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

SHIELDING OF MAGNETIC FIELDS DURING LIVE-LINE MAINTENANCE

Author/s: **GÁBOR GÖCSEI, BÁLINT NÉMETH**
Company or institution: **BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS**
Position: GÁBOR GÖCSEI (assistant lecturer), BÁLINT NÉMETH (lecturer, Head of High Voltage Laboratory)

KEY WORDS: magnetic, shielding, live, line, maintenance, high, voltage

COMPANY´S DATA
Address: Egry József u. 18.
Zip Code: 1111
Phone: +36 1 463 3236
Fax: +36 1 463 3231
E-Mail: gocsei.gabor@vet.bme.hu

SUMMARY

To protect the worker against the possibly harmful effects of electric field can be ensured effectively by a well-designed conductive clothing acting as a Faraday-cage. Inside an ideal Faraday cage – which is an enclosed metal surface – electric field is zero. Efficiency of conductive clothing are mainly determined by the maximal size of the holes on them and is usually above 99%.
In case of extra-low frequency (ELF), effects of electric and magnetic fields have to be taken into consideration separately from each other. Although conductive clothing – which are widely used during high voltage live-line maintenance – can shield the electric field effectively, based on the result of the measurements executed in the High Voltage Laboratory of Budapest University of Technology and Economics (BUTE), they are not effective enough to shield magnetic field at all.

Calculations and finite element (FEM) simulations based on the data of the Hungarian high voltage grid – as an essential part of the European power market – have proved that in some cases the current flowing through the conductors of a high voltage power line may induce currents in the human body. This induced current might be higher than the current limits. It is a practical and actual question to eliminate all the hazards which may endanger the safety of live-line workers. Although it is not easy to shield magnetic field effectively in practice, a new way of protection has been developed and introduced in the High Voltage Laboratory of BUTE. The application of this method together with the conductive clothing can be the key of totally safe high voltage live-line work with the full control of both electric and magnetic fields at any time. Safety of the worker has always to be handled as a first priority during any kind of work – especially in case of an energized network.

Introduction

Live-line maintenance can guarantee the execution of various kinds of activities on the different equipment of the low, medium and high voltage grid while the system is energized. This way of work has numerous technical and economic benefits without any consumer disturbance. The method – often called as the “future of maintenance” – is beneficial from both the side of the consumer and the TSO or DSO [1].

Lately different methods of LLM became popular because of the advantages introduced above. Besides its well-known benefits, from the other side all risks related to the LLM personnel have to be taken into consideration. The main aim of this paper is to clarify the non-visible sources of danger from the aspect of both short and long-term effects of electric, but especially magnetic fields. With the growth of TSOs and DSOs applying different LLM methods, this mostly unclarified question become up-to-date, important, practical and more and more urgent to handle in a proper way.

Electric and magnetic fields (EMF)

Electric and magnetic fields together are often referred as “electromagnetic fields” but from the aspect of the topic it is especially important to clarify the basic differences between electric, magnetic and electromagnetic fields.

Static electric/magnetic fields have two criteria to meet: drift currents have to be negligible to the current density and the length of the line cannot been in the same scale than the wavelength. In case of typical power lines with a frequency of 50 or 60 Hz, typical wavelength is 6000 and 5000 km, which is much longer than the length of any conventional power line regardless of voltage level. Drift currents are determined by material and frequency; in case of aluminium-steel conductors with a supposed conductivity of 10^7 Ω/m, critical frequency is about 10^{17} Hz.

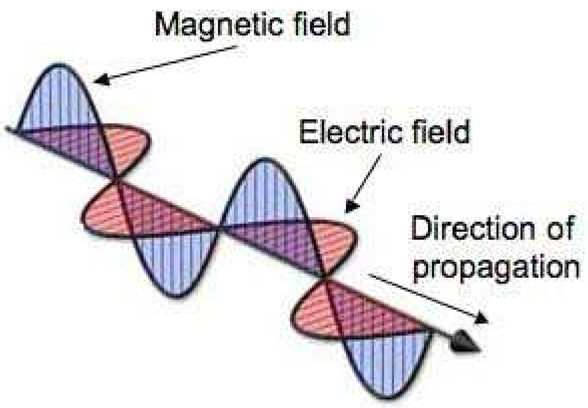

Figure 1. Electromagnetic wave [2].

Both the length- and material-related conditions show that in case of industrial frequency, and conventional material selection/design, none of the fields around the power lines can be handled as an electromagnetic field; electric and magnetic fields – and the effects of them – have to be taken into consideration separately from each other. These properties are often summarized by referring them as extra low frequency (ELF) fields, usually below 100 kHz.

