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Improved protection of working personnel during high voltage live-line maintenance

Thesis summary

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1 Introduction

Live-line maintenance is an optimal way to execute planned works both in the distribution and transmission network. Because of its numerous technical and economic advantages, various live working methods are widely used all around the world.

Many of the researches focus on the investigation of the effects of extra-low frequency electric and magnetic fields nowadays. Valid limits of non-ionizing radiations have been defined based on the results of in vitro and in vivo experiments, epidemiological inspections, calculations, simulations, measurements and several kinds of analyses.

During live-line maintenance electric and magnetic fields have influence on the workers at the same time, so the examination of their exact short and long-term health effects is crucial. The main mission of an electrical engineer has to be to ensure that both electric and magnetic fields are kept below the limits during any time of any live-line work.

2 Summary of the dissertation

From the three theses of the dissertation, one focuses on the current inspection method of conductive clothing and electric fields during live-line maintenance; two of them are related to extra-low frequency magnetic fields and the possible ways of the protection against them.

Efficiency of conductive clothing to shield electric fields is usually high. Acting as a Faraday-cage, this special equipment is widely used as a key component of bare-hand method; in my dissertation I analyzed and criticized the current way of inspection of their screening efficiency. By using the results of my 1st thesis, the measurement can be safer, more accurate and easier to repeat.

In terms of magnetic fields, the most important statement is that before the beginning of any high voltage live-line work – besides the proper handling of high electric fields – analysis of currents and geometry is also always necessary. As none of conventional conductive clothing is effective enough to shield magnetic fields, induced current density in the body of the worker may exceed even occupational limits. A novel approach is necessary to handle magnetic field-related risks properly, as well.

The inspection of common applications in the other fields of industry has determined that – mostly from the practical side – none of them is suitable to be used during high voltage live-line maintenance to shield magnetic fields effectively.

In my dissertation I introduced a new way of magnetic shielding which can be realized during live-line maintenance, as well. Besides the introduction of the theory, practical questions have also been examined in the form of a risk assessment regarding to the technology to be developed. I introduced a novel way of protection against magnetic fields based on the theory of parallel current paths to protect live working personnel. Besides the calculations and simulations, I have also validated my results by laboratory measurements, as well.

Live-line maintenance is a beneficial method based on both technical and economic aspects, but – as statistics show – the most important result of its application is the less accident compared to de-energized works; furthermore, the decrease of consumer disturbance is also a notable advantage, as well. Health-related risks can be decreased effectively by using the findings of my theses. It can be determined that safe live working might be the key of the future of maintenance works both in distribution and transmission systems.

3 Research methodology

All the results of thesis-related simulations have been estimated by preliminary analytical calculations; in the High Voltage Laboratory of Budapest University of Technology and Economics, professional equipment made it possible to validate all the results by measurements, as well.

In my dissertation I have formulated three theses. To ensure the clear structure of the dissertation, all explanation, calculation and simulation is linked to the main part as an annex. All thesis-related articles have been published in both Hungarian and international journals (Acta Technica Jaurinensis, Elektrotechnika, Journal of Electrostatics, Journal of Physics) or have been presented at numerous international conferences (Transmission and Distribution and De-Energized Maintenance in High Voltage Installations – CITTES, 19th International Symposium on High Voltage Engineering – ISH, IEEE Electrical Insulation Conference – EIC, International Conference on Live maintenance – ICOLIM, International Youth Conference on Energy – IYCE, IEEE International Symposium of Electrical Insulation – ISEI).

4 Theses

In my 1st thesis I have determined that – despite of the fact that internal field strength may exceed the current limits – conductive clothing without a proper way of face protection may pass the criteria of the related international standard regarding to the screening efficiency. All the inspections have been validated by laboratory measurements. I also determined that the current arrangement and the principle of inspection – which is based on the comparison of leakage currents of the mannequin and the conductive clothing – is not suitable to detect critical electric fields inside the clothing. I have inspected the way of measurement and determined that environmental effects have a high influence on the results. There might be some cases when stresses caused by electric fields are higher during practical high voltage live-line activities than during the inspection. I have revised the current way of measurement and suggested some modifications to make it safer, more efficient and more consequent [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [15].

