taro:** Japanese male, 173 cm and 65 kg
2. **Duke:** European male, 174 cm and 70 kg

3. **Louis:** European male, 165 cm and 50 kg

All three of the models' bodies were fully exposed to uniform 60 Hz electric (4,2 kV/m) and magnetic (200 μT) fields. All calculated internal electrical fields were significantly lower than the basic restriction level of the ICNIRP guidelines.

The authors claim that the computational procedure used in this paper may be used to estimate the internal electric field of a worker standing on a power transmission tower, in a substation or near an electric appliance.

3.6.7 Examples of Spark Discharge Under a 400 kV Power Line

Reference 2013, type: Acute

L.Korpinen, R. Pääkkönen, H.Taro and H.Kuisti: Examples of spark discharge under a 400 kV power line, ISH 2013, PA-12, pp113-116.

Article summary:

Abstract: *"The objective of this work was to investigate possible spark discharges under 400 kV power lines and when they may be felt by a human being. The experiments were conducted under a 400 kV power line in sunny weather; the temperature was 20 degrees Celsius and the humidity was 60 %. [...]*. The test person used three different umbrellas of similar styles to those normally used in the rain. She also used different shoes or boots during the testing of one of the umbrellas. In looking to detect spark discharges, the tester touched the metal rods of the umbrellas. Only one umbrella easily produced small spark discharges, and the sensations in the finger were felt to be the same or similar when using different shoes or boots with this umbrella type."*

*) see results in Table 3-8.

Although one umbrella easily produced spark discharges the sensations were not painful according to the test person.

Table 3-8 Electric and magnetic field strengths under a 400 kV power line at a height of 1,7 m above ground.

Description	Value	Unit
Electric field strength	4,2- 4,6	kV/m
Magnetic field strength	13	μT

3.6.8 Numerical Estimations of Induced and Contact Currents in Human Body in Contact with a Car in 60 Hz Electric Fields

Reference 2013, type: Acute

H. Tarao, N. Hayashi, L. Korpinen, T. Matsumoto and K. Isaka: Numerical Estimations of induced and contact currents in human body in contact with a car in 60 Hz electric fields, ISH 2013, PA-27, pp 193-195.

Article summary:

Abstract: *"When a human body touches an ungrounded object in electric fields, both two currents flow in the body: one is an induced current by the electric fields, and the other is a contact current flowing from the ungrounded object energized by the electric fields. Great many experimental and computational results regarding with electrically-induced currents in a human body have been investigated before now, while a few results on a contact current have been reported. In the present paper, numerical calculations considering both induced and contact currents are carried out when a numerical human model touches an ungrounded car in 60 Hz electric fields. In the calculation, a numerical code improving the scalar potential finite difference (SPFD) method is used, which is often applied for magnetic induction at low frequencies. As a result, total current in the human model is consistent with the sum of induced current and contact current calculated separately, as expected. It is found from the result that contact current is eight times higher than the induced current, which means that the numerical dosimetry due to such a contact current should be more investigated rather than induced currents."*

The model used was:

- **Duke:** European male, 174 cm and 70 kg

Duke is placed in a uniform vertical electric field of 1 kV/m at 60 Hz, and he is grounded by the feet. The car is insulated by the tires. See Figure 3-10.

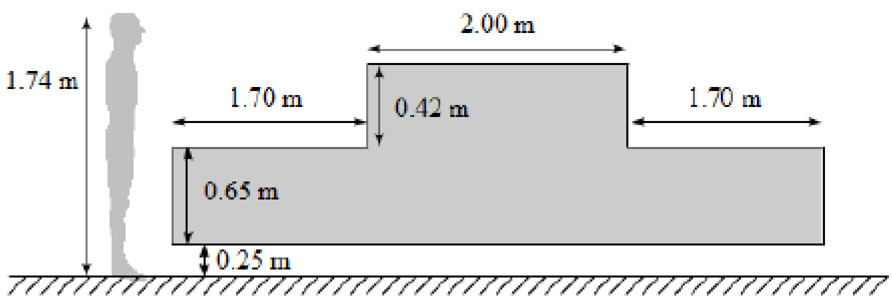


Figure 3-10 Schematics of the human model and car in a uniform electric field of 1 kV/m at 60 Hz. Duke is grounded by the feet and the car is insulated by the tires.

Three scenarios were investigated: Scenario A) the human touches the car, and scenario B) the human does not touch the car. In scenario C) the car is grounded with a conductive cable. See results in Table 3-9. The contact- and short circuit currents are much higher than the induced current.

Table 3-9 Results of the total current through the human (I_t), the contact and short circuit current from the car (I_c and I_{sc} respectively), the induced current at the ankle (I_i) for the three scenarios.

Current	Scenario A	Scenario B	Scenario C
I_t [μA]	114,9	17,9	12,8
I_c [μA]	102,3	-	-
I_{sc} [μA]	-	-	102,4
I_i [μA]	12,6	17,9	12,8

Figure 3-11 shows the electric field distribution in the model for scenarios A) and B). The left arm touches the car in scenario A). The internal electric field in the head is small in both scenarios.

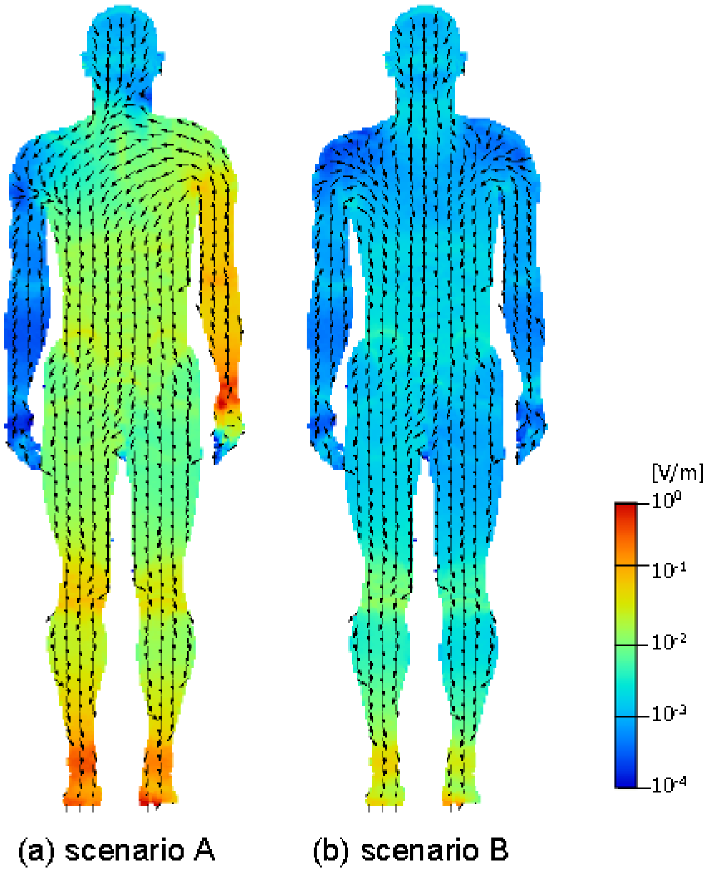


Figure 3-11 Electric field distribution in the human models for scenarios A) and B).

3.6.9 Possibility of Decreasing 50 Hz Electric Field Exposure with Different Coveralls under 400 kV Power Lines

Reference 2015, type: Acute

L. Korpinen, H. Tarao, R. Pääkkönen, F. Gobba: Possibility of decreasing 50 Hz electric field exposure with different coveralls under 400 KV power lines, ISH 2015.

Article summary:

Abstract: *"This study investigated the possibility of decreasing the 50 Hz electric field exposure with different coveralls. We tested three different coveralls under a 400 kV power line. The test person put on different coveralls, and she stood on aluminum paper, which was isolated from the ground with a plastic bag. She did not wear shoes or socks. The current between the ground and the aluminum paper (I_{gp}) was measured. The electric field was 3,8 kV/m. [...]*. Using other coveralls (2 and 3), the current induced to the test person was even higher than with ordinary clothes. Thus, the normal working clothes did not influence the exposure to the electric field when the test person was isolated from the ground. Moreover, the resistivity of shoes plays a role; some shoes isolate a person from ground better than others. In conclusion, it can be stated that normal coveralls do not decrease human exposure to electric fields, but with protective coveralls it is possible to decrease the electric field exposure. It can be possible to develop new solutions to decrease electric field exposure using different clothes or textiles."*

*) see results in Table 3-10.

Table 3-10 The current between the ground and the aluminium paper for different clothing

Coverall #	Description	I_{gp}
Reference	"Normal clothes"	41,4 µA
1	Conductive textile	3,2 µA
2	Worn by electric company workers	44,2 µA
3	Worn by electric company workers during winter	46,0 µA

3.6.10 Occupational Exposure to Magnetic Fields While Working Around a Reactor at a 400 kV Substation in Finland

Reference 2015, type: Acute

R. Pääkkönen, L. Korpinen, F. Gobba: Occupational exposure to magnetic fields while working around a reactor at a 400 kV substation in Finland, ISH 2015.

Article summary:

Abstract: *"The paper presents the investigation of occupational exposure to magnetic fields at a 400 kV substation while working around a reactor. We studied three tasks: (A) working near the fence of a reactor, (B) maintaining an operating device of a disconnector, and (C) walking near reactor cables. We performed 12 magnetic field measurements and 10 measurements of exposure ratios (magnetic field) adhering to ICNIRP occupational guidelines. [...]*. At task A, the average magnetic field was 195,5 µT, and the maximum field was 260,0 µT. At Task B, the magnetic field was 97,0 µT, and at Task C, the average magnetic field was 559,8 µT, with a maximum field of 710,0 µT. Based on the measurements, it is possible to conclude that in working around a reactor at 400 kV substations in Finland, the typical magnetic field exposure is below the low action levels of Directive 2013/35/EU."*

*) see results in Table 3-11.

The measurements were done typically 0,2-0,3 m from the surfaces of the equipment.

Table 3-11 Average and maximum magnetic field strengths during maintenance of a reactor. Values within parenthesis denote percentage of low AL of Directive 2013/35/EU.

Task	Average magnetic field strength	Maximum magnetic field strength
A	195,5 µT	260,0 µT (26%)
B	-	97,0 µT (9,7%)
C	559,8 µT	710,0 µT (71%)

3.6.11 Estimation of Induced Currents in the Human Body Exposed to Non-Uniform ELF Electric Fields

Reference 2015, type: Acute

H. Tarao, H. Miyamoto, N. Hayashi, T. Matsumoto, L. Korpinen and K. Isaka. Estimation of induced currents in the human body exposed to non-uniform ELF electric fields, ISH 2015.

Article summary:

Abstract: *"[…] In the present paper, to estimate currents induced in the neck of a human body in non-uniform fields, we calculated the induced currents numerically by considering non-uniform fields that are distorted by a rectangular conductor (0,5 x 0,5 x h m) under a uniform electric field of 1 kV/m at 60 Hz. In this situation, we investigated the relationship between the induced currents and the averaged non-uniform electric fields (E_{avg}) at three points from the ground with no human present, as recommended by IEC 62110. Calculated results show that that the induced currents in the neck can be approximately estimated by using a distance between the conductor and the human model, regardless of h. This indicates that in-situ electric fields in the brain can be estimated by the measured E_{avg}."*

The model used was:

- **Duke:** European male, 174 cm and 70 kg

The SPFD (scalar potential finite difference) method is used for calculation of the electric fields and currents. See results in Figure 3-12. It is clear that the induced electric fields in the brain are directly proportional to the neck currents which indicates that in-situ electric fields in the brain can be estimated by the neck currents (which in turn have been estimated from a three point measurement of the external electric field strength with no human present). The results hold regardless of the height of the conductor.

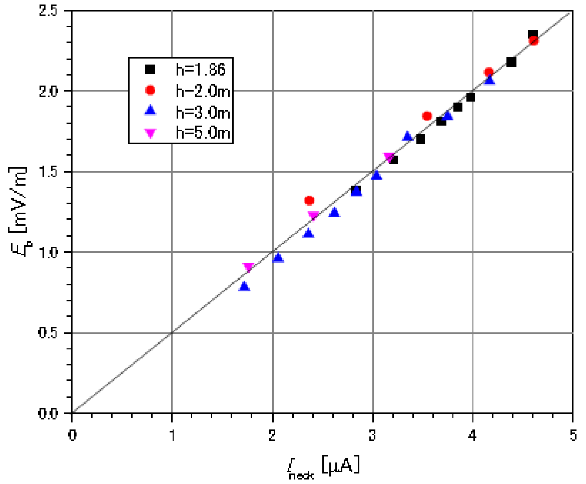


Figure 3-12 Maximum induced electric fields in the brain (E_b) of the human model plotted against the neck currents (I_{neck}) for non-uniform electric field exposures.

