Tampereen teknillinen yliopisto
Julkaisuja 422

Tampere University of Technology
Publications 422

Tommi Keikko

Technical Management of the Electric and Magnetic Fields in Electric Power System

Tampere 2003

Tampereen teknillinen yliopisto
Julkaisuja 422

Tampere University of Technology
Publications 422

Tommi Keikko

Technical Management of the Electric and Magnetic Fields in Electric Power System

Thesis for the degree of Doctor of Technology to be presented with due permission for public examination and criticism in Auditorium S1, at Tampere University of Technology, on the 6th of June 2003, at 12 o'clock noon.

Tampere 2003

ISBN 952-15-1028-5 (printed)
ISBN 952-15-1723-9 (PDF)
ISSN 1459-2045

TTY- PAINO, Tampere 2003

ABSTRACT

Electric and magnetic fields from power systems have become an important issue. The reasons for this are public concern about the possible health risks the fields may cause and disturbances caused by the fields. The aim of this thesis was to develop a technical management chain. The thesis consists of an introductory part supplemented by eight international publications. Four cases were studied: power lines, electric substations, indoor distribution substations, and arc furnace.

The methodological background of this thesis consists of theoretical background for boundary-value problems, measurements, mitigation methods and the methods for the four cases. Measurement methods were studied, to get reproducible measurements. Calculations were carried out from the same locations to get results comparable to measurements. Calculations were carried out with analytical methods, FEM and a combination of them. Mitigation methods for the cases were studied by calculations and especially with indoor distribution substations by measuring the same place before and after structural changes. A technical management chain was developed for general electric power systems and for four different management cases.

For technical management of the fields with transmission lines, the mitigation methods have been widely presented in literature. However, new viewpoints present the effect of the vegetation and the effect of the line temperature, which affects the line height having a significant effect on the fields. Based on the study, the best mitigation methods for transmission lines are the line route design and attenuation with distance to the line.

For technical management of the electric substations the occupational exposure is important, because the electric substation switchyards are forbidden areas to the public. One suitable mitigation method is attenuation with distance.

For technical management of the fields with indoor distribution substations both public and occupational exposure is possible. There is a number of possible mitigation methods. For existing structures the best mitigation method is usually a combination of several methods. Generally, the practical mitigation is forced to make a compromise for theoretic mitigation methods because of the limited space available. For new indoor distribution substations the structure can be chosen from recognized good construction methods.

Technical management of the fields with arc furnaces is highly case-specific. Generally, the occupational exposure is important. The best mitigation method is attenuation with distance, which can be taken into consideration when designing a new arc furnace. For existing structures, the best way to consider magnetic field is to avoid working near the arc furnace in the area, where the magnetic field can exceed exposure guidelines.

Based on the studied cases, it can be stated that the technical management chain for the electric system contains specification of the problem, solving of the fields with calculations and measurements, mitigation, operations and analysis of the solutions. The operational part of the technical management chain consists of electric and magnetic field mitigation. The technical management chain can be used for solving similar problems in the future.

PREFACE

This study was carried out at the Laboratory of Electrical Engineering and Health, Tampere University of Technology. The supervisor of this study was Professor Leena Korpinen, to whom I wish to express my deep gratitude. The other advisers were Professor Lauri Kettunen from Tampere University of Technology and Chief Specialist, Manager Jarmo Elovaara from Fingrid Oyj. I am sincerely grateful to them for the guidance and advice they have given me. This Doctoral thesis would not have been possible without the significant contribution of my supervisor and advisers.

In addition, I would like to thank Mauri Kauppi M.Sc., Jari Kotiniitty M.Sc., Sampsa Kuusiluoma M.Sc. (June 2003), Ossi Laitinen M.Sc., Sami Tohmola M.Sc. and Pauli Vanhala M.Sc., for their substantial contributions in the production of the publications of this thesis. I would also like to thank AvestaPolarit Chrome Oy, Fingrid Oyj, Helsinki Energy and Tampere Power Utility, for their co-operation during the research related to the publications.

Furthermore I have received guidance and co-operation from a number of other people during the research related to this topics of the thesis. I would especially like to thank Rauno Pääkkönen for his disinterested help during my research. In addition, I would like to thank the management groups of the projects related to the topics of the thesis: Kari Aarela, Jarmo Elovaara, Leena Korpinen, Matti Kuussaari, Esa Merivalli, and Per-Åke Rönnholm in "Defining and Reducing Power Frequency Magnetic Fields", Jari Eklund, Juha Haikonen, Osmo Haltia, Jarmo Elovaara, Kari Komulainen, Leena Korpinen, Sampsa Kupari, Elina Lehtomäki, Jukka Leskelä, Kari Luoma, Esa Merivalli, Reijo Munther, Anneli Nikula, Pia Oesch, Arto Puisto, Pauli Vanhala, and Esa Virtanen in "Developing Technology for Decreasing Magnetic Fields in Electric Power Transmission and Distribution", and Jarmo Elovaara, Osmo Haltia, Leena Korpinen, Elina Lehtomäki, Jukka Leskelä, and Risto Vesala in "Needs for Reducing Exposure to Broadband Electric and Magnetic Fields in Generation, Transmission and Distribution". Also, I would like to thank everyone who helped with the research related to transmission lines: Harri Hakala, and Rami Vainionmäki, electric substations: Timo Haapa, Harri Hakala, Pentti Sahinoja, and Rami Vainionmäki, indoor distribution substations: Esko Antila, Jukka Dahlström, Kari Haapala, Ilpo Häsä, Kari Jokela, Jaakko Juusela, Jari Kaitala, Jukka Karjalainen, Pekka Savolainen, Reino Seesvuori, Jorma Seitsonen, Kari Tappura, Jukka Töysä, and Veikko Veck, and arc furnace: Vesa Hänninen, Pekka Niemelä, Leo Oksanen, and Rauno Pääkkönen, and all my colleagues in Tampere University of Technology, who have taken part to the researches. Furthermore I would like to thank Mikko Hongisto for permission to use his figures.

I would like to thank Jaana and Patrick Gallagher B.A., for the final language corrections of the publications and thesis. My colleagues also deserve thanks for their support over the years.

The research related to this thesis was funded by the Graduate School in Electrical Engineering (Ministry of Education), the National Technology Agency (Tekes), ABB Transmit Oy (Medium Voltage Products, and Distribution Transformers), Fingrid Oyj, the Finnish Electricity Association (Sener), the Finnish Energy Industries Federation (Finergy) and Helsinki Energy. Financial support was also provided by the Fortum Foundation and the Ulla Tuominen Foundation. They all are gratefully acknowledged.

Finally, I want to thank my parents, Terhi and Kalevi, for their invincible support throughout my studies. My wife, Katja and my son, Lauri, deserve special thanks for their love and support, which have encouraged and given me this opportunity to study.

Tampere, May 2003

Tommi Keikko

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

1. Keikko T, Laitinen O, Isokorpi J, Tohmola S, Korpinen L. Suitability of Calculation Methods in Magnetic Field Shielding of Distribution Substation. In: Hamza, MH (ed.). Proceedings of the IASTED International Conference, Applied Modeling and Simulation, Honolulu, Hawaii, USA, August 12-14, 1998. Anaheim, Calgary, Zürich, IASTED/ACTA Press, pp. 205-208.

2. Keikko T, Isokorpi J, Korpinen L. Practical Problems in Calculating Electric Fields of Transmission Lines. Eleventh International Symposium on High-Voltage Engineering, ISH 99, IEE, London, Great Britain, August 23-27, 1999. London, Institution of Electrical Engineers, Vol. 2, pp. 103-106.

3. Isokorpi J, Keikko T, Korpinen L. Power Frequency Electric Fields at a 400 kV Substation. Eleventh International Symposium on High-Voltage Engineering, ISH 99, IEE, London, Great Britain, August 23-27, 1999. London, Institution of Electrical Engineers, Vol. 2, pp. 107-110.

4. Isokorpi J, Keikko T, Korpinen L. Power Frequency Electric and Magnetic Fields at a 110/20 kV Substation. International Conference on Electric Power Engineering, IEEE PowerTech, Budapest 99, Proceedings, Technical University of Budapest, August 29-September 2, 1999. (CD-ROM, Hungary, Hypermedia Systems Ltd., 6 p.)

5. Keikko T, Kotiniitty J, Korpinen L. Calculations of Magnetic Fields from Indoor Distribution Substation Bus Bars. Proceedings of the IEEE Power Engineering Society Summer Meeting 2000, June 9-16, 2000. Seattle, Washington, USA, IEEE, Vol. 4, pp. 2309-2314.

6. Keikko T, Isokorpi J, Korpinen L, Elovaara J, Vanhala P. Considering Electric and Magnetic Fields in Electric Power System Design in Finland. 2000 Session Papers, Group 36, 38th CIGRE Session, International Conference on Large High Voltage Electric Systems, August 27 - September 1, 2000. Paris, France, 36-102.

7. Keikko T, Kauppi M, Kuusiluoma S, Korpinen L. Magnetic Fields from Arc Furnace Considering Occupational Exposure. The Ninth International Ferroalloys Congress and the Manganese 2001 Health issues Symposium, Official Proceedings, June 3-6, 2001. Quebec City, Canada, pp. 524-529.

8. Keikko T, Kuusiluoma S, Korpinen L. Effect of Secondary Conductor Structures on Magnetic Field near Indoor Distribution Substation. Twelfth International Symposium on High-Voltage Engineering, ISH01, Bangalore, India, August 20-24, 2001. Bangalore, Department of High Voltage Engineering, Indian Institute of Science, Vol. 1, pp. 213-216.

AUTHOR'S CONTRIBUTION

The contribution of the author has been crucial in the electric and magnetic field calculations included in the publications and in the theoretical background. In publications 1, 2 and 5 … 8 the author has been the main author and has carried out the main authorial responsibility. In publications 3 and 4, the role of the author was crucial and concentrated on theoretical background.

In publication 1 the contribution of the author has been crucial in preparation, calculations and reporting.

In publication 2 the contribution of the author has been crucial in preparation, calculations and reporting, but not in electric field measurements.

In publication 3, the author of this thesis has participated in the selection of the measurement locations in the switchyard and in determining theoretical background. In the publication the author's contribution is as a co-authorial responsibility.

In publication 4 the author has participated in practical magnetic field measurements. In the publication the author's contribution is as a co-authorial responsibility.

In publication 5 the contribution of the author has been crucial in preparation, calculations and reporting.

In publication 6 the author of this thesis has participated in practical measurements of indoor distribution substations. In the publication the author's contribution has been crucial in calculations and reporting, whereas not in the further analysis included in the publication.

In publication 7 the contribution of the author has been crucial in calculations and reporting, whereas not in the preparation and measurements.

In publication 8 the contribution of the author has been crucial in the preparation, measurements, calculations and reporting.

LIST OF SYMBOLS AND NOTATIONS

a	Distance function, structural coefficient for arc furnace
A	Area of the coil
$\overline{A}$	Magnetic vector potential
A_k	Field at frequency $k \cdot 50$ Hz
$\overline{a}_x$, $\overline{a}_y$	Unit vectors
$\overline{B}$	Magnetic flux density vector
b_0	Coefficient for the length of the conductor piece
B_0	Magnetic flux density without shield, magnetic field in transformed co-ordinate system
B'_x, B'_y, B'_z	Magnetic field components in the transformed co-ordinate system
B_i	Magnetic flux density produced by the conductor piece i
$B_{i,0}$	Magnetic field calculated analytically
B_S	Magnetic flux density with shield
C	Constant
d	Span of the towers
$\overline{D}$	Electric flux density vector
d_a	Diameter of conductor a
$d\overline{a}$	Differential area vector
df	Degree of freedom
$d\overline{l}$	Differential length vector
dt	Differential time
$\overline{E}$	Electric field strength vector
E_i, E_k	Electric field at frequency i, k
$E_{L,i}$	Electric field reference level (L) at frequency i
$E_{max\,1}$, $B_{max\,1}$	Maximum measured electric or magnetic field
$E_{max\,2}$, $B_{max\,2}$	Maximum calculated electric or magnetic field
f_i, f_j	Electric or magnetic field frequency
$\overline{H}$	Magnetic field strength vector
H_j, H_k	Magnetic field at frequency j, k
$H_{L,j}$	Magnetic field reference level at frequency j
i, j	Indices
I_{before}, I_{after}	Load currents before and after the magnetic field measurement
I_k, I	Load current
I_{mean}	Mean of the load current
$\overline{J}$	Current density vector
K_1	Total distortion
K_2	Corresponding resulting cumulative field
K'_2	Corrected corresponding resulting cumulative field
l	Length of the conductor piece
$\overline{M}$	Magnetization vector
$\mathbf{P}$	Maxwell potential coefficient matrix
P_{gen}	Generated power
P_{Heat}	Power loss
P_{in}	Power in to electrical appliance
q_k	Charge per line length for conductor k
Q_E	Reactive power stored into electric field
Q_M	Reactive power stored into magnetic field
r	Viewing distance
$\overline{r}$	Viewing point vector
$\overline{r}'$	Point with source current density vector

S	Total length of the conductor in the span
S_0	Reference length of the conductor
s	Phase distance
s_k	Sag
$\mathbf{T}$	Combined transformation matrix
T_0	Reference temperature
T_i	Observation temperature
U_{mean}	Measured mean voltage
U_N	Nominal voltage
U	Voltage
v'	Volume with source current density
w	Circuit separation
x_0, y_0	Co-ordinates for observation point
x', y', z'	Transformed x, y and z co-ordinate of observation point
x_a, x_b	Horizontal co-ordinates of the conductor a and b
$x_k, y_k,$	Co-ordinates for conductor k
y_a, y_b, y	Height of the conductor a and b above ground
z	Distance from the middle span along the line
z_0	Distance from the middle span along the line to observation point
z_G	Generator impedance

α	Temperature coefficient of length
$\alpha, \beta, \gamma_1, \gamma_2$	Angles for co-ordinate system transformations
∂t	Differential time
∇V	Gradient of electric scalar potential
ΔB_{max}	Difference between measured and calculated maximum values
ΔT	Temperature change
$\varepsilon, \varepsilon_0$	Permittivity, permittivity of vacuum, $8.85419 \cdot 10^{-12}$ F/m
ϕ_k	Biological correction angle at frequency $k \cdot 50$ Hz
φ_k	Phase angle at frequency $k \cdot 50$ Hz
μ, μ_0	Permeability, permeability of vacuum, $4\pi \cdot 10^{-7}$ H/m
ρ	Volume charge density
σ	Electrical conductivity

2D-FEM	Two Dimensional Finite Element Method
AC	Alternating Current
Al	Aluminium
c	Closed integration path
CENELEC	European Committee For Electrotechnical Standardization
DC	Direct Current
EHV	Extra High Voltage (360 … 750 kV)
ELF	Extremely Low Frequency (30 … 3 000 Hz)
EMC	Electromagnetic Compatibility
EMF	Electromagnetic field
EnFo	Norwegian Electricity Association, Energiforsyningens Fellesorganisasjon
EU	European Union
FEM	Finite Element Method
GIS	Gas Insulated Substation

HVDC	High Voltage Direct Current System
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEC	International Electrotechnical Commission
IEEE	The Institute of Electrical and Electronics Engineers
LF	Low Frequency (30 … 300 kHz)
LV	Low Voltage (U<1000 V)
MV	Medium Voltage (1 … 45 kV)
n	Measurement number
P	Conductor end point
P′	Projection of point P in x-axis
P′′	Projection of point P in yz-plane
PE	Protective Earth
PEN	Common Protective Earth and Neutral conductor
p.u.	Per Unit
RMS	Root Mean Square
s	Integration surface
SE	Shielding Effectiveness
Sener	The Finnish Electricity Association
SFS	Finnish Standards Association
Std	Standard
TN-C	Grounded distribution system with common PE and N conductor
TN-S	Grounded distribution system with separate PE and N conductors
TWA	Time Weighted Average
VF	Voice Frequency (300 … 3 000 Hz)
VLF	Very Low Frequency (3 … 30 kHz)

1. INTRODUCTION

The use of electric power has increased over the past decades. Because the electric power generation and the consumption are usually in different locations, the power has to be transmitted to consumers. The Finnish transmission and distribution system consists of 400 kV, 220 kV, and 110 kV transmission lines and substations, mainly 20 kV regional distribution networks, 20/0.4 kV distribution transformers feeding the low voltage networks, and consumers.

In recent years electric and magnetic field studies have become customary. The main reason for this is the increased public concern about the possible health effects of electric and magnetic fields. Furthermore, the need to consider the fields has become more topical because of the change in the status of the guidelines considering electric and magnetic field exposure. As the interest regarding the possible health effects has increased, more information of exposure situations is being gathered.

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) published its new guidelines in 1998 [ICN98]. The guidelines cover frequency spectrum up to 300 GHz. ICNIRP has guidelines for both occupational and general public exposure. These guidelines are also the basis for a Council of the European Union recommendation on public exposure to electromagnetic fields [Cou99]. The EU Council has recommendations only for general public exposure. In Finland the Council recommendation has been taken into national legislation with the Decree on the Upper Limits of Public Exposure to Non-Ionizing Radiation by the Finnish Ministry of Social Affairs and Health, published in 2002 [Sos02].

Electric and magnetic fields may cause a problem at every stage of the system from the power production to consumption. However, electric and magnetic fields can be technically managed. Technical management of the fields covers measurements, calculations, mitigation and the design of the new system. In practice, the technical management may be complicated. Due to simultaneous sources the fields may be difficult to determine. Furthermore, mathematical formulation of the fields is difficult, and the technical structures may be complicated.

In addition, disturbances and interference caused by the fields from power systems are important in the technical management, e.g., when evaluating the need for electric and magnetic field mitigation actions. However, considering the technical management there may be an appliance that is not designed for the electromagnetic stress which occurs.

This thesis describes and analyzes the technical management chain of the electric and magnetic fields, which is the novelty value of the thesis. Other novelty values are the measurement, calculation and mitigation results.

Economic aspects have mainly been delimited from this doctoral thesis, although they are important to take into account, when carrying out technical operations in practice. In addition, measurements have been carried out before the Decree on the Upper Limits of Public Exposure to Non-Ionizing Radiation in 2002. Thus, the decree has not been taken into consideration in the measurements. Furthermore, this thesis concentrates on the power frequencies. Thus, disturbances in this thesis do not include the whole area of the electromagnetic compatibility (EMC).

2. AIMS AND PROGRESS OF THE WORK

The aim of this thesis is to develop a technical management chain of the electric and magnetic fields. To better understand the technical management in the electric power system, example cases are studied. This thesis consists of four different management cases: power lines, electric substations, indoor distribution substations, and arc furnace.

Technical management cases are studied to give examples on how calculations, measurements and mitigation can be carried out. First, electric and magnetic fields have been measured and calculated. Possible exceedings of the guidelines nearby are defined. Then, possibilities for local mitigation are determined and the theoretical background of the mitigation is described in the case. Because the examples are case-specific, the further conclusions are in general level.

Covering the cases, the author has, together with his colleagues, published the main results at international conferences. This thesis consists of an introductory part supplemented by eight international publications. This introductory part consists of four main chapters, chapters 3 … 6, followed by discussion in chapter 7 and conclusion in chapter 8.

Chapter 3 describes the main features of the Finnish power system and shortly reviews results from international literature. In addition, chapter 3 presents the Decree on the Upper Limits of Public Exposure to Non-Ionizing Radiation [Sos02]. Chapter 4 describes the theoretical background for the technical management of the electric and magnetic fields in the electric power system. Further, it is followed by example cases in chapter 5. The technical management chain of the fields in electric power systems is studied in chapter 6. The chapter presents the general operational model for the four example cases. Furthermore, a technical management chain for the general electric power system has been developed.

Publication 1 describes different calculation methods for a distribution substation. The aim of publication 1 was the suitability of the calculation methods in magnetic field shielding of the distribution substation. The main result of publication 1 was that the magnetic fields of an indoor distribution substation can be calculated analytically. The effect of the shielding can be considered with the combined finite element method (FEM) and an analytical method. The study also gives an idea to utilize the combined calculation method in other shielding cases of power systems.

Publication 2 describes practical problems when calculating electric fields of transmission lines. The aim of publication 2 was to compare calculated and measured electric fields of transmission lines and consider possible reasons for differences. The main result of publication 2 was that the calculated and measured values correspond completely to each other only in some cases. The main reasons are vegetation and variation of the ground height.

Publication 3 describes electric fields at a 400 kV electric substation. The aim of publication 3 was to study electric fields at a 400 kV substation to find out whether they exceed occupational exposure guidelines, 10 kV/m, by ICNIRP. The main result of publication 3 was that the guidelines were not exceeded. However, the highest electric field value was only slightly below the guidelines.

Publication 4 describes the electric and magnetic fields at a 110/20 kV electric substation. The aim of publication 4 was to study electric and magnetic fields at a 110/20 kV substation, find out their sources and whether or not they cause disturbances. The main result of publication 4 was that the most significant sources of magnetic fields were 20 kV cables passing below bus bars. However, the values did not exceed the magnetic field immunity levels for electric appliances in the industrial environment nor the occupational exposure guidelines.

Publication 5 describes magnetic field calculations for an indoor distribution substation. The aim of publication 5 was to calculate the magnetic fields of transformer bus bars with different calculating methods and to analyze shielding alternatives. The main result of publication 5 was that the analytical methods are accurate enough for transformer bus bar magnetic field calculations.

Publication 6 deals with electric power system design in Finland considering electric and magnetic fields. The publication describes critical locations in power systems considering the exposure guidelines: 400 kV transmission lines and indoor distribution substations. The aim of publication 6 was to investigate how the new exposure guidelines can be considered in the power system design. The main results of publication 6 show that the guidelines will create big problems for the transmission and distribution companies if they become mandatory. Based on publication 6, it is important to consider the reduction already at the design phase, because the reduction of the fields of the existing installations is difficult.

Publication 7 deals with magnetic fields of an arc furnace considering occupational exposure. The aim of publication 7 was to investigate magnetic fields from arc furnaces with measurements as well as with analytical and FEM calculations, and to compare the results with occupational exposure guidelines. The main result of publication 7 was that measured and calculated values exceeded the ICNIRP exposure guidelines.

Publication 8 describes the effect of secondary conductor structures on the magnetic field near indoor distribution substations. The aim of publication 8 was to study the effects of the secondary cable or bus bar system on the magnetic field above or beside the indoor distribution substation. The main result of publication 8 was that the secondary system of the indoor distribution substation is a significant source of magnetic fields. In addition, publication 8 describes possible mitigation methods.

Based on the results of the publications a technical management chain for the transmission lines, electric substations, indoor distribution substations, and arc furnaces has been developed. In addition, the technical management chain for a general electric power system has been described.

3. ELECTRIC AND MAGNETIC FIELDS OF ELECTRICAL POWER SYSTEM

An association for electricity co-operation in the Nordic countries Denmark, Finland, Iceland, Norway and Sweden is called Nordel. Primary task of the Nordel is to create prerequisites for efficient utilization of the Nordic electricity system. In Finland the extra high voltage (EHV) system is owned and operated by Fingrid Oyj whereas regional distribution network companies own and operate the regional networks.

The overhead line network and outdoor substations are very commonly used, whereas cable networks and indoor substations are mainly used only in municipalities. The total length of the different line types in 2001 were 3 926 km (400 kV), 2 400 km (220 kV), 15 200 km (110 kV) and 133 827 km (1 – 70 kV) [Ele03]. The number of the substations in the national grid was about 57 and in regional networks about 750 [Ele98]. The number of the medium/low voltage (MV/LV) substations was 126 108 [Ele03]. Industry and usually consumers are connected to the LV network.

A mind map for electric power system is presented as a way of helping to understand the factors of technical management. A mind map for electric and magnetic fields of electric power system is presented in figure 3.1.

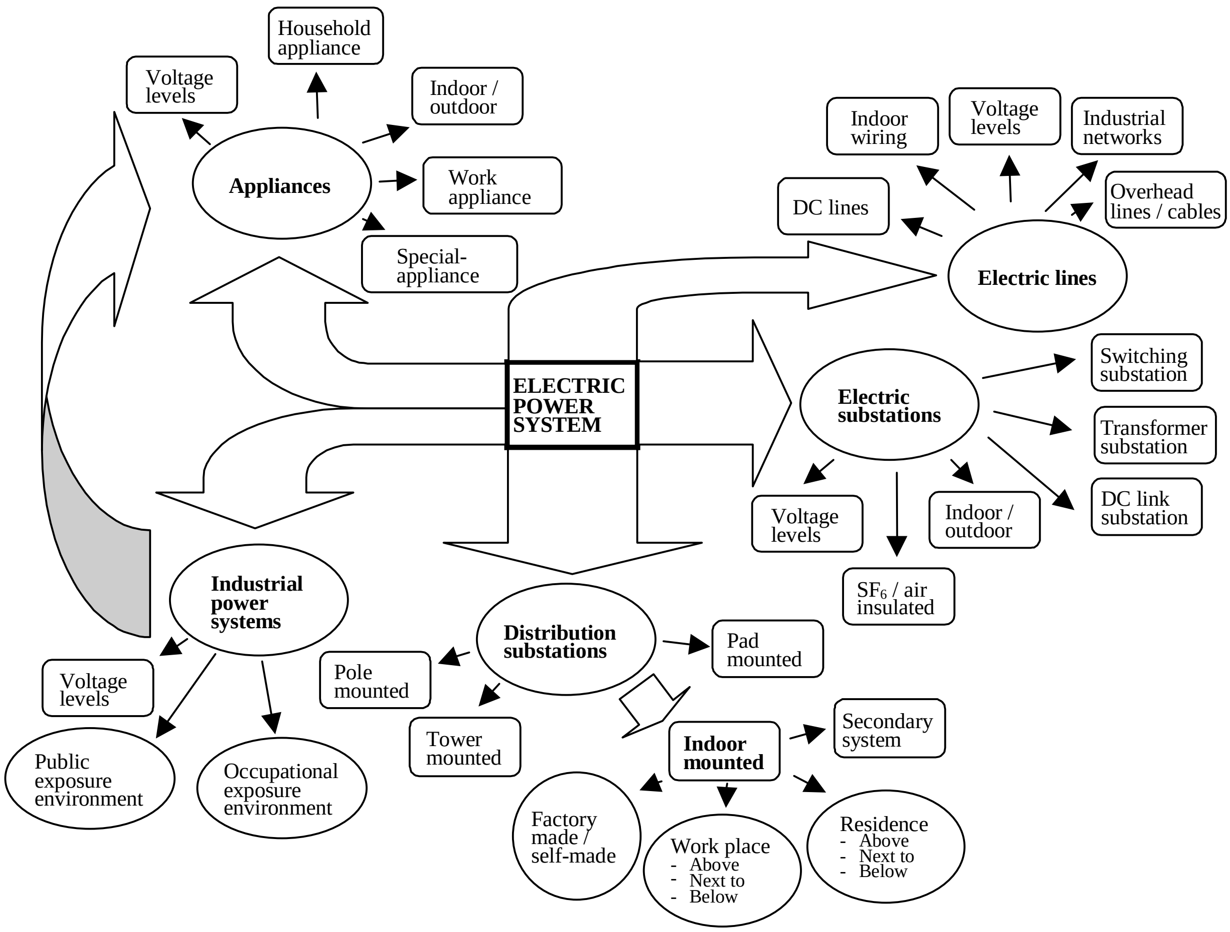


Figure 3.1. Mind map for factors of technical management of the fields.

There are two reasons for the mitigation of the electric and magnetic fields. One reason is the human exposure, and the other is the electromagnetic compatibility and disturbances.

3.1 TRANSMISSION LINES

Transmission lines are used to transfer the power long distances. The lines have three phase conductors and usually two shield wires. In field calculations the factors, which have to be taken into consideration, are phase distances, phase angles of voltages and currents, distances between conductors and observation point. Symmetry in load decreases the fields, because the fields from different phases reduce each other. However, the effect of the asymmetry is not constant.

The load changes do not have much effect on electric fields because the operational voltage of the lines is kept nearly constant. In transmission voltage levels the operation of the system is kept as balanced as possible. In Finland, the system is usually sufficient for balanced voltages. Whereas, the magnetic field is directly proportional to the current (power) transmitted through the lines and varies as a function of the load.

The load current in conductors can vary greatly depending on the consumption. That is why the current has to be used as a statistical variable. In Finnish 110 … 400 kV transmission lines the current duration in 1992 has been analyzed in references [Hon93, Hon94]. Figure 3.2 presents current duration curves for exemplary lines [Hon93].

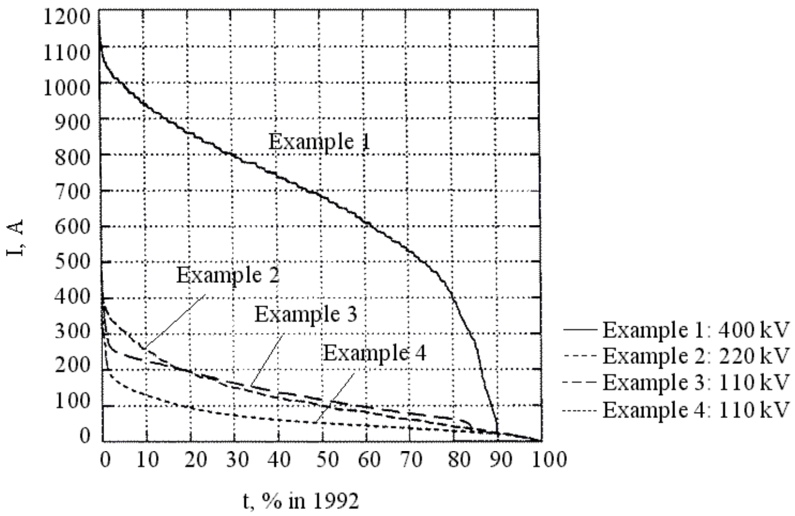


Figure 3.2. Current duration curves for exemplary 110 … 400 kV transmission lines in Finland in 1992 [Hon93].

After the study, changes in society and the liberation of the Finnish electricity market during the past decade have affected power consumption, thus the present currents may be different.

The fields have been measured and calculated widely in previous studies [Hon93, Hon94]. In foreign studies values obtained have been for 132 kV transmission lines 0.65 kV/m and 4 μT (load current 402 A) and for 400 kV double circuit line 1.25 … 6 kV/m and 4 … 9.8 μT (650 … 2325 A) [Far 97, Sri98]. In some studies only the magnetic field values have been studied, being for 765 kV single circuit line 26 μT (2000 A) and for 400 kV double circuit line 6 μT (1540 A) [Shp96, Swa95]. Load current is not specified in some magnetic field studies. Measured values have been for 120 kV double circuit line 3.5 μT, for 230 kV double circuit line 6.6 μT, for 315 kV double circuit line 9.8 μT and for 735 kV horizontal line 28.4 μT [Mar93]. However, geometrical factors of the line and towers have a high impact on the field values decreasing the comparability in the studies.

3.2 ELECTRIC SUBSTATIONS

The main purpose of the electric substation is to make switching actions possible, transform voltage to a more appropriate level, and take care of the protection of the feedings. All electrical structures may cause fields, e.g., switching equipment, feeding lines, VAR compensation, and power cables [Pre96, Won94]. The voltage level and the construction of the substation have a strong effect on the electric field. In electrical substations there may be both, disturbances and human exposure caused by the fields.

Disturbances have been reported with sensitive electrical appliances, like measurement and control equipment, and also with the displays of computers used for controlling the substation [Hof95, Jae00, Wig94]. Another source of the disturbances is switching transients, which can create harmful fields, but cannot be fully eliminated [Wig89, Wig94]. Also the grounding system may affect the fields. Nevertheless, the function of the grounding system is protection against earth faults and lightning striking the substation [Xio94].

Occupational exposure guidelines (presented later) can be exceeded in working situations in electrical substations [Jae00, Sri98]. The occupational exposure is possible with enlargement and maintenance work of the substation [Far97]. Measured and calculated results of previous studies are presented in Table 3.1.

Table 3.1. Fields levels of electric substations in previous studies. U_{oper} is operational voltage.

Electric field				
U_N, kV	**Location**	**U_{oper}, kV**	**E, kV/m**	**Additional information, reference**
750	switchyard	-	15	Measured, [Cri96]
400	switchyard	-	13.5	Measured, [Cri96]
400/220	220 kV switchyard	190	2.5	Measured, [Sri98]
Magnetic field				
U_N, kV	**Location**	**P, MVA**	**B, µT**	**Additional information, reference**
735/315/230	735 kV switchyard	-	10	Measured, [Mar93]
400/220	220 kV switchyard	39	25	Measured, operational voltage 190 kV, [Sri98]
315/25	switchyard	-	18	Measured, [Mar93]
187/66	switchyard	322	30	Calculated, [Hay92]
132/66	transformer	57 … 59	45 … 53	Measured, open type switchgear, [Far97]
120/25	transformer	-	9	Measured, [Mar93]
115/13.8	transformer	-	200	Measured, outdoor type, [Far98]
115/13.8	switchyard	80	20	Measured and calculated, [Dai94]
77/6.6	transformer	15	10	Measured, distance 2 m, [Kat99]
69/13.8	transformer	-	100	Measured, indoor type, [Far98]

The previous values in Table 3.1 are case-specific. In addition, the varying load current affects magnetic field results. The exposure guidelines (presented later) may occur with air insulated substations as well as with gas insulated substations (GIS) [Won94]. The enclosure of the gas-insulated components reduces electric and magnetic fields, though the reduction is not complete for magnetic field. Thus, the planning of the structures and locations is essential when carrying out the reduction [And94].

3.3 INDOOR DISTRIBUTION SUBSTATIONS

Indoor distribution substation transforms medium voltages (MV) to low voltage (LV). In Finland indoor distribution transformers are operated at 20/0.4 kV or 10/0.4 kV. In Finland indoor distribution substations are commonly used in areas with apartment buildings. From

MV/LV distribution substations, the indoor distribution substations are more important exposure and disturbance sources, than outer and tower MV/LV distribution substations, because they are usually closer to apartments or consumer appliances. They can cause disturbances or exposure in the apartments above the indoor substation [Miz99], or inside the indoor substation [Hof95]. Typical measured values in indoor distribution substations with load currents up to 1000 A are presented in Table 3.2 [Tik95].

Table 3.2. Typical magnetic fields (50 Hz) for indoor distribution substations. Load current is up to 1000 A. [Tik95]

Source	***B*, µT**
Inside the substation:	
General level in substation	2…5
Near the cover of the LV switchgear	5…60
Outside the substation:	
Surface of the wall	1.5…10
Above the roof (1 m)	2…12

Human exposure may appear in a residence above an indoor distribution substation especially at floor level [Häm02]. In a residence above disturbances with a computer display or television picture may also appear. Disturbances can also be caused by indoor wiring, which has not been studied as much as the other magnetic field and interference sources [Bel99, Kot00]. Interference may appear due to the electronic components, coils and current circuits, which are installed in appliances. However, the appliances are not always designed for the present field conditions, which may occur in the space above the indoor distribution substation. Appliances might be in close surroundings of electric power systems, especially near indoor distribution substations. Special attention should be paid to the immunity level of the equipment, which is installed in close proximity to the interference sources [Hei89].

One important magnetic field source is a secondary LV cable or bus bar system between the transformer and LV switchgear [Kei01c]. Bus bars are usually placed horizontally [Kei98a, Kot99]. The distance between the phases is generally 100 … 200 mm for 400 V bus bars [Tik95]. The current in secondary LV conductors is proportional to the load of the substation. In addition, the magnitude of the magnetic field depends on the observation distance, phase distance and clearances, symmetry of the load between phases and the structure of the LV conductors [EMC97, Has93, Has94, Hon93]. Also MV cables and switchgear can be significant magnetic field sources, especially, if the magnetic field from the LV structures is reduced. The length of the LV conductors especially affects the spreading of the magnetic field.

Factors, which affect magnetic fields are varying load current, varying asymmetry, vagabond current from the ground current, electrical equipment used, and loaded conductors in the building. Unbalanced loads are common with systems containing one-phase appliances, which cause unbalanced load current in feeders of the indoor distribution substation. In addition, vagabond currents can flow in all grounded conductive systems increasing magnetic fields in buildings. For example, in Finland the metallic water pipe system is grounded, which can also cause the current to flow in it. The mounting and wiring techniques and the harmonics of the current also influence the magnetic field.

Magnetic fields previously measured in industrial buildings in the space above the indoor distribution substation (11/0.36 kV) have been 48 µT and in residential building 10 - 20 µT [Far 97]. Measured values near pad mounted outdoor distribution substation have been up to 1.5 µT [Mar93].

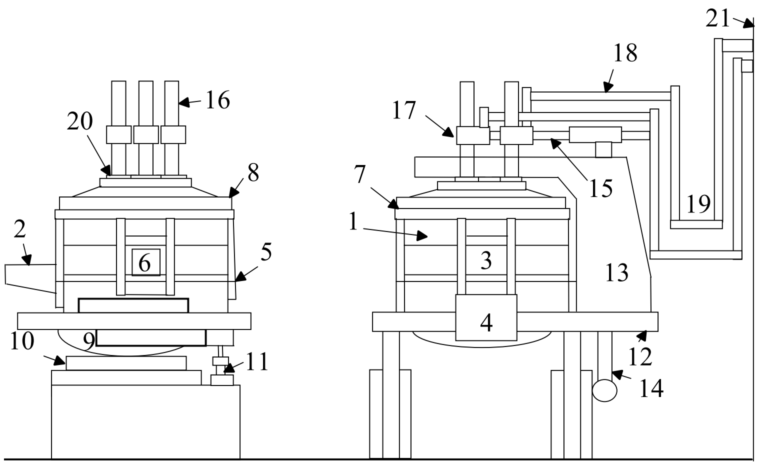
3.4 INDUSTRIAL PROCESSES: ARC FURNACE

Processes vary between industrial areas. Similarly the levels of electric and magnetic fields are different. The fields may cause disturbances or occupational exposure. However, the enclosure of the industrial apparatus or equipment, shields the ELF electric field almost completely. A capacitive interference may occur inside the enclosure. Table 3.3 presents magnetic field examples in industry [Pää99].