Inside a conductive clothing without any face protection – especially in front of the face – electric fields may occur above their current limits. In this case surface discharges, as one of the main short-term effects of high electric fields often occur; this phenomenon makes accurate and precise movements basically impossible. This phenomenon has been justified by calculations, simulations and laboratory measurements, as well.

Besides the direct, short-term effects, the possibly more dangerous long-term health-related risks of electric fields have to be inspected, as well: based on the latest results they also may endanger the safety of live working personnel.

Face mesh is an essential accessory of any conductive clothing. Its efficiency to increase the shielding factor against electric fields is certified by numerous measurements and simulations. It can be proven – both in theoretical and practical ways – that above a given size of a Faraday-hole, conductive clothing cannot be effective enough as Faraday-cages. In my 1st thesis I examined the possible root causes of questionable inspection results by the valid standard.

Analysis of current arrangement to measure the shielding capabilities of conductive clothing has shown that leakage current-based way of examination decreases the effects of local peaks of electric field inside the clothing, so increase the value of measured screening efficiency. In

case of conductive clothing without any face protection, electric fields may locally exceed their limits, so a more efficient way of inspection is necessary.

During the measurement it is crucial to prevent the formation of so-called “shielded” zones in the vicinity of the most critical parts – for example in front of the face. In the current arrangement it is possible to increase the shielding indicators of a given clothing this way.

Direct measurement of extra-low frequency electric fields is often difficult – even inside a conductive clothing, in the vicinity of energized parts. In my dissertation I made suggestions where critical stresses appear in the most critical areas, especially in front of the workers’ face.

Environment has much less influence on the results in the suggested new arrangement than in case of the current way of inspection: measurements may become safer, more accurate and more easy to repeat. By applying my suggestions, conductive clothing with openings above critical sizes can be identified clearly.

In my 2nd thesis I recognized that protection against extra-low frequency magnetic fields – categorized as „2B” (possibly carcinogenic to humans) by the International Agency for Research on Cancer of World Health Organization – may also be crucial during live-line maintenance. Based on the measurements’ results regular conductive clothing cannot shield magnetic fields effectively enough. Considering actual load data of the Hungarian transmission grid, my calculations and measurements have shown that there might be practical cases when induced current density in the human body exceeds its limits in the vicinity of the energized parts. Based on the new model I have developed, continuous monitoring and evaluation of magnetic fields and induced current densities – mainly caused by the current flowing through the conductors – is essential.

Electric fields can be handled by properly designed conductive clothing effectively; I have introduced a novel approach to take the effects of magnetic fields also into account during live-line activity. In my 2nd thesis I determined that in case of practical working conditions magnetic fields may cause health-related risks as well, so their magnitude and distribution has to be inspected before any live-line work. However today this point of view is not common at all, besides the proper shielding of extra-low frequency electric fields, effective shielding of magnetic fields might also be required [1], [2], [10], [13], [14].

According to the current international practice, conductive clothing – acting as Faraday-cages – are essential parts of the technology of high voltage live-line maintenance. These clothing are effective enough to shield extra-low frequency electric fields which have clearly detectable direct, short-term effects on the human body.

Although – based on the latest scientific results – magnetic field-related risks may be even more serious than of electric fields, the proper way of protection against them is not yet clarified. Researches related to the 2nd thesis of my dissertation have begun with the inspection of the possible root causes.

According to my findings the main problem is probably that short-term effects of magnetic fields only occur with magnitudes above their limits; such induction do not occur frequently during practical live-line activities. Although regarding to the long-term effects many questions are still unsolved, these usually do not have direct and clearly identifiable impacts on the workers' body.

Although some epidemiologic investigations have found that even less magnetic fields may cause health-related risks than the current limits, these statements have not been confirmed experimentally, yet. It is important to emphasize that currently there are not any justified conversion factor between the human body and the results of experiments executed on different species of animals.

Some possible long-term effects of magnetic fields (e.g. in relation to development and reproduction) are proven by some experimental results, as well: however, determination of critical values of exposure requires further discussions.