3.7 Physics in Medicine and Biology

3.7.1 Simple Estimation of Induced Electric Fields in Nervous System Tissues for Human Exposure to Non-Uniform Electric Fields at Power Frequency

Reference 2016, type: Acute

Hiroo Tarao, Hironobu Miyamoto, Leena Korpinen, Noriyuki Hayashi and Katsuo Isaka: Simple estimation of induced electric fields in nervous system tissues for human exposure to non-uniform electric fields at power frequency, Physics in Medicine and Biology, Vol 61, No 12, Juni 2016, pp 4438-4451

Article summary:

Abstract: *"Most results regarding induced current in the human body related to electric field dosimetry have been calculated under uniform field conditions. We have found in previous work that a contact current is a more suitable way to evaluate induced electric fields, even in the case of exposure to non-uniform fields. If the relationship between induced currents and external non-uniform fields can be understood, induced electric fields in nervous system tissues may be able to be estimated from measurements of ambient non-uniform fields. In the present paper, we numerically calculated the induced electric fields and currents in a human model by considering non-uniform fields based on distortion by a cubic conductor under an unperturbed electric field of 1 kV/m at 60 Hz. We investigated the relationship between a non-uniform external electric field with no human present and the induced current through the neck and the induced electric fields in the nervous system tissues such as the brain, heart, and spinal cord. The results showed that the current through the neck can be formulated by means of an external electric field at the central position of the human head, and the distance between the conductor and the human model. As expected, there is a strong correlation between the current through the neck and the induced electric fields in the nervous system tissues. The combination of these relationships indicates that induced electric fields in these tissues can be estimated solely by measurements of the external field at a point and the distance from the conductor."*

The model used was:

- **Duke:** European male, 180 cm

The human model was grounded for these calculations but the relationship between the current in the neck and induced electric fields in the nervous system tissues does not change. The electric field distribution and numerical setup is visualized in Figure 3-13.

The current through the horizontal layer of the body for different distances *d* from the surface of the conductive object, as well as the relationship between neck currents and both the height *h* of the object and the distance *d* to the object as a function of the external electric field can be seen in Figure 3-14. The induced electric field in the nervous system as a function of the current through the neck for non-uniform field exposures can be seen in Figure 3-15.

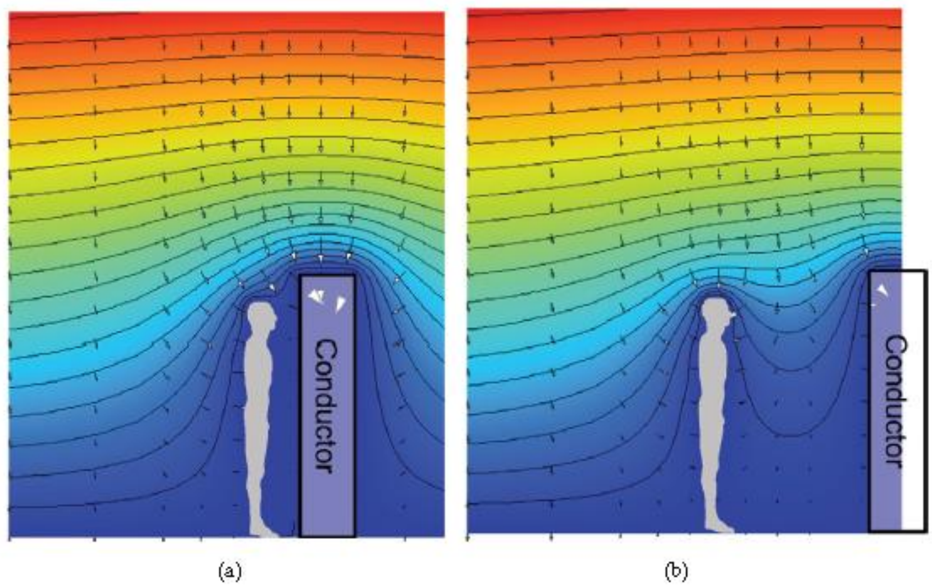


Figure 3-13 Distribution of the equipotential line and external electric fields around the conductive object when (a) d=0,25 m and (b) d=1,15 m from the surface of the object. Here the object height *h* = 2 m.

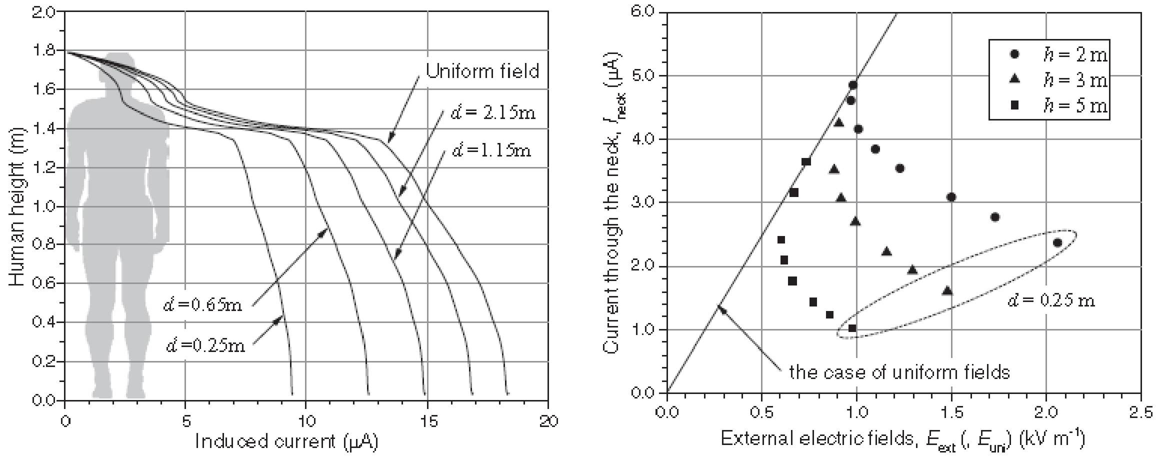


Figure 3-14 The current through the horizontal layer of the body for different distances *d* from the surface of the conductive object (left), and the relationship between neck currents and both the height *h* of the object and the distance *d* to the object as a function of the external electric field (right).

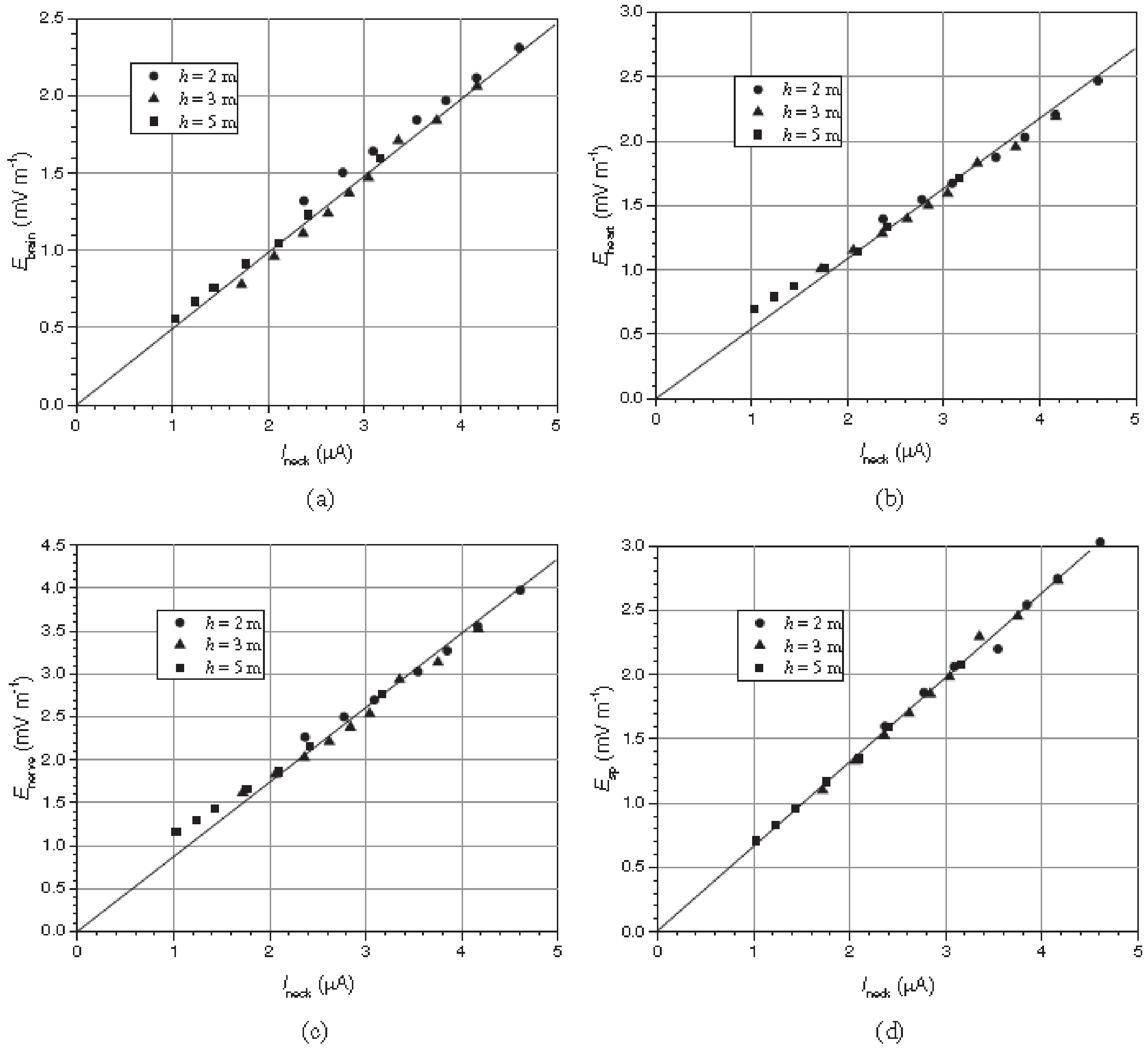


Figure 3-15 The induced electric field in the nervous system as a function of the current through the neck for non-uniform field exposures for (a) brain, slope = 500 $Vm^{-1}A^{-1}$, (b) heart, slope = 540 $Vm^{-1}A^{-1}$, (c) nerves, slope = 880 $Vm^{-1}A^{-1}$ and (d) spinal cord, slope = 660 $Vm^{-1}A^{-1}$.

The combination of these findings facilitates the estimation of the induced electric fields in those tissues from the external electric field at the central position of the human head and the distance from the object, both of which can be readily measured.

3.7.2 Effects of Tissue and Electrode Area on Internal Electric Fields in a Numerical Human Model for ELF Contact Current Exposures

Reference 2012, type: Acute

Tarao, H, Kuisti, H, Korpinen, L, Hayashi, N and Isaka, K: Effects of tissue conductivity and electrode area on internal electric fields in a numerical human model for ELF contact current exposures, Physics in Medicine and Biology, 57 (2012) 2981-2996

Article summary:

Abstract: *"Contact currents flow through the human body when a conducting object with different potential is touched. There are limited reports on numerical dosimetry for contact current exposure compared with electromagnetic field exposures. In this study, using an anatomical human adult male model, we performed numerical calculation of internal electric fields resulting from 60 Hz contact current flowing from the left hand to the left foot as a basis case. Next, we performed a varitety of similar calculations with varying tissue conductivity and contact area, and compared the results with the basis case. We found that very low conductivity of skin and a small electrode size enhanced the internal fields in the muscle, subcutaneous fat and skin close to the contact region. The 99th percentile value of the fields in a particular tissue type did not reliably account for these fields near the electrode. In the arm and leg, the internal fields for the muscle anisotropy were identical to those in the isotropy case using a conductivity value longitudinal to the muscle fibre. Furthermore, the internal fields in the tissues abreast of the joints such as the wrist and the elbow, including low conductivity tissues, as well as the electrode contact region, exceeded the ICNIRP basic restriction for the general public with contact current as the reference value."*

The model used was:

- **Duke:** European male, 174 cm, 70 kg.

The contact current was set to 0,5 mA at 60 Hz which passed between two electrodes: one on the left hand and one on the left foot. See the resulting internal electric field distribution in Figure 3-16. The internal electric field is clearly lower in the head than in the current path between the electrodes.