Table 3.3. Magnetic field examples in industrial environments during a work [Pää99].

Industrial environment	***B*, µT**
Contact welding (50 Hz)	3 000
Near arc furnace (50 Hz)	2 000
Near induction furnace (10 … 20 kHz)	<10
Use of magnetizing tools in non-destructive testing (50 Hz)	1 000
Near magnetic flux inspection bench (50 Hz)	1 000
Near high current cables in industry (50 Hz)	500 … 1 000

An arc furnace is an important magnetic field source [Bel92, Bir93, Roq97]. An arc furnace is commonly used in industrial melting processes. The arc furnace consumes AC or DC. Both of which produce high magnetic fields [Bir93]. Figure 3.3 presents a drawing of an arc furnace.



Content:
1. Shell
2. Pouring spout
3. Rear door
4. Slag apron
5. Sill line
6. Side door
7. Bezel ring
8. Roof ring
9. Rocker
10. Rocker rail
11. Tilt cylinder
12. Main (tilting) platform
13. Roof removal jib structure
14. Electrode mast stem
15. Electrode mast arm
16. Electrode
17. Electrode holder
18. Bus tube
19. Secondary power cables
20. Electrode gland
21. Electrical equipment vault

Figure 3.3. Drawing of a three-phase AC arc furnace [Jon98].

In an arc furnace a grounded steel sheet around the heat insulation acts as a Faraday's cage. The steel sheet shields the electric field from the electrodes of the arc furnace. Magnetic field from the arc furnace is a special kind of source because of the high magnitude and great variation of the field, harmonics, spatial asymmetry and individual structure of the feeding conductors [Bel92, Bir93, Roq97]. Previously, a 100 µT is exceeded at the distance of up to 10 m from the center of the arc furnace (power 40 - 50 MW, current 100 kA) [Tho92]. The highest measured value (current 120 kA, distance 7.5 m from the center) has been 1400 µT. In addition, it is estimated that a 2 mT magnetic field may occur nearby the arc furnace [Tho92].

Unhomogeneity in filling causes unbalanced load currents, which may increase magnetic field and also spatial asymmetry in magnetic field [Bel92, Bir94, Fou96, Roq97]. On the other hand, the steel sheet around the furnace reduces the field from the arc furnace outside [Bir94, Kei99a].

3.5 REVIEW OF PRESENT GUIDELINES

Guidelines for human exposure

The need to consider the fields has become more topical because of the change in the status of the guidelines considering exposure. Human exposure and biological effects from electric and magnetic fields have been studied from many point of views. The main impact of the electric and magnetic fields is the stimulation of the tissue [Nye91]. Basically occupational exposure depends on the specific characteristics of the electric and magnetic field sources present, the type of the working area and the work time patterns of the worker [Far97]. Although electric and magnetic fields are compared to the recommended reference levels in practice, basic restrictions are internal current densities.

Exposure guidelines for occupational and general public are derived from the basic restrictions of the internal current. Internal currents have been studied previously with the approximate calculation methods [Ash98, Fal98, Kor99, Kor00a, Nye91] and with the numerical finite element method (FEM) [Bar95, Ols99].

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) published its new guidelines in 1998 [ICN98] replacing previous interim guidelines [INI90]. The interim guidelines were only for 50/60 Hz fields while the new guidelines cover frequency spectrum up to 300 GHz. ICNIRP has guidelines for both occupational and general public exposure. Recommendations are based on electrical stimulation effects on humans. At frequencies from 4 Hz to 1 kHz, basic restrictions on exposure are based on the effects of internal current. From known threshold values of stimulation, 100 mA/m^2, basic restrictions are derived for induced current densities using safety factors.

The basic restriction at the power frequency band is 10 mA/m^2 [ICN98]. ICNIRP guidelines are also the basis for the Council of the European Union recommendation on public exposure to electromagnetic fields [Cou99]. The Council of the European Union (EU) has recommendations for general public exposure.

Reference levels for fields are obtained from basic restrictions by mathematical modeling or by extrapolation from laboratory investigations at specific frequencies. In reference levels for the public, additional safety factors are used [ICN98]. At 50 Hz the guidelines are 5 kV/m and 100 µT for the public and 10 kV/m and 500 µT for occupational exposure. The following requirements can be applied to the exposure [ICN98]:

$$\sum_{i=1Hz}^{1MHz} \frac{E_i}{E_{L,i}} \leq 1 \qquad (1)$$

$$\sum_{j=1Hz}^{65kHz} \frac{H_j}{H_{L,j}} \leq 1 \qquad (2)$$

where E_i and H_j are the electric and magnetic fields at frequencies *i* and *j*, respectively, and $E_{L,i}$ and $H_{L,j}$ are the reference levels at frequencies *i* and *j*, respectively.

Upper magnetic field limits are different for public and occupational exposure, respectively. Reference levels of ICNIRP guidelines are presented in Table 3.4.

Table 3.4. ICNIRP guidelines for occupational and public exposure [ICN98].

Frequency band, Hz	*E*, V/m, occupational	*E*, V/m, public	*H*, A/m, occupational	*H*, A/m, public	*B*, µT, occupational	*B*, µT, public
Up to 1	-	-	$1.63 \cdot 10^5$	$3.2 \cdot 10^4$	$2 \cdot 10^5$	$4 \cdot 10^4$
1-8	20 000	10 000	$1.63 \cdot 10^5/f^2$	$3.2 \cdot 10^4/f^2$	$2 \cdot 10^5/f^2$	$4 \cdot 10^4/f^2$
8-25	20 000	10 000	$2 \cdot 10^4/f$	$4 \cdot 10^3/f$	$25 \cdot 10^3/f$	$5 \cdot 10^3/f$
$(0.025\text{-}0.8) \cdot 10^3$	$5 \cdot 10^5/f$	$25 \cdot 10^4/f$	$2 \cdot 10^4/f$	$4 \cdot 10^3/f$	$25 \cdot 10^3/f$	$5 \cdot 10^3/f$
$(0.8\text{-}0.82) \cdot 10^3$	$5 \cdot 10^5/f$	$25 \cdot 10^4/f$	$2 \cdot 10^4/f$	5	$25 \cdot 10^3/f$	6.25
$(0.82\text{-}3) \cdot 10^3$	610	$25 \cdot 10^4/f$	24.4	5	30.7	6.25
$(3\text{-}65) \cdot 10^3$	610	87	24.4	5	30.7	6.25
$(0.065\text{-}0.15) \cdot 10^6$	610	87	$1.6 \cdot 10^6/f$	5	$2.0 \cdot 10^6/f$	6.25
$(0.15\text{-}1) \cdot 10^6$	610	87	$1.6 \cdot 10^6/f$	$0.73 \cdot 10^6/f$	$2.0 \cdot 10^6/f$	$0.92 \cdot 10^6/f$
$(1\text{-}10) \cdot 10^6$	$610 \cdot 10^6/f$	$87 \cdot 10^3/f^{0.5}$	$1.6 \cdot 10^6/f$	$0.73 \cdot 10^6/f$	$2.0 \cdot 10^6/f$	$0.92 \cdot 10^6/f$
$(10\text{-}400) \cdot 10^6$	61	28	0.16	0.073	0.2	0.092
$(400\text{-}2000) \cdot 10^6$	$3 \cdot f^{0.5} \cdot 10^{-3}$	$1.375 \cdot f^{0.5} \cdot 10^{-3}$	$0.008 \cdot f^{0.5} \cdot 10^{-3}$	$0.0037 \cdot f^{0.5} \cdot 10^{-3}$	$0.01 \cdot f^{0.5} \cdot 10^{-3}$	$0.0046 \cdot f^{0.5} \cdot 10^{-3}$
$(2\text{-}300) \cdot 10^9$	137	61	0.36	0.16	0.45	0.2

In practice, the public reference levels are obtained with equations 3 and 4, when the frequencies are 25 ... 3 000 Hz and 25 … 800 Hz, respectively.

$$E_{L,i} = \frac{250}{f_i}\, Hz \frac{kV}{m} = \frac{5}{i} \frac{kV}{m} = \frac{E_{L,1}}{i} \tag{3}$$

$$H_{L,j} = \frac{4000}{f_j}\, Hz \frac{A}{m} = \frac{80}{j} \frac{A}{m} = \frac{H_{L,1}}{j} \tag{4}$$

where f_i and f_j are the electric and magnetic field frequencies. This means that equations 1 and 2 can be converted to the forms 5 and 6 when they are applied for public exposure at frequencies 50 Hz ... 1 MHz with electric fields and at 50 Hz ... 150 kHz with magnetic fields.

$$\left(\sum_{k=1}^{60} \frac{E_k}{E_{L,1}/k} + \sum_{k=61}^{20000} \frac{E_k}{E_{L,1} \Big/ E_{L,1}/87}\right) = \frac{1}{E_{L,1}} \left(\sum_{k=1}^{60} kE_k + \sum_{k=61}^{20000} 57.47 \cdot E_k\right) \le 1 \tag{5}$$

$$\sum_{k=1}^{16} \frac{H_k}{H_{L,1}/k} + \sum_{k=17}^{3000} \frac{H_k}{H_{L,1} \Big/ H_{L,1}/5}) = \frac{1}{H_{L,1}} \left(\sum_{k=1}^{16} kH_k + \sum_{k=17}^{3000} 16 \cdot H_k\right) \le 1 \tag{6}$$

where k is index of harmonic frequency. The meaning of the ICNIRP guidelines and EU Council recommendation is that the harmonic components occur simultaneously. In practice, this may be far from the actual situation. The harmonic frequencies can even reduce the peak value of power frequency field due to phase displacements.

The Finnish Ministry of Social Affairs and Health has set a Decree on the Upper Limits of Public Exposure to Non-Ionizing Radiation in 2002 [Sos02]. The decree is based on the Council of the European Union recommendation for public exposure and the reference levels are the same up to 100 kHz. If the duration of the exposure is not significant, the values in Table 3.4 for public magnetic field exposure are applied fivefold [Sos02]. Similarly, for public electric field exposure the limit values are applied threefold [Sos02]. The short-term exposure limits are based on ICNIRP guidelines for magnetic fields, and for electric fields both ICNIRP guidelines and practical reasons. For 50 Hz fields the short-term exposure limit values are 500 µT and 15 kV/m. In addition, the phase angles of the electric and magnetic field spectrum have been taken into consideration, when coupling different frequencies. This kind of coupling can be utilized by using field meters with output connected to RC filters and voltmeter, which takes into consideration different frequencies and phase angles [Jok00].

The authorities in the UK have issued a statement based on the guidelines presented previously for limiting exposure to electric and magnetic fields [Boa93]. The legislation in Switzerland differs from the guidelines by making reference to the precautionary principle [Swi99]. In Switzerland, the exposure limit values are the same as the values in the EU Council recommendation for public exposure, but they have precautionary emission limitations for installations [Swi99]. However, in Swiss legislation there is also an economical acceptability option. Also in Italy, the precautionary principle has been presented with legislation plans [Seg01]. However, the legislation has not been passed so far. In German legislation the limit values for occupational exposure are generally higher than ICNIRP guidelines [Ele99].

Guidelines for magnetic field disturbances

The magnetic fields of power systems have caused disturbances in some sensitive electrical appliances. Any appliance is allowed neither to cause disturbances to other electrical appliances nor to be disturbed by any other appliance. To give a unique answer for the responsibilities with the EMC problems, the EMC standards set immunity levels for magnetic fields [SFS91, SFS96]. The immunity levels mentioned for 50 Hz magnetic field are in residential, commercial and light industry 3.8 μT (1.3 μT for displays) and in industry 38 μT (3.8 μT for displays). When higher magnetic fields occur the disturbances are allowed, but the function has to recover after the field has fallen below the limit value. However, small vibrations are allowed with the displays even under the limit values.

Professional electronic devices have their own environmental classifications and stress levels [SFS88]. Environmental classifications mean places with the same kind of stress conditions. Classified environments are outdoors, hospital, telecommunication station, office, industry and electrical substation. Environmental classifications are presented in Table 3.5.

Table 3.5. Immunity levels for professional electronic devices and testing with 50 Hz disturbing fields [SFS88].

Environmental classifications	Stress level, A/m (μT)	Stress level in testing, function		
		Normal, A/m (μT)	Small disturbance, A/m (μT)	Big disturbance, A/m (μT)
Outdoors	60 (75.4)	60 (75.4)	100 (126)	200 (251)
Hospital	30 (37.7)	30 (37.7)	100 (126)	200 (251)
Telecommunication station	30 (37.7)	30 (37.7)	100 (126)	200 (251)
Office	30 (37.7)	10 (12.6)	30 (37.7)	100 (126)
Industry	30 (37.7)	30 (37.7)	—	400 (503)
Electrical substation	30 (37.7)	30 (37.7)	—	400 (503)

For magnetic fields there are stress levels for environmental classifications and testing values. Values are based on measurement results and experience so that the probability of the value exceeding is 1% [SFS88].

Harmonics of the fields in electric power system

Finnish national standard gives requirements for the harmonic voltages and currents [Sen99]. Requirements for the harmonic currents in LV, MV, and above 110 kV system and harmonic voltages in 110 kV system are presented in Table 3.6 up to 50th harmonic.

Table 3.6. Harmonics guidelines in LV, MV, and above 110 kV system up to 50th harmonic. Harmonic content of voltage is $p_u(j)$ and current is $p_i(j)$. [Sen99]

	Low voltage system according to current	**Medium voltage system according to current**	**$U_N \geq 110$ kV according to current**	**$U_N \geq 110$ kV according to voltage**
j	$p_i(j)$, **p.u.**	$p_i(j)$, **p.u.**	$p_i(j)$, **p.u.**	$p_u(j)$, **p.u.**
1	1.000	1.000	1.000	1.000
2	0.070	0.070	0.030	0.015
3	0.070	0.070	0.040	0.020
4	0.070	0.070	0.020	0.010
5	0.070	0.070	0.040	0.020
6	0.070	0.070	0.010	0.005
7	0.070	0.070	0.040	0.020
8	0.070	0.070	0.004	0.002
9	0.070	0.070	0.020	0.010
…	…	…	…	…
20	0.025	0.025	0.004	0.002
…	…	…	…	…
30	0.010	0.010	0.004	0.002
…	…	…	…	…
50	0.005	0.005	0.004	0.002
THD	<0.10 (25…200 A) <0.08 (>200 A)	<0.08	<0.06	<0.03

In addition to the limit values for harmonics, the standard specifies a total harmonic distortion (THD) [Sen99]. For voltages the Finnish standard follows the corresponding CENELEC-standard 50160 [CEN94], but also gives requirements for the harmonic currents. Individual levels are given for each harmonic separately for transmission and distribution networks. Total distortion K_1 based on THD is presented in the following equation.

$$K_1 = \frac{\sqrt{\sum_{k=1}^{>1300} A_k^2}}{A_1} = \sqrt{1 + \sum_{k=2}^{>1300} \left(\frac{A_k}{A_1} \right)^2} = \sqrt{1 + THD^2} \tag{7}$$

where A_k is the field at frequency $k \cdot 50$ Hz.

The meaning of the equation 7 is that the phases of the harmonics occur randomly. The requirements presented by ICNIRP in previous equations 1 and 2 can be formatted in the same way as equation 7. The 50 Hz component is used as a reference value (1.0 p.u.) and the corresponding resulting cumulative level is labeled K_2.

$$K_2 = 1 + \sum_{k=2}^{16/60} k \frac{A_k}{A_1} + \sum_{k=17/61}^{3000/20000} C \frac{A_k}{A_1} \tag{8}$$

where the constant C has different values for the effects of voltages and currents.

To see the effect of harmonics, a simple analysis was made in publication 6 (Table 1) assuming that the voltage and current contain as much harmonics as is allowed for individual harmonics by the national Finnish standard [Sen99]. In reality, these high harmonics levels do not appear simultaneously.

The ICNIRP calculation method means, that if all 2nd … 15th harmonics of the voltage are present simultaneously in the above 110 kV network, the magnitude of the 50 Hz electric field should be limited to a value which is less than 50% of the value with no harmonics present. On the other hand, if the square root of the square sum of the components were used, even the use of the first 45 harmonics would result in a value $K_1 < 1.002$. If above 110 kV system has maximum current harmonics up to eight, the 50 Hz allowed field level 100 µT (80 A/m) is reduced by 50% to fulfill the condition of equation 2. If the LV ($U_N \leq 0.4$ kV) system has maximum current harmonics up to the fifth, the allowed field level is reduced by 50% to fulfill condition of equation 2. With the electric field there is usually no difficulty, because surrounding material nearby reduces the electric field. [Kei00b]

However, a more accurate analysis can be presented, when the harmonic components are added considering the phase angles [Jok00]. Thus, the value K'_2 for any time value t can be presented as follows.

$$K'_2 = \sum_{k=1}^{16/60} k \frac{A_k}{A_1} \cos(k\omega t + \varphi_k - \phi_k) + \sum_{k=17/61}^{3000/20000} C \frac{A_k}{A_1} \cos(k\omega t + \varphi_k - \phi_k) \qquad (9)$$

where φ_k is the phase angle and ϕ_k is a biological correction angle at frequency $k \cdot 50$ Hz. The limit value for K'_2 is less or equal to one as presented previously in equations 5 and 6. Equation 9 has the same form as is in the equations of the Decree on the Upper Limits of Public Exposure to Non-Ionizing Radiation by Finnish Ministry of Social Affairs and Health in 2002 [Sos02]. The form of equation 9 has been based in the latest ICNIRP statement, which is a guide for determining exposure to pulsed and non-sinusoidal waveforms [ICN03]. Measurement methods in the latest statement can be considered as additional methods for the methods presented in previous guidelines [ICN98].

Regulation for environmental effect analysis

There is a regulation for environmental effect analysis with transmission lines above 220 kV in Finnish legislation. Environmental effect analysis has to be carried out with new transmission lines and when the existing lines are changed or renewed. The analysis consists of effects on natural conditions, urban structure, landscape, living conditions, health, and comfort. As a part of the analysis, electric and magnetic fields are also considered in the design. [Fin99]

4. METHODOLOGICAL BACKGROUND

The vectorial character of the electric and magnetic fields is taken into consideration in measurements, calculations and mitigation. The fields can be represented by a vector field, which has a magnitude and a direction. The electric field causes a force, which strives to move charges in the field. Every individual charge creates an electric field, the direction of which is away from the positive charge. The local electric field is a vector sum of the electric field components. As well, every individual movement charge creates a magnetic field, the direction of which is perpendicular to the direction of movement and the viewing distance vector. The local magnetic field is a vector sum of the components.

4.1 THEORETICAL BACKGROUND

Both electric and magnetic field realizes the Maxwell's equations: Gauss's law, Faraday's law, Ampere's law and the law of no isolated magnetic poles. The only exception is that the displacement current can be neglected with power frequencies, because the displacement current and the energy stored in the field are small. Maxwell's equations are represented in equations 10 … 13, respectively [Rei62].

$$\oint_S \overline{D} \cdot d\overline{a} = \int_V \rho dv \qquad (10)$$

where $\overline{D}$ is electric flux density, $d\overline{a}$ is differential area, S is the integration surface, ρ is the volume charge density, dv is differential volume, and V is the integration volume, which the surface S bounds.

$$\oint_C \overline{E} \cdot d\overline{l} = -\frac{d}{dt}\int_S \overline{B} \cdot d\overline{a} \qquad (11)$$

where $\overline{E}$ is electric field strength, $d\overline{l}$ is differential length, C is the closed integration path, $\overline{B}$ is magnetic flux density and dt is differential time.

$$\oint_C \overline{H} \cdot d\overline{l} = \int_S \overline{J} \cdot d\overline{a} + \frac{d}{dt}\int_S \overline{D} \cdot d\overline{a} \qquad (12)$$

where $\overline{H}$ is magnetic field strength and $\overline{J}$ is current density.

$$\oint_S \overline{B} \cdot d\overline{a} = 0 \qquad (13)$$

The connection between different statements of electric and magnetic fields is based on the equations for the fields in medium. These equations can be represented as follows.

$$\overline{D} = \varepsilon \overline{E} \qquad (14)$$

where ε is permittivity of the medium.

$$\overline{B} = \mu \overline{H} \qquad (15)$$

where μ is permeability of the medium. The connection between electric field and current density in conductive material can be represented as follows.

$$\overline{J} = \sigma \overline{E} \qquad (16)$$

Equations 10 … 16 include the whole area of electromagnetism and cover all possible situations. However, the sources of the magnetic field can also be recognized as currents and magnetic polarization. The magnetic field produced by the currents in a single electric conductor loop can be determined with the law of Biot and Savart [Rei62].

$$\overline{B}_S(\overline{r}) = \frac{\mu_0}{4\pi}\int_V \frac{\overline{J}(\overline{r}')\times(\overline{r}-\overline{r}')}{\left\|\overline{r}-\overline{r}'\right\|^3}dv' \tag{17}$$

where $\overline{r}$ is viewing point, μ_0 is permeability of vacuum, $\overline{r}'$ is point with source current density, $\overline{J}$ is total current density and v' is volume with source current density. The current density in the previous equation can be divided into three parts, which include eddy currents, source currents and polarization. The magnetic field produced by polarization includes magnetization. The total magnetic field is a sum of the magnetic field components caused by source and eddy currents and magnetization as follows [Rei62].

$$\overline{B}(\overline{r}) = \frac{\mu_0}{4\pi}\int_V \frac{\overline{J}(\overline{r}')\times(\overline{r}-\overline{r}')}{\left\|\overline{r}-\overline{r}'\right\|^3}dv' + \frac{\mu_0}{4\pi}\int_V \nabla\times\frac{\overline{M}(\overline{r}')\times(\overline{r}-\overline{r}')}{\left\|\overline{r}-\overline{r}'\right\|^3}dv' \tag{18}$$

where $\overline{M}$ is magnetization. Thus, the magnetic flux density can always be represented with the current density terms. In another words, the magnetic field does not have isolated magnetic poles.

Alike, electric field sources are charges and polarization. Another way to solve the electrostatic problem is to make the integration over the charge distribution as follows.

$$\overline{E}(\overline{r}) = \frac{1}{4\pi\varepsilon_0}\int \frac{(\overline{r}-\overline{r}')dq'}{\left\|\overline{r}-\overline{r}'\right\|^3} \tag{19}$$

where ε_0 is permittivity of vacuum. However, this can be utilized only if the sources are well known.

4.1.1 Boundary-value Problems for Electric and Magnetic Fields

For electric field calculations a typical problem is to solve electric field involved by several conductors, with the potential given and the ground under the conductors. The problem is electrostatic boundary-value problem for which a partial differential equation (PDE) can be formulated from Gauss's law. In the analysis the primary variable is the electric scalar potential, V, which defines the electric field as:

$$\overline{E} = -\nabla V \tag{20}$$

In all ordinary points of space one has

$$\nabla\cdot\varepsilon\nabla V = -\rho \tag{21}$$

The equation is a second degree PDE, which may be solved once the functional dependence of $\rho(x,y,z)$ and the appropriate boundary conditions are known. For magnetic field calculations a typical problem is to solve a quasi-static eddy-current problem in which one part of the problem area includes conductive material. In analysis the primary variable is the magnetic vector potential, $\overline{A}$, which defines the magnetic field as

$$\overline{B} = \nabla\times\overline{A} \tag{22}$$

A PDE is formulated from Ampere's law by taking into consideration equation 22, as follows.

$$\nabla\times\frac{1}{\mu}\nabla\times\overline{A} = \overline{J} \tag{23}$$

The total current on the right-hand side can be divided into eddy currents and source currents. Further, the eddy-currents can be formulated from Faraday's law, when the equation 22 is taken into consideration.

$$\nabla \times \overline{E} = -\frac{d\overline{B}}{dt} = -\frac{\partial}{\partial t}\left(\nabla \times \overline{A}\right) \tag{24}$$

The electric field strength can be solved from previous equation, and further the eddy-current density can be represented as follows.

$$\overline{J} = -\sigma\left(\frac{\partial \overline{A}}{\partial t} + \nabla V\right) + \overline{J}_S \tag{25}$$

where σ is electrical conductivity. In two-dimensional calculations the electric scalar potential is zero. To conclude the analysis equation, in all ordinary points of space is as follows.

$$\nabla \times \frac{1}{\mu} \nabla \times \overline{A} = -\sigma\left(\frac{\partial \overline{A}}{\partial t} + \nabla V\right) + \overline{J}_S \tag{26}$$

Another way to formulate the quasi-static eddy-current problem is to make the integration over the current density distribution as presented in equation 18. However, this can be utilized only if the currents are well known.

Analytical and numerical methods can also be used to solve electric and magnetic field problems. One major trend, analytical calculation methods can be used if the geometry of the problem is simple. Analytical methods can also be used if the problem can be represented as a simple problem with some simplifications and approximations. However, analytical calculation methods are based on the previously presented laws and basal formulas. Another major trend is numerical calculation methods. FEM analysis is one common numerical calculation method. The FEM analysis is based on PDEs, which are transformed as a linear system of equations and solved approximatively. Calculation methods used in example cases are presented in the following chapters 4.2 … 4.5.

4.1.2 Electric and Magnetic Field Measurements

Measurements are needed in cases where the geometry of the electrical structures and the surroundings are difficult to calculate. Another goal for measurements is to confirm the results from a simplified calculation model.

When planning a measurement, the existing standards have to be taken account. Usually the standards for electric and magnetic field measurements give basic frames, but no practical instructions for the measurement. Whereas, for measurements of transmission lines and visual display terminals more practical standards exist [IEE95, MPR90]. However, there are specific studies in which the measurements are handled.

Measurement plans handle the amount and selection of the measurement points [Vad92]. The meter in use should fit the requirements for the particular measurement. The properties of the meter, memory and frequency response affect the decision when selecting the meter [Ols91]. The goal for the measurement may be clarifying the level of the field, spatial or temporal variations, amount and duration of the exceeding of certain field value, harmonics, polarization and human exposure [IEC98, IEE97].

Important standards that are related to the measurement of the electric power system are IEEE Std 644-1994 for the fields of power lines [IEE95], IEC 60833 for power lines and electrodes [IEC87], and IEEE Std 1460-1996 for the quasi-static electric and magnetic fields [IEE97]. The standard IEC 60883 concerns with the measurement equipment, calibration and measurements of electric field [IEC87]. The standard IEEE Std 1308-1994 deals with the measurement equipment, inaccuracy, calibration and measurements. Standard IEEE Std 1140-1994 is for the fields of visual display terminals. The standard IEC 61786 handles with the methods, defines properties for human exposure meters, and defines basic frames for measurements [IEC98]. In addition, the standard presents basics for the measurements and calibration of the meters. According to the standard, it is important to find out, if the field is homogenous or not, and if the studied person is in the field during the whole measurement period or not. There is no practical instruction for carrying out the measurements.

According to the standard IEC 60833, when carrying out electric field measurement, it is important to pay attention to proximity effects of the observer and the objects [IEC87]. According to the standard IEC 61786, the observer may be required to maintain a distance of more than two meter from the measurement equipment [IEC98]. The distance between the meter and nonpermanent objects shall be at least three times the height of the object in order to measure the unperturbed field value [IEE95]. The distance between the probe and permanent objects should be at least one meter [IEE95].

General instructions for the measurements are given in standard IEEE Std 1460-1996 [IEE97]. In measurements the information required includes the manufacturer, type and serial number of the meter, measurement date and time, total uncertainty of the measurement, the present calibration date, the size and geometry of the probe, and measured quantity. Other required information is measurement frequency, description of the human activity, drawing of the measured surroundings, measurement height, and information about possible field sources and ambient conditions. [IEC98, IEE97]

In addition to standards, different study groups have published measurement practices used in their studies. For example, the measurement methods for the transmission lines have been presented in references [Abd99, Fer99, Mar93]. Other measurement methods for appliances, space and exposure are presented in references [Bow98, Juu89, Kei96, Mar93]. In the Nordic countries, there are internal instructions in some companies. For magnetic field measurement, a Swedish company Vattenfall Utveckling AB has its own measurement practices [Lar97]. Also, the Norwegian Energiforsyningens Fellesorganisasjon (EnFo) and the Danish Danske Elvärkers Forening have their own practices for the measurements [Dan98, Smi95].

Electric and magnetic field meters

Magnetic field meters for power frequencies are based on measuring the magnetic induction [Con85, Get89], Hall effect [Gor72, Hal94, Voi76] or hysteresis [Kaw94]. The operating principle for measuring the induction is to define the voltage of a coil probe. The measured voltage is proportional to the magnetic flux density, coil area, coil turns and frequency, as can be verified from the Faraday's law in equation 11. The meter measures the magnetic field component perpendicular to the coil normal. The effect of quasi-static electric field can be shielded with a conductive and unclosed film around the coil. Figure 4.1 presents the operating principle of the magnetic field meter.

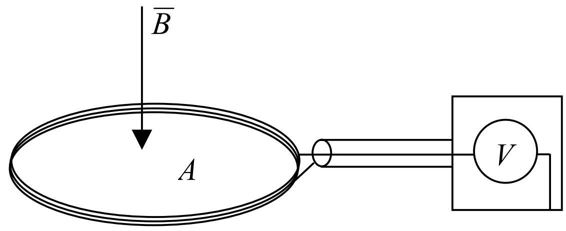


Figure 4.1. Operating principle for magnetic field meter based on measuring magnetic induction. $\overline{B}$ is magnetic flux density, *A* is area of the coil, *V* is voltage proportional to magnetic flux density. [Con85]

Electric field meters are ground free body, ground referenced or electro-optical meters. Each meter type has a different kind of probe. In the ground free body meter the probe is based on spherical, box or plate type probe [IEC87]. The meter follows current or charge between two conductive electrodes [Con85]. The signal has to be transferred to the analyzer with an optical cable to avoid disturbances or the electronics and the display has to be integrated in the probe. In ground referenced meters current or charge between ground and conductive plate is followed [IEC98]. In electro-optical meter the electric field changes optical properties of the dielectric Pockel's crystal [Con85, IEC87]. In addition, the meter may have one or three orthogonal probes depending on, whether it can measure one or three axis.

One common meter type for electric field measurements is free body meters based on box or plate type probe. Operating principle for the probe is to measure polarization caused by electric field; thus measurements are based on the Gauss's law in equation 10. Moving charge can be measured from the conductor between two electrodes by measuring the current. The electric field is proportional to the current, frequency of the field, and the area of the electrode [Con85].

4.1.3 Mitigation Methods

Local magnetic field attenuation with distance can be simply presented by a single wire conductor, return conductors, three phase single circuit conductors, small circuit and three phase double circuit lines. Local magnetic field attenuation with distance differs for different kinds of sources. The reason for this can be formulated from the previously presented laws and basal formulas. For a wire conductor the magnitude of magnetic field with the distance r_1 is as follows based on the law of Biot and Savart.

$$B_1(r_1) = \frac{\mu_0 I}{2\pi r_1} \tag{27}$$

where B_1 is the magnitude of magnetic flux density produced by single wire and r_1 is the distance between wire and observation point. Thus, the local attenuation with the distance is inversely proportional to the distance for a single wire.

When the system consists of return conductors, the direction of the field components caused by different conductors has to be taken account. However, the magnitude of the wire distances $\overline{r}_1$ and $\overline{r}_2$ are generally almost equal, thus the magnitude of the distances can be represented as *r*. If the distances are almost equal, the difference of the distances Δr vanish compared to observation distance in denominator of the law of Biot and Savart, and can be excluded [Kau92]. This leads magnetic flux density $B_{1,2}$ as follows.

$$B_{1,2}(\bar{r}_1, \bar{r}_2, r) = \frac{\mu_0 I}{2\pi r^2} \|\bar{r}_2 - \bar{r}_1\| \tag{28}$$

where $B_{1,2}$ is the magnitude of magnetic flux density produced by conductors 1 and 2, and r is distance between conductor system and observation point. Thus, the local attenuation with the distance is inversely proportional to the square of the distance for conductors.

When the system consists of three phase single circuit conductors, the magnitude of magnetic flux density has the same kind of form that is presented in equation 28 [Kau92]. However, the vectoral form of the field components caused by different conductors leads to a coefficient, which depends on the spacing of the conductors. In any case, the local attenuation with the distance is inversely proportional to the square of the distance r [Kau92].

For a small circuit in which the size vanishes compared to observation distance, the attenuation with the distance becomes from the law of no isolated magnetic poles presented in equation 13. The local attenuation with the distance is inversely proportional to the cubic of the distance for a small source compared to observation distance. The equal local attenuation with distance appears, when the question is about three phase double circuit lines. [Kau92]

For electric field the local attenuation with the distance is more complex, because electric field has isolated poles, all of which has to be taken into account in calculations. In other words, the attenuation with distance for electric field is a case-specific feature in practice.

Shielding of magnetic field is extremely complex for ELF broadband (30 … 300 Hz), because of minor deformation in materials [Iva96, Ols96, Was98]. With VF, VLF and LF broadband (300 Hz … 300 kHz) the shielding is possible, e.g., with metallized shielding enclosures [Bla88, Fri97, Tay93]. The shielding effectiveness (*SE*) is defined as a relationship of the field results without shielding and with shielding, as presented in the next equation [Bri88, Fri97, Kis96, Mos88, Ooi99, Sek91].

$$SE = 20\log_{10}\frac{B_0}{B_S} \tag{29}$$

where B_0 is magnetic flux density without the shield and B_S with the shield.

The *SE* can be calculated from the calculation or measurement results. Analytical and numerical magnetic field calculations can be used [Car00, Fri97]. In addition analytical *SE* calculation methods have been developed [Bri88, Kis96]. The effects of the shielding parameters, material properties, distance from the source and geometry of the enclosures are studied in references [Bri88, Kis96].

Mitigation methods in the technical management are based on the relationship between both electric and magnetic fields. The base for the mitigation can be presented by means of the Poynting's theorem, which is presented in equation 30 [Rei62].

$$-\int_V \bar{J}\cdot\bar{E}\,dv = \frac{d}{dt}\int_V \frac{1}{2}\left(\bar{E}\cdot\bar{D} + \bar{B}\cdot\bar{H}\right)dv + \oint_S \bar{E}\times\bar{H}\cdot d\bar{a} \tag{30}$$

Poynting's theorem describes a power transferred into electromagnetic field through the motion of a free charge in volume V. It also contains a negative Joule heating rate. The first term on the right-hand side represents reactive power stored by the fields. The second term on the right-hand side represents radiated power, which can be omitted with a quasi-static problem. Poynting's theorem means, that a locally mitigation in ELF usually has an effect on both of the fields. Which means, e.g., decreasing magnetic field with shielding the electric field is locally increased inside the shield. However, the effects are not always straightforward.

4.2 TRANSMISSION LINE

Electric and magnetic fields have mainly been calculated analytically, because considering assumptions for non-disturbed field, they can give efficient results [Bab97, Den82, Kau92, Liu96, Pet97, Ras98, Rei96]. Also, finite element method (FEM) and approximate calculation methods have been used previously [Ism99, Kau92].

Electric field calculations in case of transmission line

An analytical equation for three-phase transmission line above earth plane can be formulated based on the Gauss's law in equation 10. The “fictitious charges” method is used to set the zero-potential level. Charges and fictitious charges can be seen in figure 4.2.

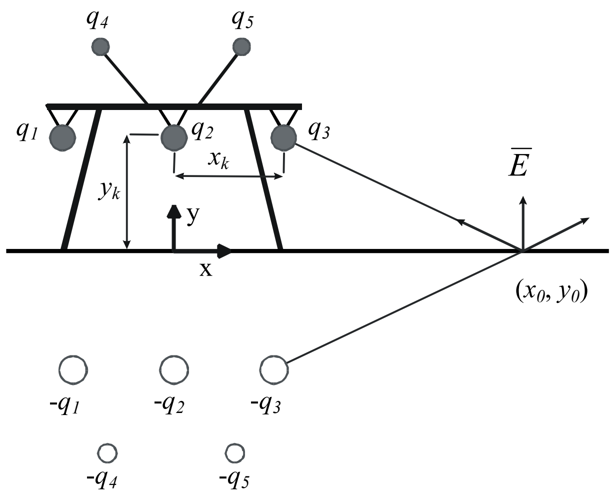


Figure 4.2. Parameters used in the calculation of electric field strength of a transmission line [Den82].

Taking into consideration the distances and charges presented in the previous figure, the analytical equation is as follows [Den82, Liu96].

$$\overline{E}(x_0, y_0) = \sum_k \frac{q_k}{2\pi\varepsilon_0}\left[\left(\frac{(x_0 - x_k)}{R_1^2} - \frac{(x_0 - x_k)}{R_2^2}\right)\overline{a}_x + \left(\frac{(y_0 - y_k)}{R_1^2} - \frac{(y_0 - y_k)}{R_2^2}\right)\overline{a}_y\right] \quad (31)$$

where q_k is charge per line length for conductor k, x_k, y_k, x_0 and y_0 are co-ordinates for conductors and observation point, respectively, $\overline{a}_x$ and $\overline{a}_y$ are unit vectors, and

$$R_1^2 = (x_k - x_0)^2 + (y_k - y_0)^2$$
$$R_2^2 = (x_k - x_0)^2 + (y_k + y_0)^2 \quad (32)$$

In equation 31 it is assumed that the ground surface is even [Ras98]. The charges are determined through the voltages and the Maxwell potential coefficients, with the matrix equation

$$q = \mathbf{P}^{-1}U \quad (33)$$

where **P** is the matrix of the Maxwell potential coefficients and U is vector of the voltages. The shield wires are assumed to be grounded densely so that the voltages U_4 and U_5 can be assumed as zeros. In the matrix **P** the diagonal terms for conductor a are

$$\mathbf{P}_{aa} = \frac{1}{2\pi\varepsilon_0}\ln\left(\frac{4y_a}{d_a}\right) \tag{34}$$

where y_a is the height of the conductor a above ground and d_a is the diameter of conductor a. The off-diagonal elements of the matrix **P** are

$$\mathbf{P}_{ab} = \frac{1}{2\pi\varepsilon_0}\ln\left(\frac{(x_a - x_b)^2 + (y_a + y_b)^2}{(x_a - x_b)^2 + (y_a - y_b)^2}\right)^{1/2} \tag{35}$$

where y_b is the height of the conductor b above ground, x_a and x_b are the horizontal co-ordinates of the conductor a and b, respectively.