Magnetic fields – as a part of non-ionizing radiations – have been classified as "2B" (possibly carcinogenic o humans). Because of the lack of knowledge regarding to the exact health effect-related risks, in this case it is particularly important to be sure that magnetic fields never exceed their limits defined based on our most up-to-date knowledge. On-line monitoring of currents – so magnetic fields and induced current densities – during live-line maintenance is crucial, because this is the only way to continuously control exposures of the live working personnel.

One of the most important issues regarding to the shielding of extra-low frequency magnetic fields during live-line work is that realization of protection does not directly lead to economic benefits, so in profit-oriented organizations motivation to take care about the health of working personnel is sadly often not a priority. In responsible decision making processes this point of view cannot been acceptable at all. Health of workers must be handled as a first priority during any time in case of any kind of work. Following the trends of currents and induced current densities in the human body is the key of safety regarding to the protection against the harmful health effects of extra-low frequency magnetic fields.

In my 2nd thesis I have inspected various types of conductive clothing which are widely used in the international practice of live-line maintenance. Results have shown that their shielding capabilities against magnetic fields are negligible.

I examined the power loads of the Hungarian transmission grid and analyzed the magnetic fields in the vicinity of the phase conductors. I have determined that in case of even usual load currents, induced current densities may exceed their limits, so it can be stated that the new model of my dissertation has an important role in the development of the practical way of protection against magnetic fields.

This topic is at least as important as the electric field-related questions – with clearly detectable short-term effects just above their limits.

In my 3rd thesis I have inspected the efficiency of currently existing methods to shield magnetic fields and their practical applicability during high voltage live-line maintenance. I have determined that none of them can guarantee both safe and practically applicable solution at the same time. I have developed a new suggestion to decrease extra-low frequency magnetic fields based on the principle of parallel current paths. By the use of this method the magnitude of induced current densities in the human body can be decreased effectively below their limits in a practically realizable way. Efficiency of this novel solution has been validated by both calculations and measurements, as well [2], [13], [14], [16].

Based on the statements of my 2nd thesis it can be determined that during high voltage live-line works – besides the proper shielding of electric fields – efficient protection against magnetic fields is also necessary. In my 3rd thesis I summarize and analyze the existing methods of magnetic shielding by identifying their weak points in terms of practical applicability during high voltage live-line maintenance.

There are numerous techniques which are suitable to shield electric, magnetic and electromagnetic fields in other fields of the industry. As high voltage live-line maintenance is a very special application, in this case many practical aspects have influence on their applicability.

The practical solution – introduced in the 3rd thesis of my dissertation – has to be capable to decrease the induced current density in the human body effectively and in a practically realizable way; however, risks occurring during the application shall not decrease the basic safety level of live-line works.

Method of parallel current paths is a promising way to shield extra-low frequency magnetic fields. Efficiency is ensured by the simultaneous effect of two phenomena: although their physical background is well-known, the practical application is completely novel in this way.

Risk analysis is also a part of my 3rd thesis. In this chapter I focus on the sources of dangers related to the new solution and make suggestions to handle and decrease them effectively.

I also determined that the applicability of the new way of shielding of magnetic fields do not have any practical barriers. Based on the results of laboratory demonstrations, method of parallel current paths can be considered as a safe, effective and realizable way of protection against induced current density in the human body during high voltage live-line maintenance to increase the safety of the workers.

5 Practical applicability of results

Conductive clothing – acting as a Faraday-cage – is a crucial equipment from the aspect of safety in case of bare-hand method, as a widely applied working technique of high voltage live-line maintenance.

My 1st thesis has shown that the currently (2016) valid standard MSZ EN/IEC 60895:2002 (Feszültség alatti munkavégzés. Vezetőképes öltözet legfeljebb 800 kV névleges váltakozófeszültségig és ± 600 kV egyenfeszültségig – „Live working - Conductive clothing for use at nominal voltage up to 800 kV a.c. and +/- 600 kV d.c.") has several deficiencies.

Based on the results it can be stated that inspection of screening efficiency is a particularly important element of the examination of any conductive clothing. It is a major issue that a given clothing in the current arrangement may pass the test while the openings are larger than the allowed size determined by simulations and validated by measurements.