Both electric and magnetic fields have several short- and long term health effects above a given limit. These limits are defined by the International Commission on Non-Ionizing Radiation Protection. Because of the non-ionizing nature of these kinds of exposures, exposure doses cannot been defined. Current values together with the past-2010 limits are summarized in Table 1.

Table 1. Current and previous limits of ICNIRP regarding to ELF electric and magnetic fields [3], [4], [5].

	Electric field limit [kV/m]		Magnetic field limit [µT]	
	Before 2010	Currently	Before 2010	Currently
Public (24 h/day)	5	5	100	200
Occupational (8h/day)	10	10	500	1000

Effects of ELF electric fields

However electric fields are not categorized as the root cause of any possibly harmful effect, short-term above-the-limit exposure values may cause discharges on the surface of the skin and generate eddy currents in the human body - as a result of drift currents - which have similar long-term effects than static magnetic fields. These are the main reasons why electric fields also have a specified limit prescribed by ICNIRP.

Effects of ELF magnetic fields

Short-term effects of above-the-limit ELF magnetic fields have several effects on body organs especially with high moisture rate (e.g. human eyes). Decrease in precision of movements is also reported in various articles based on the results of different in-vitro and in-vivo experiments inspecting bio-currents [3], [4]. Numerous epidemiological inspections have been executed lately to inspect the possibly harmful long-term effects of magnetic fields above the limits. The main reason is that ELF magnetic fields are often referred as the possible reason of childhood leukaemia [4]. As a result of the studies, WHO's cancer research institute, International Agency for Research on Cancer has qualified ELF magnetic fields as possibly carcinogenic to humans (category "2B") [6]. As it can be seen, proper shielding of ELF magnetic field is as important – or even more important – than the proper shielding of ELF electric fields. For the proper simulation of a typical high voltage power line, a cross-border Hungarian interconnection – as a part of ENSTO-E's European grid – has been selected. Based on the data of the Hungarian TSO, typical peak current load of this given power line is about 2 kA per phase. In case of localized sources (in a distance of less than 20 cm) limits of Table 1 cannot been applied directly [3], [4], [7]; dosimetric calculations have to be executed case by case instead. For this case the reference current density value is 10 mA/m^2 inside the human body. Model of IEC 62233 [8] is shown in Figure 2 with the results of the finite element calculations for current densities. The distance from the phase conductor was 10 cm (3.94”) which is typical in case of barehand method – widely applied as a technology of high voltage live-line maintenance worldwide. As it can be seen form the results, current density in the head – which is one of the most critical part of the human body – may exceed the limit during normal operational conditions. The main question about the topic is whether ELF magnetic fields can be shielded by the conductive clothing similarly to ELF electric fields or not. To clarify this question different types of conductive clothing have been inspected in the High Voltage Laboratory of Budapest University of Technology and Economics (BUTE). As results show none of the conventional clothing is effective from the shielding of ELF magnetic fields at all [9]. Because of the exposure values (induced currents) above the limits and the ineffective way of current shielding it is especially urgent and important to find a solution to prevent the workers from the possibly carcinogenic effects of these kind of fields.

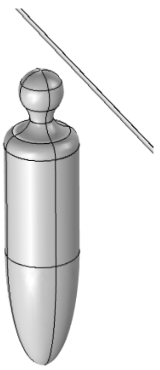

Figure 2.a2 3D human body model

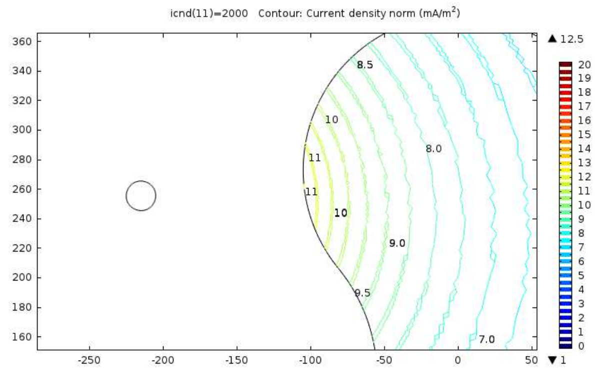

Figure 2.b. Calculated induced current densities in the head.