To calculate the fields along the line, the height of the conductors are calculated in every calculation point. The sag of the conductors follows a hyperbolic cosine function [Mam96]. The curve of a hanging flexible conductor when supported at its ends and acted upon by a uniform gravitational force is called a catenary. The height of the conductor presented with the catenary function is as follows.

$$y(z) = y_k + \frac{1}{a}(\cosh az - 1) = y_k + \frac{1}{a}(1 + \frac{(az)^2}{2!} + \frac{(az)^4}{4!} + \ldots - 1) \tag{36}$$

where y is the conductor height, z is the distance from the middle span along the line, y_k is the minimum height of the conductor and a is a function, which depends on sag and total length of the conductor in the span [Mam96]. The equation for the a is

$$a(s_k, S) = \frac{8s_k}{S^2 - 4{s_k}^2} \tag{37}$$

where s_k is the sag and S is the total length of the conductor in the span. The total length of the conductor is a hyperbolic sine function, which depends on the variable a, as well.

However, the use of the equation 36 is not simple in practice, thus the approach for the formulation can be changed as a more practical formulation. If the equation 36 is simplified by taking into consideration the first two terms of the hyperbolic cosine function, the equation achieved is a practical approximation. The approximation means that the hyperbolic cosine is represented as a second-degree function. The graph of the second-degree function is a parabola and can be represented with measurable terms as follows.

$$y(z_0) = s_k\left(\frac{2z_0}{d}\right)^2 + y_k \tag{38}$$

where z_0 is the distance from the middle span along the line to observation point and d is span of the towers.

Magnetic field calculations in case of transmission line

Magnetic field calculations of transmission lines are usually carried out with analytical equations. The calculation is based on the law of Biot and Savart in equation 17. Analytical equations are suitable for both overhead lines and underground cables because the ground reduction of magnetic field is usually insignificant [Bab97]. The factors which may have an effect on the magnetic field from transmission lines are current, symmetry of the currents, direction of the power transmission with two circuit lines, phase configurations, and the locations of the phase conductors [Rei96]. The same equations can be used with cable systems. The factors which may have an effect on the magnetic fields from cables are current, phase angle and the locations of the phase conductors [Pet97].

The equation for magnetic field calculation is

$$\overline{B}(x_0, y_0) = \sum_k \frac{\mu_0 I_k}{2\pi}\left[\frac{(y_k - y_0)\overline{a}_x}{R_1} + \frac{(x_0 - x_k)\overline{a}_y}{R_1}\right] \tag{39}$$

where I_k is load current of conductor k.

Measurements in case of transmission line

According to the IEEE Std 644 the electric and magnetic fields are measured at the height of one meter from the ground in two directions [IEE95]. The fields are measured perpendicular and parallel to the line. In the perpendicular measurement the first measurement point is under the center conductor and one measurement point is under the outer conductor. Between those two points there is five additional measurement points. In addition there is several measurement points with equal intervals up to 30 meter from the outer conductor. [IEE95]

From these perpendicular measurements the highest value and its distance from the center phase is selected. Measurements parallel with the line are carried out at that distance from the center phase in 10 points at equal intervals along the span. In addition, the conductor heights of the line at the mid-span are measured with a line height meter. Also, air temperature and humidity are measured to determine climatic factors, which may affect the measurement results. [IEE95]

Altogether, the measurement consists of 13 measurement points up to 30 meter from the outer conductor. In this study, the standard is put into practice adding two additional measurement points to the required measurement according to the standard [Kor00b]. The measurement points are presented in figure 4.3 [Kor00b].

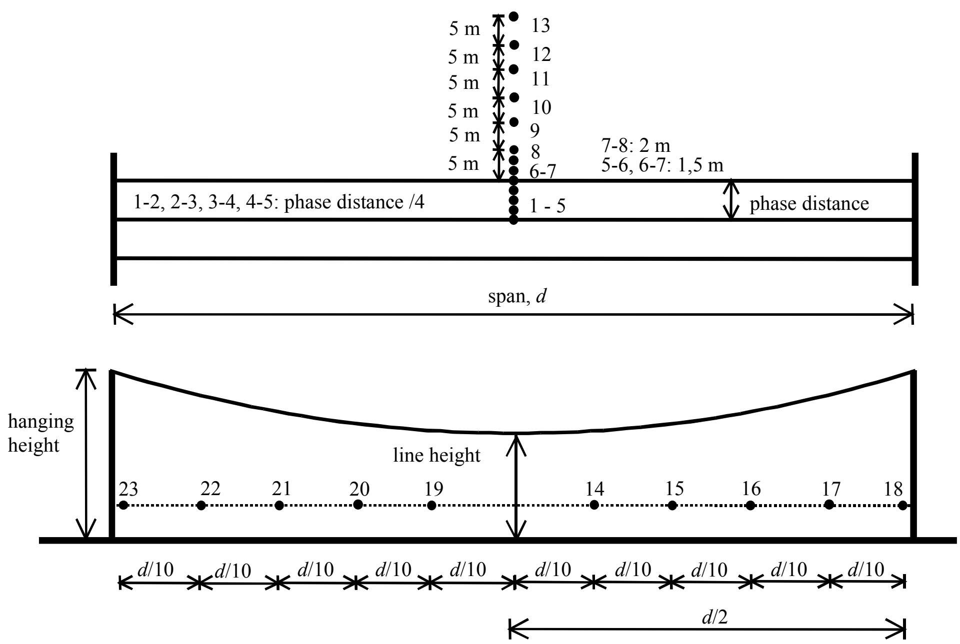


Figure 4.3. Measurement points of transmission line. *d* is distance of the span. [Kor00b]

The added points in figure 4.3 are 6 and 7, because the electric field of the transmission line is supposed to be placed slightly away from the outer conductor [Kor00b]. The total amount of the measurements was 23 points in a span. Measurements parallel with the line are carried out at the same distance where the highest value occurs in the perpendicular measurement.

According to the standard the meter should be calibrated before a long measurement period and after the measurements. Before the measurements, information from the line is marked in the log sheet, e.g., voltage, load current, locations of the conductors and measurement points. Temperature, time and date are also required. [IEE95]

Mitigation in case of transmission line

For transmission lines attenuation with distance and structural mitigation techniques can be used. The problem is that methods are not necessarily economic. However, possible methods are the use of cables and phase splitting in overhead transmission lines [Ehr99, Lan98, Ste93], compact line design [Gid88, Kau92, Lin98, Pet97, Rei96], line height increasing [Pas98] or for magnetic field the use of special reduction conductors, shields or active magnetic field compensators [Ols90]. Often the methods also have a negative influence on the visual impact of the line. Figure 4.4 presents different phase configurations of transmission line [Kau92].

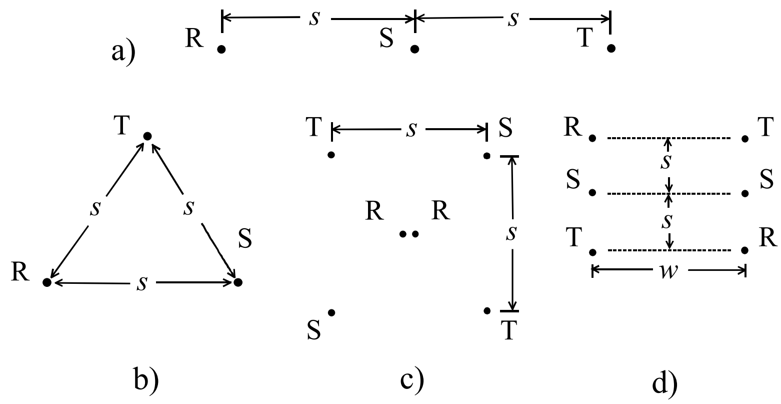


Figure 4.4. Phase configurations of a) horizontal configuration, b) triangular configuration, c) x- configuration and d) double-circuit configuration, where *s* is the phase distance and *w* is the circuit separation [Kau92].

Reference [Kau92] presents approximate equations for different transmission line configurations. The inaccuracy with the approximate equations is less than 10% [Kau92]. Thus the approximate equations help to give fast answers to the public about the magnetic fields, and also to understand the dependencies of the magnetic field parameters with different transmission lines [Kau92, Kei02a].

In addition, it is useful to consider the direction of the power flow, when planning the phase order optimization of the double-circuit configuration [Rei96]. A point symmetric line configuration is better, when the power flows in the same direction in a double-circuit configuration. When the power flows in different directions, a mirror symmetric line configuration is better [Rei96, Vuo93].

In Finland the horizontal configuration is the most common solution due to guyed portal towers with open-wire lines. Although the 20 kV distribution line poles look different from 110 kV and 400 kV line towers, the calculation is similar for each line configuration [Kau92]. Figure 4.5 presents towers for different voltage levels [Elo88].

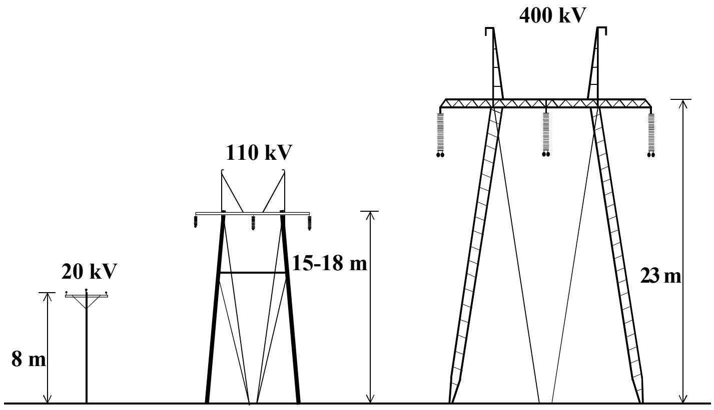


Figure 4.5. Present line towers for 20, 110 and 400 kV in Finland [Elo88].

Besides line configuration changes, the mitigation can be carried out by using reduction conductors [Mem96, Pet96]. The current in reduction conductors can be controlled actively by analyzing the maximum mitigation or it can vary passively because of induction [Mem96, Pet96, Shp96, Yam00]. Transmission line configurations can be more compact when selecting insulated phase conductors or cables [Ehr00, Kar98]. In addition, ferromagnetic or conductive shielding can be used for mitigating magnetic field, and all insulating and conductive materials for deforming the electric field [Bra99, Pap99, Was98].

4.3 ELECTRIC SUBSTATION

The main calculation methods used previously with the calculations of electric substations are the analytical calculation method and the FEM. The analytical calculation method has usually been used for magnetic fields [Hay92, Zha90], whereas the FEM has been used for both electric and magnetic fields [Daw95, Kor96]. However, electric fields in the case of electric substations were not calculated in this study. The analytical magnetic field calculation method takes into account the load currents, phase angles of the currents, phase order and the geometry of the substation [Hay92]. With FEM it is also possible to take into account stationary and movable constructions, grounding system, and biological objects [Daw95, Ver97].

Magnetic field calculations in case of electric substation

The analytical magnetic field calculation method is based on the law of Biot and Savart in equation 17. When using analytical magnetic field calculation it is assumed that nearby conductive or magnetic materials do not affect the field. The effect of the steel structures as well as the magnetization part of the equation 18 can be omitted.

Each conductor can be calculated separately, and the total magnetic field is summed as a vector sum. Calculations are simplified by dividing conductors as straight pieces and three co-ordinate system transformations. First, all conductor pieces are changed to start from the origin. Then, they are transformed parallel with x-axis using two co-ordinate system transformations. A combined transformation matrix is as follows [Sch86].

$$\mathbf{T} = \begin{bmatrix} \cos\beta & \cos\alpha\sin\beta & \sin\alpha\sin\beta \\ -\sin\beta & \cos\alpha\cos\beta & \sin\alpha\cos\beta \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix} \quad (40)$$

where angles α and β are specified in figure 4.6.

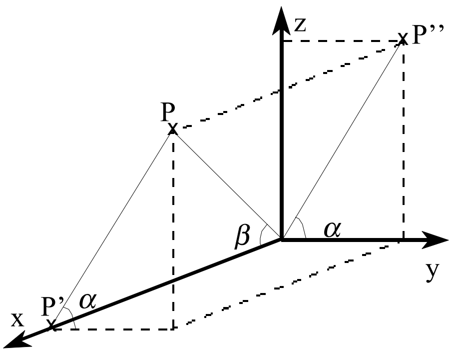


Figure 4.6. Angles α and β for equation 40 [Kei97, Kei99a]. P is conductor end point, P´´ is projection of point P in yz-plane, and P´ is projection of point P in x-axis.

The length of the conductor piece is considered with coefficient b_0, which can be calculated with equation 41 by using geometrical dimensions specified in the following figure 4.7.

$$b_0 = \cos\gamma_1 - \cos\gamma_2 = \frac{x'}{\sqrt{x'^2 + r^2}} + \frac{l - x'}{\sqrt{(l - x')^2 + l^2}} \tag{41}$$

where l is the length of the conductor piece, x' is transformed x co-ordinate of observation point, r is viewing distance and angles γ_1 and γ_2 are presented in figure 4.7.

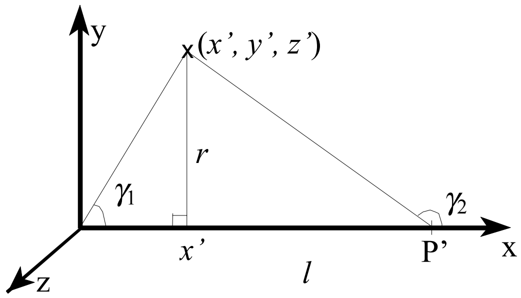


Figure 4.7. Angles γ_1 and γ_2 for equation 41 [Kei97, Kei99a].

The magnetic field in the transformed co-ordinate system can be calculated as follows.

$$B_0 = \frac{b_0}{2} \frac{\mu_0 I}{2\pi r} \tag{42}$$

where μ_0 is permeability of vacuum and I is load current in the conductor. The components (B'_x, B'_y and B'_z) of the magnetic field can be obtained from equations 43 ... 45.

$$B'_x = 0 \tag{43}$$

$$B'_y = {}^{z'}\!/_{r}\, B_0 \tag{44}$$

$$B'_z = {}^{y'}\!/_{r}\, B_0 \tag{45}$$

where z' is transformed z co-ordinate and y' is transformed y co-ordinate of observation point.

The magnetic field of each conductor is calculated separately. After the field is calculated, the field is transformed back to the original co-ordinates [Sch86]. The magnetic field in the original co-ordinate system can be calculated as follows.

$$\overline{B} = \mathbf{T}^{-1}\left[B'_x\; B'_y\; B'_z\right]^T \tag{46}$$

Magnetic fields of single conductor pieces are summed up as vectors using components, and further calculations, e.g., RMS-value with equation 47, are carried out.

$$B_{res} = \sqrt{(B_x)^2 + (B_y)^2 + (B_z)^2} \quad (47)$$

Equations 41 … 46 were scripted for Matlab 5.2 in this thesis. The magnetic field was solved with the analytical method and the results were presented in RMS values using equation 47.

Measurements in case of electric substation

In this study, the structure of the substation and its electrical system was clarified before the measurement. The measured points were in straight lines and lattice sites in measurement areas. The measurement height was 1 meter.

Mitigation in case of electric substation

The need for mitigation rises from technical aspects. For example, magnetic induction in wiring of the relay system can cause false responses, which can even cause a blackout in the whole substation [Yan96]. However, the induction has usually been taken into account in the design. The occupational exposure may occur with measurements in the outdoor switchyard of the substations (short-term) and when maintaining the substation (long-term). Usually conductors in the working area are not loaded when the substation is maintained; thus the magnetic field may be even smaller than with the normal load. But on the other hand, the special switching of the substation can also increase the magnetic field during the maintaining of the substation, because the load is forced to a limited part of the switchyard.

Possible mitigation techniques with electric substations are structural changes, shielding and attenuation with distance. The attenuation with distance is an effective mitigation technique, but there are also live wiring techniques with live powered conductors, which are an essential part of the maintaining work. Even a 9 mT value can be reached with live working in a 400 kV substation [Hut94]. In addition, protective clothing may be one possibility for electric field exposure in outdoor installations. Nevertheless, the protective clothing usually appears with hedging against electric shock and practically never from the electric field exposure point of view. One other possibility for electric field is the use of GIS in new substations. The enclosure of the GIS acts like Faraday's cage. The enclosure of the GIS also reduces magnetic field, but the reduction degree is considerably lower than with the electric field [Won94]. However, this cannot be used as a general method because of economic aspects.

In previous studies for indoor type 69/13.8 kV substation 25% mitigation has been reached by elevating bus bars by 2 ft (0.6 m) [Far98]. In outdoor type 115/13.8 kV substations the mitigation has been studied by chancing phasing of the bus bars [Far98]. The calculated mitigation with double main bus bar construction has been 33% by changing the phasing of the bus bars in horizontal construction [Hay92].

4.4 INDOOR DISTRIBUTION SUBSTATION

In previous studies the FEM has been used to calculate the magnetic field near indoor distribution substations [Has93, Has94, Sal99]. In addition, the analytical calculation method has been used with the magnetic field of the MV/LV substations in reference [Tik95]. The calculations included the analytical method, or the combined analytical method and FEM. The analytical calculation method has been presented in the previous chapter 4.3.

Numerical calculations for indoor distribution substation

The effect of eddy currents in shielding material is estimated with the 2D-FEM. FEM calculation is based on equation 26. The combined analytical method and FEM takes into consideration the *SE* values, which can be calculated with equation 29. Shielding is accounted for in those parts of the conductors, which are inside the shield. The *SE* is taken into account as a coefficient for the magnetic field produced by the conductor inside the shield, as presented in the following equation 48. The equation 48 is a solved form of equation 29.

$$B_i = 10^{-\frac{SE}{20}} B_{i,0} \tag{48}$$

where B_i is the magnetic flux density produced by the conductor piece i when the *SE* is present, and $B_{i,0}$ is the magnetic field calculated analytically in conditions without the shield. The FEM program used here was commercial MagNet 5.2.3.

Measurements in case of indoor distribution substation

Existing standards do not have an implementation of the measurement in a space above or beside indoor distribution substations. Before the measurements, the structure of the indoor distribution substation was found out according to the design drawings and by measuring the distances if needed. After that, the measurement was started by defining the measurement starting point, which was used to assign the other measurement points. The space above or beside the projection of the middle phase LV connector of the transformer was chosen as a measurement starting point. [Kor00b]

In the space above the indoor distribution substation the measurement starting point was located with the distances given in the design drawings and by measuring the distances. The measurement starting point was marked into the floor of the space. In addition, the projection of the secondary LV conductors was defined in the space. The other measurement points were located by measuring the distance from the starting point. If the walls of the space were perpendicular, the direction of the grid followed the walls. Otherwise the direction of the grid follows the direction of the closest part of the secondary LV conductors. An example of the measurement grid is presented in figure 4.8 [Kei00c]. The step of the measurement grid was 1 meter.

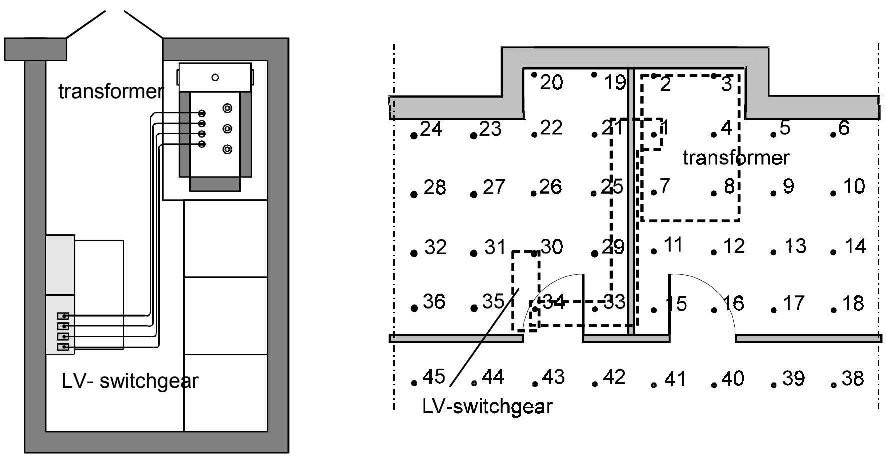


Figure 4.8. An example drawing of the transformer room and the measurement points. • is measurement point, point number 1 is measurement starting point. [Kei00c]

The measurement grid includes the secondary LV conductors of the substation. When the measurement grid was ready, the current was measured from phase conductors and the PEN conductor. Usually the current was measured with the crotch core probe, but also with the current transformers of the substation. The magnetic field was measured from the heights of 0 m (from the floor of the space), 1 m and 2 m. In the publications 5, 6 and 8 only the height of 1 meter was experienced as an interesting height. In the measurements a 3-axial Wandel&Goltermann EFA-3 magnetic field meter (accuracy ±8%, RMS) was used. Calibration of the meter was considered in measurements.

The measurement was started from the measurement starting point. The starting point was followed by one of the directions of the grid. The measurement at the direction was continued until the wall of the space or the magnitude of the field compared to the highest value was insignificant. Finally the current was measured again. The current was measured in the same way as before magnetic field measurements.

In the space beside the indoor distribution substation the measurement followed the same basic instructions. However, the measurement starting point was defined in the wall between the substation and the space beside.

Mitigation in case of indoor distribution substation

Mitigation in indoor distribution substations can be carried out by attenuation with distance, by structural mitigation techniques and by shielding. In references, the mitigation of the magnetic field near secondary LV conductors of the indoor substation was usually based on the shielding [Has93, Has94, Iva96, Mos88, O'Co93, Sal99, Sal00, Sek91, Tay93]. Shielding may result in high costs because the shielding with the LF broadband is complex [Sal00].

The shield has several parameters, which have been studied previously by different authors. The parameters of the shielding are the width, height, thickness, length and distance to shielded conductors, and the material of the shield [Has93, Has94, Iva96, Mos88, Sek91, Tay93]. Both ferromagnetic and conductive materials have been studied and tested [Has93, Has94, Ols96, Tay93]. However, in this case it depends on the structure of the secondary LV conductors and the space available, which is the better shielding material. With a 5 mm thick aluminum shield applied on the ceiling and the walls of the 10/0.4 kV substation the calculated *SE* has been 30 dB [Has94]. Also the location of shielding plates can have a major effect on the *SE* [Sal00]. In addition to shielding, the phase splitting and active reduction has also been studied with the secondary LV conductors of the substation. Phase splitting of the secondary LV conductors means that divided phase conductors are placed to better reduce the magnetic field. In active reduction the current carrying coils are located to reduce the field in certain locations [Sal00].

4.5 ARC FURNACE

The main goal of the previous arc furnace studies has been the heat transfer of the arc furnace. For this reason the calculation of the electromagnetic fields has been coupled to the heat transfer calculations [Ben91]. The goal has been to optimize the position of the electrodes in a DC-furnace, when considering forces to the electrodes, arcs and supporting structures [Bir93, Bir94, Fou96, Roq97, Sha98]. FEM is also essential, when reducing the instability caused by the magnetic field. The mitigation has been realized with conductive plates or pipes, and also with ferromagnetic shielding plates [Bir94, Cao89].

In this study magnetic fields of an arc furnace have been measured and calculated in the vicinity of an arc furnace and inside a control room. The main magnetic field sources of arc furnaces are feeders, electrodes and arcs. The calculation method was a combined analytical method and FEM, which was presented in the previous chapters 4.3 and 4.4.

Approximative magnetic field calculation

A Norwegian research group, Thomsen and Bjølseth has also studied magnetic fields of arc furnaces [Tho92]. They have developed an approximative magnetic field calculation equation for the three-phase arc furnace, which is based on measurement results:

$$B = \frac{aI}{r^3}[\mu T] \tag{49}$$

where B is magnetic field at the distance of r, a is structural coefficient, I is load current in electrodes and r is the viewing distance from the center of the arc furnace. The equation was estimated from statistical analysis of the measurements. The reference [Tho92] presents a value of 5 for the coefficient a.

Measurements in case of arc furnace

When planning the magnetic field measurement, it is important to find out how the process operates. Good knowledge of the process gives ideas about how the load current varies and how it affects the magnetic field. In this study, the measurement method, carrying out practical measurements, results and attenuation with distance are presented for magnetic field in publication 7 and references [Kei99a, Kei99c]. The magnetic field was measured with four Radians Innova ML-1 meters (accuracy ±10%). Calibrations of the meters were considered in measurements. Four meters were used to get simultaneous results with attenuation information. The meters can take 4096 values in their memory. Two meters have range 0.1 ... 1000 µT and other two 0.01 … 100 µT.

Mitigation in case of arc furnace

Possible mitigation techniques with the arc furnace are attenuation with distance, structural mitigation techniques, and shielding. The mitigation of the magnetic field external to arc furnace is easiest in the design stage with structural mitigation techniques [Bir94, Cao89, Fou96, Roq97]. The enclosure of the arc furnace shields the magnetic field. With DC arc furnaces the ferromagnetic materials are the only alternative in shielding [Bir94]. With AC arc furnaces both conductive and ferromagnetic materials are possible [Cao89].

Possible constructions for shielding with AC arc furnaces are cooling water pipes, conductive sheets and supporting structures [Cao89]. The mitigation of the magnetic field also reduces the forces affecting the structures and the arc [Cao89, Fou96]. Furthermore the symmetry of the load current is pointed out as an important parameter in magnetic field mitigation of the arc furnace [Cao89, Roq97]. In addition, in industrial environments an active reduction has utilized producing anti-EMF [Bel99]. However, the system has not been tested with arc furnaces, so far.

5. RESULTS OF EXAMPLE CASES

Four examples of technical management of electric and magnetic fields in electric power system were studied. The studied example cases were transmission lines, electric substations, indoor distribution substations, and an arc furnace.

5.1 TRANSMISSION LINES

Transmission lines have been studied as a first example case, because guidelines may be exceeded near 400 kV transmission lines. When comparing the fields with guidelines near 400 kV transmission lines, the electric field exposure is more critical than magnetic field exposure. Fields have been measured and calculated, and after that the mitigation of the fields has been analyzed.

The electric and magnetic fields of 400 kV transmission lines at the height of 1 m from the ground were measured in the surroundings of Tampere, Helsinki and Paimio (25 spans, 38 measurements) [Kor98, Kor00b]. In the electric field measurements a 3-axial Wandel&Goltermann's EFA-3 meter (accuracy ±5%, RMS) was used. The magnetic field was measured with Radians Innova ML-1 magnetic field meter (accuracy ±10%, RMS). Calibrations of the meters were considered in measurements. The line height was measured with the Suparule line height meter, which is based on measuring the time of reflected ultrasound. The inaccuracy of the meter was ±3 cm.

Electric and magnetic fields have been calculated with analytical methods. The calculation method for electric field is presented in equations 31 … 35 and for magnetic field in equation 39. Electric field calculations have been presented in publications 2 and 6.

5.1.1 Measurement and Calculation Results

Measurements validate calculations and vice versa, thus the places with regular measurement were also calculated. The results are presented in Table 5.1 [Kei99d, Kor98, Kor00b]. The table includes only the highest values near the mid-span and along the line.

In some places the regular measurement method was not carried out completely. Those measurements are marked as special measurements. These kinds of places were the spans with the transposition of the phases and a bridge under the line. There the conductors were closer to ground than usual. The location of the transposition was chosen as a measurement starting point in perpendicular measurement. Above the bridge the measurement was only carried out parallel to the bridge. For some spans the perpendicular measurement was carried out in both directions from the line. This was the case when the field of two parallel lines was measured. [Kor98, Kor00b]

Table 5.1. The highest value of the measurement and calculation results [Kei99d, Kor98, Kor00b]. n. is measurement number, reg./spec. is regular or special measurement, $E_{max\ 1}$ is maximum measured field, $E_{max\ 2}$ is maximum calculated field, V_{mean} is measured mean operational voltage over the whole measurement cycle, $B_{max\ 1}$ is maximum measured field, $B_{max\ 2}$ is maximum calculated field, I_{mean} is mean of the load current calculated from transmitted power.

Region	n.	Line type	Reg./Spec.	$E_{max\ 1}$ kV/m	$E_{max\ 2}$ kV/m	V_{mean} kV	$B_{max\ 1}$ µT	$B_{max\ 2}$ µT	I_{mean} A
Tampere	T1	horizontal	reg.	4.73	4.67	400.5	6.88	7.12	477.3
	T2	horizontal	reg.	5.19	5.07	400.8	7.13	7.54	487.1
	T3	horizontal	reg.	4.36	4.04	399.0	5.87	6.07	472.4
	T4	horizontal	reg.	1.55	4.06	401.0	5.22	3.99	295.9
	T5	horizontal	reg.	4.09	4.06	401.5	11.4	8.75	651.7
	T6	horizontal	reg.	2.91	5.59	399.0	5.17	5.07	315.3
	T7	horizontal	reg.	4.38	4.75	405.6	5.62	3.79	250.6
	T8	horizontal	reg.	4.41	5.57	401.5	4.15	4.02	242.0
	T9	horizontal	reg.	3.82	5.48	402.6	3.92	4.02	246.8
	T10	horizontal	reg.	5.06	5.67	402.3	4.42	2.91	167.2
	T11	horizontal	reg.	6.50	5.88	397.1	2.71	2.77	169.4
	T13	horizontal	reg.	5.76	5.58	400.0	3.27	3.37	191.7
Helsinki	H1	horizontal	reg.	5.04	8.47	396.4	3.33	3.50	153.2
	H2	horizontal	reg.	9.32	6.80	397.0	3.33	3.10	146.7
	H3	horizontal	reg.	1.57	3.06	400.5	3.54	3.68	365.3
	H4	horizontal	reg.	5.30	4.85	402.8	5.18	5.18	332.2
	H5	vertical	reg.	3.52	4.74	396.5	0.79	0.71	80.6
	H7	delta circuit	reg.	4.31	5.22	396.5	1.08	0.64	56.5
	H9	horizontal	reg.+4 points	4.87	5.73	396.1	4.76	2.24	121.5
	H14	horizontal	spec.	4.67	-	395.0	3.33	-	137.1
	H16	transposition	reg.	3.40	3.25	399.6	2.62	0.63	118.8
	H17	vertical	spec.	2.55	-	398.0	1.45	-	121.3
	H18	vertical	spec.	2.57	-	396.8	3.06	-	114.0
Paimio	P1	horizontal	spec.	6.46	-	399.3	5.07	-	309.3
	P5	transposition	reg.+10 points	5.67	4.99	397.9	4.35	4.96	270.4

Measured electric field values exceeded the 50 Hz maximum value of the guidelines, 5 kV/m in 10 places. The highest measured electric field was 9.32 kV/m [Sjö01]. Differences in calculated and measured values depend on varying load condition, rough ground and inaccuracy in calculation parameters. In addition, vegetation damps the electric field by changing distribution [Iso99, Kei99d, Suo01]. The effect of the vegetation can be found at places Tampere T6 and Helsinki H1, H2 and H3 in Table 5.1. Usually, the electric field is decreasing around areas where the vegetation appears. However, vegetation also affects points other than the maximum.

Measured magnetic field values did not exceed 100 µT. The highest differences in calculated and measured values depend on the same environmental parameters and inaccuracy in calculation parameters as with the electric field. However, the vegetation does not affect the magnetic field.

5.1.2 Electric and Magnetic Field Mitigation

Exposure to the fields of transmission lines can be reduced by choosing low field line configurations, decreasing the harmonic distortion, increasing the conductor height and reducing electric field with vegetation. The conductor height increase is studied as a fine tuning method by studying the line sag variation as a function of the line temperature. In practice increasing the line height is a complicated and expensive method, and is not in wide use [Pas98]. Also other mitigation methods have been presented earlier in chapter 4.2, e.g., phase splitting [Lan98, Ste93], compact line design [Kau92, Lin98, Pet97, Rei96], reduction conductors or active magnetic field compensators under the line conductors [Ols90].

Line configuration in electric and magnetic field mitigation

The current varies based on the power consumption. In Finnish 400 and 110 kV transmission lines the mean current was analyzed in 1989. The study included 100% of the 400 kV transmission lines and 88% of the 110 kV transmission lines in Finland in 1989 [Hon93, Hon94]. The current has to be used as a statistical variable in practical calculations. In the following example calculations 95% fractal has been used. The fractal means that during one year the current is on average less than 299 A in 95% of 110 kV transmission lines. For 400 kV lines the corresponding current is 777 A. The mean value for 20 kV lines has been evaluated to be about 100 A. Although the 20 kV distribution line poles look different compared to 110 kV line towers, the calculation is similar for each voltage level [Kau92]. Calculated line configurations were presented previously in figure 4.4. Magnetic field calculation results are presented in figure 5.1.

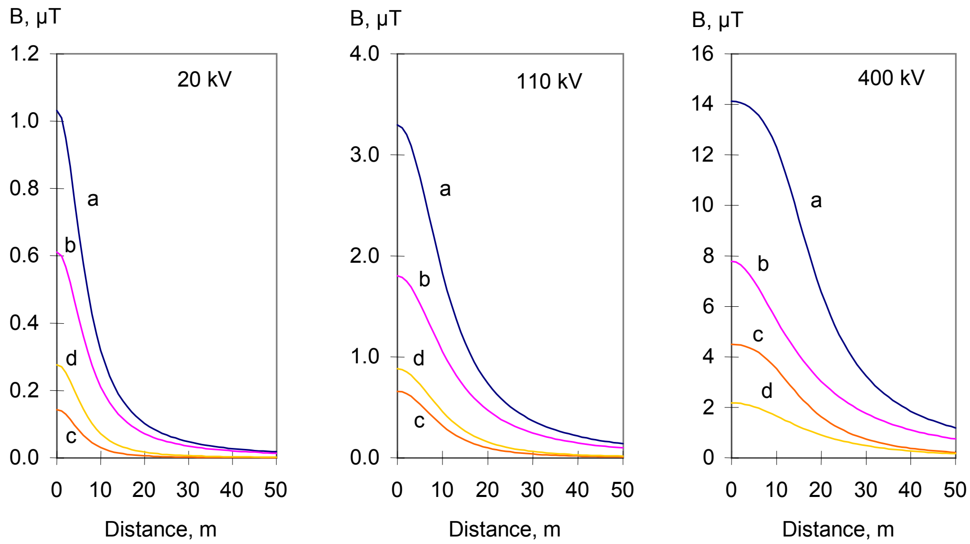


Figure 5.1. Analytical magnetic field results for 20 kV (current 100 A), 110 kV (299 A) and 400 kV (777 A) lines: a) horizontal configuration, b) triangular configuration, c) x-configuration and d) double-circuit configuration.

In the order of the lowest maximum magnetic field the results seem to be similar for 20 and 110 kV lines. The order is x-configuration (20 kV: max. 0.14 µT; 110 kV: max. 0.66 µT), double-circuit configuration (20 kV: max. 0.28 µT; 110 kV: max. 0.88 µT), triangular configuration (20 kV: max. 0.61 µT; 110 kV: max. 1.8 µT) and horizontal configuration (20 kV: max. 1.0 µT; 110 kV: max. 3.3 µT). The order for 400 kV lines is double-circuit configuration (max. 2.2 µT), x-configuration (max. 4.4 µT), triangular configuration (max. 7.8 µT) and horizontal configuration (max. 14 µT). The difference is due to the distance relations.

Electric field was also calculated for the same line configurations. The nominal line voltage was used in calculations. Calculated electric field results are presented in figure 5.2.

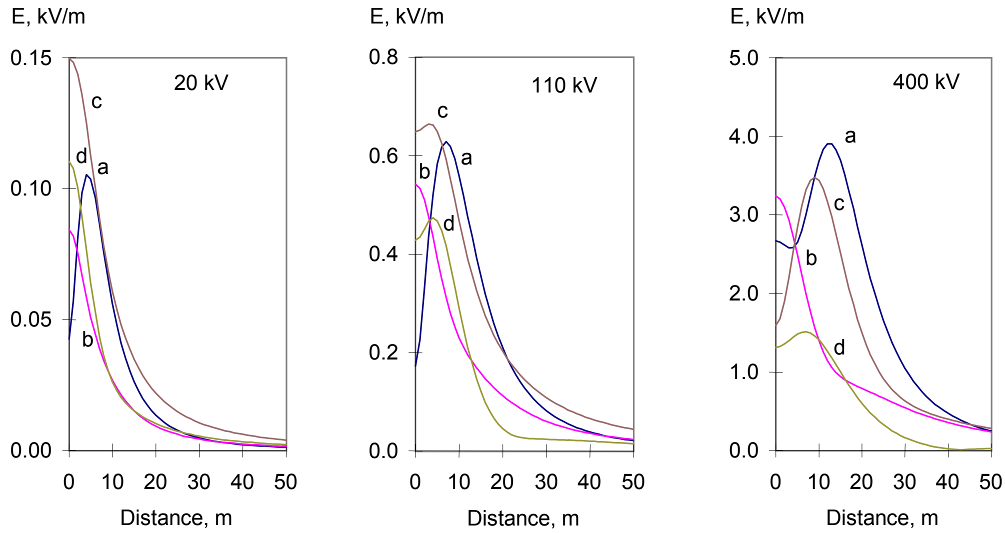


Figure 5.2. Analytical electric field results for 20 kV, 110 kV and 400 kV lines a) horizontal configuration, b) triangular configuration, c) x-configuration and d) double-circuit configuration.

The order differed with studied line voltages. Results for 20 kV line in the order of the lowest maximum electric field is triangular configuration (max. 0.08 kV/m), horizontal configuration (max. 0.11 kV/m), double-circuit configuration (max. 0.11 kV/m) and x-configuration (max. 0.15 kV/m). The order for 110 kV line is double-circuit configuration (max. 0.47 kV/m), triangular configuration (max. 0.54 kV/m), horizontal configuration (max. 0.63 kV/m) and x-configuration (max. 0.66 kV/m). The order for 400 kV line is double-circuit configuration (max. 1.51 kV/m), triangular configuration (max. 3.24 kV/m), x-configuration (max. 3.48 kV/m) and horizontal configuration (max. 3.90 kV/m). The difference between lines is due to the distance relations of the different lines.