The contact current 0,5 mA is the reference level of the ICNIRP guidelines but the 99th percentile of the internal electric field strengths in muscle, skin and subcutaneous fat exceed the basic restriction (400 mV/m) of the ICNIRP guidelines for the general public. However, it is argued that the numerical results of internal fields in the context of contact currents should not be compared with the basic restriction since the reference level is only intended to avoid painful shocks.

The strength of internal electric fields is highly influenced by variations of the total or sectional tissue resistance. Small contact surfaces or skin with very low conductivity markedly increases the internal electric field in the tissues beneath the electrode contact. Other locations where the internal electric field is typically exceeded are joints.

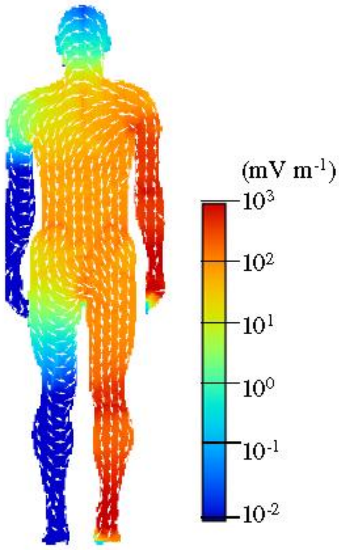


Figure 3-16 The internal electric field distribution with contact current 0,5 mA at 60 Hz with one electrode on the left hand, and the other attached to the left foot.

3.7.3 Computational Analysis of Thresholds for Magnetophosphenes

Reference 2012, type: Acute

I. Laakso and A. Hirata: Computational analysis of thresholds for magnetophosphenes Physics in Medicine and Biology, No 57 (2012), pp 6147-6165.

Article summary:

Abstract: *"In international guidelines, basic restriction limits on the exposure of humans to low-frequency magnetic and electric fields are set with the objective of preventing the generation of phosphenes, visual sensations of flashing light not caused by light. Measured data on magnetophosphenes, i.e. phosphenes caused by a magnetically induced electric field on the retina are available from volunteer studies. However, there is no simple way for determining the retinal threshold electric field or current density from the measured magnetic flux density. In this study, the experimental field configuration of a previous study, in which phosphenes were generated in volunteers by exposing their heads to a magnetic field between the poles of an electromagnet, is computationally reproduced. The finite element method is used for determining the induced electric field and current in five different MRI-based anatomical models if the head. The direction of the induced current density on the retina is dominantly radial to the eyeball, and the maximum induced current density is observed at the superior and inferior sides of the retina, which agrees with literature data on the location of magnetophosphenes at the periphery of the visual field. On the basis of computed data, the macroscopic retinal threshold current density for phosphenes at 20 Hz can be estimated as 10 mA/m^2 (-20% to +10%, depending on the anatomical model); this current density corresponds to an induced eddy current of 14 μA (-20% to +10%), and about 20% of this eddy current flows through each eye. The ICNIRP basic restriction level for the induced electric field in the case of occupational exposure is not exceeded until the magnetic flux density is about two to three times the measured threshold for magnetophosphenes, so the basic restriction limit does not seem to be conservative. However, the reasons for the non-conservativeness are purely technical: removal of the highest 1% of the electric field values by taking the 99th percentile as recommended by the ICNIRP leads to underestimation of the induced electric field, and there are difficulties in applying the basic restriction limit for the retinal electric field."*

Five numerical models of a human head were used;

1. **Taro:** Japanese male
2. **Hanako:** Japanese female
3. **Duke:** European male
4. **Ella:** European female
5. **Norman:** European male

Since none of the existing models included a model for the retina an automatic algorithm was added to replace the original eyes with new more suitable ones. See the computed thresholds in Figure 3-17.

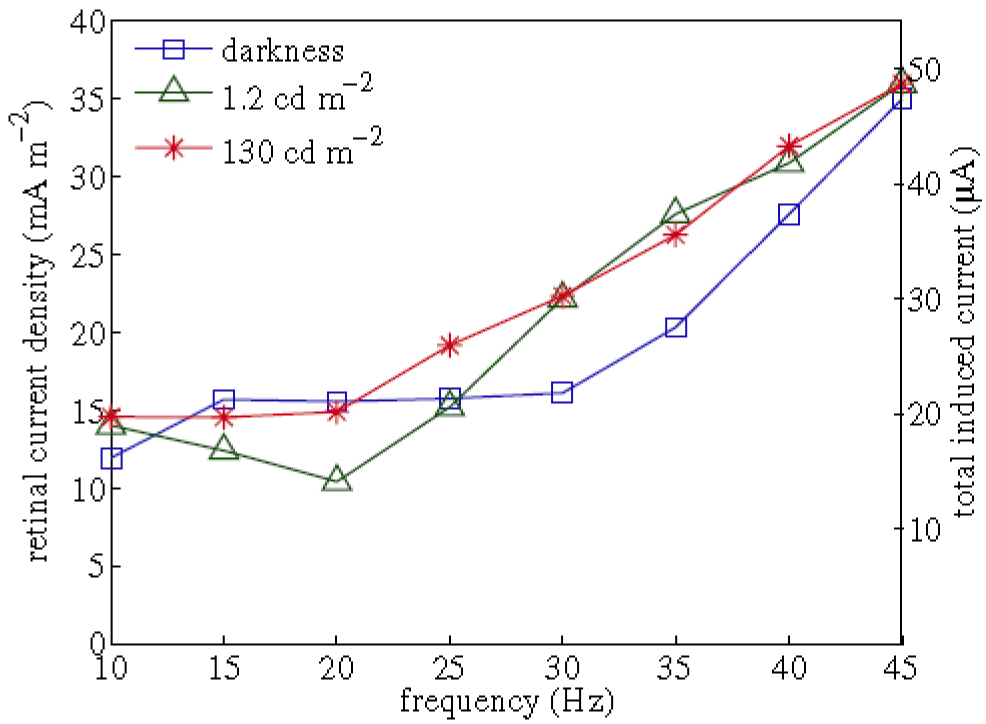


Figure 3-17 Computed threshold for the maximal retinal current density or total induced current as a function of the frequency and luminosity of the background lightning.

The lowest threshold is seen to be 10 mA/m^2 at 20 Hz. Considering the ICNIRP guideline the lowest threshold electric field for phosphenes (50 mV/m), a conductivity of 0,1 S/m would yield a threshold current density of 5 mA/m^2 which is conservative compared to the computed values.

Comparisons with experimental data are difficult since the sensitivity to phosphenes depend on eye movement, blinking, background lightning, frequency, keeping the eyes open or closed, repeated application of stimuli, etc.

It may be worth noting that using only the 99th percentile as recommended by ICNIRP may greatly underestimate the maximum induced field for localized exposure.

3.8 International Symposium on Electromagnetic Theory

3.8.1 Computational Estimation of Threshold Currents for Electrophosphenes

Reference 2013, type: Acute

I. Laakso and A. Hirata. Computational Estimation of Threshold for Currents for Electrophosphenes. International Symposium on Electromagnetic Theory, 23AM1B-01, 2013, pp 350-353.

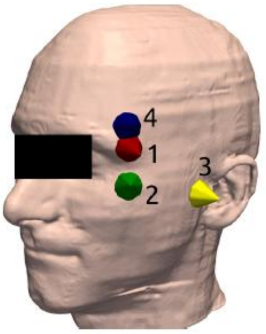
Article summary:

Abstract: *"Electrophosphenes are subjective sensations of light that are generatied through electric stimulation at frequencies lower than 100 Hz. During electrical stimulation, an electric current flows through the human body between stimulation electrodes. Part of the current passes through the eye, where the current can activate or alter the function of retina, which results in the perception of electrophosphenes. Human exposure limits in international guidelines for the electric field in the central nervous system are set with the objective of preventing the generation of phosphenes. However, while it is still possible to measure thresholds for phosphenes in terms if the applied electrode current, there is no straightforward way for determining the local threshold current density on the retina from measured data. In this tidy, current distributions induced by electrode setups of a precious experimental study are analyzed computationally in four different anatomical human models. Computed results together with experimental data are used for determining local electrophosphene thresholds. At the frequency of highest sensitivity, 20 Hz, the threshold in terms of the maximum radial current density on the retina appears not to be less than 10-30 mA/m^2, where the variation is mainly caused by uncertainty due to electrode positioning. The threshold in terms of the total current that flows through eyeball is 2-4 µA. These thresholds are comparable with those previously determined for magnetically induced phosphenes."*

A model of a human head was used;

1. **Duke:** European male

The electrode placements were shifted throughout the experiment. See Figure 3-18. It appears that shifting the electrodes can alter the retinal current density up to +/-50%.



Electrode placement	Electrodes	
	first	second
A(left)	1(left)	3(right)
A(right)	1(right)	3(left)
B(left)	1(left)	2(right)
B(right)	1(right)	2(left)
C	4(left)	4(right)

Figure 3-18 Four different electrode placements.

3.9 World Congress on Ergonomics

3.9.1 Occupational Exposure to 50 Hz Electric Fields at Substation

Reference 2006, type: Acute

Långsjö, T; Latva-Teikari, J; Kurikka-Oja, J; Kuussaari, M; Elovaara, J; Kuisti, H and Korpinen, L: Occupational exposure to 50 Hz electric field at substations, 16th World Congress on Ergonomics, Maastricht, the Netherlands,10-14 July, 2006.

Article summary:

Abstract: *"[…] According to measurements near ground level in 2004 the E-field action value was exceeded at 75% of eight Finnish 50 Hz 400 kV substations measured. The maximum electric field strength 1 m above ground was 14,3 kV/m. A new series of measurements were conducted in 2005 to evaluate induced current density in workers at 400 kV substations in real working conditions. The current induced in the head area was measured at seven different substations in altogether 125 situations, which include 12 different working tasks, with the largest electric fields. The amount of induced current in the head was measured with the help of a helmet having a conductive outer surface and a transparent and conductive mask. Results suggest that the exposure limit value will not be exceeded in any of the studied conditions."*

See the helmet measuring system in Figure 3-19 and the electric field strength distribution of a Finnish 400 kV substation in Figure 3-20.

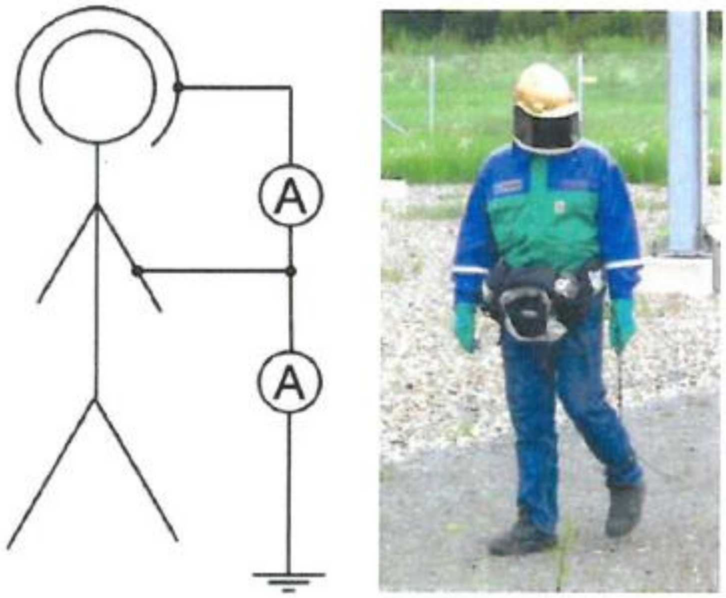


Figure 3-19 Schematic and photo of the helmet measuring system.

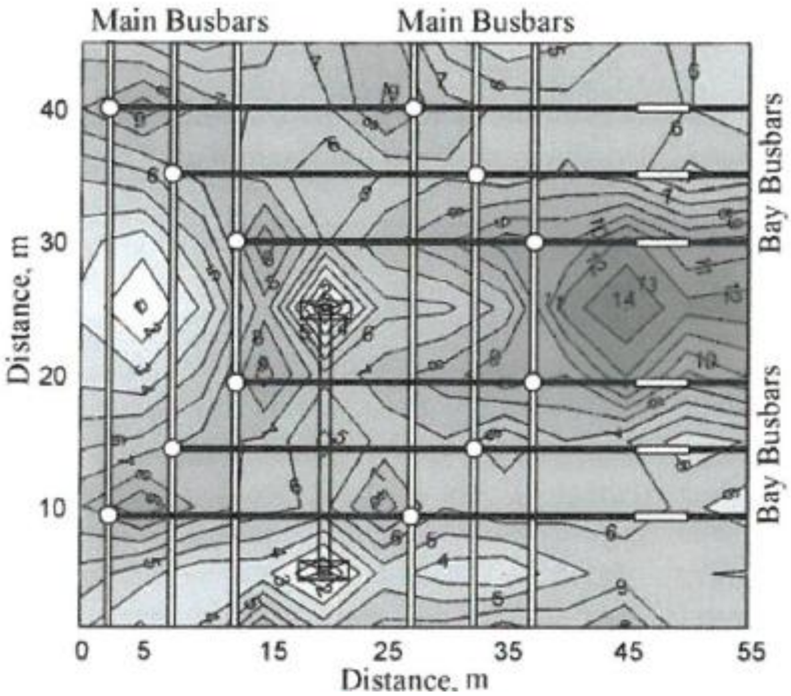


Figure 3-20 Electric field strength (kV/m) distribution 1 m above ground and assembly of busbars at a Finnish 400 kV substation.