The lack of face mesh is crucial as increasing the size of Faraday-holes, so decreasing the efficiency of any conductive clothing significantly. In Hungary complains of live-line workers justify the presence of local peaks of electric fields exceeding their current limits inside the clothing. This is a practical proof of the necessity of proper face protection.

Besides the fact that current arrangement for the inspection of screening efficiency contains some unnecessary sources of dangers – such as energized instruments connected to the high voltage side – this way of measurement decreases the accuracy, as well. The environment has a significant influence on the results.

The suggestions made as a part of my 1st thesis make inspections safer, more accurate and more easy to repeat. As the most important result of the new arrangement, conductive clothing with Faraday-hole sizes exceeding the critical values can be clearly identified, ensuring the safety of workers during any time of any live-line work.

The working committee of International Electrotechnical Commission (IEC) has been used the results of my thesis – published at numerous international conferences and introduced in several journals – during the preparation of the next edition of the related standard.

Magnetic field-related questions – raised as a part of my 2nd thesis – have been answered in my 3rd thesis in a form of a practically applicable method during high voltage live-line maintenance. It is crucial to handle health-related risks as particularly important topic to guarantee the maximal protection of the workers. In this case, responsible way of decision-making is especially important both on distribution and transmission levels, as well.

The precondition of the improvement of a complete technology for continuous, on-line monitoring of magnetic fields and induced current density during live-line works is the existence of a risk assessment introduced as a part of my 3rd thesis. This work is under realization (2016) as a part of one of the biggest research and development project of the European Union („Seventh Programme for research, technological development and demonstration under grant agreement No 612748 – BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal HVDC Systems").

6 Thesis-related publications of the author

Total: 16

[1]	Authors:	Gábor Göcsei, Bálint Németh, Dr. István Kiss, Dr. István Berta
	Title:	Shielding efficiency of conductive clothing in magnetic field
	Journal:	Journal of Electrostatics (impact factor: 1,286 – 7 July, 2016)
	Volume:	71 (3)
	Publisher:	Elsevier, Amsterdam, Netherlands
	Identifier:	pp. 392-395
	Other:	ISSN: 0304-3886

[2]	Authors:	Gábor Göcsei, Dr. István Kiss, Bálint Németh
	Title:	Effects of magnetic fields during high voltage live-line maintenance
	Journal:	Journal of Physics
	Volume:	646
	Publisher:	IOP Publishing, Bristol, Anglia
	Identifier:	012026
	Other:	ISSN: 1742-6596 (online), 1742-6588 (print)

[3]	Authors:	Gábor Göcsei, Dr. István Berta, Bálint Németh
	Title:	Safety considerations regarding to the shielding of electric fields during high voltage live-line maintenance
	Journal:	Acta Technica Jaurinensis
	Volume:	8 (2)
	Publisher:	Szechenyi Istvan University
	Identifier:	pp. 153-164
	Other:	ISSN: 2064-5228 (online), 1789-6932 (print)

[4] Authors: Göcsei Gábor, Németh Bálint, Dr. Kiss István, Tamus Ádám
Title: Vezetőképes öltözetek villamos paramétereinek vizsgálata
Journal: Elektrotechnika
Volume: 105
Publisher: MEE, Budapest, Hungary
Identifier: pp. 15-19
Other: ISSN: 0367-0708

[5] Authors: Gábor Göcsei, Bálint Németh
Title: New challenges in live-line maintenance
Conference: Electrical Insulation Conference (EIC)
Location, date: Seattle, USA, 2015.06.07-2015.06.10.
Publisher: IEEE, New York, USA
Identifier: pp. 185-188
Other: ISBN:978-1-4799-7352-1

[6] Authors: Gábor Göcsei, Bálint Németh
Title: Current issues regarding to the inspection of conductive clothing
Conference: 7th International Congress on "Live Working and Safety in Electrical Power Transmission and Distribution and De-Energized Maintenance in High Voltage Installations" (CITTES)
Location, date: Buenos Aires, Argentina, 2015.09.14-2015.09.17.
Publisher: CACIER, Buenos Aires, Argentina
Identifier: TT21