Electric and magnetic field harmonics

Based on the results the electric field values of the 400 kV transmission lines are slightly below or even exceed the guidelines. If the value is near the specification, the effect of the harmonics may be significant. The effect of the harmonics has been presented in publication 6. However, when operating near the guidelines, vegetation and temperature are more important factors of uncertainty. In addition, the owner of the 400 kV transmission lines operates the network, but does not usually produce the harmonics.

Vegetation

The reduction effect of the vegetation has been observed especially with the electric field, because all dielectric or conductive materials cause deformation. With the vegetation longer than the measurement height the electric field may be smaller than without vegetation, because of the screening effect of the vegetation presented in references [Hal01, Iso99, Kei99b, Kei99d, Suo01]. If the measurement point of the electric field is between the vegetation and the conductors of the transmission line, the effect may be similar or even opposite [Hal01].

The electric field reduction of the forest was nearly complete inside the forest and almost as complete near the forest. For 20-meter high spruce or mixed forest the electric field reduction effect from a distance of one to five meter was even 70%. The reduction effect could be observed even at the distance of 20 meters. With alder bushes with the height of 5 … 10 meter, the reduction effect was just a little under 70%, but the observation distance was smaller than with the higher forest. [Hal01]

The electric field reduction effect of individual trees has also been measured [Hal01]. For example pine with the height of 15 meters, the reduction was 99% nearby the tree. For birch with the height of 3 … 10 meters, the reduction was 41 … 100% depending on the height. Whereas, for shorter trees, e.g., juniper, with the height of 2 … 4 meters the reduction was only 24 … 44% [Hal01].

Figure 5.3 presents an exemplary span (Tampere T11, results presented previously in Table 5.1), where calculation and measurement results differ because of vegetation damping effect and ground height variations. [Suo00]

Figure 5.3. View from measurement location T11. [Suo00]

In figure 5.3 cut tree branches were at the distance of 14 m, and after the distance of 21 m spruce trees were damping the field. Still another problem is the ground, which is usually regarded as an even plane. Yet in reality there are hollows and hills, which have an effect on the calculation results. The ground was ascending from the middle conductor to the measurement direction. The maximum difference between measured and calculated values was 2.3 kV/m at the distance of 21 m, because of spruce trees damping the field.

Effect of line height

Line height increasing is considered in previous studies [Kuu00, Pas98]. The height of the transmission line may be critical also with the lines scantily below the guidelines. When evaluating the fields, the line sag variation as a function of temperature or load may cause differences in measurement results at different times [Kei99b]. In this study the measurements were carried out in summer while the yearly peak load in Finland is in winter. However, the yearly peak transmission is not always in winter.

In Finland, the highest mean of the annual absolute maximum was +31°C and the lowest mean of the annual absolute minimum was -38°C between 1931 and 1960 [Atl88]. When heating of sunshine and resistive heating of load current are considered in temperature, the line conductor temperature may be much higher. The value of +70°C … +80°C is used in line design [Paa75]. As an example, one span (445 m) from a 400 kV horizontal transmission line was selected. The structure of line towers in figure 5.4 was received from the network owner. [Kei99b]

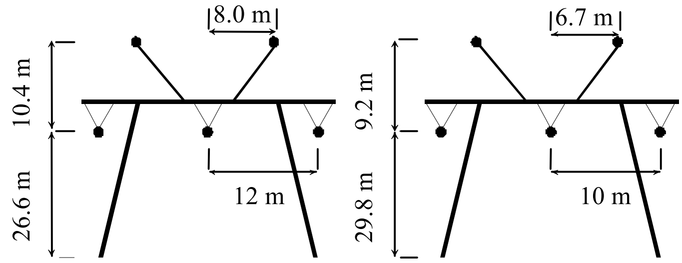


Figure 5.4. Structure of the example case line towers. [Kei99b]

The total diameter of the bundled 3×Finch phase conductors is 0.45 m. The diameter of shield wires is 0.015 m. The sag is considered in y-coordinate of the phase conductors. The effect of temperature on sag can be calculated from the conductor length of the span.

$$S = S_0(1+\alpha\Delta T) = S_0(1+\alpha(T_i - T_0)) \tag{51}$$

where S_0 is reference length of the conductor, α is temperature coefficient of length, ΔT is temperature change, T_0 is reference temperature and T_i is observation temperature. By considering the parabola approximation for the conductor height and some simplifications in the conductor length integration, an estimate for the conductor length is as follows [Paa69].

$$S = d + \frac{8}{3}\cdot\frac{{s_k}^2}{d} \tag{52}$$

where d is span of the towers. The error in the integration of the conductor length is a function of the span and sag length, being small (below $2\cdot 10^{-3}$% from the span length) for a typical 400 kV transmission line. Furthermore, the sag as a function of the conductor length is as follows.

$$s_k = \sqrt{\frac{3}{8}\left(Sd - d^2\right)} \tag{53}$$

The measured average line height near the mid-span was 13.8 m. The air temperature was +9.5°C during the measurements [Kei99b]. Results for electric and magnetic fields as a function of sag variation (conductor temperatures -38°C … +70°C) are presented in figures 5.5 … 5.8.

As a function of the temperature, the difference between the highest and the lowest maximum magnetic field values was 4 μT this example case. The difference between electric field values was 3 kV/m in.

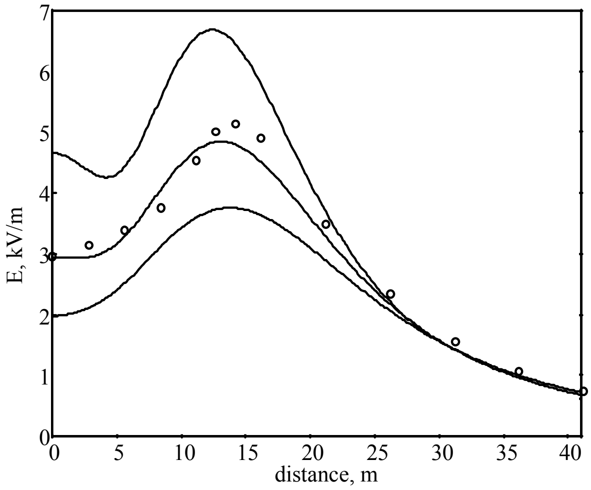


Figure 5.5. Calculated electric field of the transmission line at maximum, minimum and in measurement conditions, and measured fields near the mid-span [Kei99b].

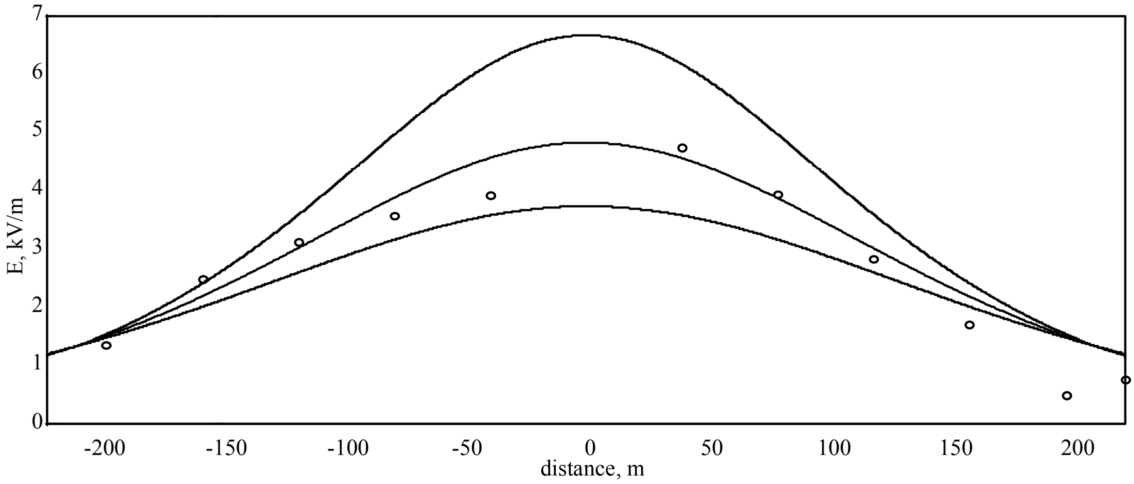


Figure 5.6. Calculated electric field of the transmission line at maximum, minimum and in measurement conditions, and measured fields along the line.

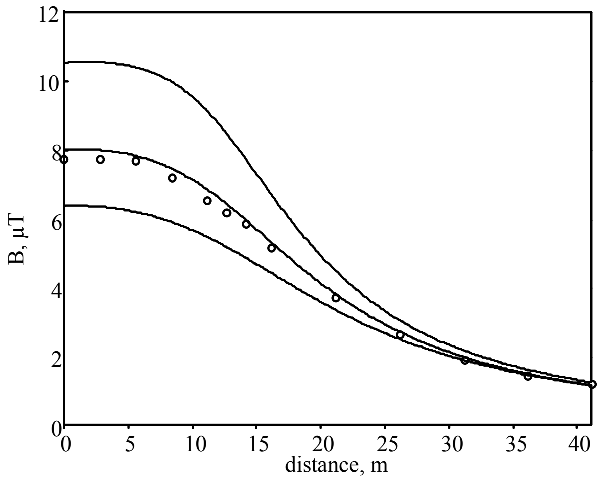


Figure 5.7. Calculated magnetic field of the transmission line at maximum, minimum and in measurement conditions, and measured fields near the mid-span.

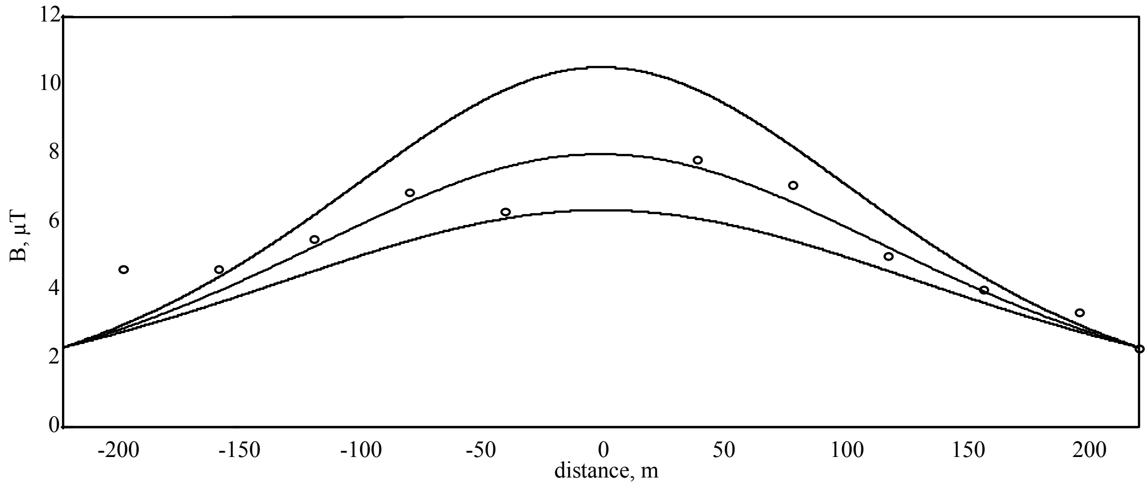


Figure 5.8. Calculated magnetic field of the transmission line at maximum, minimum and in measurement conditions, and measured fields along the line.

Table 5.2 presents calculation results for all studied regular measurement places for present temperature ($E_{max\ 2}$, $B_{max\ 2}$). In addition Table 5.2 presents results for conductor temperatures -38°C and +70°C. The temperature has previously been presented in reference [Hal01].

Table 5.2. Calculation results for different conductor temperatures. $E_{-38°C}$ is electric field at temperature -38°C, $E_{+70°C}$ is electric field at temperature +70°C, $B_{-38°C}$ is magnetic field at temperature -38°C, $B_{+70°C}$ is magnetic field at temperature +70°C.

Region	n.	Temperature ( )°C	$E_{max\ 2}$ kV/m	$E_{-38°C}$ kV/m	$E_{+70°C}$ kV/m	$B_{max\ 2}$ µT	$B_{-38°C}$ kV/m	$B_{+70°C}$ kV/m
Tampere	1	12°C	4.67	3.38	6.53	7.12	5.37	9.55
	2	15°C	5.07	4.06	6.18	7.54	6.30	8.97
	3	17°C	4.04	2.77	5.41	6.07	4.38	7.93
	4	13°C	4.06	2.89	5.80	3.99	2.91	5.39
	5	18°C	4.06	2.75	5.55	8.75	6.18	11.5
	6	10°C	5.59	4.64	7.02	5.07	4.34	6.10
	7	13°C	4.75	4.00	5.55	3.79	3.29	4.43
	8	17°C	5.57	4.48	6.63	4.02	3.38	4.72
	9	20°C	5.48	4.06	6.84	4.02	3.14	4.92
	10	8°C	5.67	5.05	6.39	2.91	2.67	3.27
	11	7°C	5.88	4.94	7.70	2.77	2.41	3.51
	13	15°C	5.58	4.96	5.74	3.37	3.16	3.59
Helsinki	1	16°C	8.47	7.68	9.33	3.50	3.23	3.80
	2	16°C	6.80	6.36	7.27	3.10	2.93	3.28
	3	25°C	3.06	2.11	3.63	3.68	2.67	4.46
	4	25°C	4.85	3.73	5.83	5.18	4.10	6.09
	5	15°C	4.74	4.31	5.29	0.71	0.64	0.79
	7	15°C	5.22	4.88	5.76	0.64	0.60	0.70
	9	14°C	5.73	5.26	6.28	2.24	2.07	2.44
	16	16°C	3.25	3.04	3.38	0.63	0.60	0.67
Paimio	5	17°C	4.99	3.93	5.57	4.96	4.21	5.78

As can be seen in Table 5.2, electric field values at conductor temperature +70°C exceeded the value of 5 kV/m in all except two measurements. Exceedings depended significantly on the present conductor temperature, which was unknown. However, it was approximated to be the same as the outside air temperature. This simplification leads to lower electric and magnetic fields. However, none of the measurements exceeded 15 kV/m, which is a short-term limit value in Finnish decree for 50 Hz electric field. When considering the variation of the conductor temperature, the magnetic field values were still clearly below guidelines.

5.2 ELECTRIC SUBSTATIONS

Measurements have been carried out in the 110/20 kV transformer substation (publication 4 and reference [Kei98b]), 110 kV GIS, 400 kV switching substation (publication 3) and 400/110 kV transformer and DC link substation. In the measurements a 3-axial Wandel&Goltermann's EFA-3 electric and magnetic field meter was used. Magnetic fields were calculated at the outdoor substations.

Electric and magnetic field measurement in the substation is principally case-specific, because they are different from the structure. Measurements can be carried out from an occupational exposure or disturbance point of view. When the question is about the occupational exposure, the measurements are concentrated in places where the workers are. With the disturbances caused by the fields, the goal is usually to find out the source of the disturbing magnetic field.

5.2.1 110/20 kV Transformer Substation

Publication 4 represents the results of the electric and magnetic field measurements performed in a 110/20 kV outdoor substation. The substation has double bus bar systems, three outgoing feeders and three 110/20 kV power transformers. The height of the two bus bars is 6.6 m and the height of the connecting lines is 4.3 m. The 20 kV underground cable is laid about 0.7 m beneath ground level.

Appendix 1 presents the 110 kV switchyard [Kei98b, Kor00, Toh98]. After a brief survey at the switchyard, one rectangular area was selected for measurements. In addition, two straight lines 1 and 2 for magnetic field perpendicular to each other and two parallel straight lines 3 and 4 for electric field were selected for measurements. The measurement height was 1.0 m. The distance between the measurement points was 4.0 m on the electric field measurement area and 2.0 m on the other measurements. In the magnetic field measurements bus bar 1 was grounded and not in use.

The variation of currents in transmission lines and cables were recorded during the magnetic field measurements. Current values are presented in publication 4. The measurement results of the rectangular area in contours of magnetic field are presented in figure 5.9. Calculation results are presented in figure 5.10.

The highest magnetic field values of the 110 kV switchyard were near transformer 4, where the magnetic field was from the 20 kV system. The highest measured value was 18.6 µT and at the same point the calculated value was 17.4 µT. The reason for the location of the highest value is that the current of the secondary LV system is 5.5 times higher than in the primary system. In addition, the secondary LV cables (current 703 A) are wired close to the observation points of the measurement and calculation. The distance from 20 kV cables was 1.8 m. Nevertheless, phase distance in 20 kV system is much less than in 110 kV system. In the area close to the 110 kV connecting lines the highest measured value was 18.0 µT. The line was carrying the highest 110 kV line current, 324 A.

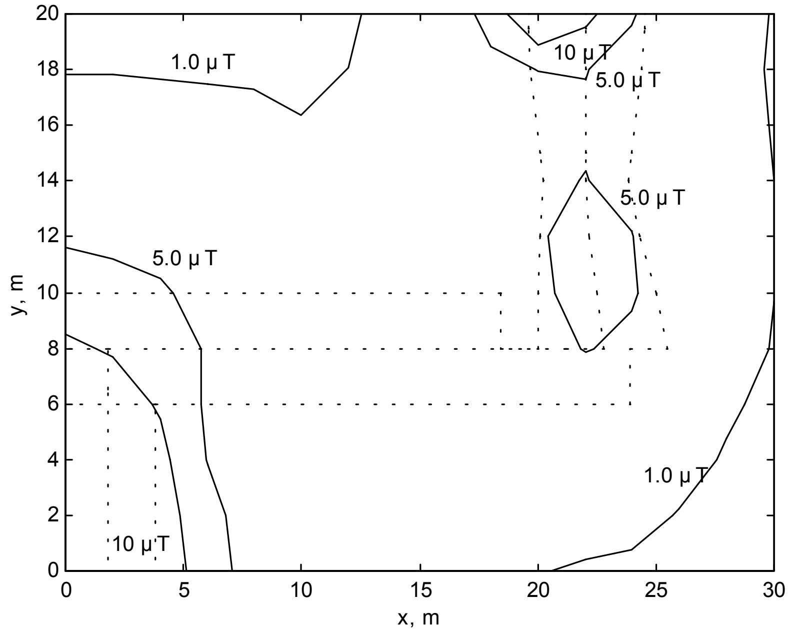


Figure 5.9. Contour line measurement results of magnetic field (RMS) at the 110/20 kV substation (n=176, dotted lines are bus bars). [Kei97]

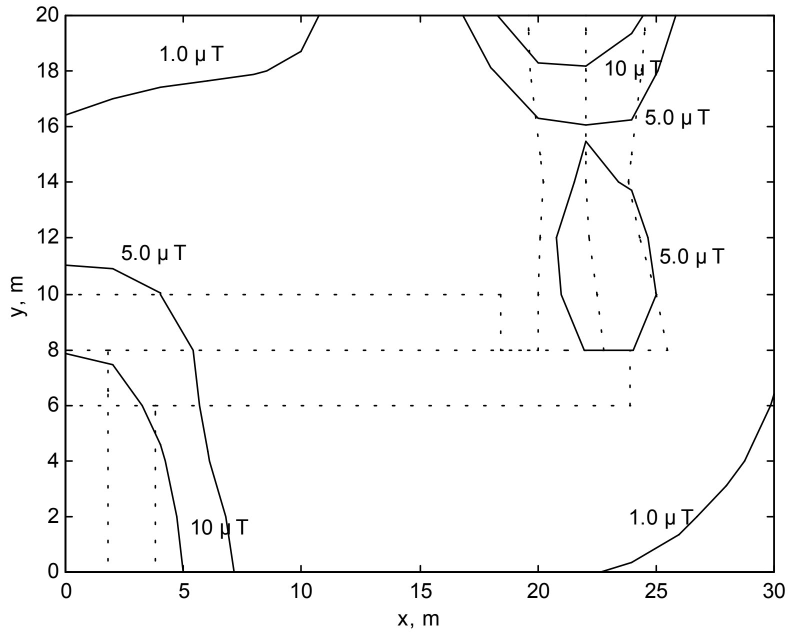


Figure 5.10. Contour line calculation results of magnetic field (RMS) at the 110/20 kV substation (n=176, dotted lines are bus bars). [Kei97]

Results for magnetic field in the lines 1 and 2 are presented in publication 4. The maximum differences between measurement and calculation results at the height of 1 meter were -0.76 μT for line 1 and -2.31 μT for line 2. One reason for the difference was varying load current and phase difference, which were not taken into account as time-dependent calculation factors.

The voltage at the 110 kV switchyard in the beginning of the electric field measurements was 116.0 kV. The measurement results on the rectangular area are presented in figure 5.11.

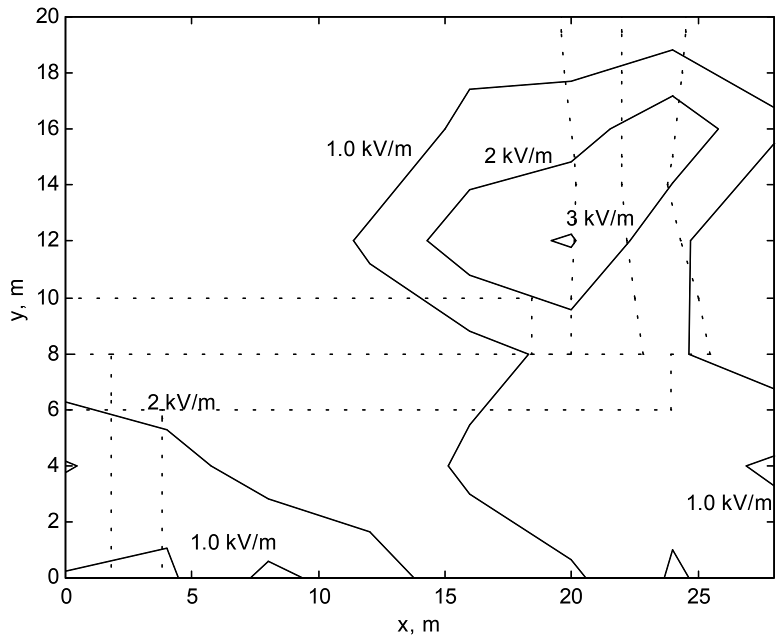


Figure 5.11. Contour line measurement results of electric field (RMS) at the 110/20 kV substation (n=48, dotted lines are bus bars) [Kor98].

In the rectangular measurement area the highest value was 3.1 kV/m. The highest electric fields are caused by the conductors feeding transformer 4. Also, the outgoing transmission line feeders 3 and 4 cause local peaks to the electric field. The bus bars do not cause clear peaks to the electric field since they are located higher than the conductors of the outgoing feeders.

The electric field measurement results on the measurement lines 3 and 4 are presented in publication 4. The measurement line 3 was located near the place where the feeders of the outgoing transmission lines pass below the bus bar 1. The highest measured value 4.6 kV/m was measured on measurement line 3 near transmission line 3. Also other transmission line feeders on measurement line 3 caused clear peaks in the electric field. The highest value 3.5 kV/m on the measurement line 4 was between transmission line 5 and transformer 5 feeders.

5.2.2 110 kV Gas Insulated Substation

Electric and magnetic field measurements were carried out in a 110 kV GIS. The substation consists of eight outgoing feeders, which have single phase gas insulated module components. Two generator feeders were open at the moment of the measurements. Two straight lines 1 and 2 were measured. Lines were under the connecting cables (line 1, 21 points) and away from the switchyard (line 2, 8 points). In line 1, the harmonics were measured from the point, where the field was the highest. In line 2, the attenuation with the distance from the switchyard was measured. Distance between the measurement points was 1 m. The measurement height was 1 m above the substation floor. Figure 2 in Appendix 1 presents the measurement points.

The load currents in feeders were measured before and after the magnetic field measurements. Figure 5.12 shows the direction of the power transfer. Table 5.3 shows the load current values in specific feeders during the measurements.

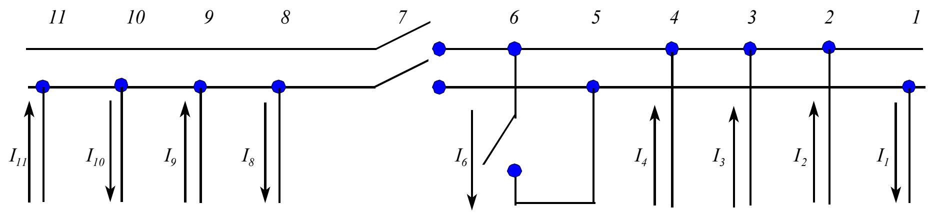


Figure 5.12. The load current of the feeders in 110 kV GIS. [Sau02]

Table 5.3. Load currents before and after the magnetic field measurement in 110 kV GIS. [Sau02]

Current	I_{before}, A	I_{after}, A
I_1	303	303
I_2	361	361
I_3	117	115
I_4	0	0
I_6	480	480
I_8	230	234
I_9	108	111
I_{10}	52	54
I_{11}	0	0

The magnetic field was measured under the connecting cables. The measurement results for magnetic field in line 1 are presented in figure 5.13.

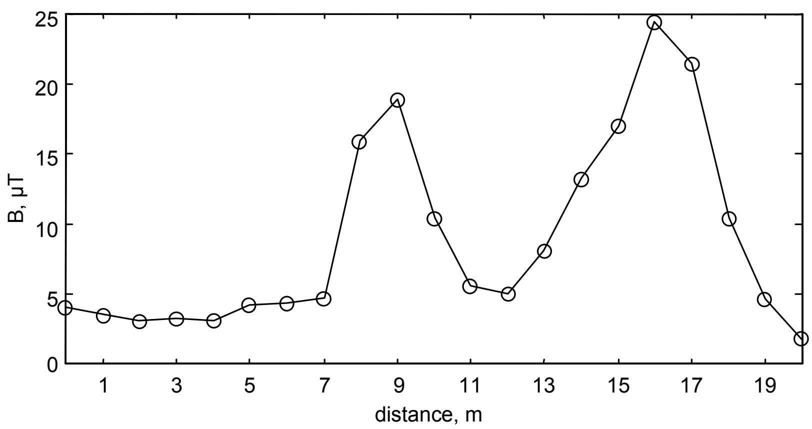


Figure 5.13. Magnetic field on measurement line 1 in the 110 kV GIS. [Sau02]

Magnetic field was the highest near cables, which carried the highest load current. The highest magnetic field value was 24.5 µT. After line 1 was measured the harmonics content of the magnetic field was measured from point 17, where the magnetic field was the highest. The harmonic distortion, K_1 of the magnetic field according to equation 7 was 1.000009 and K_2 according to equation 8 was 1.049. The K_2 value means, that the magnetic field value of the nominal frequency 50 Hz is allowed to be 476.8 µT according to ICNIRP occupational exposure guidelines. Magnetic field attenuation as a function of distance along line 2 is presented in figure 5.14.

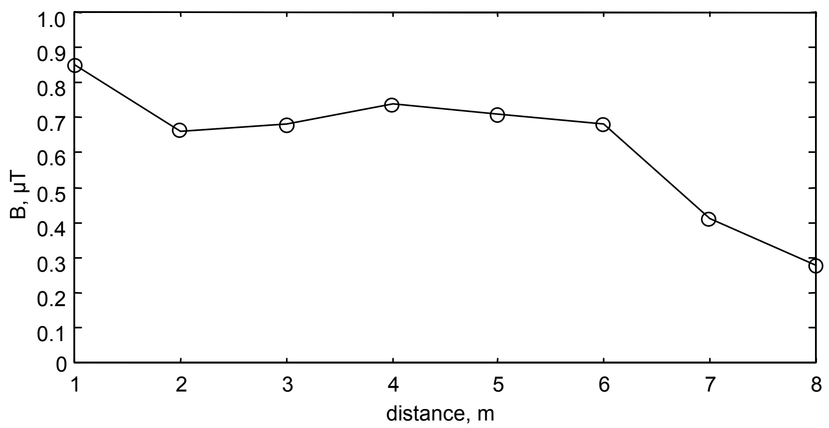


Figure 5.14. The magnetic field away from the switchyard along line 2 in the 110 kV GIS. Measurement point 22 was 1 m from the corner of the switchyard. [Sau02]

At the corner of the switchyard the magnetic field values were small compared to the values under the connecting cables. The workbench of the substation was at a distance of 6 meters from the switchyard. No disturbances have been observed from electrical appliances on the workbench. In addition, magnetic field harmonics were measured near the 110 kV cables in the cable tunnel behind the 110 kV GIS. The cable tunnel was an additional route for workers to go to the substation. The K_2 value was 1.028 meaning the limit value 486.6 µT for 50 Hz. However, the measured 50 Hz magnetic field value was 145 µT.

All electric field values under the connecting cables were about 0.002 kV/m in measurement line 1. The reason for this was that all the conductors were insulated. Also all the metallic structures in the substation were grounded.

5.2.3 400 kV Switching Substation

Electric and magnetic fields were measured on the switchyard of a 400 kV switching substation. The substation consists of two-breaker system (duplex), four outgoing feeders and two power transformers (400/110 kV, 400 MVA) and there was no air core coil.

Measurement lines were chosen based on the substation structure, a survey measurement, and locations of the service corridors. Measurements were taken in 71 points on lines 1 … 3, and in 38 points on line 4. The distance between the measurement points was 2 m. The measurement height was 1 m. The voltage in bus bars and powers were recorded during the measurements. Figure 3 in Appendix 1 presents the layout of the 400 kV switchyard. [Kor98]

Electric field results on the four measurement lines are presented in publication 3. The results varied according to the position relative to the line feeders. For example in the beginning of the measurement lines 1 … 3 the electric field increased until the outer phase of the first feeder bay (10 m) and then decreased below the center phase (15 m) due to the symmetry of the three phase system. All feeders had a similar effect. In line 4, the results were more stable since the distance to the feeders was constant. Variation was caused by the different height of conductors in the feeder bay. Electric and magnetic field results are presented in figures 5.15 … 5.18.

The highest electric field was 9.92 kV/m (voltage 404.6 kV) measured from line 1. The other highest values were 9.35 kV/m (402.5 kV) in line 2, 9.49 kV/m (403.9 kV) in line 3 and 9.86 kV/m (405.3 kV) in line 4 [Kor98]. The highest magnetic field values were 9.19 µT measured from the line 2 and 7.92 µT calculated from the same line.

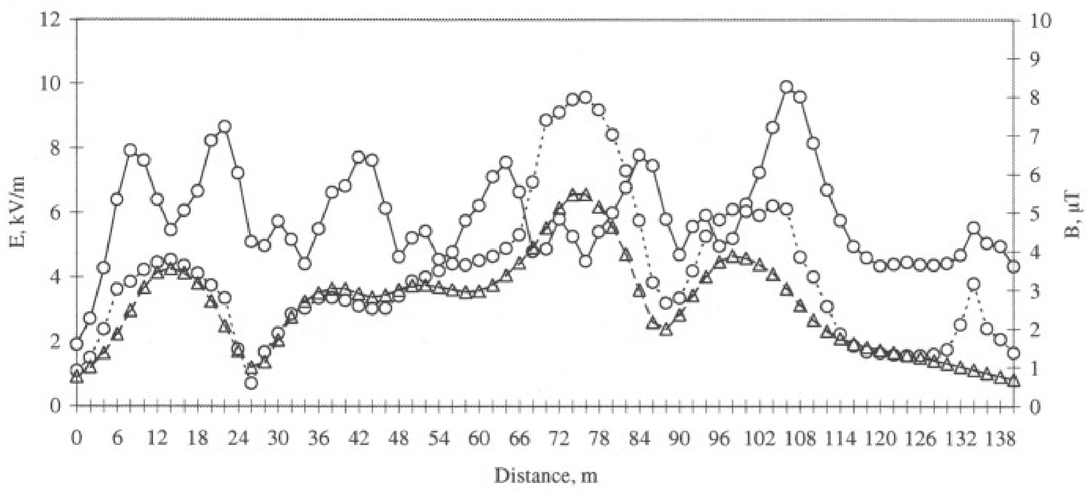


Figure 5.15. Electric field (—) and magnetic field (- -) on line 1 (o measured, △ calculated) in the 400 kV switching substation.

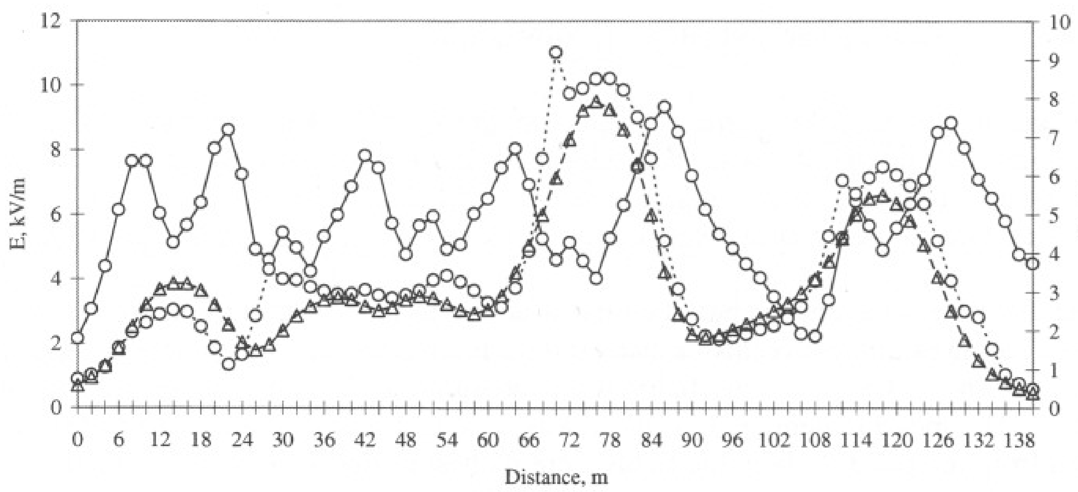


Figure 5.16. Electric field (—) and magnetic field (- -) on line 2 (o measured, △ calculated) in the 400 kV switching substation.

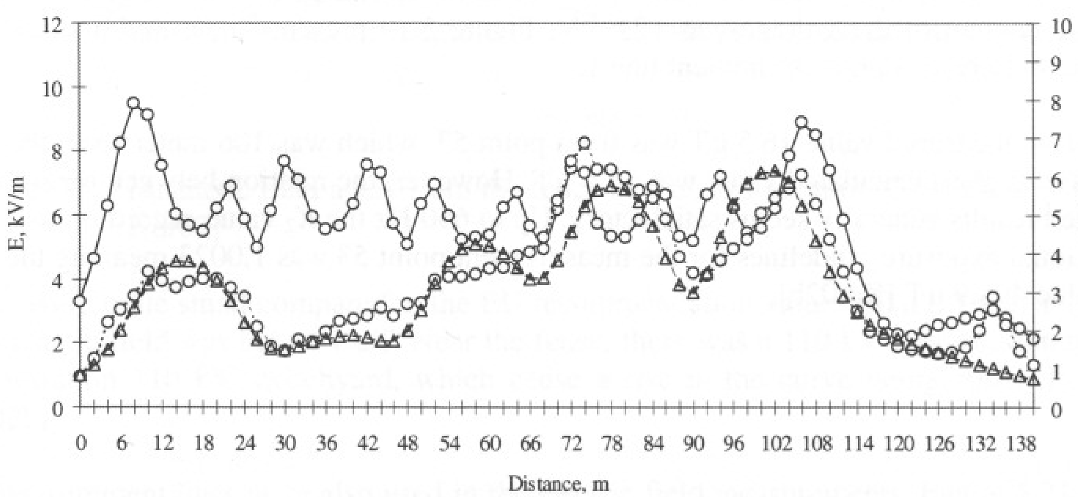


Figure 5.17. Electric field (—) and magnetic field (- -) on line 3 (o measured, △ calculated) in the 400 kV switching substation.

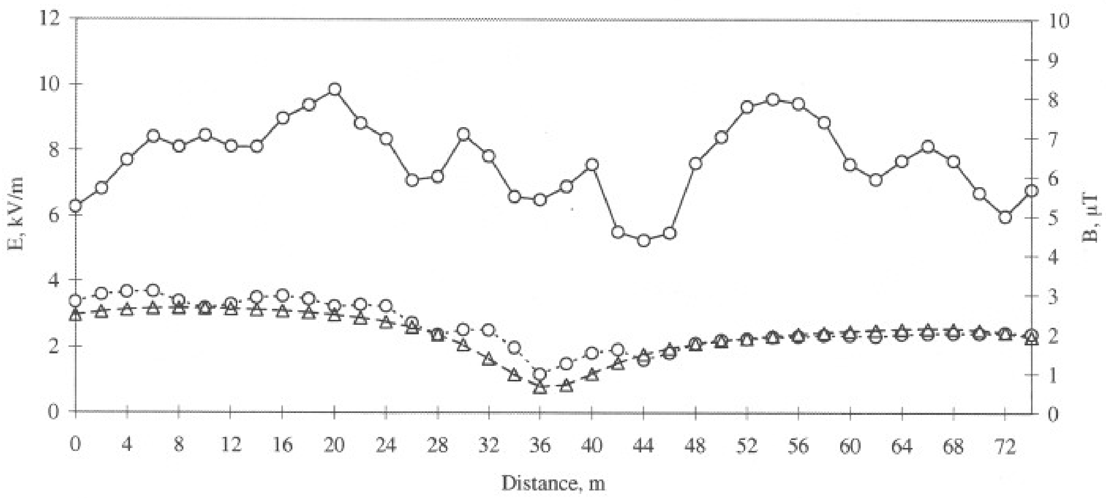


Figure 5.18. Electric field (—) and magnetic field (- -) on line 4 (o measured, △ calculated) in the 400 kV switching substation.

5.2.4 400 kV Transformer and DC Link Substation

Electric and magnetic fields were measured in the 400/110 kV transformer and DC link substation and in the vicinity of it. The substation 400 kV AC-switchyard consists of a two-breaker system (duplex), four outgoing feeders and two feeders for 400/110 kV power transformers. One of the outgoing feeders was a link to the converter feeding a HVDC line.