3.10 Annals of occupational hygiene

3.10.1 Occupational Exposure to Electric and Magnetic Fields While Working at Switching and Transforming Stations of 110 kV

Reference 2011, type: Acute

Korpinen, Lena; Kuisti, Harri; Pääkkönen, Rauno; Vanhala, Pauli; Elovaara, Jarmo., "Occupational exposure to electric and magnetic fields while working at switching and transforming stations of 110 kV", Annals of occupational hygiene, Vol 55, No 5, pp. 526-536, 2011

Article summary

"The aim of the study was to measure occupational exposure to electric and magnetic fields during various work tasks at switching and transforming stations of 110 kV (in some situations 20 kV), and analyze if the action values of the European Union Directive 2004/40/EC or reference values of International Commission on Non-Ionizing Radiation Protection (ICNIRP) were exceeded. The electric (n = 765) and magnetic (n = 203) fields were measured during various work tasks. The average values of all measurements were 3.6 kV/m and 28.6 μT. The maximum value of electric fields was 15.5 kV/m at task 'maintenance of operating device of circuit breaker from service platform'. In one special work task close to shunt reactor cables (20 kV), the highest magnetic field was 710 μT. In general, the measured magnetic fields were below the reference values of ICNIRP."

The evaluation in this article is based on ICNIRP 2010 and Directive 2004/40/EC. In 2009, 765 electric field measurements and 203 magnetic field measurements were collected at 20 substations of 110 kV. One of the substations was a GIS and the others were air insulated.

Electric and magnetic fields were measured during a number of maintenance tasks for equipment such as disconnectors, circuit breakers, current and voltage transformers, in the vicinity of power transformers, reactors or capacitors, bushings, outside fences, earthing switches, lamps as well as walking on ground level. The measurement heights and positions were adjusted depending on the approach normally required to perform the maintenance (e.g. if the maintenance is usually performed from a man hoist or a service platform the measurement height and position was adjusted accordingly).

No workers were present during the measurements, and the results show that the highest measured electric field is 15.5 kV/m during 'maintenance of operating device of circuit breaker from service platform'. The highest magnetic field measured was 710 μT when walking in the close vicinity of reactor cables (20 kV). The second highest value measured was 260 μT.

The authors conclude that it can be stated generally that, at 110 kV substations, workers are not exposed to EMF's higher than 10 kV/m and 500 μT.

Editor's note: Compared to EU Directive 2003/30/EU neither the maximum measured electric or magnetic fields exceed the action levels of 20 kV/m (high AL) or 1 mT (low AL).

3.11 International Journal of Occupational Safety and Ergonomics

3.11.1 Occupational exposure to electric and magnetic fields during tasks at ground or floor level at 110 kV substations in Finland

Reference 2016, type: Acute

Korpinen, Lena; Pääkkönen, Rauno: "Occupational exposure to electric and magnetic fields during tasks at ground or floor level at 110 kV substations in Finland", International journal of occupational safety, Vol 22, No. 3, pp. 384-388, 2016.

Article summary

"The aim was to investigate occupational exposure to electric and magnetic fields during tasks at ground or floor level at 110 kV substations in Finland and to compare the measured values to Directive 2013/35/EU. Altogether, 347 electric field measurements and 100 magnetic field measurements were performed. The average value of all electric fields was 2,3 kV/m (maximum 6,4 kV/m) and that of magnetic fields was 5,8 μT (maximum 51,0 μT). It can be concluded that the electric and magnetic field exposure at ground or floor level is typically below the low action levels of Directive 2013/35/EU. The transposition of the directive will not create new needs to modify the work practice of the evaluated tasks, which can continue to be performed as before. However, for workers with medical implants, the exposure may be high enough to cause interference."

The electric and magnetic field strengths were measured for different maintenance tasks: Maintenance of an operating device of a circuit breaker at ground level (only electric field, magnetic field measurement excluded), walking in a 110 kV substation, and maintenance of an operating device of a disconnector at ground or floor level. The results show that the field strengths are typically very low for maintenance tasks on ground level in 110 kV substations, and that maintenance can be performed in the same manner as before.

3.12 Progress In Electromagnetics Research

3.12.1 Decreasing the extremely low-frequency electric field exposure with a faraday cage during work tasks from a man hoist at a 400 kV substation

Reference 2016, type: Acute

Pirkkalainen, Herkko; Elovaara, Jarmo; Korpinen, Lena: "Decreasing the extremely low-frequency electric field exposure with a faraday cage during work tasks from a man hoist at a 400 kV substation", Progress in electromagnetic research, Vol 48, pp. 55-66, 2016.

Article summary

"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. 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 work environment. The Faraday cage was constructed from a steel net 0,5 m in with 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 96,8-99,8%, validating the efficacy of Faraday cages."

The aim of the study was to show how effective a Faraday cage is in decreasing the electric field exposure at 400 kV substations, and especially during maintenance work from a man hoist. The electric field was measured in positions relevant for circuit breaker maintenance. Photos of the cage are presented in Figure 3-21.

Figure 3-21 Photos of the Faraday cage installed on a man hoist.

The cage can be constructed on site with common materials and it has a net-free opening for the hands to reach out. Only the torso and head were considered in this construction, therefore omitting net to cover the lower limbs. The authors conclude that there might be negative aspects to this solution, such as reduced work efficiency and difficulties using a fall protection harness. The benefit however is a significant reduction in the electric field exposure.

4 Article summary: Swedish literature

4.1 Elforsk

4.1.1 Gnisturladdningar och kontaktströmmar

Reference 2007

A. Larsson, G. Olsson. ”Gnisturladdningar och kontaktströmmar”, Elforsk rapport 07:36, November 2007.

Article summary

”Contact currents and spark discharges may occur between a person in an electric field and a conductive object. Contact currents are limited to 1.0 mA for occupational exposure and to 0.5 mA for the general public. For spark discharges, however, there are no formal restrictions but they can still result in unpleasant sensations and even to pain.

These two phenomena are previously well discussed in the literature and their relation to the electric field is well known. Their importance for the maximum acceptable electric field has also been discussed. The reference level at 50 Hz is 10 kV/m for occupational exposure and 5 kV/m for the general public, while the corresponding basic restrictions are 10 mA/m^2 respectively 2 mA/m^2. However, it has been demonstrated that humans could be exposed to higher fields levels without exceeding the basic restriction, if only the current density level is considered.

Four exposure cases can be studied:

- *Contact currents from a charged person to ground.*
- *Spark discharges between a charged person and ground.*
- *Contact currents from a charged object to a person.*
- *Spark discharges between a charged object and a person.*

It can be demonstrated that the two first cases – involving a charged person – neither can result in large contact currents nor more serious spark discharges.

The third case – contact current from a charged object like a vehicle and to a person – can be calculated with some simplifications. The maximum values can usually be calculated while the more realistic ones, generally lower, can often be estimated. Also this case should not normally result in any more serious problems.

The fourth case – spark discharges between a charged object and a person – can result in unpleasant sensations. The size of the object is one important factor and, in case of vehicles, the resistance of the tires and also the ground conditions. Measurements have shown that the maximum charging voltage will never exceed 50% of the unperturbed electric field level.

Spark discharges can be a problem for people working in substations, but the problems are easier to handle than these occurring in public areas. Larger vehicles should not be parked in areas with high electric fields and fixed objects should be grounded. Vehicles *can also be equipped with a chain for continuous grounding. Shoes with conductive soles are recommended for work in substations and other areas with high field levels.*

In the specific case of restricted areas and occupational exposure, there are certain conditions when the maximum acceptable electric field can be increased from 10 kV/m to 20 kV/m. Measures must be taken to limit the capacitive charging of objects and humans and the basic restriction value of 10 mA/m^2 must not be exceeded."

Elforsk rapport 07:36 is a report from november 2007 which summarizes literature on EMF in power grids and electric substations, acute effects from EMF on humans, contact currents and spark discharges, measurements, calculations, verifications and more.

4.1.2 Arbete i höga elektriska och magnetiska fält: Luftledningar 70 – 400 kV

Reference 2009

A. Larsson, G. Olsson. "Arbete i höga elektriska och magnetiska fält: Luftledningar 70 – 400 kV", Elforsk rapport 09.99, October 2009.

Article summary

"Overhead lines are always associated with the exposure for electric and magnetic fields. The exposure levels depends on the conductor configuation, voltage level, current and the distance to the line. This project has focused on the exposure of maintenance team working very close to the lines. The most exposed group are the live line workers and especially these working with the so called Bare hand method (i.e. in contact with the live conductors).

The actual field levels and the exposure of workers have been related to the distances Live working zone and Vicinity working zone, defined in standards.

Electric and magnetic fields have been calculated for nine different line configurations and for 70 – 400 kV. The fields have been calculated both at the tower and at a minimum height above ground. Field levels in all sections have been calculated with a 2D analytical method and one 130 kV and one 400 kV section have also been calculated with a FEM program (COMSOL Multiphysics), suitable for 3D calculations with grounded structures.

The environment close to the lines can be divided into three zones, with different conditions for the field calculations.

- *Field at ground level and a few meters above.*
- *Field in the vicinity of the phase conductors.*
- *Field close to tower legs, cross-arms and other grounded objects.*

Calculations for the third group can only be performed with 3-dimensional numerical methods, but the two first ones can also be analyzed analytically.

Verifying measurements of both the electric and magnetic fields have been carried out to check the influence of different steel constructions.

The assessment of the different exposure scenarios have been based on the existing documents from ICNIRP and EU, i.e. ICNIRP Guidelines from 1998 and the EMF Directive 2004/40/EC issued by the European Union in 2004. New Guidelines from ICNIRP can be expected during the later part of this year 2009 and they may give a base for the assessment.

It can be concluded that high magnetic fields are more local than high electric fields. Magnetic field levels above the Reference level of 500 µT exist only very close to the conductors. The electric field, however, may exceed the Reference level of 10 kV/m even at a rather long distance from the conductors. Highest E.field levels can be found in the area between the phase conductors. High levels (20-35 kV/m) can also be found along the upper part of the grounded tower legs. As a consequence of this, the Reference levels may be exceeded even at ordinary maintenance work, but exposure more to the Basic restrictios should be limited to Live working only. However, the risk for unpleasant spark discharges during work in high voltage environment must not be neglected.

The consequences of high electric fields can be limited by using a special conductive suit and such protective suits are recommended for live line working with the bare hand method. Magnetic fields are most easily reduced by increasing the distance to the current carrying conductors. In general, all work in high field environment require careful planning and discipline."

Elforsk rapport 09.99 is a report from 2009 which summarizes literature as well as guidelines for exposure to electric and magnetic fields. The report discusses and categorises work assignments inside the vicinity zone and inside the live working zone on high voltage AC transmission lines. To some extent, tools and equipment which might be utilized in such work are discussed as well.

The electric field strength and the magnetic flux density are calculated analytically and numerically for different cases:

1. Fields a few meters above ground.
2. Fields close to the current carrying conductors.
3. Fields close to steel support frames and other details.

The analytical and numerical results are compared to determine where an analytical calculation may be sufficient or if a numerical calculation is required. Generally, to include steel support frames etc. a 3D numerical model is required.

To conclude the study measurements were made to verify the theoretical results. Although the models are simplifications of reality, the measurements verify that the theoretical and measured values go well together. In other words, the theoretical results are reasonable and can be used as estimations.

Work inside the vicinity or live working zone is primarily for specialized maintenance personnel only. Bare hand techniques will in most cases yield high field exposures. Planning, discipline and proper personal protective equipment should however solve most issues.

4.1.3 Arbete i höga elektriska och magnetiska fält: Ställverk 70 – 420 kV

Reference 2010

A. Larsson, G. Olsson. ”Arbete i höga elektriska och magnetiska fält: Ställverk 70 – 420 kV”, Elforsk rapport 10:108. May 2010.