Ways of EMF shielding EMF

Although generation of both ELF electric and magnetic fields are regardless from voltage level or current load, in case of most low and medium voltage overhead lines, relatively low voltage and current (or relatively high distances) can guarantee the safety of the worker without any additional need of any kind of shielding. In case of high voltage LLM, both electric and magnetic fields might be above their valid limits [10], [11], [12]. Electric fields can be shielded effectively by a conductive clothing acting as a Faraday cage. Inside an ideal Faraday cage (an enclosed conductive surface) electric field is zero from outer source. However ideal Faraday cages cannot been applied practically during any kind of live-line work, conductive clothing – with a face screen [13] – usually act as an effective way of shielding, with screening efficiencies above 99%. However shielding of ELF electric fields is solved practically during LLM, in the current practice magnetic fields cannot been reduced significantly at all during any kind of live-line work. The main aim of this paper is to present a possible (currently mainly theoretical) way of shielding ELF magnetic fields during high voltage live-line maintenance. Development of practical way of application is under development in the High Voltage Laboratory of Budapest University of Technology and Economics as a part of an international research and development project in co-operation with European TSOs.

Principle of shielding ELF magnetic fields

It is possible to “shield” ELF magnetic fields by the application of basic physical laws. If an additional current path is ensured in parallel with the original current-carrying conductor, two effects of the distributed currents will decrease magnetic flux density simultaneously:

- Original magnetic field of phase conductors is generated by the phase current flowing through them. In case of parallel current path(s) ensured at the site of the work, summarized current is divided by a ratio depending on the number of branches; current of each branch will be lower than the original value.
- If there are two or more conductors with a current in the same direction a given area between the conductors will be “shielded” by the cancellation of the magnetic field between the conductors. The size and the shape of this area depends on the currents of each branch and the geometry of the arrangement.

As a result of the reasons above a so-called “protected area” is being generated between the conductors. If the worker remains inside this area, this kind of shielding can guarantee the safety of the work at any time. An example for the shielding in case of 2 conductors (1 original phase conductor and 1 additional conductor installed at the working site) is shown in Figure 3. Protected area marked with “P” is also shown both in the magnetic flux density distribution map and the magnetic flux density strength curve as a function of distance.

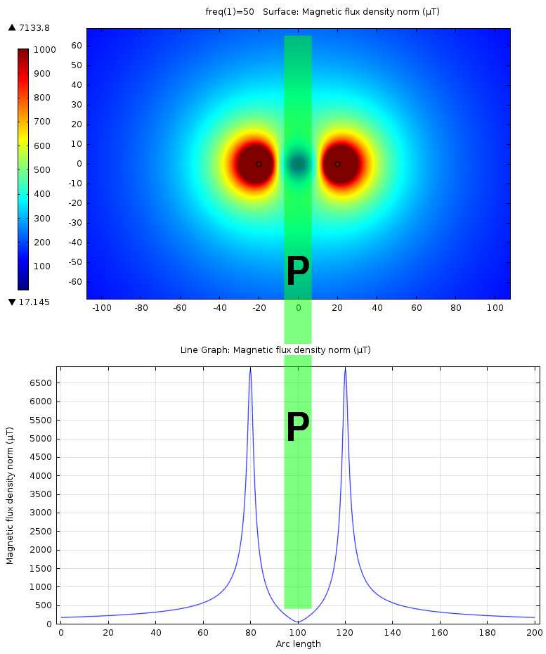

Figure 3. Principle of shielding ELF magnetic fields.

Current issues regarding to high voltage LLM equipment

Nowadays different types of equipment are used depending on the live-line technology applied. During high voltage LLM a common point of them is that the potential of conductive parts is established being the same than the potential of the phase conductor itself. Practically one or more “potential clamps” are applied to ensure the proper connection between the equipment and the phase conductor(s). In case of more than one potential clamp, an unknown amount of current of the current phase flows through the structure of the equipment itself. This ratio depends on many environmental circumstances (such as impedance of material, connection, design of structure, etc.) These currents have to be handled at any time of any live-line work properly; in case of their unknown ratio, in extreme cases voltage drops caused by the inhomogeneous potential distribution may endanger the safety of the worker. In case of proper regulations and guidelines for designing these high-current paths the structure of the live-line equipment itself might be used as an additional current path of Chapter 4. To investigate some practical total and equipment current ratios, a widely used type of conductor car has been inspected in the High Voltage Laboratory of BUTE. Arrangement of the measurement is shown in Figure 4. Results are summarized in Table 2.

Table 2. Total and equipment currents in a practical case.

I_{sum} [A]	I_{eq} [A]	I_{eq}/I_{sum} [%]
1200	72.22	6.02

Figure 4. High current circuit in the High Voltage Laboratory of BUTE.

As it can be seen, a notable amount of current of a given phase flows through the structure of the conductor car, but in a totally uncontrolled way. This current might cause inhomogeneous potential distribution as it is shown in Figure 5. Impedance values (including contact impedances) are based on measurements in the arrangement at the High Voltage Laboratory.