Measurement lines were chosen based on the structure of the substation. Figure 4 in Appendix 1 presents the measurement points on two straight lines 1 and 2. Measurements were taken in 83 points on line 1. On line 2 the fields were measured at 21 points away from the 400 kV switchyard. The measurement step in line 1 was 2 m, and 5 m in line 2. The harmonics were measured from the points, where the fields were highest in line 1. In addition, harmonics were also measured at one point near the converter. [Kei02b]

The voltage and the power of the nearest feeder were called from the control center of the system. The current was calculated from the power values. The highest harmonic content of the current was 7.16 A in the feeder with a 911.1 A load current. In DC link feeder, the highest harmonic content of the voltage was 12.6 kV. Figure 5.19 presents measured and calculated magnetic field results on measurement line 1.

The highest measured value 16.5 µT was from point 53, which was 106 meter from the end of line 1. The highest calculated value was 14.5 µT. However, the relation between measured and calculated results generally seems satisfactory. Up to 650 Hz the K_2 value according to ICNIRP occupational exposure guidelines for the measurement point 53 was 1.0023 meaning the 50 Hz limit value 498.9 µT [Kei02b].

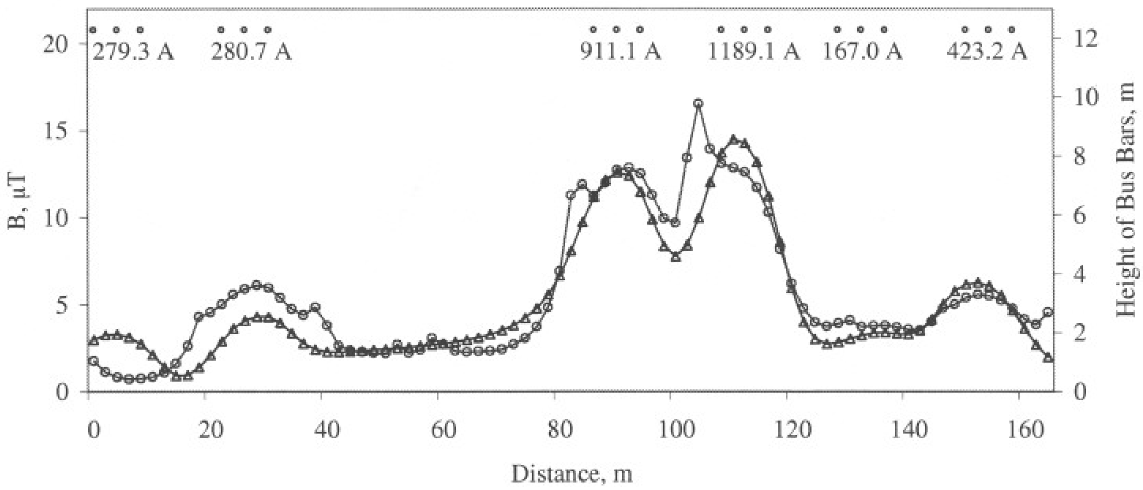


Figure 5.19. Magnetic fields (o measured, △ calculated) on line 1 at the 400 kV switchyard (n=83). The load current at the present feeder during the magnetic field measurement and the bus bars (ooo) are marked in the figure.

The K_2 value was the only goal for the measurement near the converter of the DC link. The point was chosen based on the default, that harmonic distortion might have been high. Based on the measurements the K_2 value was 1.024 meaning the limit value 488.3 µT for 50 Hz. Because of the harmonic filtering and transformers between the substation and consumption the magnetic field does not have high content of harmonics. [Kei02b]

Magnetic field was measured on the line 2 away from the fence of the substation. Figure 5.20 presents the results on line 2. [Kei02b, Kor02]

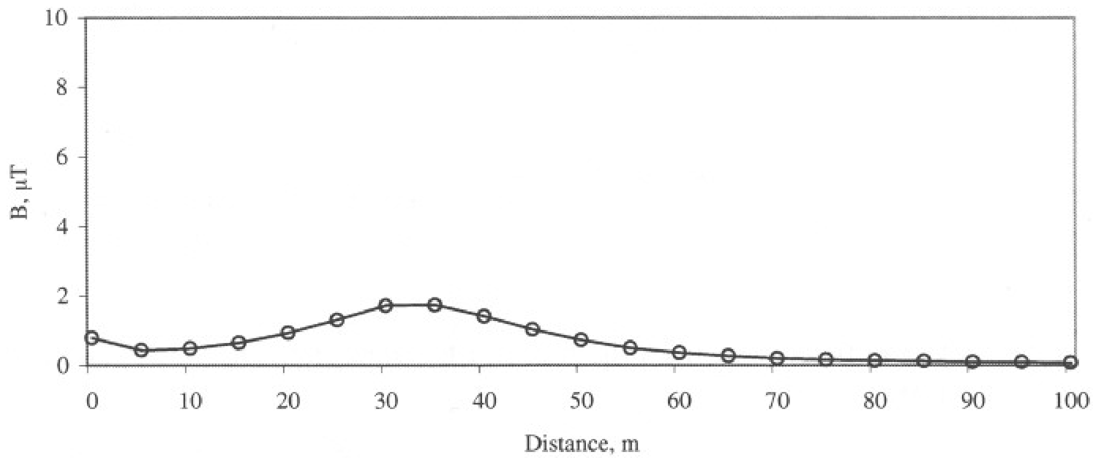


Figure 5.20. Magnetic field away from the fence of the substation (n=21) on line 2. [Kei02b, Kor02]

Values were quite small compared to the EU recommendation value 100 µT. Even at the fence the magnetic field was below 1 µT. Near the fence, there was a 110 kV transmission line from the substation 110 kV switchyard, which cause a rise in the curve being still below 2 µT. [Kei02b]

The measurement lines were also used in the electric field measurements. Figure 5.21 presents electric field results on measurement line 1.

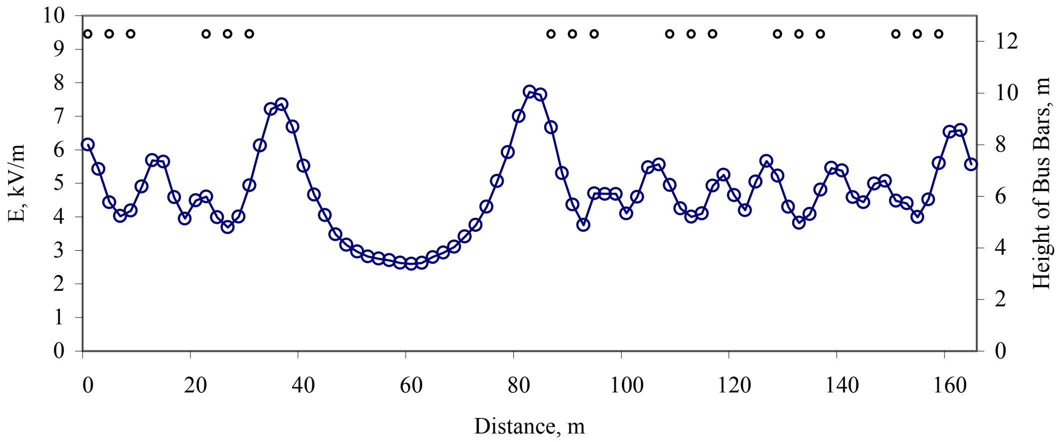


Figure 5.21. Electric fields on line 1 at the 400 kV switchyard (n=83, bus bar ◦◦◦). [Kei02b]

The highest value 7.64 kV/m was measured from point 43, which was 86 meters from the western end of line 1. Also, the harmonic content of the point was measured. Up to 650 Hz the K_2 value was 1.067 meaning the limit value 9.37 kV/m for 50 Hz. [Kei02b]

The K_2 value for the measurement near the converter of the DC link was 1.033 meaning the limit value 9.68 kV/m for 50 Hz. Electric field away from the fence of the substation on line 2 is presented in figure 5.22. [Kei02b, Kor02]

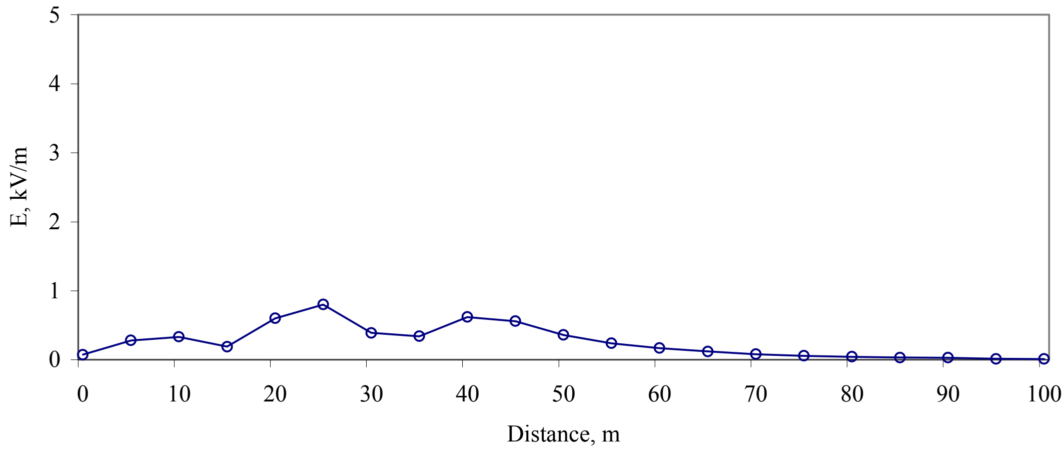


Figure 5.22. Electric field away from the fence of the substation (n=21) on line 2. [Kei02b, Kor02]

Values away from the fence of the substation were quite small compared to the EU recommendation value 5 kV/m. The 110 kV transmission line cause a relatively similar peak as in the magnetic field results in figure 5.20. The electric field values were still even below 1 kV/m.

5.2.5 Electric and Magnetic Field Mitigation

The mitigation of the fields in the substation is effective at the design. One possibility is to plan a GIS instead of an outdoor substation if it is economically possible. By using the GIS, the external electric field is almost completely eliminated, because all the metallic structures are grounded and outgoing lines are cables. Instead, the magnetic field with GIS may be even higher than with air insulated substations, because switchgear apparatus may be closer to workers. In addition, due to contact protection workers may do installations near powered outgoing cables or switchgear, which may cause high magnetic field exposure.

In the measured substations the highest maximum field 9.9 kV/m was slightly below occupational exposure reference value 10 kV/m. However, the bus bar voltages were considerably below the maximum continuous operational voltage 420 kV. The guidelines could be exceeded with the maximum operational voltage. The level of the harmonics was not significant. Thus reducing the harmonics of the voltage or current may have a minor effect on the exposure.

With live wiring techniques, which are an essential part of maintenance work, the protective clothing may be one possibility with electric field exposure. However, protective clothing has practically never been used or considered from an electric field exposure point of view (So far only with hedging against electric shock).

5.3. INDOOR DISTRIBUTION SUBSTATIONS

Electric and magnetic fields in the case of indoor distribution substations are principally case-specific, because structures and devices vary. However, the electric field is not a problem in the space above or beside the indoor distribution substation, because the ceiling and the walls of the substation eliminate it. The secondary LV system of the indoor distribution substation is a significant source of the magnetic field.

Construction drawings of the 200 indoor distribution substation structures were analyzed to get a secondary LV system classification. There was not enough information for classification in 37 construction drawings. The only information for the 15 structures was that they contain bus bars and cables in 29 structures [Kot99]. Structural distribution of the secondary LV in 119 indoor distribution substations is presented in figure 5.23 [Kot99].

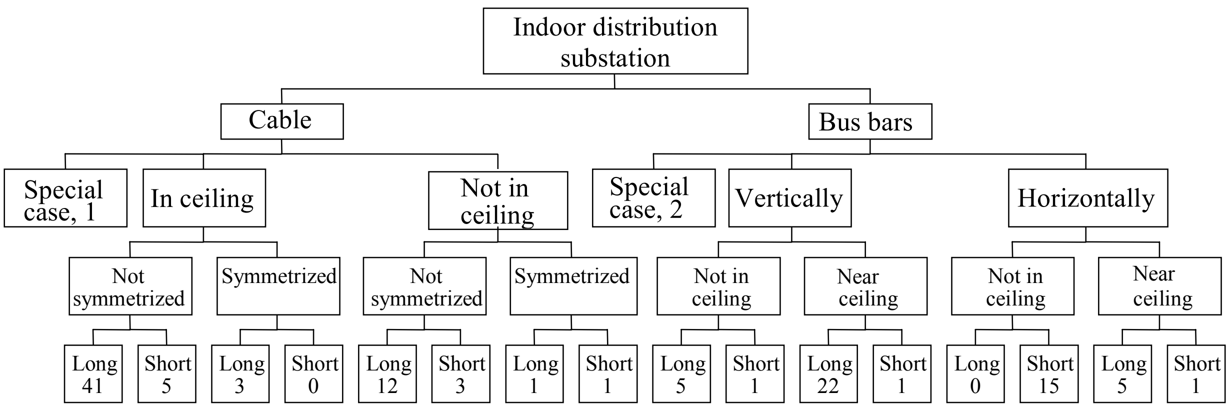


Figure 5.23. Structural distribution of indoor distribution substations [Kot99].

Magnetic field with original structures, 20 situations, and different mitigation methods, 15 structures, were measured and calculated. The total amount of the studied structures of secondary LV conductor systems was 35. Studied examples of indoor distribution substations are presented in Table 5.4. In the name of indoor distribution substation a subscript A is original structure and subscripts B … D are adapted mitigation methods. [Kei00c]

Table 5.4. Studied examples of indoor distribution substations. Subst is substation, subscript A in substation name is original structure, subscripts B … D are adapted mitigation methods. [Kei00c]

Subst	Structures of the secondary conductor system
$S1_A$	Bus bars horizontally, mounted near ceiling
$S1_B$	Bus bars changed to cables, placed optimally in a lower position
$S2_A$	Bus bars vertically, mounted near ceiling
$S2_B$	Bus bars changed to cables and placed on the floor of the substation
$S3_A$	Bus bars horizontally, mounted near ceiling, dry type transformer
$S3_B$	Installed instead two oil insulated 1000 kVA transformers, bus bars changed to cables and placed on the floor of the substation
$S4_A$	Bus bars vertically, mounted near ceiling
$S4_B$	Bus bars changed to cables and placed on the floor of the substation, 5 mm thick Al groove added
$S5_A$	Cables near ceiling and placed not optimally
$S5_B$	Cables placed partially on the floor of the substation
$S5_C$	Cables placed on the floor of the substation
$S5_D$	5 mm thick Al plate behind the LV switchgear
$S6_A$	Bus bars horizontally, transformer and the LV switchgear put together lying back to back
$S6_B$	3 mm thick Al enclosure added
$S7_A$	Cables near ceiling and placed optimally
$S7_B$	Cables placed in a 1 m lower position
$S8_A$	Bus bars vertically, mounted near ceiling
$S8_B$	Bus bars changed to cables, placed optimally in a lower position, 5 mm thick aluminum groove added
$S8_C$	Groove completed with the cover
$S8_D$	5 mm thick Al plate added above MV switchgear
$S9_A$	Bus bars horizontally, mounted near ceiling
$S9_B$	5 mm thick Al enclosure added
$S10_A$	Cables near ceiling and placed not optimally
$S10_B$	5 mm thick Al plate added to one wall of the substation
S11	Cables placed on the floor of the substation and placed not optimally
S12	Transformer and the LV switchgear put together lying back to back
S13	Bus bars horizontally, mounted near ceiling
S14	Bus bars horizontally
S15	Cables near ceiling and placed optimally
S16	Cables near ceiling and placed not optimally
S17	Cables placed on the floor of the substation and placed not optimally
S18	Cables near ceiling and placed not optimally
S19	Cables placed on the floor of the substation and placed not optimally
$S20_A$	Bus bars horizontally, mounted near ceiling
$S20_B$	4 mm thick Al plate added to one wall of the substation

The length of the secondary systems mainly affects the spread propagation of the magnetic field. Thus the effect of the length of the secondary is not presented as a mitigation method in the following analysis. In two structures of the indoor distribution substations magnetic field mitigation was utilized as separate parts and the field was measured between changes. One substation included a dry type transformer. The magnetic field compared to the nominal power may be higher with dry type than with oil insulated transformers, because differences in stray capacitance and casing [Tik92].

5.3.1 Measurement and Calculation Results

Magnetic field calculation method for the indoor distribution substations is presented in publications 1, 5, 6, 8 and in references [Kei01a, Kei01b]. The measurement method has been presented in publications 6 and 8. Calculation and measurement results are widely presented in publication 6 and 8, and references [Kei00c, Kei01a, Kei01b]. Table 5.5 presents maximum measured values (at the floor of the room above or next to, and at the height of 1 m), maximum calculated values (1 m), and the difference between the values ΔB_{max} (1 m). [Kei00c]

Table 5.5. Measured (B_M) and calculated (B_C) magnetic field values and the difference ΔB_{max}. [Kei00c]

Substation	I_{load}, A	B_M (floor), µT	B_M (1 m), µT	B_C (1 m), µT	ΔB_{max} (1 m), µT	ΔB_{max} (1 m), %
$S1_A$	505	-[1]	-[1]	2.56	-[1]	-[1]
$S1_B$	505	7.93	1.56	1.58	-0.02	-1.28
$S2_A$	380	20[2,3]	-[2,3]	10.7	-[1]	-[1]
$S2_B$	380	3[2,3]	-[2,3]	1.51	-[1]	-[1]
$S3_A$	1500	-[1]	-[1]	458.7[4]	-[1]	-[1]
$S3_B$	630+585	224.0[4]	151.6[4]	166.6[4]	-15.0	-9.89
$S4_A$	250	-[1]	3.3[3]	3.33	-0.03	-0.91
$S4_B$	250	-[1]	-[1]	0.70	-[1]	-[1]
$S5_A$	715	-[1]	10[3]	13.6	-3.6	-36.0
$S5_B$	715	-[1]	8[3]	10.8	-2.8	-35.0
$S5_C$	700	-[1]	1.3[3]	1.60	-0.3	-23.1
$S5_D$	680	-[1]	1.3[3]	1.60	-0.3	-23.1
$S6_A$	850	-[1]	2.3[3]	2.54	-0.24	-10.4
$S6_B$	850[5]	-[1]	1.7[3]	0.27	-[1]	-[1]
$S7_A$	300[5]	-[1]	1.5[3]	1.22	-[1]	-[1]
$S7_B$	300[5]	-[1]	1.0[3]	0.90	-[1]	-[1]
$S8_A$	382	17.5	4.23	5.23	-1.00	-23.6
$S8_B$	246	1.31	0.40	0.31	0.09	22.5
$S8_C$	294	1.30	0.39	0.39	0.00	0.0
$S8_D$	294	-[1]	-[1]	0.39	-[1]	-[1]
$S9_A$	1200	-[1]	12.0	12.2	-0.2	-1.7
$S9_B$	1200	-[1]	2.1[3]	0.99	1.11	52.9
$S10_A$	500	-[1]	-[1]	5.42[6]	-[1]	-[1]
$S10_B$	500	-[1]	-[1]	2.61[6]	-[1]	-[1]
S11	138	0.88	0.49	0.49	0.00	0.0
S12	331	2.40	0.60	0.49	0.11	18.3
S13	730	41.6	5.51	6.32	-0.81	-14.7
S14	975	26.2	3.83	2.98	0.85	22.2
S15	511	6.95	2.19	1.61	0.58	26.5
S16	356	6.19	2.05	1.74	0.31	15.1
S17	500	-[1]	-[1]	2.81	-[1]	-[1]
S18	500	-[1]	-[1]	3.10	-[1]	-[1]
S19	500	-[1]	-[1]	0.72	-[1]	-[1]
$S20_A$	428	-[1]	-[1]	0.36	-[1]	-[1]
$S20_B$	428	0.37[6]	0.26[6]	0.31[6]	0.5	19.2

[1] no results; [2] on the floor of the space above; [3] measured by the electric utility;
[4] inside the substation; [5] estimated; [6] in the space beside

The measured maximum values in the room above (excluding the results remarked with 1 … 4) were 0.26 … 5.51 µT, and the calculated values were 0.31 … 6.32 µT at the height of 1 meter. If the difference is compared to measured values the differences were 0.0% … 26.5%. The differences were partly due to the fact that measurements were non-accessible in some locations where, however, the calculations have been carried out. At the floor level the results were between 0.37 … 41.6 µT, being 1.4 … 7.5 times higher than at the height of 1 meter. The public exposure guideline was not exceeded. However, when considering the harmonics, the exceedings may be possible at floor level.

One major factor, which affected the differences, was the difficulty to determine the location of the secondary LV conductors in the space above or beside. Also, the thickness of the floor of the space above, or the wall of the space beside was difficult to measure with the meters used.

The load current and the thickness of the floor were studied for the indoor distribution substations $S8_A \ldots S8_C$. The results are presented in Table 5.6.

Table 5.6. The effect of the measured load current *I* and varied floor thickness Δh [Kei00c].

Subst.	***I*, A**	**Calculated *B*, µT**	***B*/*I* µT/A**	**Δh = -0.1 m ΔB, %**	**Δh = +0.1 m ΔB, %**	**Δh = +0.2 m ΔB, %**	**Δh = +0.3 m ΔB, %**	**$\Delta B/\Delta h$ %/m**
$S8_A$	382	5.2	+1.37	+11.9	-10.3	-19.3	-27.1	-119 … -90
$S8_B$	246	0.3	+0.13	+5.2	-4.9	-9.5	-13.8	-52 … -46
$S8_C$	294	0.4	+0.14	+5.1	-4.8	-9.4	-13.7	-51 … -46

The load current is a linear factor for the magnetic field. In addition, the thickness of the floor was almost a linear factor in the scales presented in the Table 5.6. For the original structure the dependency on the thickness of the floor was remarkably high. Whereas, the dependencies were considerably lower for mitigated substations $S8_B$ and $S8_C$. The other affecting factors are varying asymmetry of the load current, vagabonding ground currents, all electrical equipment in the building producing magnetic field, and all loaded conductors.

5.3.2 Magnetic Field Mitigation

The means for the magnetic field mitigation have been presented in publications 6 and 8 and in references [Kei00c, Kei00d]. Magnetic field values in a room above or beside are usually below the exposure guidelines, whereas disturbance problems may appear. In addition, the guidelines may be exceeded at floor level. When reducing magnetic fields, the most significant perspective is to consider the structure of the secondary LV conductor system between the transformer and the LV switchgear.

Satisfactory solutions can be achieved by simultaneously applying several methods [Kei00b]. Also factory-made, low-field substations can be applied. Possible structural changes are changing bus bars to cables, optimal positioning of the cables, increasing the distance between the secondary system and the ceiling, installing two substations instead of one in the same place, reducing harmonics of the load current, and putting transformer and LV switchgear together lying back to back. Table 5.7 presents magnetic field reduction effect for both the highest calculated and the highest measured values.

The transformer is not usually a remarkable magnetic field source, because nearly all of the magnetic flux stays inside the transformer core or the field is reduced in the transformer tank [Tik92]. However, the magnetic field from the LV switchgear becomes significant, when the magnetic field from the secondary LV conductor structure is reduced.

The shielding of the secondary system can be realized with a metallic groove, enclosure or plate. In shielding the materials may be highly conductive aluminium and copper or ferromagnetic iron [Kei00a]. With highly conductive materials the shielding effect is based on the eddy currents induced in the material. With the ferromagnetic materials the shielding effect is due to ferromagnetic ability to lead magnetic flux inside the material away from the object. In practice, the most common material is very pure aluminium [Suo93].

The heat transfer worsening effect has to be considered in high current systems, when estimating the load capacity of the system. The shielding may worsen the convection; in other words the heat transfer from the secondary LV conductors to the surroundings is deteriorated or is completely prevented. In addition, when conductors are shielded the air cannot flow freely between the conductors. The shielding may be critical, e.g., in industry.

Table 5.7. Reduction effect of the structural change between the initial structure A and changes B … D based on the highest values. The effect of the changing load current has been eliminated. [Kei00c]

Subst.	**Initial calc., µT**	**Initial meas., µT**	**Structural change**	**Changed calc., µT**	**Changed meas., µT**	**Calc. reduct., %**	**Meas. reduct., %**
$S1_{A...B}$	2.56	-[1)]	Bus bars changed to cables, placed optimally in a lower position	1.58	1.56	38.3	-[1)]
$S2_{A...B}$	10.7	About 20[2)]	Bus bars changed to cables, placed on the floor of the substation	1.51	About 3[2)]	85.9	85.0[2)]
$S3_{A...B}$	458.7	-[3)]	Installed two transformers, bus bars changed to cables, placed on the floor	166.6	151.6	55.2	-[3)]
$S4_{A...B}$	3.33	About 3.3	Bus bars changed to cables and placed on the floor of the substation, 5 mm thick aluminum groove added	0.70	-[3)]	79.0	-[3)]
$S5_{A...B}$	13.6	About 10	Cables placed partially on the floor	10.8	About 8	20.6	20.0
$S5_{A...C}$	13.6	About 10	Cables placed on the floor	1.60	About 1.3	88.0	86.7
$S5_{A...D}$	13.6	About 10	5 mm thick aluminum plate behind the LV switchgear	1.60	About 1.3	87.6	86.3
$S6_{A...B}$	2.54	About 2.3	3 mm thick Al enclosure added	0.27	About 1.7	89.4	26.1
$S7_{A...B}$	1.22	About 1.5	Cables placed in a 1 m lower position	0.90	About 1.0	26.2	33.3
$S8_{A...B}$	5.23	4.23	Bus bars changed to cables, placed optimally in a lower position, 5 mm thick aluminum groove added	0.31	0.40	90.8	85.3
$S8_{A...C}$	5.23	4.23	Groove completed with 5 mm thick Al cover	0.39	0.39	90.3	88.0
$S8_{A...D}$	5.23	4.23	5 mm thick aluminum plate added above MV switchgear	0.39	-[3)]	90.3	-[3)]
$S9_{A...B}$	12.2	12.0	5 mm thick Al enclosure added	0.99	About 2.1	91.9	82.5
$10_{A...B}$	5.42	-[3)]	5 mm thick aluminum plate added to one wall of the substation	2.61	-[3)]	51.8	-[3)]
S11	-[3)]	-[3)]	Cables placed on the floor of the substation and placed optimally	0.49	0.49	-[3)]	-[3)]
S12	-[3)]	-[3)]	Transformer and the LV switchgear put together lying back to back	0.49	0.60	-[3)]	-[3)]
S13	6.32	5.51	Bus bars horizontally, mounted near ceiling	-[3)]	-[3)]	-[3)]	-[3)]
S14	-[3)]	-[3)]	Bus bars not in ceiling	2.98	3.83	-[3)]	-[3)]
S15	-[3)]	-[3)]	Cables near ceiling and placed optimally	1.61	2.19	-[3)]	-[3)]
S16	1.74	2.05	Cables near ceiling and placed not optimally	-[3)]	-[3)]	-[3)]	-[3)]
S17	2.81	-[3)]	Cables near ceiling and placed not optimally	-[3)]	-[3)]	-[3)]	-[3)]
S18	3.10	-[3)]	Cables near ceiling and placed not optimally	-[3)]	-[3)]	-[3)]	-[3)]
S19	-[3)]	-[3)]	Cables placed on the floor of the substation, placed not optimally	0.72	-[3)]	-[3)]	-[3)]
$S20_{A...B}$	0.36	-[3)]	4 mm thick aluminum plate added to one wall of the substation	0.31	0.26	13.9	-[3)]

[1)] another measurement from different height, [2)] on the floor, [3)] no another case

The shielding may be expensive, thus the goal is important to define before shielding. In addition, shielding can increase power losses. Thus the shielding has to be designed keeping in mind both the technical and the financial aspects. In the design of techniques, the experimental know-how and numerical calculations are vitally important. Both techniques have many factors of uncertainty, which may result in the desired results not being achieved.

Changing bus bars to cables

Decreasing the clearance between phases of the secondary system reduces the magnetic field. The decrease can be achieved by using insulated one or three phase cables instead of bus bars. Another advantage is that the required space is decreased. In three-phase cable the phasing of the conductors is rather symmetric, but also one-phase cables can be placed symmetrically.

This method was not applied in any of the studied examples of indoor distribution substations as the only mitigation method. Bus bars were changed to cables as a part of the structural change in example substations $S1_B$, $S2_B$, $S3_B$, $S4_B$, $S8_B$ and S17. The cables were usually spaced optimally on the floor of the substation. The results of the magnetic field reduction effect were presented previously in Table 5.7.

The magnetic field reduction effects considering calculation results in the example substations were between 40% … 90%. The reason for high deviation in the reduction effect was the other structural changes rather than changing bus bars to cables. The effect of the other changes may be even more remarkable. In those substations, which were measured before and after the change, the reduction effects considering measurement results were about 85%.

Optimal placing of cables

Magnetic field mitigation by placing cables optimally is suited for cable systems, which contain more than two cables per phase. The intention is to achieve as symmetric a structure as possible. There are many possible placing alternatives. One possibility is to place cables with a supporting insulator of the high current cable system. Figure 5.24 presents two examples for symmetrical placing for having two cables per phase and one PEN conductor.

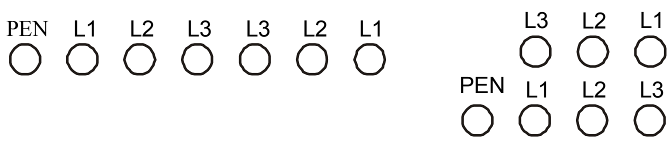


Figure 5.24. Two cables per phase placed symmetrically. [Kei00c]

When there are more than two conductors per phase, the amount of possible symmetric structures becomes higher. In addition to the reduction effect, the choice of the structural change depends on the available space. Usually, the space reserved for the cable system cannot be enlarged. In electrically symmetric system, the location of the PEN conductor does not effect the magnetic field, because the current is zero. Nevertheless, in real system the current of PEN conductor is not zero and the conductor is recommended to wire nearby phase conductors.

Optimal placing of cables was applied in substations $S1_B$, $S7_B$, $S8_B$, S11 and S15. However, it was not applied as the only mitigation method. The results of the magnetic field reduction effect were presented previously in Table 5.7. The magnetic field reduction effects considering calculation results were between 40% … 90%. The reduction effect was in the same limits for the measured substation. However, the other structural changes also effected the results.

Placing secondary system in a lower position from the ceiling

Even a small increasing of the distance between the disturbed appliance and the secondary system has a significant effect on magnetic field. Transferring the secondary system is considerably more difficult with bus bar system than with cable system. If the disturbed appliance is above the indoor distribution substation, the secondary system can be replaced in a lower position from the ceiling.

This method was applied in example substations $S1_B$, $S2_B$, $S3_B$, $S4_B$, $S5_B$, $S5_C$, $S7_B$, $S8_B$, S11, S14 and S19. Replacing secondary system from the ceiling was applied in substation $S7_B$ as the only mitigation method. In other substations other reduction methods were also applied. The results of the magnetic field reduction effect were presented previously in Table 5.7. To conclude, the reduction effects were between 20% … 90%

In substation $S7_B$ secondary LV cables were placed in a 1 m lower position than in initial structure. The reduction effect considering calculation results was 25% and considering measurement results the effect was 35%. Even placing cables partially on the floor of the substation, case $S5_B$, have the effect of 20%. However, when the cables in the same place were placed on the floor, case $S5_C$, the effect was over 80%.

Installing two substations instead of one

Structural changes may be required to renovate the substation. If the load has increased, a new transformer may be needed. Thus, it is possible to construct two substations instead of one. Further, the secondary LV conductors can be located optimally considering the possible disturbances. This method is applied in the example substation $S3_B$. The calculated reduction effect was 55%. However, the bus bars were changed to cables and placed on the floor, as well.

Reducing magnetic field harmonics

Magnetic field harmonics could cause disturbances particularly near indoor distribution substations. If the quality of the electricity is improved, the disturbance may disappear. Table 5.8 presents the harmonics measurement results. The amount of the harmonics was significant, but the guidelines were not exceeded. The amount of the 3rd magnetic field harmonic was especially significant.

Table 5.8. Magnetic field harmonics in the example substations [Kei00c].

Substation	*I*, A	B_{max}, µT	*B* (50 Hz), µT	*B* (150 Hz), %	*B* (250 Hz), %	*B* (350 Hz), %	*B* (450 Hz), %	*B* (550 Hz), %	K_1	K_2
S11	138	0.49	0.16	62.03	5.06	3.80	14.56	2.53	1.19	4.97
S12	331	0.60	0.47	47.98	2.97	3.61	11.46	4.03	1.12	4.32
S15	511	2.19	1.20	100.75	9.91	4.25	15.57	2.59	1.43	6.50
S16	356	2.05	1.83	65.85	3.28	1.20	21.37	2.51	1.22	5.42

In the Table 5.8 the effect of the harmonics considering the exposure guidelines was significant, because the induced currents are directly proportional to the time derivative of the magnetic field. The highest K_1 up to 550 Hz was 1.43 and the highest K_2 was 6.50 according to ICNIRP public exposure guidelines and EU Council recommendation. The highest K_2 value means, that the 50 Hz value is allowed to be 15.4 µT. However, the K'_2 would probably have been smaller, being usually 1.5 … 3 [Jok03].

The electricity system of the building may cause stray currents to conductive and grounded structures like supporting structures, heating radiators, pipe and drainpipe systems [Hof95]. If the electricity system is a grounded TN-C distribution system, the common PE and N conductor leads to the stray currents. Whereas, in TN-S system with the separate PE and N conductors, stray currents are better taken into consideration. In addition, electricity system of the distribution substation may cause stray currents in the building. An old installation practice was to ground the transformer both to the PEN or N conductor and to the grounding bus bar. This causes a closed loop circuit for stray currents, which again have an effect on the magnetic field in the building. This especially affects harmonics divisible by three, which may cause disturbances. The mitigation method is to cut the stray current circuit, as presented in figure 5.25.

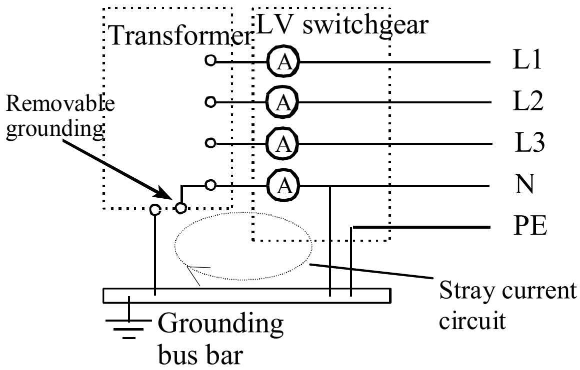


Figure 5.25. Substation $S8_A$ electricity installation drawing. [Kei00c]

With the substation $S8_A$ the magnetic field was measured before and after the additional grounding was cut. When the loop was opened the harmonics divisible by three were reduced by 60%. The action did not cause any additional costs besides labor costs.

Putting transformer and LV switchgear together lying back to back

Spreading of the magnetic field is reduced by making secondary system as short as possible. The secondary system is short, if the transformer and LV switchgear are laying back to back. Another effect is the increase of the distance to the space above due to the rigid structure. The back-to-back structure was applied in example substations $S6_A$ and S12. However the structures were implemented at the beginning.

Installing aluminium groove

The use of an aluminium groove is one of the shielding methods. It is important to make the groove as conductive as possible. This means also, that thick material is better than thin. Thus, if any joints are needed, it is worth to do it by welding [Suo93]. The groove directions upward, downward, leftward or rightward are not important for the shielding results. The direction may be chosen on the basis of ease of installation.

This method was applied in substations $S4_B$ and $S8_B$. The results of the magnetic field reduction effect were presented previously in Table 5.7. The reduction effects were between 80% … 90%. However, the secondary LV bus bars were also changed to cables in both substations. Regardless, the groove also had a significant effect on the results.

Installing aluminium enclosure

Use of aluminium enclosures may be difficult in some structures. This problem has been solved by first installing an aluminium groove and then completing it with a cover. The cover was not welded to be sure the insulators inside were not damaged. This negligence may cause deterioration in the shielding effect, due to the current insulation in joints.

The method with aluminium enclosure was applied in substations $S6_B$, $S8_C$ and $S9_B$. The results of the magnetic field reduction effect were presented previously in Table 5.7. Installation of aluminium enclosure was the only mitigation method in substations $S6_B$ and $S9_B$. The calculated reduction effects were about 90% and measured between 25% … 90%.

The reduction effect was supposed to be better on the basis of calculations. Especially with the substation $S6_B$, one reason for the lower shielding effect was the other conductors and feedings in the substations, which were not considered in calculations. Conductivity of the enclosure was another reason for the failures being deteriorated when bending or welding the plate.

Installing aluminium plate

The facing of the ceiling and walls of the substation with aluminium plate is an expensive shielding method. Instead the use of the aluminium plate behind LV bus bars or LV switchgear may be useful. When the plate is installed near the switchgear, the reduction has an effect in a room above on the presumption that the main source is focused to the switchgear.

This method was applied in example substations $S5_D$, $S8_D$, $S10_B$ and $S20_B$. The results of the magnetic field reduction effect were presented previously in Table 5.7. The calculated reduction effects were between 15% … 90%. The measured reduction effect was 85% in the substation $S5_D$. Installing aluminium plate was the only mitigation method in substations $S10_B$ and $S20_B$. In the substation $S10_B$ the reduction effect was about 50%, when 5 mm thick aluminum plate was installed behind the LV switchgear. In the substation $S20_B$ the shielding effect was considerably smaller, because the distance between the plate and secondary LV bus bars was longer than in other structures.

5.4. ARC FURNACE

Magnetic field has been measured and calculated nearby an arc furnace. Measurements were carried out with Tampere Regional Institute of Occupational Health in 1996. The rated power of the arc furnace in question was 75 MVA. The power is fed with three single-phase transformers. Measurements were carried out from the occupational exposure and disturbance point of view. The goal was to reduce the magnetic field. Measurement periods were set up as three experiments.