Article summary

”The electric field strength (E-field) and the magnetic flux density (B-field) have been studied in air-insulated substations for 70 – 420 kV, with the intention to describe the fields in the working environment. Both ordinary inspections from ground level and more planned working activities, like live working have been studied. The distances between live conductors and the worker have been related to the distances to the outer limit of the live working zone respectively the outer limit of the vicinity zone.

Measured and calculated values have been related to the existing guidelines for exposure. The ”Guidelines” from ICNIRP, published in 1998, are under revision but a draft version was published in 2009. The assessments have therefore been based on the new version, but with guidance of the older one. There is a distinction between ”Basic” restrictions and ”Reference” levels for exposure. The first ones are based on established health effects, while the later ones are coupled to the Basic restrictions by physical relations. The basic restriction has been expressed as a current density in the human body, with a maximum level of 10 mA/m^2 at 50 Hz. The new version uses the internal electric field (in situ) as basic restriction, with the limit 100 mV/m for workers and at 50 Hz. The Reference levels are the same in both versions; 10 kV/m and 500 µT for workers and at 50 Hz.

The field levels have been calculated with both analytical and numerical methods. The analytical ones are often faster but only limited models with cylindrical conductors can be used. The numerical methods can handle more complex models but the input of geometrical data can take a long time. In some cases the calculated results have been compared with measured values, with quite different result. The electric field is often distorted in the vicinity of grounded objects and high horizontal field components may result in rather large differences between measured and calculated values.

The calculations and the measurements can be summarized as follows:

400 kV: >20 kV/m close to grounded frames etc. At longer distances from frames > 15 kV/m in older substations and about 12 kV/m in younger ones. 15-45 kV/m at the outer limit of the live working zone.

220 kV: The calculated max. value at 2 m height and at some distance from the frames is about 15 kV/m. 15-20 kV/m at the limit of the live working zone.

130 kV: The calculated max. value at 2 m height and at some distance from frames is about 5 kV/m. 15-20 kV/m at the limit of the live working zone.

70 kV: The calculated max. value at 2 m height and at some distance from frames is about 5 kV/m. 15-20 kV/m at the limit of the live working zone.

Grounded frames etc. will have an influence on the level and the direction of the E-field, but it is the vertical component the is most important for the current density and the in-situ electric field. Attention should therefore be put more on the level of the vertical field *component and not as much on the total field level, that can be increased by large horizontal field components.*

Calculation of the magnetic field levels close to simplified models have shown that the flux density will not exceed the reference level of 500 µT other than at work very close to current carrying conductors."

There are some major differences between electric substations and AC transmission lines. Substations are, for example, fenced in with limited access as opposed to transmission lines which are accessible to anyone. In other words this means that since transmission lines are accessible to the public (at least on ground level) extra security margins for exposure are required. However, this study is aimed at maintenance personnel working in substations.

The electric and magnetic fields were calculated both analytically and numerically and then compared to measured values. Some common work assignments were analysed:

- General security/maintenance rounds and visual inspections.
- Work on de-energized equipment.
- Work on live equipment (both in the vicinity and in the live zone).

4.1.4 Magnetfält i kabelmiljö

Reference 2010

A. Larsson, G. Olsson. "Magnetfält i kabelmiljö", Elforsk rapport 10:109, May 2010.

Article summary

"The increasing use of HV cables for distribution networks and for transmission of power to the centre of big cities has initiated more studies of the magnetic field in different cable environments. The studies for Stockholms Ström have included a number of magnetic field studies. Most of these have been focused on the exposure of the general public and of fields on the ground caused by cables in ducts and tunnels. There have not been so many studies including the exposure of workers in their usual working environment, close to cables and other installations. This work will therefore focus on the exposure of workers in their normal working environment. It can also be mentioned that shielded cables do not cause any electric field in their environment.

Magnetic fields around cables can be decreased by a suitable arrangement of the phase conductors. A small distance phase-phase will give a low magnetic field. If possible, an arrangement with the phases in trefoil form can be used to minimize the magnetic field. Shielding is more expensive than a changed cable layout and may also result in a reduced current rating factor of the cable. A careful shielding can result in an attenutation of 10 times or even more in some cases. Shielding of rooms and larger areas is complicated and will be expensive as necessary holes and joints will have a large impact on the final result. The total effectiveness of a shield is mostly determined by such imperfections rather than the shielding effectiveness of the individual plates.

Two different cable locations have been studied more in detail – Cable distribution cabinets for low voltage and high voltage cables in tunnels. Results from measurements close to cabinets have previously been published by the University of Tempere, Finland, and also by Elforsk. The study from Finland was focused on the worker and the influence of the harmonics on the exposure for magnetic fields. However, the result from the previous study by Elforsk and from this study does not support the opinion that the harmonics should have a large impact on the total exposure level. Calculations based on a ”worst scenario” indicate that the maximum magnetic field level may reach 90 µT at a distance of 30 cm from the busbars in the cabinet. At 50 cm distance the field level has decreased to about 40 µT.

The second working place – tunnels with HV cables will be more common and a possible scenario is working with a cable joint when the load is taken up by the remaining cables in the tunnel. The magnetic field close to the cables still in service will be high, with levels of about 300 - 400 µT at a high load, but the field will decrease rather quickly away from the conductors. Working in tunnels with cables in service will require careful planning and attention.”

Elforsk rapport 10:109 is a report from May 2010 which summarizes literature on workers exposure to magnetic fields close to cables in low voltage cabinets and high voltage cables in tunnels. Theory, numerical calculations and COMSOL simulations are also performed to show the magnetic field around different cable geometries.

The ICNIRP Guidelines from 1998 as well as underlying data from studies and reports covering acute and long term effects on the human body are presented. The results do not show any negative health effects although caution is advised.

Shielding of the magnetic field is an expensive solution and it is shown in the report that there is much to gain by using a compact design instead. A trefoil configuration may reduce the magnetic field compared to a plane configuration, provided that the load is symmetrical

Early planning and awareness in the design phase is probably the easiest and cheapest solution to reduce the magnetic field exposure.

4.1.5 Elektriska och magnetiska fält i arbetsmiljön: Inverkan av nytt regelverk

Reference 2012

G. Olsson. ”Elektriska och magnetiska fält i arbetsmiljön: Inverkan av nytt regelverk”, Elforsk rapport 12:44, July 2012.

Article summary

”Work in substations and close to overhead lines is necessarily associated with the exposure to electric and magnetic fields (EMF). The magnetic field levels are in most cases moderate compared to existing international guidelines for exposure and also to the proposals for a new EU-directive regarding the exposure of workers to EMF. On the other hand, the electric field levels existing today in working zones and in some public zones are of the same order as the action levels given by these guidelines.

There are a number of specific working procedures that motivates a more careful investigation of existing field levels and also of the intention and consequences of these proposals for a new EU-directive within this field.

Three types of ”exposure scenarios” are described in this report; overhead lines, substations and high-voltage cables. These exposure scenarios have been described in four previous report from Elforsk: ”Gnisturladdningar och kontaktströmmar”, ”Arbete i fält – Luftledningar”, ”Arbete i höga fält – Ställverk” and in ”Magnetfält i kabelmiljö”. The results of an updated literature review give some more input to the chapter regarding the assessment of different exposure situations.

The existing guidelines for exposure and the proposals for a new EU-directive within this field are both discussed in the report. The new EU-directive is unfortunately still an open question and the date for the member states to bring into force necessary law and regulations have now been postponed until 2014. The recommendations given in this report must therefore be given in a ”flexible” form, possible to adapt to different future protection levels.

There will in the future certainly be two different guidelines for exposure to EMF, both the ”Guidelines for limiting exposure to time-varying electric and magnetic fields” published by the organization ICNIRP and a workers directive from EU. The given limits will probably not be the same and this can certainly be a source for misunderstanding and for other difficulties.

In general, exposure to EMF should therefore be limited as far as technically and economically possible.

The lowest proposed limitation for electric fields at 10 kV/m will be difficult to comply with. The next level, 20 kV/m, will give increased flexibility and will be possible to maintain with most the working tasks practiced today. To cover all tasks it will be necessary also to limit the effect of spark-discharges. A conductive suit together with semi-conductive shoes would be an alternative.

The proposed limitations for the magnetic field will have only minor impact on the work performed today. For work on overhead lines and in substations, there will be no limitations for working outside the live-working zone. Restrictions will therefore only be necessary for live-line working and in particular with the bare-hand method. There will probably not be necessary to modify the working procedures, but the working instructions will certainly have to be revised. The limitation for exposure of the limbs may require a short hot-stick. Also, the instructions for cable work may have to be revised and a new tool for lifting current carrying cables without touching them with the hands will probably have to used.”

While the magnetic flux density should not pose a problem, the electric field might do so. The lower action level of 10 kV/m is tough to meet considering how some maintenance work assignments are performed today. The higher action level at 20 kV/m is less critical, and it should be possible to perform most work assignments up to 130 kV, including work inside the live zone using electrically insulated equipment. Electric shielding, personal protective equipment and proper tools will help to reduce the exposure.

4.2 Arbete och Hälsa

4.2.1 Exposition för elektriska fält: En kartläggning av den elektrofysikaliska arbetsmiljön i ställverk

Reference 1980

K. G. Lövstrand, S. Bergström. ”Exposition för elektriska fält: En kartläggning av den elektrofysikaliska arbetsmiljön i ställverk”, Arbete och Hälsa, 1980:4.

Article summary

”Electrophysical factors in high voltage substations such as corona, ELF electric and magnetic fields, have been surveyed. The electric fields there reach very high values which do not occur in other working environments.

Three measuring instruments were developed for surveying the substations and for determination of the exposure of the workers for electric fields: 1) A field meter which measured the unperturbed field strength. With this instrument the electric field was surveyed in high voltage substations at a height of 1.8 m. 2) A dose-meter which was used for measurement of the exposure at different working operations. 3) An instrumented full-size dummy which was used for determination of the distribution and strength of induced currents in a man exposed to ELF electric fields.

Measurements were made in 20 substations throughout Sweden, mainly 400 kV substations but also in stations for lower voltages. The results show that the exposure of the workers is below 5 kV/m during more than half of the working day. The working time in field strengths higher than 10 kV/m is normally less than a few percent of the working day.”

4.2.2 Akuta effekter av lågfrekventa elektromagnetiska fält: En fältstudie av linjearbetare i 400 kV ledningar

Reference 1988, type: Acute

F. Gamberale et al. ”Akuta effekter av lågfrekventa elektromagnetiska fält: En fältstudie av linjearbetare i 400 kV ledningar”, Arbete och Hälsa 1988:12. 1988.

Article summary

”The aim of the study was to investigate the possible acute effects of exposure to electric and magnetic fields. Twentysix experienced linemen, 25 to 52 years old, were studied for two work days while they performed simulated, routine inspections of insulators in steel poles carrying a 400 kV power line. On one of the work days, the inspection was performed on a power line in service. On the second day the same work was performed in an identical power line which, however, was not in service. The two days were found to be comparable in terms of physical workload. On the basis of heart rate measurement, this workload was estimated to be very heavy. Exposure to electric and magnetic fields was measired with a personal sampling device on each lineman. Mean exposure for the work day was estimated at 2.8 kV/m (SD=0.35) and 23.3 μT (SD=4.2) respectively.

The possible effects of exposure were studied using a battery of four automated behavioral performance tests, EEG, a mood scale and a questionnaire for the assessment of subjective symptoms. All workers were examined before and after each work day. Blood samples were also collected for each subject on three different occassions during the work day. The battery of behavioral tests comprised a test of simple reaction time (SRT), a vigilance test (CWV), a test of short-term memory (Digit Span) and a perceptual test (Symbol Digit). The four EEG recordings for each worker were judged on a blind basis and sorted with regard to the amount and stability of alpha activity. The blood samples were used for analysis of possible changed during the work day with regards to the following hormones: thyroid stimulating hormone, luteinizing hormone, follicle stimulating hormone, prolactin, cortisol, testosteron and neopterin.

Detailed analysis, using both parametric and non-parametric tests, did not reveal any statistically significant difference between the two conditions which could be attributed to exposure to electric and magnetic fields.”

4.2.3 Exponering för elektriska och magnetiska fält hos anställda inom kraftindustrin

Reference 1996, type: Long-term

T. Lindh, S. Törnqvist, L-I. Andersson. ”Exponering för elektriska och magnetiska fält hos anställda inom kraftindustrin”, Arbete och Hälsa 1996:2. 1996.