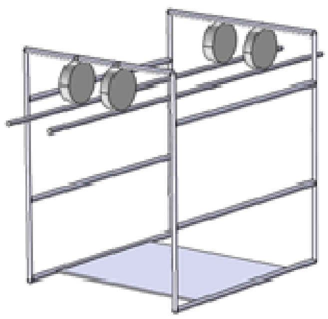

Figure 5.a. 3D model of the conductor car for FEM simulations

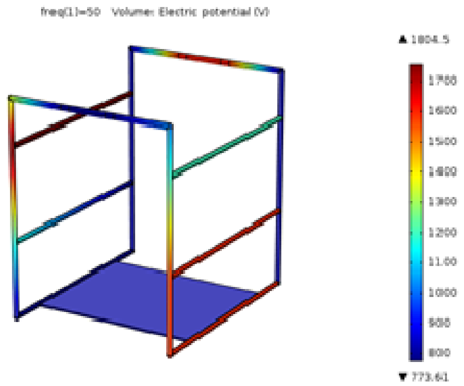

Figure 5.b. Results of potential distribution.

As it can be seen in Figure 5, if there are more than one potential clamps on a live-line equipment, an unknown amount of current may flow through the equipment itself, which may cause dangerous voltage drops in case of improper design and handling of this phenomena.

Summary

Extra-low frequency magnetic fields have several long-term effects based on the latest results of WHO IARC. During high voltage live-line maintenance magnetic field might be higher than current limits defined by ICNIRP. None of conventional conductive clothing have significant shielding effect on ELF magnetic fields. ELF magnetic fields can be shielded effectively by a parallel conductor as a summarized result of two basic physical laws. In case of conductive live-line equipment with more than one potential clamps, an undefined amount of current may flow through the structure of the equipment itself. The risks related to these currents have to be handled during any kind of live-line work. In case of proper design guidelines the conductive structure itself can be used as an alternate current path for ELF magnetic field shielding. Principle of a possible way to shield ELF magnetic fields has been introduced in this paper. Practical application is under development in the High Voltage Laboratory of Budapest University of Technology and Economics.

References

[1] CIGRÉ Report 561: Live Work – A Management Perspective, Joint Working Group, B2/B3.27, December 2013

[2] http://fab.cba.mit.edu/classes/MIT/862.06/students/alki/GA.html,
date of visit: 02 February, 2015

[3] International Commission On Non-ionizing Radiation Protection, ICNIRP Statement, General Approach to Protection Against Non-Ionizing Radiation Protection, Health Physics 82(4):540-548, 2002

[4] International Commission On Non-ionizing Radiation Protection, ICNIRP Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz – 100 KHz), Health Physics 99(6):818-836, 2010

[5] Directive 2013/35/EU of the European Parliament and of the Council of 26 June 2013 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (20th individual Directive within the meaning of Article 16(1) of Directive

89/391/EEC) and repealing Directive 2004/40/EC

[6] World Health Organization International Agency For Research On Cancer: IARC Monographs On The Evaluation Of Carcinogenic Risks To Humans, Volume 80, Non-Ionizing Radiation, Part 1: Static And Extremely Low-Frequency (ELF) Electric And Magnetic Fields, IARCPress, Lyon, France, 2002

[7] Wojciech Krajewski: BEM evaluation of eddy currents induced in a live-line worker body, IEEE Proceedings, Science Measurement and Technology, April, 1997

[8] IEC 62233 ed1.0: Measurement methods for electromagnetic fields of household appliances and similar apparatus with regard to human exposure, International Electrotechnical Commission, 2005

[9] Gábor Göcsei, Bálint Németh, István Kiss, István Berta: Shielding efficiency of conductive clothing in magnetic field, Journal of Electrostatics, 71:(3) pp. 392-395, 2013

[10] Gábor Göcsei, Bálint Németh, Dániel Tarcsa: Extra low frequency electric and magnetic fields during live-line maintenance, IEEE Electrical Insulation Conference, Ottawa, Ontario, Canada, 2013

[11] G. Göcsei, B. Németh, I. Kiss, I. Berta: Health effects of magnetic fields during live-line maintenance, International Conference on Live Maintenance (ICOLIM) 2014, Budapest, Hungary Paper 235, pp. 6, ISBN: 978-1-4799-5993-8

[12] G. Göcsei, B. Németh, Á. Tamus, I. Kiss, J. Meixner: Shielding efficiency of conductive clothing during live-line maintenance, International Conference on Live Maintenance (ICOLIM) 2014, Budapest, Hungary, Paper 306, pp. 5, ISBN: 978-1-4799-5993-8

[13] G. Göcsei, B. Németh, Z. A. Tamus, I. Kiss: Face Protection Investigation Against Electric Field On Live Line Workers (keynote), 2012 IEEE International Symposium of Electrical Insulation, San Juan, USA, pp. 535-539, ISBN: 978-1-4673-0486-3