In the first experiment the magnetic fields were measured at the distance of 3.45 m from the surface of the arc furnace. Two different directions, points A and B, were measured at the same time. The measurement took one day (measurement interval 20 sec, record time for full memory 22 h 43 min). In the second experiment the magnetic fields were measured in the direction of the electrode I at points C … E. Magnetic fields were measured with higher range meters in points C and D and with the lower range meter in point E. One day (22 h 43 min) was measured. In the third experiment the magnetic fields were measured in the direction of the electrode III at points T1 … T4. The higher range meters were first placed into measurement points T1 and T2 and 11 min 50 sec was measured. Then the meters were placed into measurement points T3 and T4 and 11 min was measured. The measurement intervals were 1 sec. Measurements (n=1311) took 24 min with the meters' transportation. Measurement points of the experiments are presented in figure 5.26.

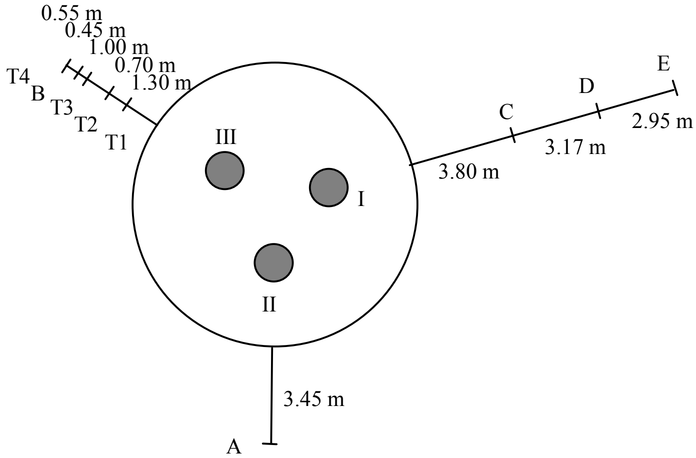


Figure 5.26. The arc furnace measurement points. The distances are for the segments.

The current of the electrodes was also measured during the magnetic field measurements. Ten or one minute average currents were given from the control room of the furnace. After measurements the load currents were printed.

5.4.1 Measurement and Calculation Results

One common feature with arc furnaces is that load currents vary much during the melting process. Furthermore the amount of harmonics and concentration of harmonics vary greatly. In addition it is important to clarify the content of the magnetic field harmonics and measure the long-term load current. A summary of the measured currents is presented in Table 5.9.

Table 5.9. Phase currents and angles during the experiments 1 ... 3. Electr. corresponds electrodes, mean is mean phase current value for average currents I_I, I_{II} and I_{III}, φ is phase angle, max. is maximum and min. is minimum phase current value. [Kei97]

Electr.	Experiment 1				Experiment 2				Experiment 3			
	mean kA	**φ ( )°**	**max kA**	**min kA**	**mean kA**	**φ ( )°**	**max kA**	**min kA**	**mean kA**	**φ ( )°**	**max kA**	**min kA**
I	99.0	0.9	121.1	75.4	100.8	0.0	132.2	77.3	99.5	0.0	119.2	88.7
II	108.3	116.4	132.7	84.1	104.7	117.4	131.8	76.0	113.9	123.8	126.6	102.8
III	110.9	242.7	132.0	80.6	106.9	240.5	132.1	79.4	101.3	246.4	110.5	95.0

Shielding effect of the enclosure material and the feeders of the arc furnace were taken into account in calculations. Calculations of the arc furnace are presented in publication 7 and references [Kei97, Kei99a, Kei99c]. To calculated magnetic fields, the conductivity of the enclosure material of the furnace shell was estimated on the basis of table books. Permeability μ_r of the enclosure material was interpolated and found by comparing measurement and calculation results since the real value was not known. Then the *SE* was calculated with and without enclosure material being 5.0 dB (in publication 7 the value 77% is B_0 minus B_S divided by B_S).

The magnetic field calculated with the mean current of the first experiment is presented in figure 5.27. The origin of the figure is in the center of the arc furnace.

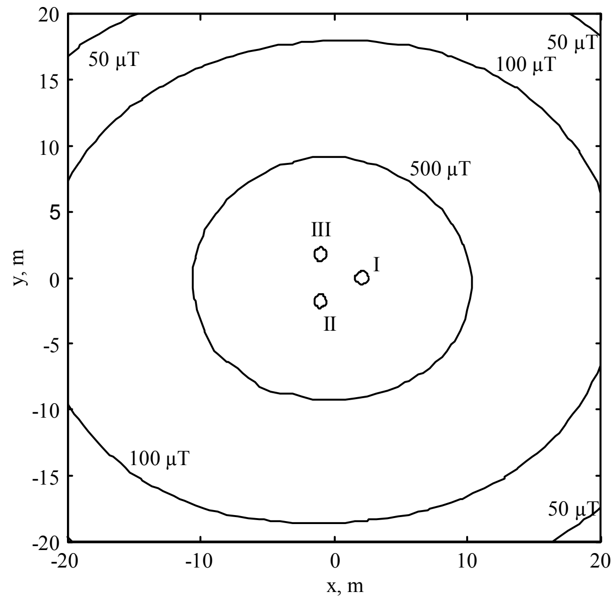


Figure 5.27. Calculated contour lines of the magnetic field nearby the arc furnace.

The ICNIRP occupational guideline for 50 Hz magnetic field is 500 µT. The guideline value was exceeded at the distance of 10 m. The results for all three experiments and for all nine points are presented in Table 5.10.

Table 5.10. Measured and calculated magnetic fields for the experiments 1 ... 3. $B_{measured}$ is measured magnetic field, mean is average value, SD is standard deviation, $B_{calculated}$ is magnetic field calculated with average currents in Table 5.9.

Experiment	Point	$B_{measured}$ (mean ± SD), µT	$B_{calculated}$, µT
Experiment 1	A	542 ± 52	533
	B	470 ± 44	508
Experiment 2	C	346 ± 30	332
	D	142 ± 13	171
	E	68 ± 7 µT	107
Experiment 3	T1	782 ± 26	805
	T2	602 ± 16	706
	T3	479 ± 9	498
	T4	366 ± 7	420

The coefficient *a* for the equation 49 was calculated for the studied arc furnace. For measurement point A the coefficient value of 5.55 was obtained with the least squares method. Coefficient for the measurement point B was 4.93. In practice, the equation 49 was tested in publication 7, where the mean value 5.2 for the coefficients in points A and B was used.

Harmonics content of the current was 0.61% for 2nd harmonics, 2.50% for 3rd harmonics, 0.35% for 4th harmonics, 0.61% for 5th harmonics, and 0.31% for 6th harmonics. The occupational K_2 was 1.17 and the adjusted reference level for 50 Hz magnetic field was 426 µT.

5.4.2 Magnetic Field Mitigation

For the arc furnace the calculated *SE* of the enclosure material was 5 dB. Results for experiment 2 were calculated with the original *SE*, 0 dB and ∞ dB. Because the enclosure affects inside the arc furnace, the feeders cause a magnetic field even when the *SE* is ∞ dB. Figure 5.28 presents the results with studied *SE* and with the approximated equation 49.

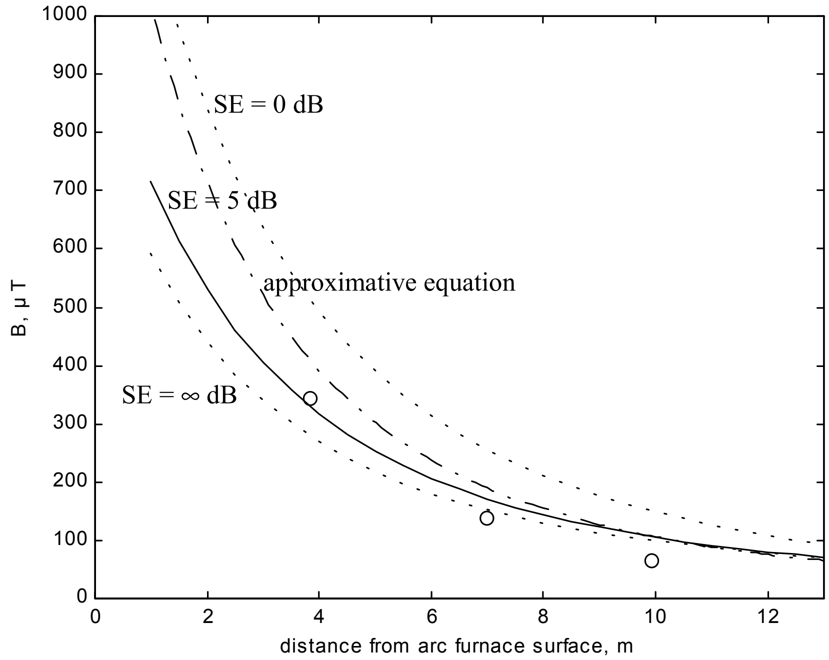


Figure 5.28. The magnetic field attenuation with distance for the example arc furnace. The *SE* of the enclosure material is 5 dB continuous line, and 0 dB and ∞ dB dashed lines. The dash-dot line is approximative equation 49, and ‘o’ -marks presents measured values. [Kei97, Kei99a]

Figure 5.28 shows that improving the shielding from 5 dB (present situation) to ∞ dB does not have a considerable effect on the magnetic fields. Based on this, the positioning of the feedings is an important factor. One possibility to reduce magnetic fields is to design more symmetric feeding cables [Kei99a]. Another possibility is to locate working posts far enough away from the arc furnace [Kei99a].

6. TECHNICAL MANAGEMENT CHAIN IN ELECTRIC POWER SYSTEMS

Technical management of the electric and magnetic fields includes specification of the problem, solving of the fields with calculations and measurements, mitigation, operations and analysis of the solutions. The technical management can be presented by means of the figure 6.1.

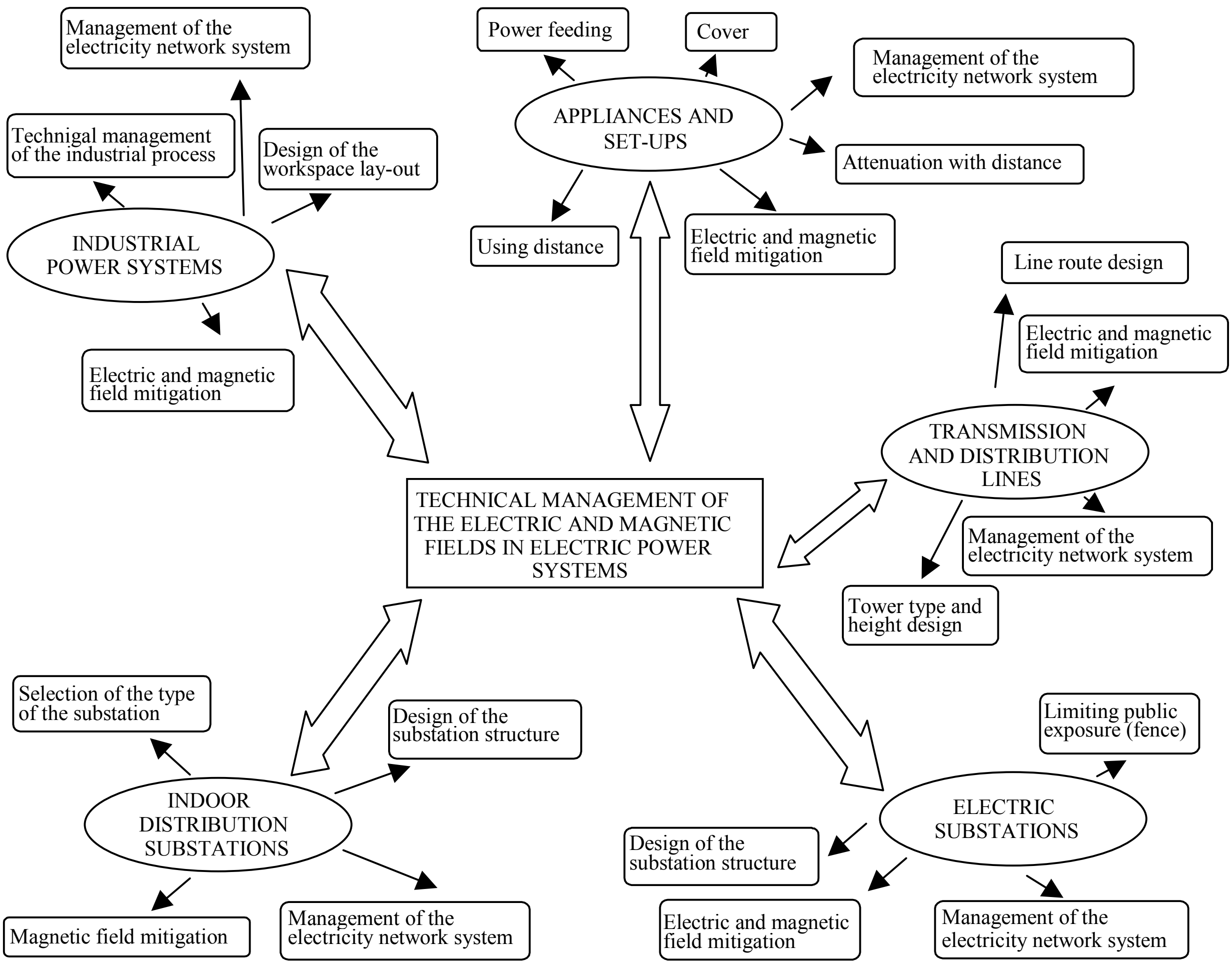


Figure 6.1. Technical management of the electromagnetic fields in electric power systems.

As presented in figure 6.1, the technical management can be divided into different pieces. The management of the electricity network system influences and is an important factor in all management areas in figure 6.1.

6.1 GENERAL ELECTRIC POWER SYSTEMS

Handling of the technical management chain of the general electric power system contains the basal questions, the goal of which is to specify the problem, theory, methods and operational part. For the general electric power system the chain can be presented by means of the following figure 6.2.

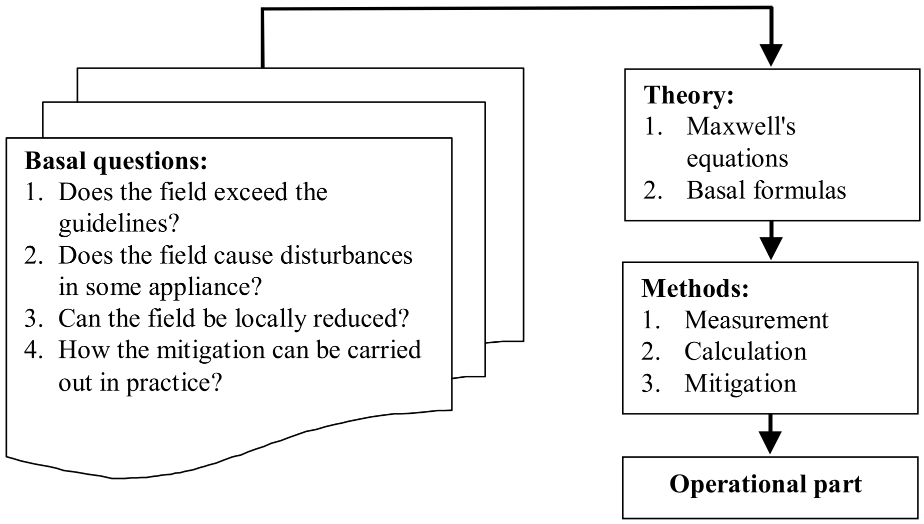


Figure 6.2. Technical management chain of the general electric power systems.

The problem can be solved, e.g., with FEM and analytical calculation methods. The theory to solve the boundary value problem is based on the Maxwell's equations and on the other basic formulas. Practical methods for solving the problems are measurement, calculation, and mitigation. Theory and methods in the technical management chain can be presented by means of the following figure 6.3.

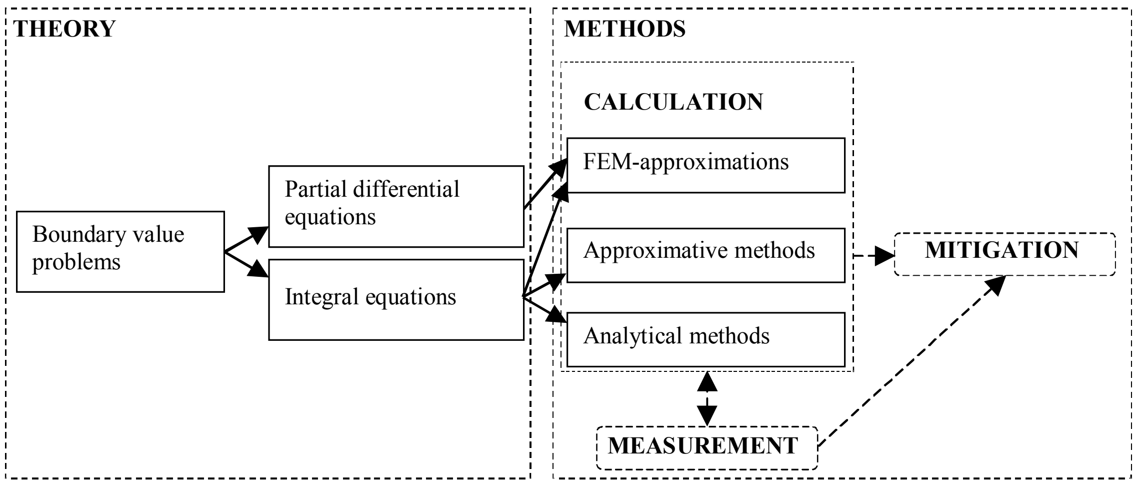


Figure 6.3. Theory and methods in the technical management chain.

Theory gives possibilities to solve the boundary value problems with FEM or with analytical and approximative integration methods. Analytical calculation methods are needed in measurements to understand measured field values. The mitigation can be carried out based on the measurements and calculations.

The mitigation is possible, e.g., by decreasing the sources of the fields or by placing the sources so that they attenuate one another. In mitigation methods the relationship between electric and magnetic field is important. The third important affecting factor is the power This relationship can be presented by means of the Poynting's theorem, as was presented previously in equation 30. The following figure 6.4 describes quantities of the Poynting's theorem.

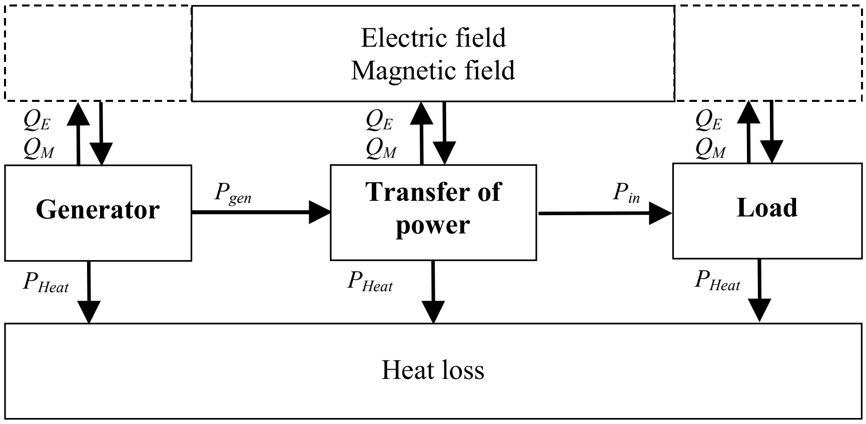


Figure 6.4. Quantities of the Poynting's theorem. P_{gen} is generated power, Q_E is reactive power stored into electric field, Q_M is reactive power stored into magnetic field, P_{Heat} is power loss, P_{in} is power fed in electrical appliance.

In figure 6.4 the final form of the energy is always heat loss, which cannot be restored. Generally, transferring the power, e.g., in generation, transmission and utilization produces reactive power. In the power generation and utilization is used technical methods, which are based on the production of the fields. According to Poynting's theorem there is balance between powers, which are: fed into system, loosened by power loss, stored by electric and magnetic fields and used by consumption. If the power cannot be changed to heat, or the mechanical load and used power is constants, the fields can be mitigated only locally. This means that by decreasing reactive power locally, the local field is increased in some other location.

The figure 6.4 can also be represented with the terms of circuit theory. The generator can be replaced by a voltage source and by generator impedance and the rest of the figure 6.4 can be replaced with Thevenin-Norton equivalent circuit [Ket01]. This can be represented as in figure 6.5.

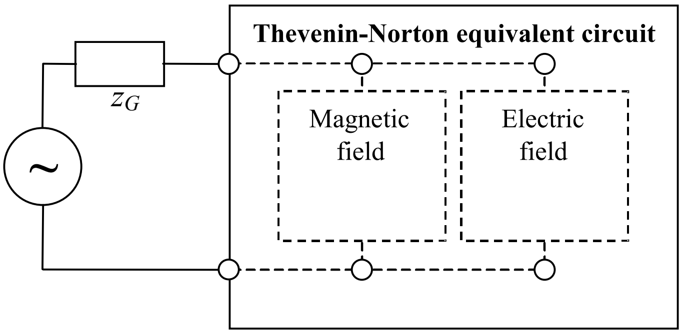


Figure 6.5. The Poynting's theorem with the terms of circuit theory. z_G is generator impedance. [Ket01]

The mitigation of the fields includes the use of isolated cables instead of bus bars, compact conductor profile design, increasing the distance between the source and the observation point, use of special reduction conductors and use of active magnetic field compensators.

When the theoretical and methodological parts of the technical management chain are described, it is possible to handle the problem in practice. Measurement, calculation, and mitigation are the methods for the operational part of the technical management chain. The technical management chain in general electric power system is presented in the figure 6.6 excluding basal questions.

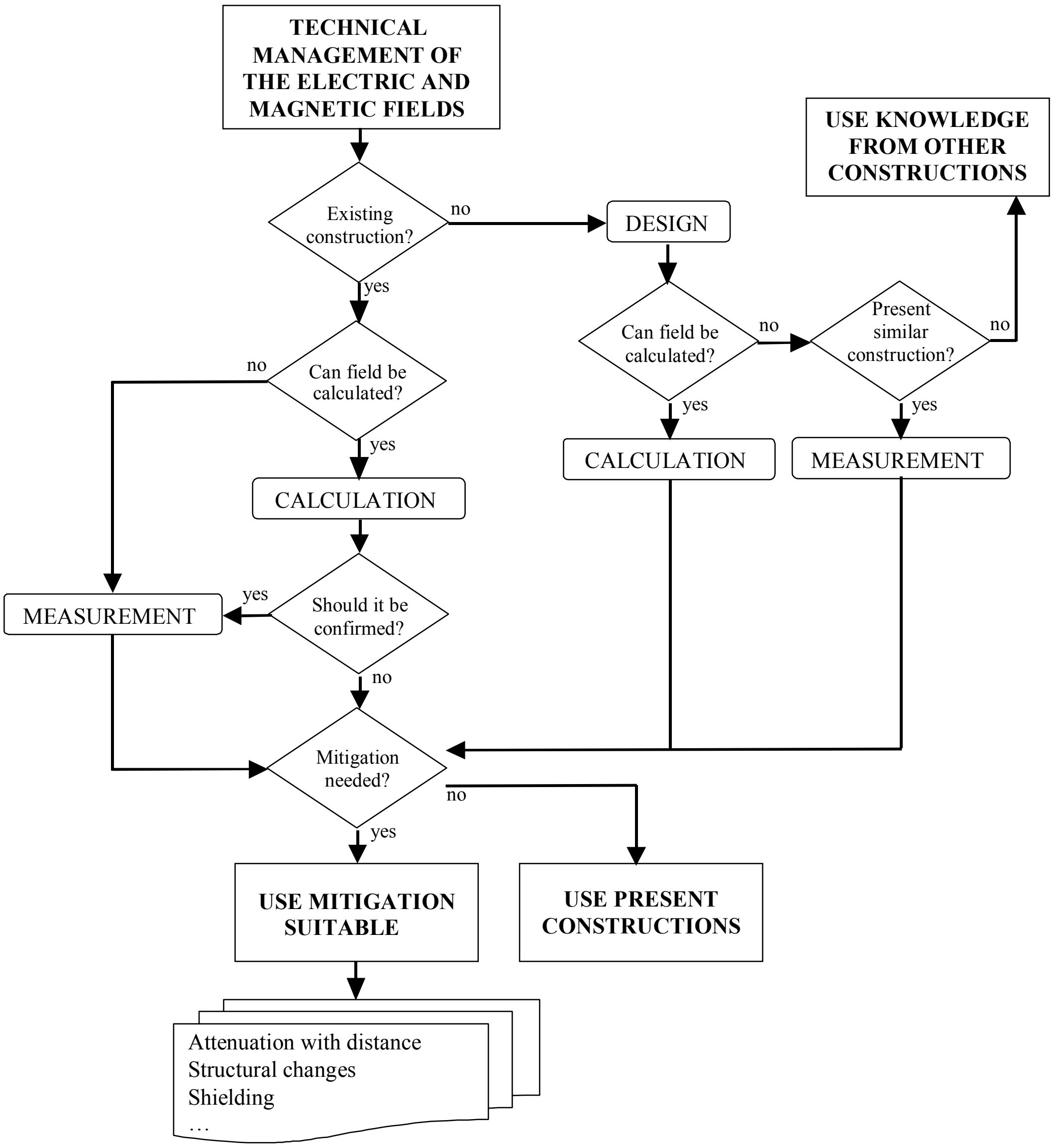


Figure 6.6. Technical management chain in a general electric power system (excluding basal questions).

The best way is to consider fields at the design. Afterwards, the mitigation may be time and money consumptive, and the results may be worse or the mitigation can even fail.

6.2 TRANSMISSION LINES

In case of transmission lines, analytical calculations and measurements are both usable methods for the field determination. In general the calculation is also a sufficient method when designing a new transmission line. Electric field is more critical than magnetic field, because the exposure guidelines of electric field may be exceeded in several locations, whereas the magnetic fields are far from the guidelines.

Mitigation methods presented previously are using cables, phase splitting, compact line design, reduction, and line height increasing. Nevertheless, they may also have a negative influence on the visual impact of the line. The technical management chain in case of transmission lines is presented in the figure 6.7.

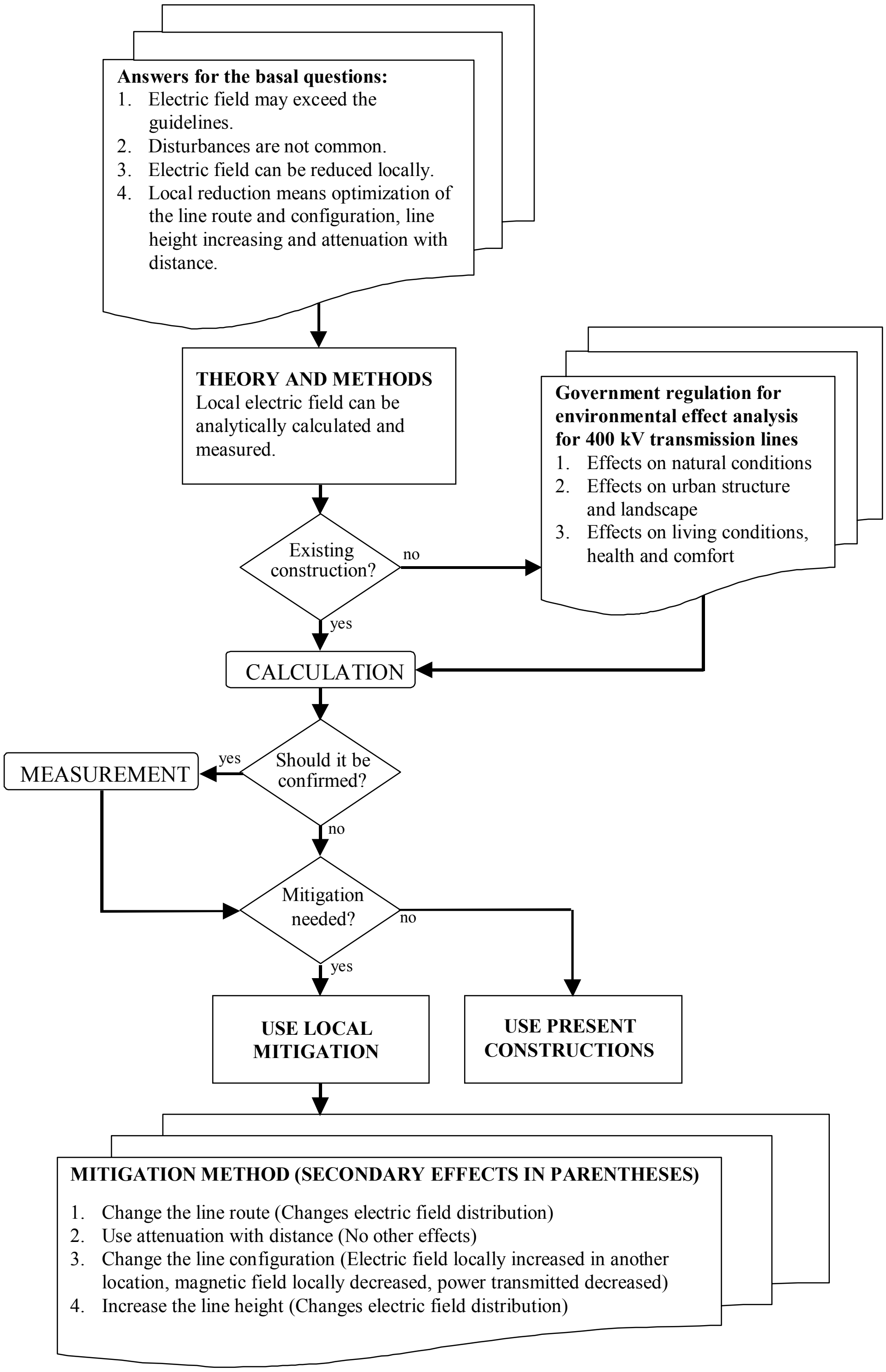


Figure 6.7. Technical management chain in case of transmission lines.

Public exposure to electric field has not previously been a design criterion. Present design criterions are the line height considering the clearances and the choice of the tower type with economic aspects. Another present design criterion is a line route design considering the shape of the land and the height of the conductors. The line route design would be much more economic choice for mitigation than the methods presented previously. This does not necessarily cause any operational change into the design. Critical locations to avoid in line routes are rocks, large stones, and hills. Another noteworthy factor is the field attenuation with distance. Nevertheless, the locations under the line cannot be forbidden to the public.

6.3 *ELECTRIC SUBSTATIONS*

In case of electric substations with outdoor constructions, electric field is usually more critical than magnetic field, which is clearly below ICNIRP exposure guidelines. For GIS the magnetic field is usually more critical than electric field. Generally, electric substations inside the fence or the hall are forbidden to the general public. The occupational exposure may occur with measurements in the switchyard and when maintaining the substation. Figure 6.8 presents the technical management chain in case of electric substation.

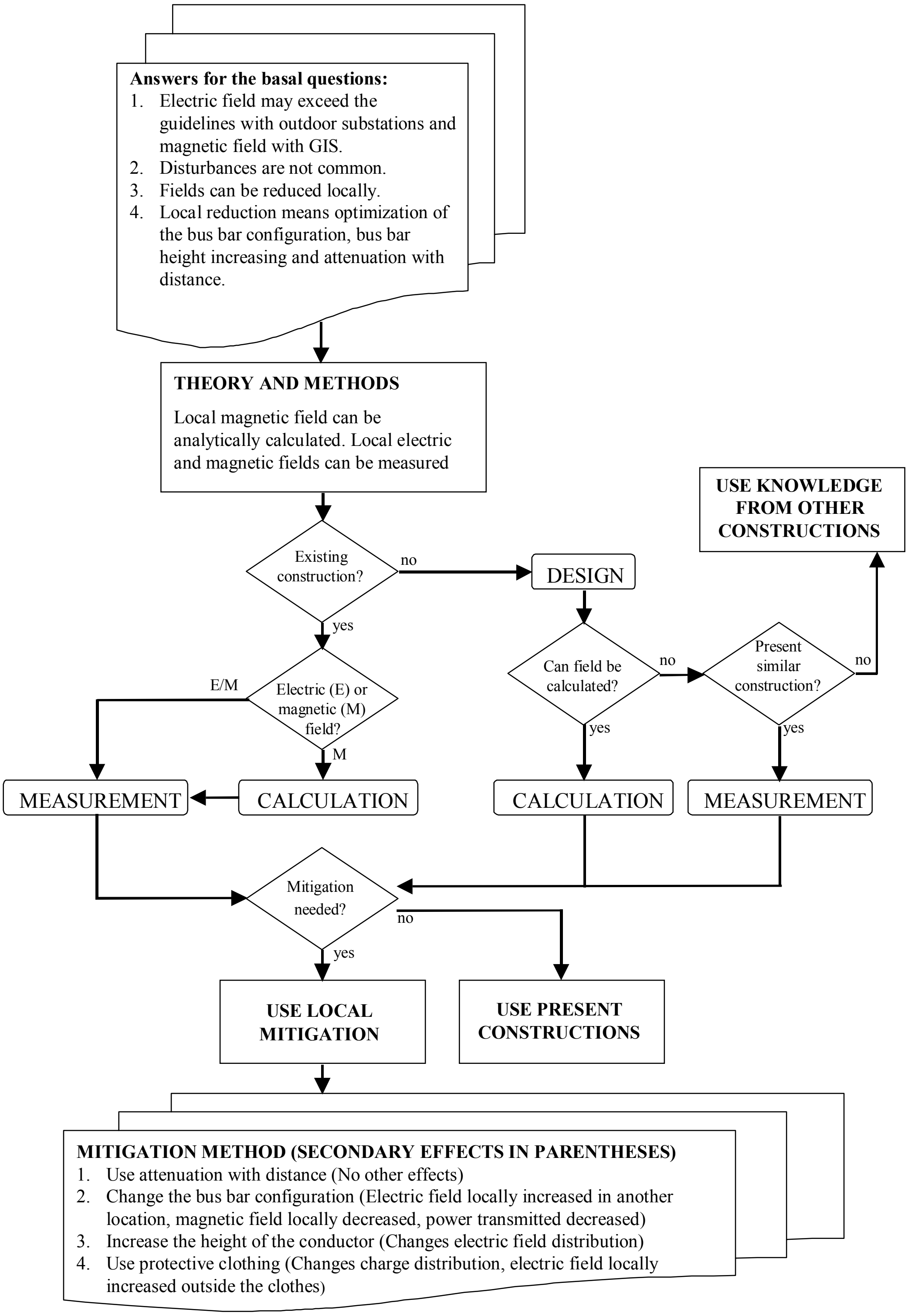


Figure 6.8. Technical management chain in case of electric substation.

The calculation of the electric field is complex and the calculations to support design of substation may be only superficial. For these reasons the measurements are essential to get basic information for the fields. Meanwhile, for outdoor substations the less critical magnetic field may be better calculated even with analytical methods than measured.

Because electric substations have case-specific constructions, only basic conclusions for the mitigation can be made. Structural mitigation methods are possible if the technical management of the fields is considered when designing a new electric substation.

For outdoor constructions the factors, which should be taken into consideration are the height of the feeders, cables and bus bars and the configuration of the conductors, which go to appliances in a lower position. For these conductors, the attenuation with distance may be exploited if possible.

With live wiring techniques, protective clothing may be one possibility with electric field exposure. However, protective clothing has practically never been used or considered from an electric field exposure point of view (So far only with hedging against electric shock).

6.4 INDOOR DISTRIBUTION SUBSTATIONS

In case of indoor distribution substations, there is no electric field in the space above or beside. In Finland, indoor distribution substations are often located in apartment and office buildings. The problem is usually a disturbance in some electrical appliances, or in apartments human exposure at floor level. Thus, one important problem in technical management is the mitigation of magnetic field.

The observation distance to adjacent devices and constructions can be increased, when the transformer tanks and switchgears are of minimum size. In designing new indoor distribution substations, the transformer and the LV switchgear may be put together principally by being laid back to back.

Good methods in magnetic field mitigation were placing secondary LV cables on the floor of the substation, putting transformer and the LV switchgear together lying back to back and shielding with aluminum cover, groove or plate. In addition, the distance from the secondary LV bus bars affects the magnetic field much. The electricity system of the building also has significant influence on the harmonic content of the magnetic field.

Indoor distribution substations have case-specific constructions. Based on the calculation results in this study, the magnetic field in case of indoor distribution substation may be calculated with the analytical method and combined analytical method and FEM. Furthermore, the magnetic field can be calculated to support design. Technical management chain in case of indoor distribution substation is presented in the figure 6.9.

The mitigation of the existing indoor distribution substation consists of the six steps presented in the lower part of the figure 6.9. For improving the present existing structure the mitigation method is presented as a starting level for the possible methods. For example, if the present structure leads to the level one, all six levels can be used for mitigation.