Article summary

”Exposure to 50 Hz electric and magnetic fields were estimated for 485 participants in the ”elmiljö-study”. The calculations were based upon information given by each worker about time-in-occupational subgroup and dosimeter measurement made in the occupational subgroups. The results showed that half of the workers were exposed to a 9-year time weighted average magnetic flux density in excess of 0,56 µT and every forth in excess of 1,15 µT. The exposure to electric fields divided the cohort into ”high” and ”low” exposed. When exposure measured as a time weighted average value was regarded as a surrogate for any of the four the ”correct” metrics GSD, Sd, GM and 25:e percentile, the observed relative risk was attentuated by approximately the same amount.”

This is a dosimetric study with 485 workers with 16 different work areas within the power industry. These are the results for exposure to the magnetic field, presented as time weighted averages over 9 years:

- 25% of the workers were exposed to < 0,56 µT
- 50% of the workers were exposed to > 0,56 µT
- 25% of the workers were exposed to > 1,15 µT

4.2.4 Hälsorisker i arbete med elproduktion och eldistribution – slutrapport från en prospektiv studie

Reference 1998, type: Long-term

S. Törnqvist et al. ”Hälsorisker i arbete med elproduktion och eldistribution – slutrapport från en prospektiv studie”, Arbete och Hälsa 1998:9. 1998.

Article summary

”The aim of this prospective study was to investigate health outcomes over a nine year time period among first employed power industry workers. Health outcomes were analysed in relation to work environmental factors, with special emphasis given to exposure to extremely low frequency electric and magnetic fields. At baseline the cohort consisted of 706 electric workers in the power industry. Information on health outcomes was obtained and clinical examinations were made every third year over a nine year period resulting in an ultimate group of 460 workers for which data was available. A total dropout in the cohort of 34% occurred, of which 25% appeared during the first three years.

The results suggest that these electric workers as a whole exhibit and experience good health as seen over the nine years, even if a number of workers showd increased health problems in general terms as well as in terms of specific outcomes. With a few exceptions the study was unable to find any relationship between changes in the health outcomes and specific factors in the work environment. However, some of the findings should be further commented on.

An increased risk was found for neurasthenic symptoms in the highest magnetic field exposure group, > 1.2 µT, and the risk increase appeared to be more pronounced with years of such exposure. The level of cortisol in serum did show an uncertain association with exposure to electric field exposure. The level of Tissue Polypeptid Antigen in serum showed a statistical association with one specific occupational group which has also reported increased loads of other environmental factors such as exhaust gases. Back and knee disorders tended to increase over time especially among linemen.

Children of fathers in this study showed no increased risks for low birth weight, perinatal death, malformations or late effects like cancer. Neither were any relationships verified between white blood cells or blood chemical profiles with exposure to fields.

In conclusion, this study has not been able to detect any major effects on health in the young cohort of electric workers examined, although some individual changes in health status did occur over the nine year period.”

4.3 British Journal of Industrial Medicine

4.3.1 Acute effects of ELF electromagnetic fields: a field study of linesmen working with 400 kV power lines

Reference 1989, type: Acute

F. Gamberale, B. Anshem Olson, P. Eneroth, T. Lindh, A. Wennberg. ”Acute effects of ELF electromagnetic fields: a field study of linesmen working with 400 kV power lines”, British Journal of Industrial Medicine, 1989:46, 1989, pp 729-737.

Article summary

This is the same article as ”Akuta effekter av lågfrekventa elektromagnetiska fält: En fältstudie av linjearbetare i 400 kV ledningar” published in Arbete och Hälsa 1988:12, albeit in english. See article summary in section 4.2.2.

4.4 Cigré

4.4.1 Long-term exposure to electric fields: A cross-sectional epidemiologic investigation of occupationally exposed workers in high-voltage substations

Reference 1979, type: Long-term

B. Knave et al. ”Long-Term exposure to electric fields: A cross-sectional epidemiologic investigation of occupationally exposed workers in high-voltage substations”, Cigré Electra no 65. 1979, pp 41-54.

Article summary

”In the present epidemiologic study, 53 workers with a long-term (more than 5 years) exposure to the electric field of 400 kV substations were examined and compared with a matched reference group of 53 nonexposed workers from the same power companies. Matching variables included age, geographic location and employment time. The aim of the study was to investigate the possibility of persistent, chronic health effects in the exposed group as a consequence of exposure. The investigation included the nervous system (neurasthenic symptoms, psychological tests, electroencephalography), cardiovascular system (symptoms, blood pressure, electrocardiography), the blood (hemoglobin, red blood cells, reticulocytes, white blood cells including differential count, thrombocytes, sedimentation rate). Fertility was also assessed. The results showed no differences between the exposed and the reference groups as a consequence of the long-term exposure to the electric fields. The groups differed, however, in that the exposed group had (a) consistently better results on the psychological performance tests, (b) fewer children, especially boys, and (c) somewhat higher education. The differences in test results were due to the higher education among the exposed. The difference in number of children was also thought to be related to dactors other than exposure since the difference in number och children was found to be present already 10 – 15 years before the work in 400 kV substation began.”

4.5 Scandinavian Journal of Work, Environment & Health

4.5.1 Determination of exposure to electric fields in extra high voltage substations

Reference 1976

K-G. Lövstrand. ”Determination of exposure to electric fields in extra high voltage substations”, Scandinavian Journal of Work, Environment & Health, 1976;2(3). 1976, pp 190-198.

Article summary

”Electrophysical effects related to extra high voltage are surveyed for the determination of the exposure of personnel to electric fields in substations. It is concluded that the electric field strengths and the electric discharges to the personnel are the important electrophysical factors. Instruments for measuring the field strength at grounded surfaces and at nonzero potentials were constructed. Results are presented of measurements with these instruments in substations. A dummy was used for the measurement of the distribution of capacitive currents to a man. The dummy can also be used for measuring the effectiveness of special shielding clothes.”

A new tool was developed during this study to measure the capacitive current to different parts of a dummy. The principles used herein are found years later in many studies with so called conductive helmets used to measure and estimate the current density through the neck.

4.6 Svenska kraftnät

4.6.1 Elektriska fält – Så fungerar de och så undviker du besvär

Free translation: Electric fields – How they work and how to avoid discomforts

Reference 2016

E. Friman, Svenska kraftnät: ”Elektriska fält – Så fungerar de och så undviker du besvär”, 2016.

Article summary

Introduction: *”For those working in environments with electric and magnetic fields there are two action levels and limits for the field strengths in the EU Directive for electromagnetic field exposure to workers. In Svenska kraftnäts plants the magnetic field strengths are way below the action levels. The electric fields, however, can be high. This paper provides suggestions to how you as an employer can protect your employees working in our plants.”*

Svenska kraftnät has produced a fact sheet about electric fields which targets employers, entrepreneurs and personnel working with or close to electric substations or HV AC transmission lines. The sheet provides the reader with general theory on electric fields and a practical approach on how to shield or protect workers from discomforts and injuries. The sheet takes into account the EU-Directive for electromagnetic field exposure to workers.

In general, the fact sheet provides suggestions on the following to reduce the risk:

- Reduce the electric field inside the work area.
  - Shielding can be done with e.g. meshed, grounded metal structures.
  - Use proper PPE (personal protective equipment).
- Reduce potential differences that causes spark discharges.
  - Ground the equipment that you are working on and with.

It is important to remember that different methods to mitigate electric field exposure must never increase the overall risk for injury, damages or consequence thereof.

4.6.2 Anvisning för arbetsmiljö vid arbete i E-fält

Free translation: Directive for work environment during work in E-fields

Reference 2016

”Anvisning för arbetsmiljö vid arbete i E-fält”, Svenska kraftnät, Styr.dok/18, edition 1, 2016-06-29

Article summary:

This directive (henceforth *the directive*) encompasses all of Svenska kraftnäts operative work with the purpose to ensure that Svenska kraftnät follows the EU Directive 2013/35/EU and Arbetsmiljöverkets AFS 2016:3, with regards to electric fields at 50 Hz to ensure a good work environment. Furthermore, the directive identifies responsible parties with regards to electric field exposure mitigation. Work inside the live working zone is not included.

The directive, approved in its current state, is a work in progress which currently includes electric field exposure during maintenance, construction work or reconstruction of substations and transmission lines. Magnetic field exposure is excempt from the directive based on assessments that the magnetic field strength during aforementioned activities is way below the action levels in the EU Directive.

The plant owner is responsible to inform of existing electric fields in the plant, but the work environment is the responsibility of the company of the employer and is usually delegated internally to the line organization, i.e. to management of the employees that will perform the work. A risk analysis shall always be performed and documented in an ”action plan” to identify necessary actions to minimize the risks.

Action levels and exposure limit values, contact currents etc. follows Arbetsmiljöverkets provision AFS 2016:3 and the directive 2013/35/EU, and a few examples of situations are mentioned where the electric field might pose an issue:

- Large foundations cast on site: Up to 4-5 times amplification of the undisturbed E-field at a distance of 4-5 dm.

- Pole foundations and lesser foundations cast on site: Up to 2 times amplification of the undisturbed E-field at a distance of 3-4 dm.
- Work close to high metal structures: Up to 2-3 times amplification 2 dm from the top of the structure.
- Pointy and/or prominent objects: Caution should be taken at undisturbed E-fields even as low as 5 kV/m where there are pointy or prominent objects. Keep at a distance from head and body.
- Exposure to lower arms and hands: Up to 50 kV/m can be accepted for lower arms, with an undefined but higher accepted amplitude for the hands.

Svenska kraftnäts process for risk mitigation is as follows:

1. Identify
2. Evaluate
3. Remedy
4. Document
5. Follow up

4.6.3 Anvisning för mätning och beräkning av elektriska fält

Free translation: Directive for measurement and calculation of electric fields

”Anvisning för mätning och beräkning av elektriska fält”, Svenska kraftnät, Styr.dok/18, edition 1, 2016-08-16

The purpose of this directive is to ensure that calculations and measurements are performed consistently and correctly for risk analyses with regards to E-fields at 50 Hz in the work environment.

Measurements

Measurements must be performed in the absence of the employee so as not to perturb the electric field. Handheld instruments should therefore not be used since the operator will disturb the measurements. A 3D-”free-body-meter” shall be used instead and the instrument management shall follow standards SS-EN 61786-1 and IEC 61786-2, and there must be routines in place for calibration. Additionally, the the measuring probe must have at least a 0,2 m distance to conductive materials, as described in IEC 62110.

Calculations

Calculations of the unperturbed E-field shall be performed without additional metal structures, i.e. conductors only. This exercise is always necessary if the electric field levels are unknown and have not been documented previously.

Simpler geometries require that an evaluation is performed to determine the field amplification from nearby metal structures. If the geometry is complicated more detailed calculations or measurements might be required.

This directive mentions a few software alternatives for calculation, for example EPRI or COMSOL Multiphysics. Self-scripted programs in e.g. Matlab or Scilab must always be verified through measurements.

There are also a number of example calculations using different software alternatives for different applications as well as an appendix with E-field theory.

4.6.4 STRI Report R16-1232: Elektrisk fältstyrka vid rondning och underhållsarbete i stationsmiljö

Free translation: Electric field strength during visual inspectoion and maintenance in substation environments

Reference 2016

J. Törnqvist, G. Olsson, ”Elektrisk fältstyrka vid rondning och underhållsarbete i stationsmiljö”, STRI report R16-1232, 2016-12-22

[Editor’s note: Each substation layout is different and the results may vary significantly depending on geometry and topografy. These results are applicable to Swedish substations similar in layout, but not necessarily elsewhere.]

Article summary:

This report is a summary of measurements performed in substation environments in a collaboration between STRI and Svenska kraftnät during the years 2009 to 2016. The focus has been to map E-field exposure during maintenance tasks and visual inspection/walking rounds.

Measurements were performed in 130 kV-, 220 kV- and 400 kV substations in southern and middle Sweden and have been divided into categories based on type of activity: Walking rounds and maintenance of different apparatus.

The results are presented in Table 4-1.

Table 4-1 Summary of measurement results from 2009 to 2016, starting with walking rounds and then in falling order of severity sorted from highest to lowest with regards to E_{max} [kV/m].