[7]	Authors:	Gábor Göcsei, Bálint Németh, Dr. István Berta
	Title:	Electric fields and arc protection during live-line maintenance
	Conference:	19th International Symposium on High Voltage Engineering (ISH)
	Location, date:	Plzen, Czech Republic, 2015.08.23-2015.08.28.
	Publisher:	CIGRÉ, Paris, France
	Identifier:	631
	Other:	ISBN: 978-80-261-0477-3

[8]	Authors:	Gábor Göcsei, Bálint Németh, Ádám Tamus, Dr. István Kiss
	Title:	Face Protection Investigation Against Electric Field On Live Line Workers
	Conference:	2012 IEEE International Symposium of Electrical Insulation (ISEI) – keynote
	Location, date:	San Juan, USA, 2012.06.10 -2012.06.13.
	Publisher:	IEEE, New York, USA
	Identifier:	pp. 535-539
	Other:	ISBN: 978-1-4673-0486-3

[9]	Authors:	Gábor Göcsei, Bálint Németh
	Title:	Comparison of conductive clothing's effectiveness
	Conference:	4th International Youth Conference on Energy (IYCE)
	Location, date:	Siófok, Hungary, 2013.06.06-2013.06.08.
	Publisher:	IEEE, New York, USA
	Identifier:	GG-5
	Other:	978-1-4673-5556-8

[10] Authors: Gábor Göcsei, Bálint Németh, Dániel Tarcsa

Title: Extra low frequency electric and magnetic fields during live-line maintenance

Conference: Electrical Insulation Conference (EIC)

Location, date: Ottawa, Canada, 2013.06.02-2013.06.05.

Publisher: IEEE, New York, USA

Identifier: pp. 100-104

Other: ISBN: 978-1-4673-4739-6

[11] Authors: Gábor Göcsei, Bálint Németh

Title: Investigation of different conductive clothing's shielding efficiency

Conference: 6th International Congress on "Live Working and Safety in Electrical Power Transmission and Distribution and De-Energized Maintenance in High Voltage Installations" (CITTES)

Location, date: Concordia , Argentina, 2013.05.07 -2013.05.10.

Publisher: CACIER, Buenos Aires, Argentina

Identifier: TT072

[12] Authors: Gábor Göcsei, Bálint Németh, Ádám Tamus, István Kiss, József Meixner

Title: Shielding efficiency of conductive clothing during live-line maintenance

Conference: 11th International Conference on Live Maintenance (ICOLIM)

Location, date: Budapest, Hungary, 2014.05.21-2014.05.23.

Publisher: IEEE, New York, USA

Identifier: 306

Other: ISBN:978-1-4799-5993-8

[13] Authors: Gábor Göcsei, Bálint Németh
Title: Shielding of magnetic fields during live-line maintenance
Conference: 7th International Congress on "Live Working and Safety in Electrical Power Transmission and Distribution and De-Energized Maintenance in High Voltage Installations" (CITTES)
Location, date: Buenos Aires, Argentina, 2015.09.14-2015.09.17.
Publisher: CACIER, Buenos Aires, Argentina
Identifier: TT22

[14] Authors: Gábor Göcsei, Bálint Németh, Dr. István Kiss, Dr. István Berta
Title: Health effects of magnetic fields during live-line maintenance
Conference: 11th International Conference on Live Maintenance (ICOLIM)
Location, date: Budapest, Hungary, 2014.05.21-2014.05.23.
Publisher: IEEE, New York, USA
Identifier: 235
Other: ISBN:978-1-4799-5993-8

[15] Authors: Gábor Göcsei, Dr. Bálint Németh
Title: Current issues regarding to the inspection of conductive clothing
Conference: IEEE 13th International Conference on Transmission & Distribution Construction, Operation & Live-Line Maintenance (ESMO)
Location, date: Columbus, USA, 2016.09.11-2016.09.15.
Publisher: IEEE, New York, USA
Identifier: 16ESMO0039

[16] Authors: Gábor Göcsei, Dr. Bálint Németh

Title: Shielding of magnetic fields during high voltage live-line maintenance

Conference: IEEE 13th International Conference on Transmission & Distribution Construction, Operation & Live-Line Maintenance (ESMO)

Location, date: Columbus, USA, 2016.09.11-2016.09.15.

Publisher: IEEE, New York, USA

Identifier: 16ESMO0040