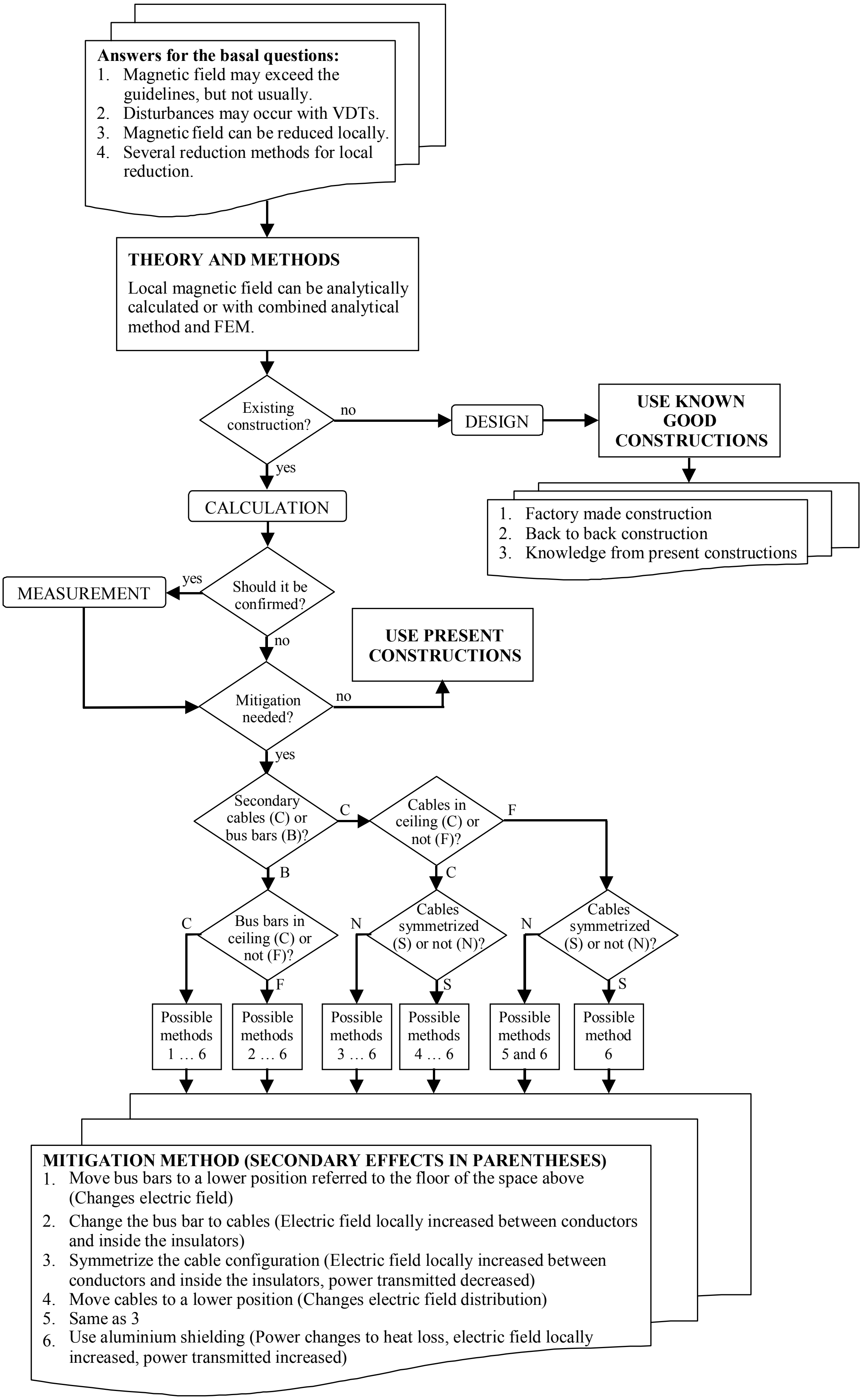


Figure 6.9. Technical management chain in case of indoor distribution substation.

6.5 ARC FURNACES

In case of arc furnace, magnetic field may be significant compared to ICNIRP occupational exposure guidelines. Based on the calculation results in this study, the magnetic field may be calculated with combined analytical method and FEM. The technical management chain in case of arc furnace is presented in the figure 6.10.

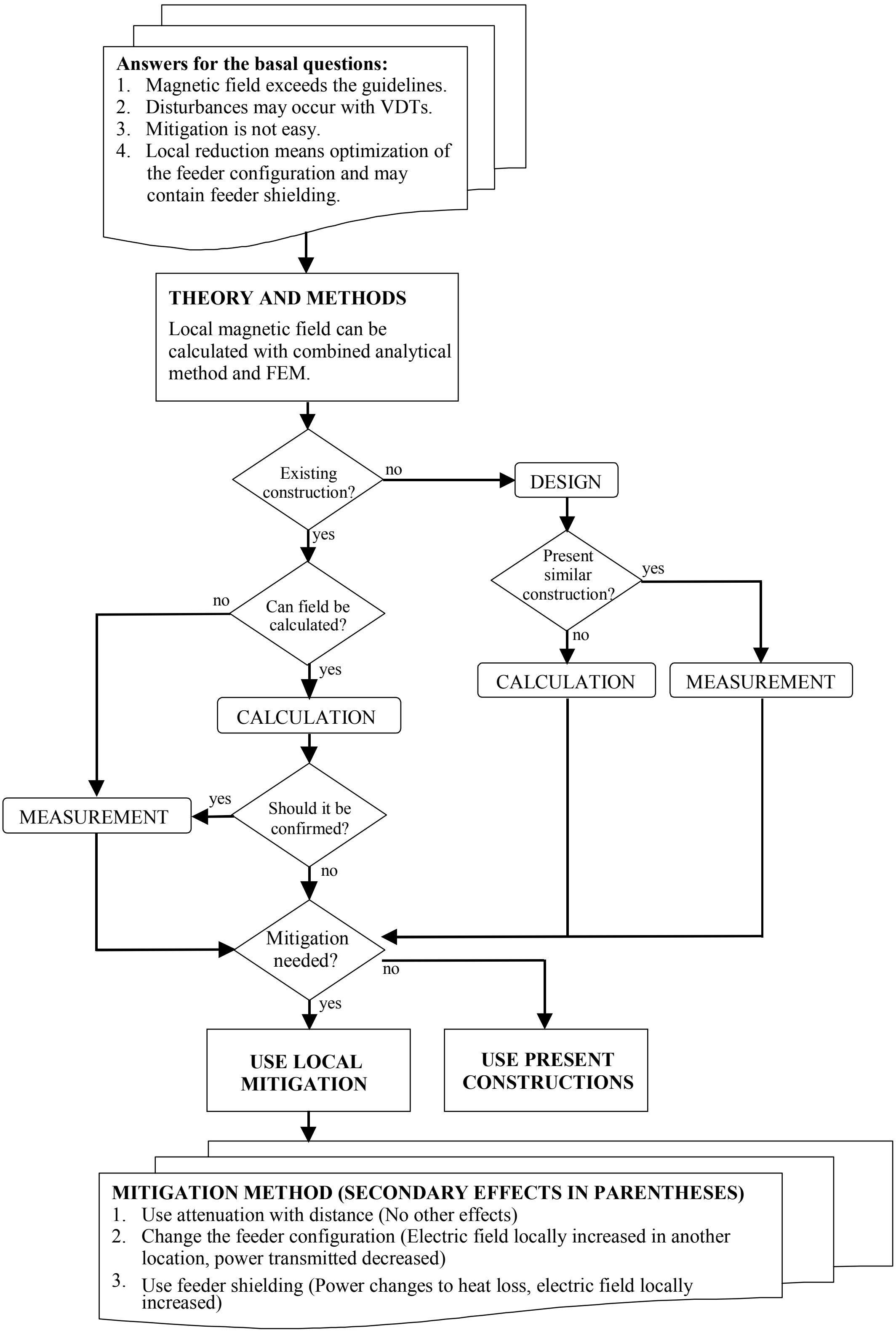


Figure 6.10. Technical management chain in case of arc furnace.

The approximative calculation method presented was satisfactory for general design calculations. To support design, magnetic field can be calculated both with combined analytical method and FEM, and approximative method.

For mitigation in case of arc furnace the best methods are attenuation with distance and considering magnetic field in design. One possibility to consider the magnetic field exposure is to avoid working in the area, where the ICNIRP occupational exposure guidelines are exceeded. The area around the studied arc furnace was about 10 meters from the center of arc furnace. Meanwhile, the reduction effect of the enclosure material was found not to completely shield the magnetic field, because the feedings cause still high magnetic field.

7. DISCUSSION

Technical management chain of the electric and magnetic fields requires specification of the problem, solving of the fields with calculations and measurements, mitigation, operations and analysis of the solutions. Because the technical management of the fields in electric power systems is case-specific, general methods may be superficial and too simple in practice. The mitigation of the fields may be expensive, because a part of the electricity system might have to be renewed.

Analytical equations, 2D-FEM and a combination of them were used in this thesis. Measurement and calculation results seem to be quite different in some cases. One reason for the difference is the varying voltage and load current. When calculating the fields or shielding effectiveness, momentary phase angles for the voltage or current are representing the general situation. When the load changes, the phase angles may change as well. Additional reasons for the differences may be the sensitivity of the field meter, measurement method and additional field sources.

Also the measurements contain uncertain sources. Present measuring standards of the fields deal with measurements in general, but do not give measurement heights, places or frequencies or other necessary conditions for repeatable measurements. Differences in the electricity system of the different counties have to be considered. Also differences with measurement protocols and instruments may cause a variation in results.

7.1 TRANSMISSION LINES

Technical management with transmission lines is based on the exposure guidelines and as well on environmental effect analysis for voltages above 220 kV. Both occupational and public exposure guidelines may be exceeded with electric field, whereas magnetic field exposure is usually far away from the present guidelines. Once the line has been built the mitigation is difficult afterwards. The possible methods presented previously are not necessarily economic. A careful line route design considering the shape of the land and the height of the conductors is easier, more economic, and may be even more efficient than mitigation afterwards. In addition, a visual impact can be minimized by careful line route design. Because the transmission line may be in service for even 70 years, the society will change significantly during that period.

If the mitigation of the fields is needed, the methods can be chosen based on economic and technical factors. Possible, but not necessarily economic, methods are the use of cables and phase splitting, compact line design, increasing of line height or the use of special reduction conductors or active magnetic field compensators. Line configurations can be more compact when selecting insulated phase conductors or cables. Also vegetation could reduce the electric fields, but it makes the line maintenance more time consuming and more expensive. Nevertheless, the effect of vegetation depends on the location, height, type, density and freshness. Thus, the reduction effect may vary spatially throughout a year.

Increase of line heights cannot be used as a general mitigation method for existing lines, because the change work is complicated and can be expensive. However, no final design calculations have been made so far to increase the 400 kV line heights, but even preliminary studies have indicated high costs. At the same time the visual impact of the tower is becoming heavier, which might make public acceptance of the lines more difficult to achieve.

Practical problems when evaluating electric fields are surroundings, electrical properties, climate and change of the harmonic contents. The fields can be calculated accurately above an even plane with analytical methods, when the environment has no disturbing objects and structures. Vegetation also distorts and disturbs the electric field. Rocks, stones, and gently sloping hills may influence the results. In practice, junipers, spruce trees, forest, cut tree branches, and willow bushes have deformed the field. In measurements, if the probe of the meter is inside the vegetation, the effect may be the opposite of being below the probe.

One practical measurement problem was the line height measurement. The inaccuracy of the meter was ±3 cm. Nevertheless, the ground level cannot be exactly defined, because the ground is not even and there are holes, bumps and ditches under the lines. Thus the inaccuracy of the line height measurement was closer to ±30 cm. Because of the vegetation, the ground level is not a zero-potential level and the inaccuracy of the measurement was even worse. However, calculations and measurements are both suitable methods for transmission lines.

The results for the electric and magnetic fields of the 400 kV transmission line in this study were relatively close to the results which Hongisto et al. had [Hon93, Hon94]. In this study the results were also close to the results of Srinivasa et al. for 400 kV double circuit line in India [Sri98]. Similar results were also obtained by Shiperling et al. for 345 kV single and double circuit lines and by Maruvada for 315 kV double circuit line [Mar93, Shp96]. Whereas, in this study the results were higher than Farag et al. had for electric and magnetic fields [Far97] and Swansson had for magnetic field [Swa95] of 400 kV double circuit lines.

7.2 ELECTRIC SUBSTATIONS

Technical management with electric substations is based on the exposure guidelines and disturbances. From the occupational exposure point of view the electric field is usually more critical than the magnetic field. Magnetic fields can cause disturbances in measurement or control systems of a substation. The electric substation is forbidden to the public, thus there would not be public exposure at all. Field levels outside the fences are usually small and the public exposure outside the fence is not significant.

In electric field measurements the grounded steel structures significantly affect the field. With the 400 kV open-air substations the highest electric fields were measured near transmission line feeders. With the GIS the electric field was small due to the insulated and grounded enclosure. In this study the magnetic field exceeded EMC-standard for industry [SFS96] in the cable tunnel, whereas all the measured fields were below the ICNIRP occupational exposure guidelines. Nevertheless, electric field values measured at the height of one meter in 400 kV electric substation were close to occupational exposure guidelines. The guidelines would have been exceeded, if the operational voltage had been higher or the observation point closer to sources. In previous study the guidelines were exceeded [Kor96].

For field mitigation, only a few previously used methods have been presented. However, careful design considering apparatus and conductors may be efficient mitigation methods. In addition, a GIS enclosure decreases electric field, because its shell material acts as a Faraday's cage. It also reduces the magnetic field. Nevertheless, chancing the outdoor switchyard to GIS may not be a practical method nor even possible. Thus increasing the distance from the sources is a good mitigation method. However, working in the vicinity of powered or live structures may be necessary, because the use of the network would not allow switching off the substation for different jobs. In outdoor installations protective clothing may be used for exposure to electric fields.

In this study the magnetic field results for 400 kV transformer and DC link substation were similar to the results which Maruvada et al. had for 315/25 kV substation [Mar93]. The electric field results for 400 kV substations in this study were lower than the results which Cristescu et al. had for 400 kV substation [Cri96]. The results for the 110/20 kV switchyard presented in this study were relatively close to the results which Daily et al. had for 115/13.8 kV switchyard and Maruvada et al. had for 120/25 kV substation [Dai94, Mar93]. However, the results were lower than Hayashi et al. had for 187 kV switchyard and Farag et al. had nearby the 132/66 kV transformer [Far97, Hay92].

7.3 INDOOR DISTRIBUTION SUBSTATIONS

Technical management with indoor distribution substations aims at the elimination of the disturbances or mitigation of the exposure. Field levels near MV/LV substations are not normally above exposure guidelines. However, at floor level in the space above the distribution substation the public exposure guidelines may be exceeded. At the height of one meter maximum magnetic fields vary from a few µT to some tens of µT. Thus, they may cause disturbances in appliances, e.g., in computer displays.

By using analytical methods, the secondary LV conductors can be modeled in three dimensions and the accuracy in basic construction is quite good. Application of the FEM model is essential in calculating of the effect of conductive or ferromagnetic material. Dissimilar scale problems occur when calculating the magnetic field in distribution substations. The 2D-FEM can accurately model the shielding material and the geometry of the structures, but it does not take into account the lengths of the secondary LV conductors and the shield. Whereas, the load current, current distribution, and eddy currents in shielding material were considered. Thus the *SE* value was calculated from FEM results and was used to analytically calculate the magnetic field.

Based on the comparison of the measured and calculated values, the reason for the highest difference could be the consideration of the shielding. One reason for this was a varying asymmetry of the load current. In the calculation a momentary load current was selected. The change of the load current may be fast, which leads to a difference between the load in momentary measurements. That also means a difference between the measured and calculated values in different calculation points.

The thickness of the floors and walls was difficult to evaluate, which caused inaccuracy in the distances from the transformer room. In addition, calculated and measured values differed significantly in cases, where the fields were small. In those cases the disruptive fields from other systems have been significant. Furthermore, the heat effect of the constructions should be considered when planning the shielding for high current systems especially in industry.

In this thesis the applied mitigation method was usually a simplification of a theoretical one, because the methods cannot always be followed as such. Improvements to the solution have been tried by combining several mitigation methods. Another reason for combining mitigation methods may be the target level, which can be achieved only by adding several mitigation methods together. One effective mitigation method is to omit indoor distribution substations by designing pad-mounted substations instead. However, this is not always possible.

It is possible to consider magnetic field at the design stage and it may not always result in extra costs. However, the mitigation is also possible with existing indoor distribution substations, but the methods may be expensive. Because the load current varies in different distribution substations, it was considered when comparing different structures of the secondary systems. The comparison of the structures was carried out by dividing the magnetic field by load current. The highest calculated and measured magnetic field and the field divided by 100 Amps are presented in publication 8 (Table 2). There were seven indoor distribution substations (presented in Table 5.4), where the divided value was smaller than 0.2 μT/100 Amps (value means 1 μT for 500 Amps).

Based on the divided values the best secondary structures were $S5_C$, $S5_D$, $S6_B$, $S7_B$, $S7_C$, $S7_D$, $S9_B$, S12, S19, $S20_A$ and $S20_B$ (presented in Table 5.4). In the indoor distribution substations $S5_C$, $S5_D$ and $S6_B$ the secondary LV cables were placed on the floor of the substation. In $S6_B$, and S12 the transformer and the LV switchgear were put together lying back to back and in $S6_B$ there was also a 3 mm thick aluminium cover. In $S8_B$ the secondary LV cables were shielded with a 5 mm thick aluminium groove and in $S8_C$ with a 5 mm thick aluminium enclosure. In $S8_D$ the change from the $S8_C$ was a 5 mm thick aluminium plate, which was added above MV switchgear. Nevertheless the plate only affects locally. In $S9_B$ the secondary LV cables were shielded with a 5 mm thick aluminium cover. In $S20_B$ the magnetic field was studied in the space beside and there was a shielding plate inside the wall. However, in the case $S20_B$ a more important factor than the plate was the distance.

Good structures for a new indoor distribution substation are the back-to-back structure or other find best structures. Another possibility is to use a factory made construction, which produces small magnetic field. The advantage of the factory made construction is that the magnetic field is measured beforehand in the laboratory. Manufacturers present the fields with certain load currents and in certain locations. When the magnetic field of the space above or beside is estimated, the measured magnetic field is compared considering the supposed load current and the distance from the secondary LV conductors. If the current is balanced, and it does not contain harmonics, it is possible to be estimated the magnetic field beforehand.

Hasselgren et al. and Salinas have studied indoor distribution substations in Sweden, where the electricity system is same as in Finland [Has93, Has94, Sal99, Sal00]. The objective of these Swedish studies has been the development of the magnetic field shielding methods. The calculated shielding effects [Has93, Has94] have been close to the results in this study, as presented in publication 1. In addition to shielding, the reduction potential with structural changes has been considered in this study. Farag et al. has measured indoor distribution substation (11/0.36 kV transformer) in industrial building in the space above the substation [Far 97]. The results were higher than results in this study. Furthermore the results presented in this study were lower than Farag et al. had for indoor distribution substation of a residential buildings [Far 97].

7.4 ARC FURNACE

Technical management with arc furnace is based on the exposure guidelines and the elimination of the disturbances. It is important to consider fields at the design stage, because afterwards the mitigation is more difficult or even impossible without enormous structural changes. Magnetic fields may be considered in the design of the electricity feeders of the arc furnace, which is an important magnetic field source. Possible locations for exceedings may be taken into account with layout plans of the melting mill. In addition, it can be concluded that additional shielding on the shell is not useful, because even when the *SE* of the enclosure is ∞ dB (figure 5.28), the magnetic field was not decreased significantly. The results for the equation 49 (developed by a Norwegian research group Thomsen and Bjølseth [Tho92]) were also practical in the case of the Finnish arc furnace.

For magnetic field mitigation, some previously used methods have been presented in literature, but only a few of them are practical with existing arc furnaces. An efficient way is to avoid working in the areas, where the exposure guidelines are exceeded. Workers should have knowledge about the field level in the vicinity of the arc furnace. Those places may be marked or enclosed and not be used in long-term work. In addition the control room may not be located nearby. However, in this study the employees do not work for long periods of time in the places, where the measured magnetic fields were the highest.

The reasons for differences between calculated and measured results were assumptions in calculations of shielding effectiveness, all metal constructions in the mill, varying load currents, harmonics in load currents, and inaccuracies in distances and calculation model. The harmonics of the current have a significant impact on guideline exceedings in the study. However, the amount of harmonics was small in the case. The adjusted reference level of 50 Hz magnetic field considering harmonics up to 300 Hz, 426 µT, was exceeded. For the control room, there is a calculated minimum distance, 10 m, where the occupational exposure guidelines are not exceeded. However, the distance depends on the maximum load of the arc furnace.

7.5 HARMONICS OF THE FIELDS

Studied example cases showed that ICNIRP guidelines will create problems for transmission and distribution companies and industry, if they become mandatory and if they should be applied in existing installations [ICN98].

The K_2 values for electric substations, indoor distribution substations and arc furnace considering ICNIRP exposure guidelines [ICN98] are gathered in Table 7.1. For transmission lines the K_2 values were analyzed only with calculations in publication 6, thus they are not presented in the Table 7.1.

Table 7.1. Summary of the K_2 values from the measured harmonics.

Place	Exposure type	K_2	
		Magnetic field	**Electric field**
110 kV GIS, nearby feeders	occupational	1.05	-
110 kV GIS, cable tunnel behind GIS	occupational	1.03	-
400 kV transformer and DC link substation, switchyard	occupational	1.00	1.07
400 kV transformer and DC link substation, near the converter	occupational	1.02	1.03
Indoor distribution substation S11	public	4.97	-
Indoor distribution substation S12	public	4.32	-
Indoor distribution substation S15	public	6.50	-
Indoor distribution substation S16	public	5.42	-
Arc furnace (calculated from current harmonics)	occupational	1.17	-

The K_2 values are considerably high with indoor distribution substations. The highest K_2 value in this study, 6.50 means that the 50 Hz value is allowed to be 15.4 µT in that case. The K_2 has been considerably smaller in later Finnish studies of indoor distribution substations [Sau03]. In addition, the K'_2 value based on simultaneous measurements (based on the Finnish decree [Sos02]) is usually 1.5 … 3 for indoor distribution substations [Jok03].

In this study, the harmonics for the K_2 values were momentary values and were not measured simultaneously. The harmonics situation of the system varies as a function of the varying load. Due to that, these K_2 values cannot be used as a base for the further conclusions nor the legislation in future. The K'_2 value based on simultaneous measurements would probably have been smaller [Jok03, Kei03, Sau03].

In addition, in measurements of the harmonics the Fast Fourier Transform (FFT) of the meter may be a significant source of uncertainty. These problems do not occur with the measurements based on the Finnish decree, because it takes phase angles into consideration and FFT is not necessary.

Harmonics may cause difficulties since the ICNIRP guidelines require reducing the fields due to the conservative assumptions concerning the occurrence of the harmonics [ICN98]. Exceeding may be possible with the power systems [Sos02]. However, the 50 Hz electric and magnetic field values with electric substations, and indoor distribution substations were not exceeded in this thesis. Whereas, with the arc furnace and the transmission lines the guidelines may be exceeded.

8. CONCLUSION

Technical management of the electric and magnetic fields in electric power systems has become an important issue because of the new exposure guidelines which have been published, e.g., in Finland. In addition, disturbances caused by electric and magnetic fields have become a more common problem when simultaneously the use of electric and electronic devices has increased.

The objective of this thesis was to develop a technical management chain of the electric and magnetic fields. This thesis consists of four different management cases: power lines, electric substations, indoor distribution substations, and an arc furnace. In practice, calculations, measurements and mitigation were case-specific; thus further conclusions based on the studied cases cannot be made.

The technical management chain for transmission lines was studied, because guidelines may be exceeded nearby them. The electric field exposure was more critical than magnetic field exposure (based on the guidelines). For transmission lines the evaluation of the fields can be carried out with measurements and calculations. For example, the line height, vegetation and line temperature may cause differences between measured and calculated values. Based on the results of this thesis and literature, the fields can best be affected in the design, e.g., by using attenuation with distance to the line.

Technical management chain for electric substations was studied. Measurements were carried out in the 110/20 kV transformer substation, 110 kV GIS, 400 kV switching substation and 400/110 kV transformer and DC link substation. Public exposure is not possible, because the electric substation switchyards are closed off e.g., with a fence. The fields can best be defined with measurements. With the new electric substations the fields can be evaluated by using knowledge from other substation constructions or by calculation. For occupational exposure, one mitigation method is attenuation with distance.

Technical management chain for indoor distribution substations was principally case-specific, because structures and devices vary. Public and occupational exposure may occur. The secondary system was a significant source of magnetic fields. Magnetic fields can be both measured and calculated. For indoor distribution substations, there is a number of possible mitigation methods. For existing structures the best mitigation method was usually a combination of several methods. For new indoor distribution substations, the structure can be chosen from recognized, good construction methods.

Technical management chain for an arc furnace is carried out because the occupational exposure guidelines may be exceeded. For arc furnaces, the measurements are easier than calculations, but calculations can also be used. An AC arc furnace was studied and the magnetic field was measured and calculated nearby. For arc furnaces, a good mitigation method is attenuation with distance, when designing a new arc furnace. For existing structures, the best way to consider magnetic fields is to avoid working near an area, where the exposure guidelines can be exceeded.

As a conclusion, it can be stated that the technical management chain for the electric system contains specification of the problem, solving of the fields with calculations and measurements, mitigation, operations and analysis of the solutions. In the future, the technical management chain for the electric and magnetic fields can be used for solving similar problems.

9. REFERENCES

[Abd99] Abdallah AS. Electric fields from transmission lines nearby populated areas in Egypt: theory versus experiment. 11th IEE International Symposium on High-Voltage Engineering, 23.-27.8.1999, London, Great Britain. Vol. 2, pp. 119-122.

[And94] Anders GJ, Ford GL, Horrocks DJ. The Effect of Magnetic Field on Optimal Design of a Rigid-Bus Substation. IEEE Transactions on Power Delivery, vol. 9, issue 3, 1994, pp. 1384-1390.

[Ash98] Ashley JR, Beatie RE, Heneage JF. Power Lines, Cancer, and Erroneous Physics. Electro 98, 1998, pp. 171-179.

[Atl88] Atlas of Finland. Appendix 131 (1987) Climate, Helsinki, National Board of Survey, and Geographical Society of Finland, 1988, 32 p.

[Bab97] Babic S, Gavrilovic MM. New Expression for Calculating Magnetic Fields due to Current-Carrying Solid Conductors. IEEE Transactions on Magnetics, vol. 33, issue 5, 1997, pp. 4134-4136.

[Bar95] Baraton P, Hutzler B. Magnetically Induced Currents in the Human Body. IEC Technology Trend Assessment, EDF-DER, 1995, 45 p.

[Bel92] Bellan PM, Higley JW. Magnetic Suppression of Arc Blowout in a Arc Furnace. IEEE Transactions on Plasma Science, vol. 20, issue 6, 1992, pp. 1026-1035.

[Bel99] Beltzer A, Schenkman A, Sonkin N. A System of Active Protection from Hazards of Industrial Electro-Magnetic Field. Power Tech ´99, Budapest, Hungary, August 29 - September 2, 1999, 58 p.

[Ben91] Bendzsak GJ, Ma TW. Parallel Computation of 3-D Electric and Magnetic Fields. IEEE Transactions on Magnetics, vol. 27, issue 5, 1991, pp. 4205-4209.

[Bir93] Biro O, Preis K, Vrisk G, Richter KR, Ticar I. Computation of 3-D Magnetostatic Fields Using a Reduced Scalar Potential. IEEE Transactions on Magnetics, vol. 29, issue 2, 1993, pp. 1329-1332.

[Bir94] Biro O, Preis K, Richter KR, Aigner B, Schuchlenz WH, Nix E. FEM Computation of the Forces on the Arc of a DC-Furnace. IEEE Transactions on Magnetics, vol. 30, issue 5, part 2, 1994, pp. 3507-3510.

[Bla88] Blanchard JP, Tesche FM, Sands SH, Vandre RH. Electromagnetic Shielding by Metallized Fabric Enclosure: Theory and Experiment. IEEE Transactions on Electromagnetic Compatibility, vol. 30, issue 3, 1988, pp. 282-288.

[Boa93] Board Statement on Restrictions on Human Exposure to Static and Time Varying Electromagnetic Fields and Radiation. National Radiological Protection Board NRPB, Chilton, Great Britain. 1993.

[Bow98] Bowman JD, Kelsh MA, Kaune WT. Manual for measuring occupational electric and magnetic field exposures. U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health (NIOSH), Publication No 98-154. Cincinnati, Ohio, USA. 1998. 149 p.

[Bra99] Brakelman H. EMC-measures for Underground Power Cables. Power Tech ´99, Budapest, Hungary, August 29 - September 2, 1999, 214 p.

[Bri88] Bridges JE. An Update on the Circuit Approach to Calculate Shielding Effectiveness. IEEE Transactions on Electromagnetic Compatibility, vol. 30, issue 3, 1988, pp. 211-221.

[Cao89] Cao M, Biringer PP. IEEE Transactions on Magnetics, vol. 25, issue 4, 1989, pp. 2849-2851.

[Car00] Caruso C, Feliziani M, Maradei F. Validation of Analytical and Numerical Techniques to Predict the Magnetic Shielding Effectiveness of Finite Extension Shields. Electromagnetic Compatibility (IEEE), vol. 2, 2000, pp. 861-866.

[CEN94] CENELEC EN 50160, Voltage characteristics of electricity supplied by public distribution systems, European Committee for Electrotechnical Standardization, 1994.

[Con85] Conti R. Instrumentation for measurement of power frequency electromagnetic fields. Biological effects and dosimetry of static and ELF electromagnetic fields. ENEL-Electrical Research Center, Milan, Italy, 1985, pp. 187-210.

[Cou99] Council of the European Union, Council Recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz), "Official Journal of the EC: L" 199 on 30 July 1999, pp. 59-70.

[Cri96] Cristescu D, Conecini I, Munteanu DJ, Gary C. Survey on the Health of Workers in Romanian 400-750 kV Substations And Lines Exposed to Electric And Magnetic Fields. Cigre 1996 session, Paris, France, 1996, 36-102/10 p.

[Dai94] Daily WK, Dawalibi F. Measurements and Computations of Electromagnetic Fields in Electric Power Substations, IEEE Transactions on Power Delivery, vol. 9, issue 1, 1994, pp. 324-333.

[Dan98] Danske Elvärkers Forening. 1998. Teknisk Håndbog - Elektriske og Magnetiske Felter: Chapter C11a. Måleprotokol for 50 Hz elektromagnetiske felter, 16 p. (in Danish)

[Daw95] Dawalibi FP, Wei Xiong, Jinxi Ma. Transient Performance of Substation Structures and Associated Grounding Systems. IEEE Transactions on Industry Applications, vol. 31, issue 3, 1995, pp. 520-527.

[Den82] Deno DW, Zaffanella LE. Field Effects of Overhead Transmission Lines and Stations. Transmission Line Reference Book - 345 kV and above, 2. ed., Palo Alto, 1982, pp. 329-419.

[Ehr99] Ehrich M, Fichte LO. Magnetic Field Reduction of Twisted Three-Phase Power Cables of Finite Length by Specific Phase Mixing. International Symposium on Electromagnetic Compatibility, 1999, pp. 448-451.

[Ehr00] Ehrich M, Fichte LO, Luer M. Magnetic Field Reduction of Power Cables by Multi-Splitting of Conductors and Compensation Effects. Asian Pacific Conference on Environmental Electromagnetics (CEEM 2000), 2000, pp. 33-38.

[Ele98] Electricity Statistics for Finland 1997. Helsinki: Finnish Electricity Association, 1998, 90 p.

[Ele99] Elektromagnetische Felder, Berufsgenossenschaftliche Vorschrift für Sicherheit und Gesundheit bei der Arbeit, BGV B11, 1999, 46 p. (in German)

[Ele03] Electricity and district heating in 2001. Helsinki: Adato Energia Oy, 2003, 64 p.

[Elo88] Elovaara J, Laiho Y. Sähkölaitostekniikan perusteet, Otakustantamo, Hämeenlinna, 1988, p. 487. (in Finnish)

[EMC97] EMC ja rakennusten sähkötekniikka. 1997. Sähkötieto, Espoo.198 p. (in Finnish)

[Fal98] Falck E, Keikko T, Isokorpi J, Korpinen L. Application of Geometrical Models in the Evaluation of Health Effects of Transmission Line Electric and Magnetic Fields. The IASTED (the International Association of Science and Technology for Development) International Conference on Applied Modelling and Simulation, Honolulu, Hawaii, USA, 1998.

[Far97] Farag AS, Dawoud MM, Cheng TC, Cheng JS. Occupational Exposure Assessment for Power Frequency Electromagnetic Fields. Energy Conversion Engineering Conference (IECEC-97), vol. 3, 1997, pp. 2107-2113.

[Far98] Farag AS, Dawoud MM, Cheng TC, Bakhashwain JM, Shahzad F. Magnetic Field Measurement And Management in And around Substations in Saudi Arabia. Cigre 1998 session, Paris, France, 1998, paper 36-101, 12 p.

[Fer99] Ferreira LF, Soibelzon HL. Problems in the definition of magnetic field values to be measured on overhead power lines. 11th IEE International Symposium on High-Voltage Engineering, 23.-27.8.1999, London, Great Britain, Vol. 1, 1999. pp. 352-355.

[Fin99] Finnish government regulation for environmental effect analysis, (268/1999). Helsinki, Finland 5.3.1999. (in Finnish)

[Fou96] Fouladgar J, Develey G. Non-Linear Optimization of the Positions of the Anodes in a DC-Furnace. IEEE Transactions on Magnetics, vol. 32, issue 3, part 1, 1996, pp. 1270-1273.

[Fri97] Frix WM, Karady GG. A Circuital Approach to Estimate the Magnetic Field Reduction of Nonferrous Metal Shields. IEEE Transactions on Electromagnetic Compatibility, vol. 39, issue 1, 1997, pp. 24-32.

[Get89] Gettys WE, Keller FJ, Skove MJ. Physics: Classical and Modern. McGraw-Hill, 1989, 1093 p.

[Gid88] Gidlund J, Pettersson Å, Ruritz R, Söderberg L, Jansson R. Swedish State Power Board Adopts the T-Tower Design for 420 kV Lines. Cigre SC22-88 (WG8) -13, 1988.

[Gor72] Gordon DE, Brown RE, Haben JF. Methods for measuring the magnetic field. IEEE Transactions on Magnetics MAG-8, Issue 1, 1972, pp. 48-60.

[Hal94] Halttunen J. Anturitekniikan jatkokurssi. Tampere, Tampere University of Technology, Electric Department, 1994, 171 p. (in Finnish)

[Hal01] Halinen S, Pulakka A, Lajunen A, Kivelä T, Sauramäki T, Keikko T, Korpinen L. Sähkökenttien vaimentaminen kasvillisuuden avulla 400 kV:n voimansiirtojohtojen alla, II osa. Tampere, Tampereen University of Technology, Laboratory of Electrical Engineering and Health, Report 1-2001, 2001, 59 p. (in Finnish)

[Has93] Hasselgren L, Moller E, Hamnerius Y. Three Dimensional FEM Calculations on Shielding of Power Frequency Magnetic Fields from a Substation. Electromagnetic Compatibility (IEEE), 1993, pp. 158-159.

[Has94] Hasselgren L, Moller E, Hamnerius Y. Calculation of Magnetic Shielding of a Substation at Power Frequency Using FEM. IEEE Transactions on Power Delivery, vol. 9, issue 3, 1994, pp. 1398-1405.

[Hay92] Hayashi N, Isaka K, Yokoi Y. Analysis of 60 Hz Magnetic Fields Near Ground Level in 187-kV Switchyard of a 187/66-kV AC Substation. IEEE Transactions on Power Delivery, vol. 7, issue 1, 1992, pp. 237-244.

[Hei89] Heiss W, Hirsch F. Measurement with Respect to the Electromagnetic compatibility (EMC) of Telecontrol Systems in Substations of Medium Voltage Distribution Networks. 10th CIRED Conference, vol. 2, 1989, pp. 116-120.

[Hof95] Hofmann H, Preston G. Reduction of Stray Currents and Magnetic Fields from Single-Phase Power Distribution System. IEEE Transactions on Power Delivery, vol. 10, issue 2, 1995, pp. 1112-1118.

[Hon93] Hongisto M, Valjus J. Magneettikenttäaltistus 110-400 kV johtojen läheisyydessä. Vantaa, IVO-A-05/93 study reports. IVO Oy, ympäristönsuojeluyksikkö. 1993. 141 p. (in Finnish)

[Hon94] Hongisto M, Valjus J. Magnetic Field Exposure in the Vicinity of The National Grid of Finland, *CIGRE Session*, 28th August - 3rd September, 1994, Paper no. 36-104.

[Hut94] Hutzler B, Baraton P, Vicente JL, Antoine JC, Roux M, Urbain JP. Exposure to 50 Hz Magnetic Fields During Live Work. Cigre 1994 session, Paris, France, 1996, 36-106/9 p.

[Häm02] Hämäläinen M. Pientaajuiset magneettikentät ja kiinteistömuuntamot. Kuopio, University of Kuopio, 2002, 79 p. (in Finnish)

[ICN98] ICNIRP, Guidelines for Limiting Exposure to Time-varying Electric, Magnetic, and Electromagnetic Fields (Up to 300 GHz), Health Physics, 74(4), 1998, pp. 494-522.

[ICN03] ICNIRP, Guidance on Determining Compliance of Exposure to Pulsed and Complex Non-Sinusoidal Waveforms below 100 kHz with ICNIRP Guidelines, Health Physics, 84(3), 2003, pp. 383-387.

[IEC87] IEC 60833. Measurement of power frequency electric fields. International Electrotechnical Commission, 1987, 46 p.

[IEC98] IEC 61786. 1998. Measurement of low-frequency magnetic and electric fields with regard to exposure of human beings - Special requirements for instruments and guidance for measurements. International Electrotechnical Commission. 177 p.

[IEE95] IEEE Std 644-1994. 1995. IEEE Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields from AC Power Lines. The Institute of Electrical and Electronics Engineers, New York, NY, USA. 25 p.

[IEE97] IEEE Std 1460-1996. IEEE Guide for the Measurement of Quasi-Static Magnetic and Electric Fields. The Institute of Electrical and Electronics Engineers, New York, 1997. 19 p.

[INI90] INIRC/IRPA, Interim Guidelines on Limits of Exposure to 50/60 Hz Electric and Magnetic Fields, “Health Physics”, 58(1), 1990, pp. 113-122.

[Ism99] Ismail HM. Magnetic Field Calculations and Management of Kuwait HVTLs Using the Vector Magnetic Potential Concept. Power Tech ´99, Budapest, Hungary, August 29 - September 2, 1999, p. 92.

[Iso99] Isokorpi J, Keikko T, Korpinen L. Electric Field Measurement Disturbances Caused by Vegetation with 400 kV Transmission Lines. IASTED (MS´99), Philadelphia, USA, May 5-8, 1999.

[Iva96] Ivanyi A. Shielding for Phase Conductors. IEEE Transactions on Magnetics, vol. 32, issue 3, part 1, 1996, pp. 1481-1484.

[Jae00] Jaekel BW. Power Frequency Magnetic Fields of Medium Voltage Switchgear, a Concept for Evaluating the Field Strengths under an Exposure Limit Point of View. Environmental Electromagnetics (CEEM 2000), 2000, pp. 226-231.