Apparatus or situation	**E_{tot}: min-max [kV/m]**	**Comments**
Walking rounds	1 – 17	The E-field might be higher than 10 kV/m but highest measured field does not exceed 20 kV/m. Local amplification responsible for the highest fields.
Light posts	17 – 44	Routines for changing of lamps or a redesign of the lamp posts required.
Current transformers	2 – 36	Shielding is recommended during cable marking. The placement of the apparatus in relation to grounded structures is decisive for the amplitude of the exposure.
Voltage transformers	5 – 34	
Breakers: checking density guard and operating mechanism.	7 – 27	There are tools available to move the density guards. Work on operating mechanism can be performed with use of simple shielding.
Two column rotary disconnectors	16 – 23	This type of disconnector is opened towards other apparatus which can yield high fields at the contacts. A skylift with shielded basket is recommended.
Surge arresters: Check of surge counter	1 – 7	High field amplification close to the grounded steel support.
Electric distribution central/board	~5	Normally not an issue with regards to high electric fields.
Reactor, transformer: check density guard etc.	1 – 2	

The technical guidelines should be complemented with relevant requirements that apparatus and equipment are designed to support a good work environment with regards to electric fields. The supplier should be able to provide documentation that shows the local field around the apparatus and locally where maintenance is required. These results should be declared for both 1- and 3-phase configurations and relate to those environments where the apparatus are normally placed.

5 Article summary: Norwegian literature

5.1 State Institute of Radiation Hygiene

5.1.1 Elektriske felt i høyspenningsanlegg

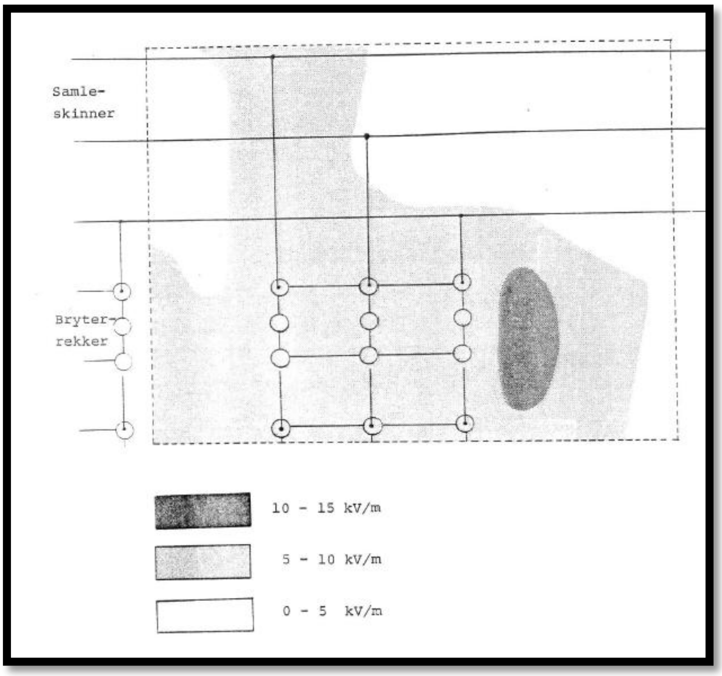
Free translation: Electric fields in high voltage substations

Reference 1982

M. Waskaas, “Elektriske felt i høyspenningsanlegg”, SIS report 1982:5, State institute of radiation hygiene, ISBN 82-554-0320-5, 1982.

The electric field was measured to determine the electric field strength at 1,8 m above ground. The distance between operator and measurement equipment was 1,6 m and was kept by utilizing an isolating rod. Two cases were investigated:

- High voltage substations (300 kV and 420 kV). Measurements were performed in the vicinity of breakers and busbars. The highest measured electric field was 11 kV/m, see Figure 6-1. The breaker bus is lower (closer to the ground) than the busbars which yields higher measured field strengths. Additionally, horizontally perpendicular busbars of the same phase configuration will also increase the electric field strength.



Figur 5-1 Electric field distribution in a 420 kV substation. The maximum field strength measured 11 kV/m at 2,5 m horizontal distance from the breakers (”bryter-rekker”) and 1,8 m above ground.

- Measurements were performed close to, and inside, buidings located close to 300 kV transmission lines. The maximum measured electric field was 1,5 kV/m with a line height of 9 m, at a horizontal distance of 9 m from the transmission line, 2 m from a wooden building wall. The electric field strength inside the house measured was 0 kV/m.

5.2 International Journal of Cancer

5.2.1 Residential and occupational exposure to 50-Hz magnetic fields and brain tumours in Norway: A population-based study

Reference 2005

L. Klaeboe, K.G. Blaasaas, T. Haldorsen, T. Tynes, “Residential and occupational exposure to 50-Hz magnetic fields and brain tumours in Norway: A population-based study”, International Journal of Cancer 115, pp. 137-141, 2005.

Article summary:

“Our case control study was conducted to investigate whether residential and occupational exposure to magnetic fields increased the risk for brain tumours in adults. Data from an occupational exposure matrix was also evaluated. The study population in this nested case-control study was made up of subjects aged 16 years and older who had resided in a broad corridor around a high-voltage power line in 1980 or during one of the years from 1980-96. Two controls were matched to each case by year of birth, sex, municipality and first year entering the cohort. The time-weighted average exposure to residential magnetic fields generated by the power lines was calculated for the exposure follow-up from 1 January 1967 to diagnosis. In addition, job titles and branches of industry were classified as categories of hours per week in a magnetic field above background level (0,1 µT). Exposures were cumulated over occupationally active years for the exposure follow-up from 1 January 1955 to diagnosis. When residential magnetic fields are evaluated, the 2 upper residential, time-weighted, average magnetic field categories showed elevated odds ratios (ORs) for all brain tumours (OR=1,6; 95% confidence interval [95% CI] 0,9-2,7 and OR=1,3; 95% CI 0,7-2,3). Occupational exposure showed no association to exposure for any site. We found an elevated risk for residential exposure to magnetic fields and brain tumours, although the risk was not significant, and no clear exposure-response pattern was found. The findings for the occupational exposure groups showed an inverse association.”

Adults spend a large portion of their time working from home, potentially exposed to magnetic fields. Previous residential studies have not taken this into account, so a considerable number of subjects classified as unexposed may, in fact, be exposed at work.

In this study, this has been considered, and the main finding is a moderately elevated risk for residential exposure to magnetic fields and brain tumours. However, the data provide no evidence of an association between brain tumours and magnetic fields when evaluating time-weighted averages.

5.3 American Journal of Epidemiology

5.3.1 A pooled analyses of extremely low-frequency magnetic fields and childhood brain tumours

Reference 2010

L. Kheifets et al., "A pooled analyses of extremely low-frequency magnetic fields and childhood brain tumours", American Journal of Epidemiology, Vol. 172, No. 7, pp. 752-761, 2010.

Article summary:

"Pooled analyses may provide etiologic insight about associations between exposure and disease. In contrast to childhood leukaemia, no pooled analyses of childhood brain tumours and exposure to extremely low-frequency magnetic fields (ELF-MFs) have been conducted. The authors carried out a pooled analysis based on primary data (1960-2001) from 10 studies of ELF-MF exposure and childhood brain tumours to assess whether the combined results, adjusted for potential confounding, indicated as association. The odds ratios for childhood brain tumours in ELF-MF exposure categories of 0,1-<0,2 µT, 0,2-<0,4 µT, and ≥0,4 µT. were 0,95 (95% confidence interval: 0,65, 1,41), 0,70 (95% CI: 0,40, 1,22), and 1,14 (95% CI: 0,61, 2,13), respectively, in comparison with exposure of <0,1 µT. Other analyses employing alternate cutpoints, further adjustment for confounders, exclusion of particular studies, stratification by type of measurement or type of residence, and a nonparametric estimate of the exposure-response relation did not reveal consistent evidence of increase childhood brain tumour risk associated with ELF-MF exposure. These results provide little evidence for an association between ELF-MF exposure and childhood brain tumours."

6 Article summary: Nordic joint papers

6.1 British Journal of Cancer

6.1.1 A pooled analysis of magnetic fields and childhood leukaemia

Reference 2000

A. Ahlbom et al*., "A pooled analysis of magnetic fields and childhood leukaemia", British Journal of Cancer (2000) 83(5), pp. 692-698, 2000.

***Swedish A. Ahlbom and Norwegian T. Tynes co-authored the article together with 10 other auhors**

Article summary:

"Previous studies have suggested an association between exposure to 50-60 Hz magnetic fields (EMF) and childhood leukaemia. We conducted a pooled analysis based on individual records from nine studies, including the most recent ones. Studies with 24/48-hour magnetic field measurements or calculated magnetic fields were included. We specified which data analyses we planned to do and how to do them before we commenced the work. The use of individual records allowed us to use the same exposure definitions, and the large numbers of subjects enabled more precise estimation of risks at high exposure levels. For the 3203 children with leukaemia and 10338 control children with estimated residential magnetic field exposures levels <0,4 µT, we observed risk estimates near the no effect level, while relative risk was 2,00 (1,27-3,13), Pvalue = 0,002). Adjustment for potential confounding variables did not appreciably change the results. For North American subjects whose residences were in the highest wire code category, the estimated summary relative risk was 1,24 (0,82-1,87). Thus, we found no evidence in the combined data for the existence of the so-called wire-code paradox. In summary, the 99,2% of children residing in homes with exposure levels <0,4 µT had estimates compatible with no increased risk, while the 0,8% of children with exposure ≥0,4 µT had a relative risk estimate of approximately 2, which is unlikely to be due to random variability. The explanation for the elevated risk is unknown, but selection bias may have accounted for some of the increase."

The purpose of the study is to answer the question whether the combined results of previous studies indicate if there is an association between EMF exposure and childhood leukaemia risk, which is larger than one would expect from random variability. The conclusion is that there is no evidence of an increased risk at magnetic field levels <0,4 µT. There is however a statistically significant relative risk estimate of 2 for childhood leukaemia in children with residential exposure to magnetic field exposure ≥0,4 µT during the year prior to diagnosis. No explanation to this result is presented other than that some of the increase might be contributed to selection bias.

6.2 ENTSO-E: Guide for implementing Directive 2013/35/EU on electromagnetic fields

Reference 2016

”Guide for implementing Directive 2013/35/EU on electromagnetic fields”, Asset implementation 2016-04-13

[Both E. Friman, Svenska kraftnät, and Mika Penttilä, Fingrid, participated in this report.]

Article summary:

”This document is intended to help the European Transmission System Operators (TSOs)/ ENTSO-E member implement the Directive. The objective is to explain how to assess exposure and to evaluate compliance, and to indicate the most critical situations for transmission activities and formulate possible measures to be taken.”

The report considers various exposure situations of TSO employees to electric and magnetic fields in order to assure compliance with Directive 2013/35/EU. The document discusses direct and indirect health effects (e.g. contact currents) of EM-fields as well as Exposure Limit Values (ELV) and Action Levels (AL) and focuses solely on occupational exposure.

When AL’s are exceeded it is necessary to assess compliance against the ELV which is the maximum allowed internal electric field. This is determined via dosimetric studies, where the relationship between the external and internal field is studied, and form the foundation to the Limit Equivalent Field (LEF).

LEF is the lowest homogenous external field value which induces internal electric field values equivalent to the ELVs. Deriving LEF from the dosimetric studies in ICNIRP 2010 would result in a LEF for the health ELV of 24-66 kV/m and 13-40 mT, while the corresponding LEF for sensory effects would be 1-3 mT.

An overview of the AL’s and LEF’s is presented in Figure 6-1

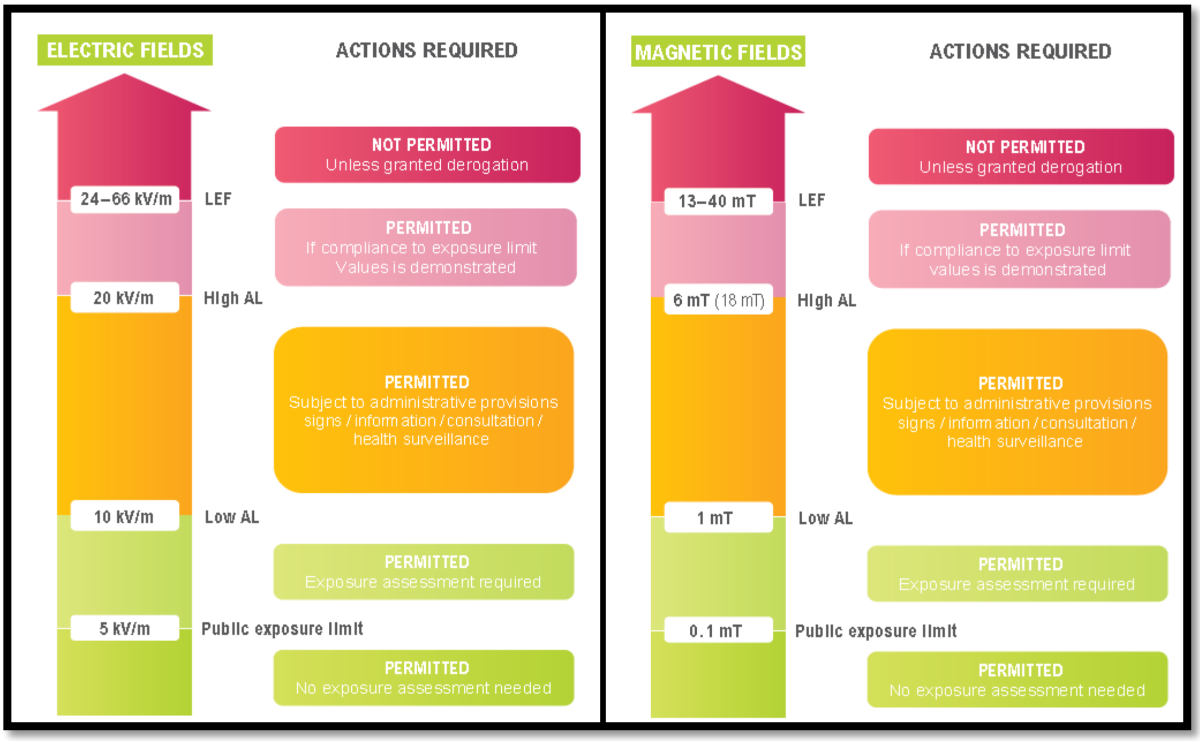


Figure 6-1 An overview of the AL's and LEF's together with permitted levels of external electric (left) and magnetic (right) field exposure.