[Jok00] Jokela K. Restricting Exposure to Pulsed and Broadband Magnetic Fields. Health Physics, vol. 79, issue 4, 2000, pp. 373-388.

[Jok03] Jokela K. Rakennusten magneettikenttien mittaaminen. STUK. 13 p. (manuscript May 2, 2003, in Finnish)

[Jon98] Jones JAT, Bowman B, Lefrank PA. Electric Furnace Steelmaking. In book: Fruehan RJ (ed.): The Making, Shaping and Treating of Steel - Steelmaking and Refining, Volume 11, The AISE Steel Foundation, Pittsburgh, 1998.

[Juu89] Juutilainen J, Saali K, Eskelinen J, Matilainen P, Leinonen A-L. Measurements of 50 Hz Magnetic Fields in Finnish Homes. Helsinki, IVO Oy, Study report IVO-A-02/89. 1989. 31 p.

[Kar98] Karady GG, Nunez CV Raghavan R. The Feasibility of Magnetic Field Reduction by Phase Relationship Optimization in Cable Systems. IEEE Transactions on Power Delivery, vol. 13, issue 2, 1998, pp. 647-654.

[Kat99] Kato K, Uga Y, Goto N, Shimizu M, Okubo H. Magnetic Field Characterization Based on Line Current Conditions in 77kV/6.6kV Substation. Eleventh International Symposium on High-Voltage Engineering (ISH99 / IEE), London, UK, August 23-27, 1999, Vol. 2, pp. 95-98.

[Kau92] Kaune WT, Zaffanella LE. Analysis of Magnetic Fields Produced Far from Electric Power Lines. IEEE Transactions on Power Delivery, vol. 7, issue 4, 1992, pp. 2082-2091.

[Kaw94] Kawahito S, Sasaki Y, Sato H, Nakamura T, Tadakoro Y. A fluxgate magnetic sensor with micro-solenoids and electroplated permalloy cores. Sensors and Actuators A, Issue 43, 1994, pp. 128-134.

[Kei96] Keikko T, Isokorpi J, Korpinen L. Pientaajuisten magneettikenttien mittaaminen. Tampere University of Technology, report 11-96. 1996. 117 p. (in Finnish)

[Kei97] Keikko T, Isokorpi J, Korpinen L. Pientaajuisten magneettikenttähäiriöiden pienentämismenetelmiä. Tampere University of Technology, report 9-97. 1997. 76 p. (in Finnish)

[Kei98a] Keikko T, Laitinen O, Isokorpi J, Tohmola S, Korpinen L. Suitability of Calculation Methods in Magnetic Field Shield of Distribution Substation. The IASTED (the International Association of Science and Technology for Development) International Conference on Applied Modelling and Simulation, Honolulu, Hawaii, USA, 1998, pp. 205-208.

[Kei98b] Keikko T, Tohmola S, Isokorpi J, Korpinen L. Calculations of Power Frequency Magnetic Field Disturbances at a 110/20 kV Substation. Power Systems World '98 Power Quality Conference, Santa Clara, CA, USA, November 7-13, 1998.

[Kei99a] Keikko T, Isokorpi J, Korpinen L. Calculating Magnetic Fields of Arc Furnace. IASTED (MS´99), Philadelphia, USA, May 5-8, 1999.

[Kei99b] Keikko T, Isokorpi J, Korpinen L. Practical Problems in Calculating Electric Fields of Transmission Lines. Eleventh International Symposium on High-Voltage Engineering (ISH99 / IEE), London, UK, August 23-27, 1999, pp. 103-106.

[Kei99c] Keikko T, Isokorpi J, Korpinen L. Magnetic Fields in Industry: Arc Furnace. Eleventh International Symposium on High-Voltage Engineering (ISH99 / IEE), London, UK, August 23-27, 1999, pp. 111-114

[Kei99d] Keikko T, Isokorpi J, Korpinen L. Electric Fields in 400 kV Transmission Lines, "IEEE Power Tech ´99", Budapest, Hungary, August 29 - September 22, 1999, 5 p., CD-ROM.

[Kei00a] Keikko T, Kotiniitty J, Korpinen L. Calculations of Magnetic Fields from Indoor Distribution Substation Bus Bars. IEEE Power Engineering Society Summer Meeting 2000, Seattle, Washington, USA, June 9-16, 2000, (CD-ROM).

[Kei00b] Keikko T, Isokorpi J, Korpinen L, Elovaara J, Vanhala P. Considering Electric and Magnetic Fields in Electric Power System Design in Finland. 2000 Session - 38th CIGRE Session, Paris, France, August 27 - September 1, 2000, 36-102/7 p.

[Kei00c] Keikko T, Kuusiluoma S, Menonen P, Korpinen L. Käytännön kokemuksia kiinteistömuuntamoiden magneettikenttien pienentämisestä. Tampere University of Technology, Electrical Engineering in Industry, report 4-2000. 106 p. (in Finnish)

[Kei00d] Keikko T, Kantell T, Kuusiluoma S, Kotiniitty J, Korpinen L. Low Frequency Magnetic Field Reduction of the Bus Bars of Indoor Distribution Substation. EMC Europe 2000 – Fourth European Symposium on EMC, Brügge, Belgium, September 11 – 15, 2000, Vol. 1, pp. 315-320.

[Kei01a] Keikko T, Kuusiluoma S, Suojanen M, Korpinen L. Calculations of Magnetic Fields Near Secondary Conductors of Indoor Distribution Substation. IASTED (MS 2001), Philadelphia, USA, May 16-18, 2001.

[Kei01b] Keikko T, Suojanen M, Kuusiluoma S, Menonen P, Korpinen L. Examples of Magnetic Field Calculations in Indoor Distribution Substations. CMEM 2001, Alicante, Spain, June 4-6, 2001.

[Kei01c] Keikko T, Kuusiluoma S, Korpinen L. Effect of Secondary Conductor Structures on Magnetic Field Near Indoor Distribution Substation. Twelfth International Symposium on High-Voltage Engineering (ISH2001), Bangalore, India, August 20-24, 2001.

[Kei02a] Keikko T, Sauramäki T, Kuusiluoma S, Korpinen L. Comparison of Magnetic Field Calculation Methods for Transmission Lines. IASTED (MS 2002), Los Angeles, USA, May 13-15, 2002, pp. 167-172.

[Kei02b] Keikko T, Kuusiluoma S, Sauramäki T, 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 Exhibition 2002, Asia Pacific, Yokohama, Japan, October 6-10, 2002, Vol 2, pp. 1230-1234.

[Kei03] Keikko T, Sauramäki T, Korpinen L. Laajakaistaisille sähkö- ja magneettikentille altistuminen työympäristössä, erityisesti sähkön tuotannon, siirron ja jakelun työpaikoilla. Tampere University of Technology, Laboratory of Electrical Engineering and Health, report 3-2003, 88 p. (in Finnish)

[Ket01] Kettunen L. Fields and Circuits in Computational Electromagnetism. IEEE Transactions on Magnetics, vol. 37, issue 5, 2001, pp. 3393-3396.

[Kis96] Kistenmacher P, Schwab A. Low-Frequency Shielding Effectiveness of inhomogeneous Enclosures. Electromagnetic Compatibility (IEEE), 1996, pp. 347-352.

[Kor96] Korpinen L. Cardiovascular Effects of Short Term Exposure to Electric and Magnetic Fields of Electricity Power Transmission, Tampere, Tampere University of Technology, Publications 182, 1996, 147 p.

[Kor98] Korpinen L, Isokorpi J, Keikko T. Kartoitus pientaajuisista sähkökentistä elin- ja työympäristössä. Tampere University of Technology, report 6-98. 1998. 35 p. (in Finnish)

[Kor99] Korpinen L, Isokorpi J, Keikko T. Calculation of induced currents in a human body represented by a spheroidal model. CMEM 99, Sorrento, Italy, April 27-29, 1999.

[Kor00a] Korpinen L, Kotiniitty J, Kuusiluoma S, Kantell T, Keikko T. Evaluation of Health Effects of 400 kV Power Transmission Line Electric and Magnetic Fields with Prolate Spheroid Model. The Bioelectromagnetics Society (BEMS), Munich, Germany, June 9-16, 2000, pp.116-117.

[Kor00b] Korpinen L. Measurement of electric and magnetic fields from appliances and in living environment. Ministry of Trade and Industry, Finland, Report 6/2000, 2000, 131 p. (in Finnish)

[Kor02] Korpinen L. Sähkö- ja magneettikenttien terveysvaikutuksista kysellään. Sähkö&Tele, vol. 75, issue 4, 2002, pp. 40-43. (in Finnish)

[Kot99] Kotiniitty J, Reivonen S, Kantell T, Keikko T, Korpinen L. Kiinteistö-muuntamoiden magneettikentät. Tampere University of Technology, report 1-99. 90 p. (in Finnish)

[Kot00] Kotiniitty J, Vehmaskoski J, Suojanen M, Keikko T, Kuusiluoma S, Korpinen L. EMC Problems in Buildings. EMC Europe 2000 – Fourth European Symposium on EMC, Brügge, Belgium, September 11 – 15, 2000, Vol. 2, pp. 111-114.

[Kuu00] Kuusiluoma S, Keikko T, Korpinen L. 400 kV:n siirtojohtojen laskenta- ja mittaustulosten vertailu. Tampere University of Technology, report 2000. 28 p. (in Finnish)

[Lan98] Landers TL, Richeda RJ, Krizanskas E, Stewart JR Brown RA. High Phase Order Economics: Constructing a New Transmission Line. IEEE Transactions on Power Delivery, vol. 13, issue 4, 1998, pp. 1521-1526.

[Lar97] Larsson A. Att mäta magnetfält. Vattenfall Utveckling AB, 12-05. 1997. 10 p. (in Swedish)

[Lin98] Lindberg L. Reduction of Magnetic Fields from Electric Power and Installation Lines. Science, Measurement and Technology / IEE, Vol 145, issue 5, 1998, pp. 215-221.

[Liu96] Liu Y, Zaffannella LE. Calculation of Electric Field and Audible Noise from Transmission Lines with Non-Parallel Conductors. IEEE Transactions on Power Delivery, vol. 11, issue 3, 1996, pp. 1492-1497.

[Mam96] Mamishev AV, Nevels RD, Russell BD. Effects of Conductor Sag on Spatial Distribution of Power Line Magnetic Field. IEEE Transactions on Power Delivery, vol. 11, issue 3, 1996, pp. 1571-1576.

[Mar93] Maruvada PS. Characterization of Power Frequency Magnetic Fields in Different Environments. IEEE Transactions on Power Delivery, vol. 8, issue 2, 1993, pp. 598-606.

[Mem96] Memari AR, Janischewskyj W. Mitigation of Magnetic Field near Power Lines. IEEE Transactions on Power Delivery, vol. 11, issue 3, 1996, pp. 1577-1586.

[Miz99] Mizuno Y, Naito K. Effect of Power Frequency Magnetic Field on Image of Computer Monitor. Power Tech ´99, Budapest, Hungary, August 29 - September 2, 1999, 59 p.

[Mos88] Moser JR. Low-Frequency Low-Impedance Electromagnetic Shielding. IEEE Transactions on Electromagnetic Compatibility, vol. 30, issue 3, 1988, pp. 202-210.

[MPR90] MPR. 1990. Test Methods for Visual Display Units. MPR 1990:8. 66 p.

[Nye91] Nyenhuis JA, Mouchawar GA, Bourland JD, Geddes LA. Energy Considerations in the Magnetic (Eddy-Current) Stimulation of Tissues. IEEE Transactions on Magnetics, vol. 27, issue 1, 1991, pp. 680-687.

[O'Co93] O'Connor H. Shielding and Magnetic Field Reduction for Small and Medium Size Transformers and Reactors. Electrical Electronics Insulation Conference and Electrical Manufacturing & Coil Winding, Chicago '93 EEIC/ICWA Exposition, 1993, pp. 719-724.

[Ols90] Olsson H, Petterson P, Eriksson A. Reduction of transmission line magnetic fields – possibilities and constrains. Cigre 1990 session, Paris, France, 1990, paper 36-101, 8 p.

[Ols91] Olsen R, Bracken D, Chartier V, Dovan T, Jaffa K, Misakian M, Stewart J. An Evaluation of Instrumentation Used to Measure AC Power System Magnetic Fields. IEEE Transactions on Power Delivery, vol. 6, issue 1, 1991, pp. 373-383.

[Ols96] Olsen RG, Moreno P. Some Observations about Shielding Extremely Low-Frequency Magnetic Fields by Finite Width Shields. IEEE Transactions on Electromagnetic Compatibility, vol. 38, issue 3, 1996, pp. 460-468.

[Ols99] Olsen RG, Kaune WT, King RWP. Comments on "Fields and Currents in the Organs of the Human Body When Exposed to Power Lines and VLF Transmitters", IEEE Transactions on Biomedical Engineering, vol. 46, issue 6, 1999, pp. 760-763.

[Ooi99] Ooi Tian Hock, Foo Chew Houw B. Automated Shielding Effectiveness Test System for Shielded Enclosures. Electromagnetic Compatibility (IEEE), 1999, pp. 682-685.

[Paa69] Paavola M. Sähköjohtojen laskeminen. 3. ed. Helsinki, Finland, WSOY, 1969, 255 p. (in Finnish)

[Paa75] Paavola M. Sähköjohdot. Helsinki, Finland, WSOY, 1975, 319 p. (in Finnish)

[Pap99] Paperno E, Sasada I, Naka H. Self-Compensation of the Residual Field Gradient in Double-Shell Open-Ended Cylindrical Axial Magnetic Shields. IEEE Transactions on Magnetics, vol. 35, issue 5, part 2, 1999, pp. 3943-3945.

[Pas98] Paschen R, Example of tower height regarding EMF, "37th Cigre Session", Paris, France, 30.8.-5.9. 1998, Vol I, pp. 70-71.

[Pet96] Pettersson P. Principles in Transmission Line Magnetic Field Reduction. IEEE Transactions on Power Delivery, vol. 11, issue 3, 1996, pp. 1587-1593.

[Pet97] Pettersson P, Schonborg N. Reduction of Power System Magnetic Field by Configuration Twist. IEEE Transactions on Power Delivery, vol. 12, issue 4, 1997, pp. 1678-1683.

[Pre96] Pretorius PH, Britten AC. ELF Magnetic Fields in Close Proximity to a Large Static VAR Compensator: a Case Study. IEEE AFRICON 4th, vol. 2, 1996, pp. 1056-1061.

[Pää99] Pääkkönen R, Keikko T, Isokorpi J, Korpinen L. Examples of Exposure to High Level Magnetic Fields in Work Environments. Sixth Nordic Workshop on Biological Effects of Electromagnetic Fields, Skejby Sygehus, Denmark, August 19-21, 1999, p. 17.

[Ras98] Rashkes VS, Lordan R. Magnetic Field Reduction Methods: Efficiency and Cost. IEEE Transactions on Power Delivery, vol. 13, issue 2, 1998, pp. 552-559.

[Rei96] Reichelt D, Scherer R, Braunlich R, Aschwanden T. Magnetic Field Reduction Measures for Transmission Lines Considering Power Flow Conditions. Transmission and Distribution Conference (IEEE), 1996, pp. 486-492.

[Rei62] Reitz JR, Milford FJ. Foundations of Electromagnetic Theory. Addison-Wesley Publishing Company Inc., 2nd ed., 1962, 387 p.

[Roq97] Roquemore L, Zweben SJ, Wurden GA. Stability measurements of PPl Atmospheric Pressure Arc. Plasma Science (IEEE), 1997, 136 p.

[Sal99] Salinas E. Magnetics Conference (IEEE/INTERMAG 99), 1999, p. DF10.

[Sal00] Salinas E. Passive and Active Shielding of Power-Frequency Magnetic Fields from Secondary Substation Components. Powercon 2000 -IEEE-PES/CSEE International Conference on Power System Technology, Perth, Australia, December 4 – 7, 2000, Vol II, pp. 855-860.

[Sau02] Sauramäki T, Keikko T, Kuusiluoma S, Korpinen L. Exposure to Electric and Magnetic Fields at 110 kV Gas Insulated Substation (GIS). IEEE/PES

Transmission and Distribution Conference and Exhibition 2002, Asia Pacific, Yokohama, Japan, October 6-10, 2002, Vol 2, pp. 1226-1229.

[Sau03] Sauramäki T, Keikko T, Korpinen L. Väestön altistuminen laajakaistaisille sähkö- ja magneettikentille. Tampere University of Technology, Laboratory of Electrical Engineering and Health, report 2-2003, 56 p. (in Finnish)

[Sch86] Schweitz P. Ein verfahren zur berechnung von dreidimensionalen magnetfeldern im nachbereich von leitungen der elektrischen energieversorgung, "Elektrizitätswirtschaft", 85(21), 1986, pp. 827-831. (in German)

[Seg01] Seguinot M. Presentation and Follow-up of the Community Initiatives. Conclusions on the Electromagnetic Fields and Health Conference - Which Regulatory Framework for the European Community?, Luxembourg, November 30, 2001.

[Sek91] Seki Y, Nitta S. Degradation of EM Shielding Effectiveness Due to Resonance in the Low Frequency Region. Electromagnetic Compatibility (IEEE), 1991, pp. 109-113.

[Sen99] Sener, Loistehon kompensointi ja yliaaltojen rajoittaminen, Adato Energia Oy 1999, 72 p. (in Finnish)

[SFS88] SFS 5467. Ammattielektroniikkalaitteiden häiriönsieto; Ympäristöluokitus ja rasitusasteet. 1988. (in Finnish)

[SFS91] EN 50082-1. Electromagnetic compatibility - Generic immunity standard. Part 1: Residential, commercial and light industry. 1991.

[SFS96] EN 50082-2. Electromagnetic compatibility - Generic immunity standard. Part 2: Industrial environment. 1996.

[Sha98] Sharifi M, Lavers JD, Gyimesi M. A Method to Compute the Shielding of a 3-D Conductor Array by a Semi-Infinite Permeable Layer. IEEE Transactions on Magnetics, vol. 34, issue 4, part 1, 1998, pp. 2111-2113.

[Shp96] Shiperling IB, Menemenlis-Hopkins L, Fardanesh B, Clairmont B, Childs D. Reduction of Magnetic Fields from Transmission Lines Using Passive Loops. 1996 CIGRE Session, Paris, France, 1996, 36-103/6 p.

[Sjö01] Sjöblom T, Keikko T, Halinen S, Kivelä T, Korpinen L. Electric Fields Caused by Transmission Lines in Finland. Twelfth International Symposium on High-Voltage Engineering (ISH2001), Bangalore, India, August 20-24, 2001.

[Smi95] Smith E. 1995. Måleprotocoll for 50 Hz elektromagnetiske felter. Energiforsyningens Fellesorganisasjon (EnFO), Publikasjon nr 68-1995. 10 p. (in Norwegian)

[Sos02] Sosiaali- ja terveysministeriö. Sosiaali- ja terveysministeriön asetus ionisoimattoman säteilyn väestölle aiheuttaman altistumisen rajoittamisesta (294/2002). Helsinki, 2002. 47 p. (in Finnish)

[Sri98] Srinivasa KM, Maruti R, Rajesh Kumar O, Namudiri PVV, Lalli MS, Srinivasan KN, Goswami MM. Field Measurements of Electric and Magnetic Fields on HV and EHV Transmission Lines and Substations. Electrical Insulation (IEEE), Vol 2, 1998, pp. 347-350.

[Ste93] Stewart JR, Dale SJ, Klein KW. Magnetic Field Reduction Using High Phase Order Lines. IEEE Transactions on Power Delivery, vol. 8, issue 2, 1993, pp. 628-636.

[Suo93] Suomen sähkölaitosyhdistys ry. Kiinteistömuuntamon aiheuttaman magneettikentän vaimentamiskeinoja. Publication 4/93. 1993. 48 p. (in Finnish)

[Suo00] Suojanen M, Vehmaskoski J, Korpinen L. Sähkökenttien vaimentaminen kasvillisuuden avulla 400 kV:n voimansiirtojohtojen alla. Tampere University of Technology, Electrical Engineering in Industry, report 1-2000. 75 p. (in Finnish)

[Suo01] Suojanen M, Lederle C, Heim R, Keikko T, Korpinen L. The Effect of Trees on Calculation of Electric Fields Near 400 kV Transmission Lines. CMEM 2001, Alicante, Spain, June 4-6, 2001.

[Swa95] Swanson J. Magnetic fields from transmission lines: comparison of calculations and measurements. IEE proceedings - Generation, Transmission and Distribution, vol. 142, issue 5, 1995, pp. 481-486.

[Swi99] Swiss Federal Council, Ordinance Relating to Protection from Non-Ionising Radiation (ONIR). Publication 814.710. 1999. 20 p.

[Tay93] Taylor CD, Harrison CW, Younan NH. On Predicting the Effectiveness of Magnetic Shields at Low Frequencies. Electromagnetic Compatibility (IEEE), 1993, pp. 176-178.

[Tho92] Thommesen G, Bjølseth PS. Statiske og lavfrekvente magnetfelt i norske smelte- og elektrolyseverk, Statens Institut for Strålehygiene (SIS), Østerås, Norge, 1992, 44 p. (in Norwegian)

[Tik92] Tikkanen J. Verkkotaajuiset magneettikentät jakelumuuntajan ympäristössä. M.Sc. Theses, Lappeenranta, Lappeenranta University of Technology, 1992, 125 p. (in Finnish)

[Tik95] Tikkanen J, Vanhala P, Virtanen E. Reduction of 50 Hz Magnetic Fields Caused by Indoor Substations. 13th International Conference on Electricity Distribution 1995, Vol. 1, Session 2, pp. 2.20.1-2.20.6.

[Toh98] Tohmola S. Reduction of Magnetic Fields at Substations. Tampere University of Technology, M.Sc. Thesis, 1998, 64 p.

[Vad92] Vadivic R. Aspects Concerning the Choice of Measuring Points and Specification of Parameters Needed for a Proper Determination of Magnetic Fields. IEEE Transactions on Magnetics, vol. 28, issue 3, 1992, pp. 1826-1832.

[Ver97] Vereshchagin IP, Beloglovsky AA, Burmistrov MM, Vinokurov VN. Calculation of the Electric and Magnetic Fields Near of the Energy Objects. Electromagnetic Compatibility Proceedings, 1997, pp. 446-449.

[Voi76] Voipio E. Sähkö- ja magneettikentät. Otakustantamo, 1976, 388 p. (in Finnish)

[Vuo93] Vuola R. Voimajohtojen aiheuttamien magneettikenttien pienentämismahdollisuudet, M.Sc. thesis, Helsinki University of Technology, Espoo, 1993, 99 p. (in Finnish)

[Was98] Wassef K, Varadan VV, Varadan VK. Magnetic Field Shielding Concepts for Power Transmission Lines. IEEE Transactions on Magnetics, vol. 34, issue 3, 1998, pp. 649-654.

[Wig89] Wiggins CM, Nickel FS, Haney J, Wright SE. Measurement of Switching Transients in a 115 kV Substation. IEEE Transactions on Power Delivery, vol. 4, issue 1, 1989, pp. 756-769.

[Wig94] Wiggins CM, Thomas DE, Nickel FS, Salas TM, Wright SE. Transient Electromagnetic Interference in Substations. IEEE Transactions on Power Delivery, vol. 9, issue 4, 1994, pp. 1869-1884.

[Won94] Wong PS, Rind TM, Harvey SM, Scheer RR. Power Frequency Electric and Magnetic Fields from a 230 kV GAS-Insulated Substation. IEEE Transactions on Power Delivery, vol. 9, issue 3, 1994, pp. 1494-1501.

[Xio94] Xiong W, Dawalibi FP. Transient Performance of Substation Grounding System Subjected to Lightning and Similar Surge Currents. IEEE Transactions on Power Delivery, vol. 9, issue 3, 1994, pp. 1412-1420.

[Yam00] Yamazaki K, Kawamoto T, Fujinami H. Requirements for Power Line Magnetic Field Mitigation Using a Passive Loop Conductor. IEEE Transactions on Power Delivery, vol. 15, issue 2, 2000, pp. 646-651.

[Yan96] Yang C-F, Hwang J-T, Lee T-H, Yang J-S, Lin C-T. Effects of Magnetic Field Induction and Ground Potential Rise on Pilot Wire Relay System Operations. Generation, Transmission and Distribution (IEE), vol. 143, issue 3, 1996, pp. 250-254.

[Zha90] Zhang W, Kasten DG, Addis GA. Three-Dimensional Magnetic Field Calculation Computer Program for 60 Hz Substations. Power Symposium (IEEE), 1990, pp. 212-221.

LAYOUTS AND MEASUREMENT POINTS IN ELECTRIC SUBSTATIONS

Case 1: 110/20 kV Transformer Substation

Figure 1 presents the layout and measurement points in the switchyard of the 110 kV transformer substation.

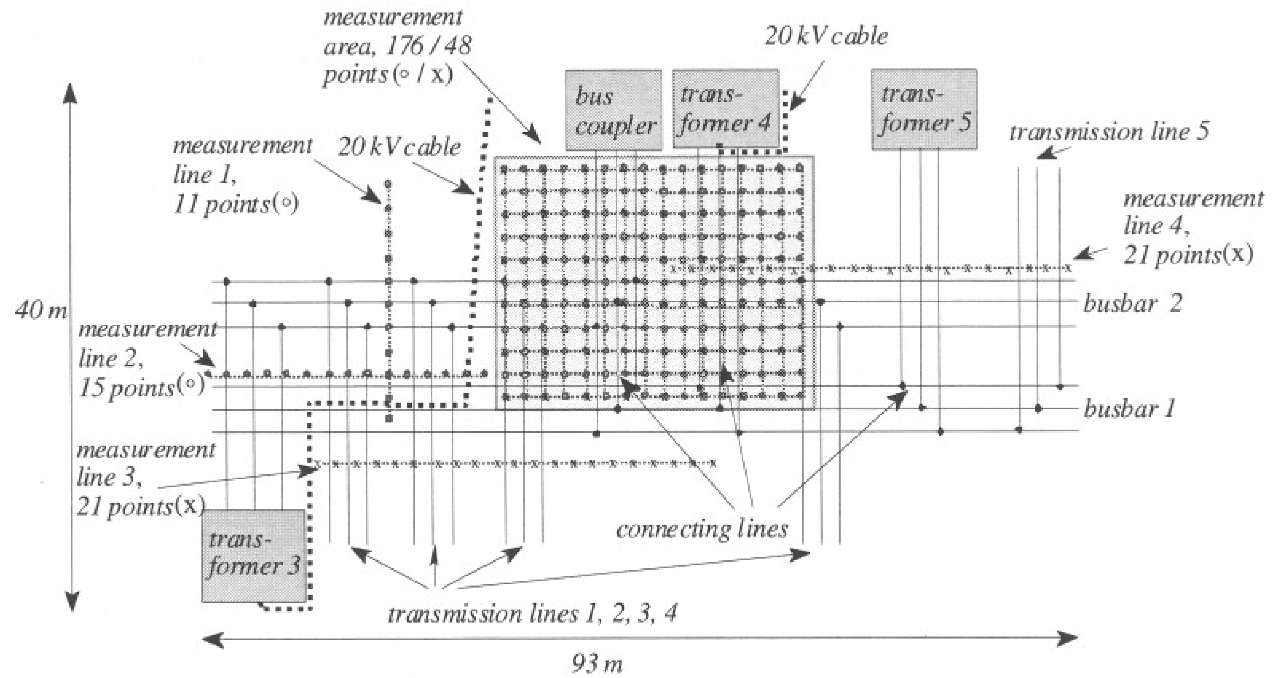


Figure 1. Measurement points (o is magnetic field, × is electric field) at the 110 kV switchyard (layout). [Kei98b, Kor00, Toh98]

Case 2: 110/20 kV GIS Transformer Substation

Figure 2 presents the layout and measurement points in the switchyard of the 110 kV GIS transformer substation.

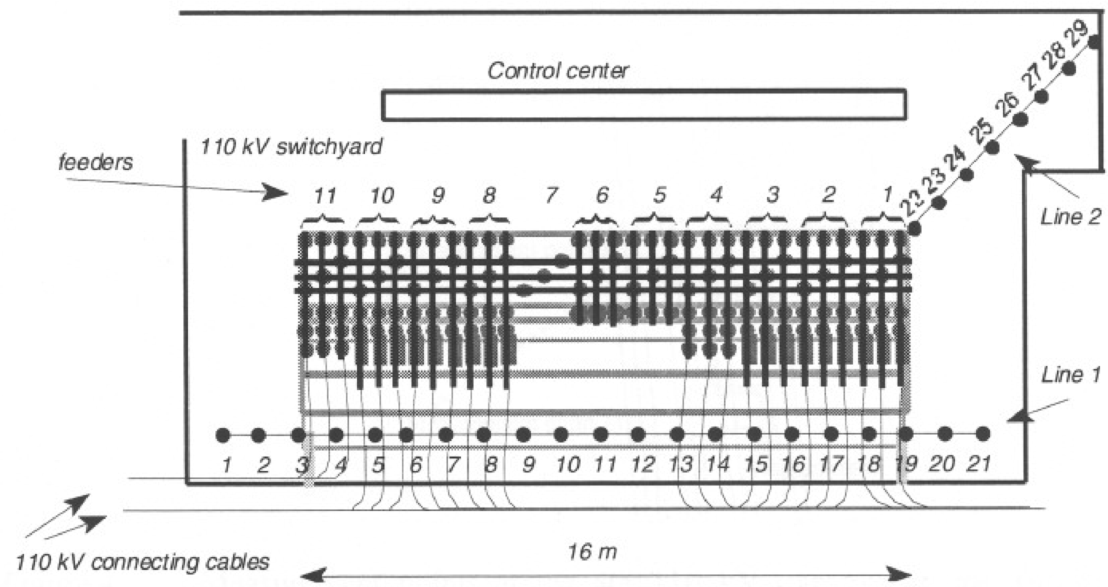


Figure 2. Measurement points (•) at the 110 kV switchyard (layout). [Sau02]

APPENDIX 1

Case 3: 400 kV Switching Substation

Figure 3 presents the layout and measurement points in the switchyard of the 400 kV switching substation.

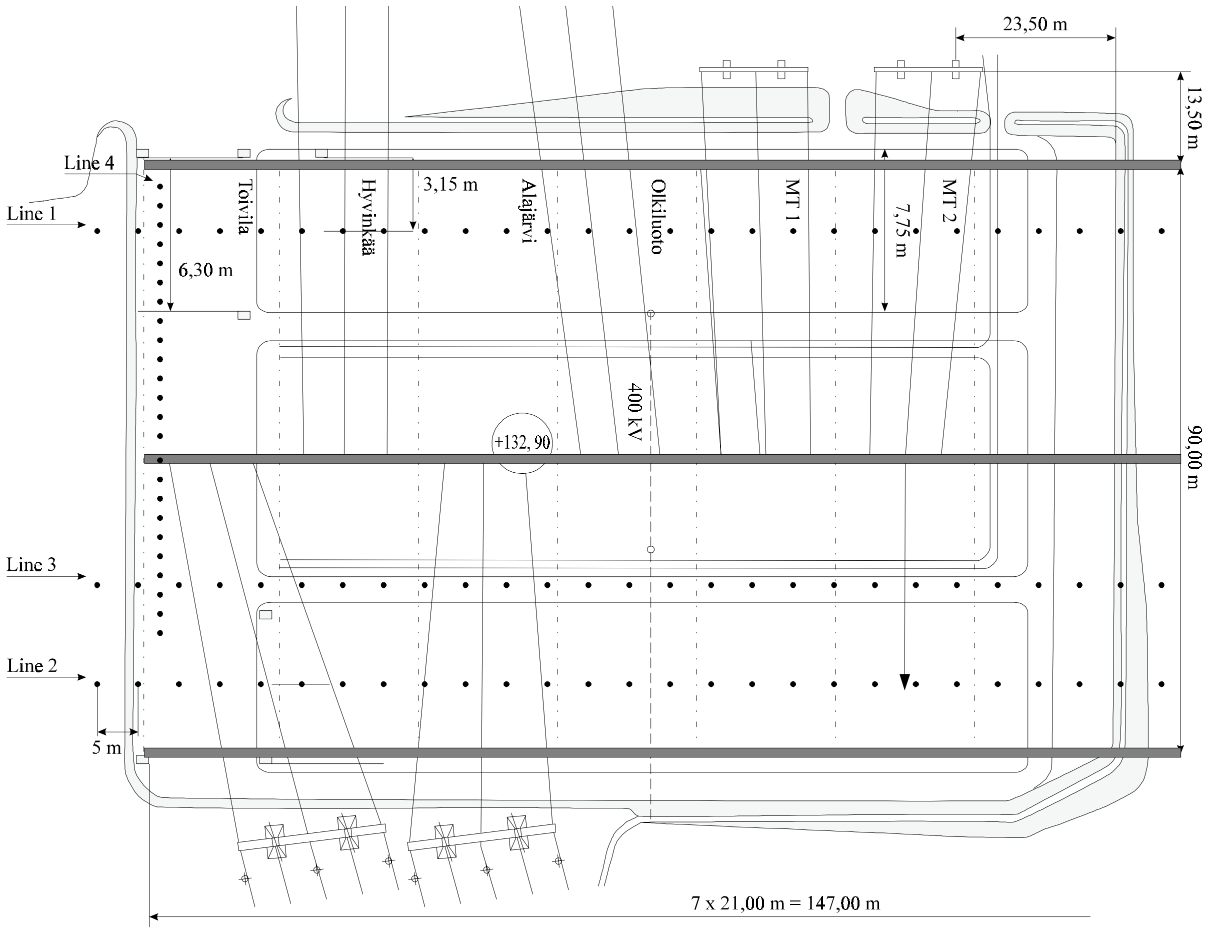


Figure 3. Measurement points at the 400 kV switchyard (layout). [Kor98]

Case 4: 400 kV Transformer and DC Link Substation

Figure 4 presents the layout and measurement points in the switchyard of the 400 kV transformer and dc link substation.

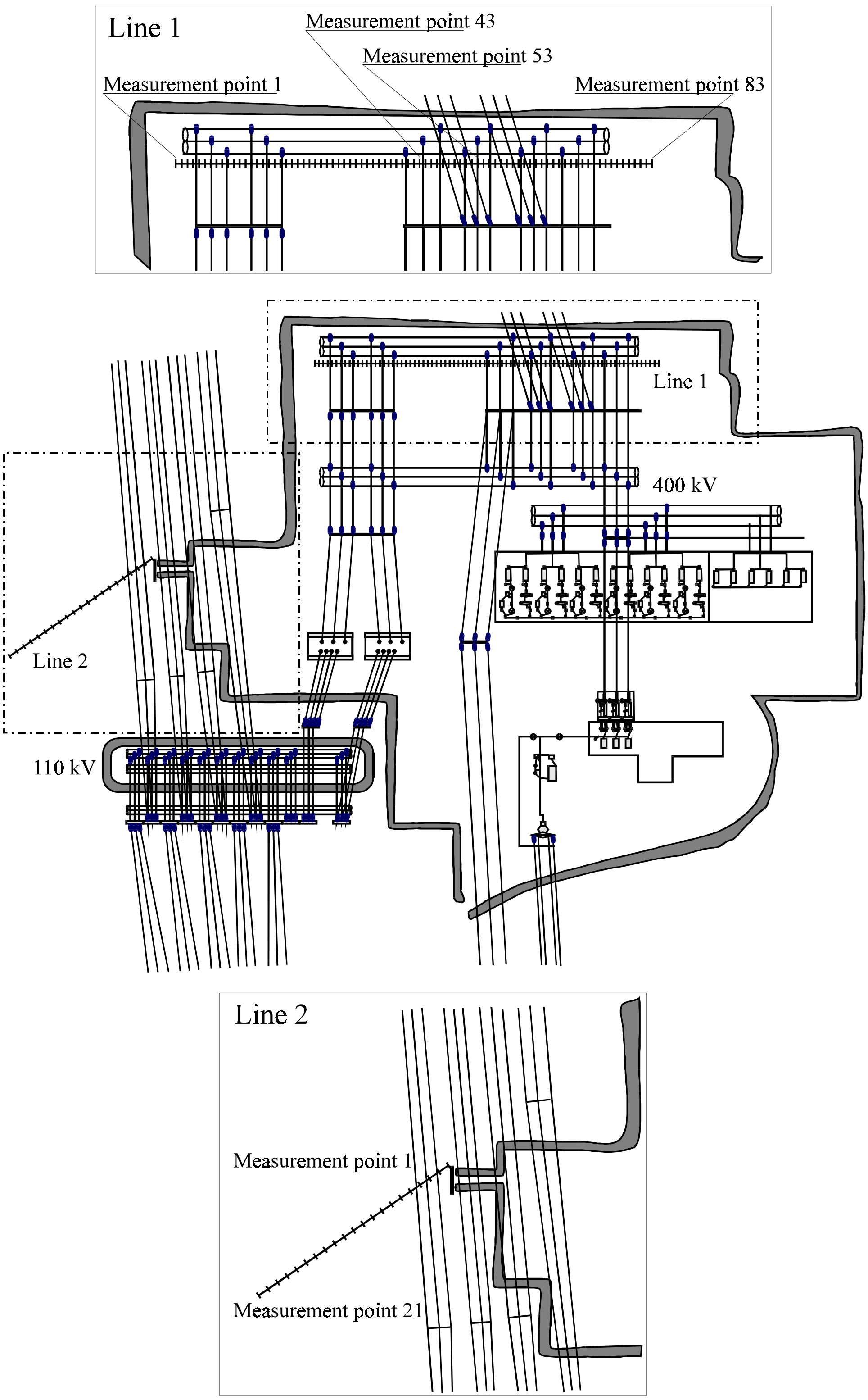


Figure 4. Measurement points at the 400/110 kV transformer and DC link substation (layout). [Kei03]

Tampereen teknillinen yliopisto
PL 527
33101 Tampere

Tampere University of Technology
P. O. B. 527
FIN-33101 Tampere Finland