The document continues with a focus on provision aimed at or avoiding risks as well as worker information and training.

An appropriate health examination is required when ELV is exceeded or when workers report health effects. However, long term effects are not covered by the EU Directive.

Public exposure limits are normally considered to prove adequate protection for workers at particular risk such as pregnant women. TSO's should take steps to ensure that workers carrying medical implants does not walk into high fields able to cause interference.

The report also covers a summary of exposure situations for common work tasks and situations associated with high voltage electrical work. However, the summary is general and a separate risk analysis is always recommended whenever there is a risk for high field exposures.

7 Discussion and conclusions

7.1 Swedish literature

This report covers Swedish authored studies, articles and reports on ELF electric field and magnetic flux density exposure dating as far back as to 1976 up to modern day. All articles were, however, published before June 2016 and the Swedish AFS 2016:3.

The effect of ELF fields on the human body is the main topic throughout the years. In 1976 it was concluded via measurements that elecric fields in general, and spark discharges in particular, were the most important electrophysical factors.

Not long after, in 1979, Cigré followed up with an article on a large epidemiologic study on 53 workers over a time period of 5 years to investigate the effects of long term exposure from electric fields in 400 kV substations. Neither nervous system, blood, fertility, psychological or other showed any differences (neither positive nor negative) compared to the control group. The results are supported by a study in Arbete och Hälsa from 1998, which strongly indicate very low to no impact on the human body over long time periods. Hence, attention should be directed towards acute effects.

In the 1980's Arbete och Hälsa published two articles on acute effects due to exposure to ELF electric and magnetic fields. The measurements that were performed in mainly 400 kV substations, but also for lower voltages, show that maintenance workers in substations are exposed to around 5 kV/m during more than half of the working day. The working time in electric fields above 10 kV/m typically only amounts to a few percents of the working day. A larger study of acute effects on linesmen with a mean exposure of around 3 kV/m and 23 μT during a typical work day did not reveal any statistically significant difference in their health condition which could be attributed to electric and magnetic fields.

In 2007 Elforsk started publishing reports on the subject to interpret and understand the proposal for a EU Directive from 2004. Since then Elforsk has published five reports, with the latest one being from 2012 (the 6th one will be issued in 2017). They are all good sources to background, directives, calculations, simulations and verifications as well as a short up-to-date literature reviews (not limited to the Nordic countries).

Electric field levels were calculated analytically and numerically to investigate typical exposure levels at electrical substations. The undisturbed homogenous electric field 2 m above ground at some distance away (20 – 40 cm) from steel frames can reach levels of about 15-20 kV/m for typical substations of voltages between 70 – 400 kV. The main contributor in this case is the horizontal field component, although the vertical component is most important for the current density.

A common issue arising from high electric fields is spark discharges and contact currents, which can be divided into four subcategories: 1) contact currents from a charged person to ground, 2) spark discharges between a charged person and ground, 3) contact currents from a charged object to a person, and 4) spark discharges between a charged object and a person. Normally the first three subcategories do not pose an issue, but number 4 might result in unpleasant sensations and indirect injuries (e.g. dropping equipment or falling). To help reduce the potential build up a conductive suit together with semi-conductive shoes would be an alternative.

Work inside the vicinity- or live zone is also discussed. It is primarily for specialized maintenance personnel only (in this case linesmen), but bare hand techniques will in most cases result in high electric field exposure, 20-35 kV/m along the upper part of the grounded tower legs. Planning, discipline and proper PPE (personal protective equipment) should however solve most issues. It is shown with verifications from measurements that the level of field exposure during these types of work assignments can be calculated analytically and/or numerically rather accurately.

Magnetic fields, however, are much more difficult to shield. Although possible with attenuation up to 10 times, shielding is often impractical and expensive since necessary holes and joints in the shielding material will have a large impact on the final result. The magnetic field close to cables in service will be high, with levels of about 300 - 400 µT at a high load (max 500 µT at work very close to current carrying conductors), but the field will decrease rather quickly away from the conductors. At 50 cm distance the field level has decreased to about 40 µT. Early planning and awareness in the design phase is probably the easiest and cheapest solution to reduce the magnetic field exposure. For example, a trefoil cable configuration may reduce the field provided that the load is symmetrical.

While the magnetic flux density should not pose a problem, the electric field might. The lower action level of 10 kV/m is hard to meet considering how some maintenance work assignments are performed today. The higher action level at 20 kV/m is less critical, and it should be possible to perform most work assignments up to 130 kV, including work inside the live zone using electrically insulated equipment. Electric shielding, personal protective equipment and proper tools will help to reduce the exposure.

In section 4.6.2, "Anvisning för arbetsmiljö vid arbete i E-fält", Svenska kraftnät states a few general examples of situations where the electric field might pose an issue:

- Large foundations cast on site: Up to 4-5 times amplification of the undisturbed E-field at a distance of 4-5 dm.
- Pole foundations and lesser foundations cast on site: Up to 2 times amplification of the undisturbed E-field at a distance of 3-4 dm.
- Work close to high metal structures: Up to 2-3 times amplification 2 dm from the top of the structure.
- Pointy and/or prominent objects: Caution should be taken at undisturbed E-fields even as low as 5 kV/m where there are pointy or prominent objects. Keep at a distance from head and body.

There is also an increased risk of overexposure during maintenance in substation environments. The report "Electric fältstyrka vid rondning och underhållsarbete i stationsmiljö" in section 4.6.4 presents a summarizing table with results from electric field exposure during different types of maintenance. The measurement results were collected between 2009 and 2016 and forms an important basis to understanding exposure levels in Swedish substations at 130, 220 and 400 kV. Examples of activities with high risk for overexposure (>20 kV/m) in 400 kV substations include:

- Changing lights in light posts: up to 44 kV/m

- Cable marking at current and voltage transformers: up to 36 kV/m
- Checking density guards and operating mechanism on breakers: up to 27 kV/m.
- Maintenance of two column rotary disconnectors: up to 23 kV/m.

Neither acute or long term negative health effects due to electric or magnetic field exposure under low action levels have been found, but caution is advised nevertheless. Risk groups, including for example children, pregnant women and people with pacemakers, were not included in the studies.

7.2 Finnish literature

Finland has a few prominent researchers that have made a lot of progress in this field since the late 1990’s. Studies from before the launch of Directive 2013/35/EU in 2013 (with ICNIRP guidelines and EU Directive 2004/40/EC both as applicable) primarily investigate the relationship between averaged and/or maximum current densities in the neck, contact currents and external (in-)homogeneous electric and magnetic field strengths at power frequency (50 or 60 Hz). For this purpose, a helmet/mask measuring system and human models were introduced.

Different scenarios were investigated; mainly substation maintenance tasks and public and occupational exposure close to power lines. Also, early on (late 1990’s, early 2000’s) there was a high focus on magnetic fields in living environments partly due to public awareness of theories on magnetic field induced leukaemia.

When Directive 2013/35/EU launched the focus switched to determine the internal electric field instead. A lot of the research for pre-“Directive 2013” could be re-used to further investigate the relationship between current densities, contact currents and the external field (electric or magnetic). The research now required more elaborate experiments on the human models including both measurements and numerical calculations to determine the relationship between current densities, contact currents and the internal electric fields.

Since the new Directive 2013/35/EU also states that the local maximum value shall be deciding, and not time averaged values, there is now a higher focus on inhomogeneous fields (local peak values). So far, the following areas have been investigated: Substation maintenance tasks, public and occupational exposure close to power lines, pacemakers and protective clothing.

Reviewing articles from both before and after 2013, it is not uncommon for an external electric field under power/transmission lines to slightly exceed 5 kV/m, which exceeds the European Council recommendation for public exposure from July 1999 [3].

Maintenance personnel in 400 kV substations are often over-exposed to the external electric field (above low AL in 2013/35/EU). For substations below 200 kV the electric fields tend to stay below low AL. However, there is a high risk of over exposure to external magnetic fields when working very close to energized LV switchgear.

For pacemakers the instructions given to patients remain vague although the setting of the pacemaker (uniform or bipolar) is of importance. For exposures to a 50 Hz magnetic field lower than 100 μT interference is rare.

Clothes worn by electric company workers, although flameproof, does not shield the worker from external electric field exposure any better than ”normal” clothing.

Lastly, contact currents at or below action level values may result in a local over-exposure to the internal electric field. It is argued however that the main reason for a severely limited contact current is to avoid painful shocks.

7.3 Norwegian literature

Tore Tynes has, in cooperation with Norwegian and foreign colleagues published a great number of articles since 1990 regarding long time residential and occupational exposure to magnetic fields for both adults and children. Exposure to magnetic fields $<0,4$ µT showed risk estimates close to no effect level with regards to childhood leukaemia and childhood brain tumours, and a slightly increased relative risk for exposure to magnetic fields $\geq 0,4$ µT. The results do however provide little evidence for an association between magnetic field exposure and childhood leukaemia/brain tumours, and no theory as to how these might be related.

In 1982 M. Waskaas published an article on the topic of electric field measurements in substations (occupational exposure) and at transmission lines (residential exposure). The maximum measured electric field was 11 kV/m in the 420 kV substation, and the results show very low residential exposure levels near houses close to transmission lines (<1,5 kV/m). Neither acute or long-term health effects are discussed.

8 Recommendations and further studies

To continue the work in this field it is important to understand the present situation. This can be done in a number of ways, most commonly via measurements, and both numerical and analytical calculations with the method chosen as applicable depending on the complexity of the issue.

The following topics should be investigated further:

- Overview of the current situation:
  - Due to different station/transmission line layouts and choice of apparatus the exposure levels should be calculated, mapped out and measured for both old and new substations and transmission lines, for both workers and the public.
- Tools and work routines:
  - The current market should be reviewed to compare tools and methods. Changes or upgrades should be proposed if they are deemed to be required based on experience and current literature.
- Field exposure and mitigation in the live working zone:
  - Do established procedures fulfil the requirements in ICNIRP and EU/country directives? Propose actions.
- Information and transfer of knowledge:
  - To project-, tender-, supply management and contractors. How is it done today and are there established procedures in place?
  - Develop educational material for maintenance- and other personnel working in electrical substations.
  - The technical guidelines should be complemented with relevant requirements on electric field exposure to ensure that apparatus and equipments are adapted to ensure a good work environment already in the design phase. The supplier should in other words be able to provide documentation showing the electric field around the apparatus, and locally where maintenance is required. These results should be declared for both 1- and 3-phase configurations for environments inside the substations where the apparatus are normally installed.

As a first step this literature review can be extended to include publications worldwide (or Europe at least). There is more applicable information available that would simplify the efforts to find practical approaches to comply with the EU Directive from 2013.

Proposed actions and changes must not increase the overall risk for accidents, injuries or material damages, neither directly or indirectly.

9 References

[1] DIRECTIVE 2013/35/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 26 June 2013 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (20th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC) and repealing Directive 2004/40/EC.

[2] Non-binding guide to good practice for implementing Directive 2013/35/EU. Electromagnetic Fields. Volume 1: Practical Guide. EU 2015.

[3] Council recommendation 1999/5 19/EG of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz – 300 GHz), (EGT L 199, 30.7.1999, p. 59)