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THE INFLUENCE OF PHASE SEQUENCE SELECTION ON MAGNETIC FLUX DENSITY CURVE OF EHV CABLE LINE

Martin Belatka[1], Martin Paar[1], Przemyslaw Chodura[2]
[1]Brno University of Technology, [2]Eindhoven University of Technology

Abstract. *The article deals with the hygienic limits in the Czech Republic for electric and magnetic fields radiated by Extra High Voltage cables with focus on phase sequence selection for minimization of magnetic fields in the surroundings of cables and the change of magnetic flux density in the case of one cable set outage of EHV line.*

Keywords: hygienic limits, cable line, magnetic field, phase sequence

WPŁYW WYBORU KOLEJNOŚCI FAZ NA KRZYWĄ GĘSTOŚCI STRUMIENIA MAGNETYCZNEGO W LINII KABLOWEJ NAJWYŻSZYCH NAPIĘĆ

Streszczenie. *Artykuł dotyczy limitów środowiskowych w Republice Czeskiej dla pól elektrycznych oraz magnetycznych w okolicach linii kablowych najwyższych napięć (NN), a zwłaszcza wyborem kolejności faz w celu minimalizacji pól magnetycznych w otoczeniu kabli oraz zmian gęstości strumienia magnetycznego w przypadku awarii jednej wiązki kabli.*

Słowa kluczowe: limity środowiskowe, linia kablowa, pole magnetyczne, kolejność faz

Introduction

Development of any linear construction in densely populated areas is in Europe very difficult and leads to complicated and lengthy permission processes involving many parties. Transmission systems are not an exception. Transmission system operators have faced many obstacles in their efforts to build new lines for several last decades. Constrains are mostly given by legislation and objections of environmental organizations or local authorities. For example in Germany 800 km of EHV (Extra High Voltage) lines was planned to be built during last decade with only some 10 % actually put in operation [1].

One of the ways to solve this difficult situation is the usage of cables instead of overhead lines. This solution is considerably more expensive than construction of overhead lines and brings new issues to planning and operation of power systems as well. However, in some cases the usage of cables may be the only suitable solution. While the application of HV cables up to voltage levels around 100 kV is common, installation of EHV cables remains rather rare both in and outside Europe. The situation in the Czech Republic is even less developed than in an average European country. There were only few applications of EHV cables on the 400 kV level in the Czech Republic in 2013. Installations are typically short cable connections in the area of substations; no EHV cable was installed in public area. As for today, there is no standard for 400 kV cable lines in the Czech Republic. Future development in this area is expected.

1. Extra High Voltage Cables

High voltage and extra high voltage cables have been successfully used for more than 80 years now. Conventional cables with paper insulation have used pressurized oil to prevent partial discharge activity. While in the U.S. pipe-type cable has been typical – HPFF/HPLF (high-pressure fluid-filled/liquid-filled) – self-contained cable has been dominating (SCFF/SCLF) in Europe and Asia. SCFF has proven high reliability and long lifetimes. However, oil leakage has been an environmental concern; installation and maintenance has been complicated due to the pressurized oil as well. The development of polyethylene insulation brought extruded XLPE (cross-linked polyethylene) cables to high voltage levels in 1970s and since then the voltage levels have increased, reaching EHV level in late 1990s. Extruded cables offer low environmental risk (so-called dry insulation), lower losses, easier handling and manipulation and today also slightly lower cost. Nowadays the EHV AC cable market segment is dominated by single core extruded XLPE cables.

The magnetic properties of both of the cable types are practically the same. Magnetic field outside long single-core cable (i.e. around long conductor) can be derived from Ampere – Maxwell law. The insulation material of a cable does not play significant role in magnitude of the magnetic field. Experience with laying SCFF cables is to a certain extent transferable to XLPE cables as well, as the requirements for good heat transfer and strength of magnetic field remain the same. Various configurations of installation and geometric configurations are possible, for 380 kV (or 400 kV) cable usage of trenches (often with back-fill to improve heat transfer of dry soil) and ducts in flat formation is common. The topic of geometrical configuration and its impact on magnetic field is discussed in following chapters.

The statistics presented by CIGRE in 2007 [5] show that for voltages range 315 – 500 kV only 0.5 % of circuits is underground. The leader in usage of EHV cables is Singapore, with total length 111 km covering 100 % of all EHV circuits. Denmark, Korea, Austria and United Kingdom use cables for 4 – 1.5 % of circuits; substantial length is also installed in the U.S. (536 km), but it represents only 0.4 % of total EHV circuit length. The main reasons for such low share are high investment costs (up to 20 times higher than for overhead line of the same transmission capacity; varies by case) and high capacitance resulting to need of substantial compensation for long cables. Therefore the arguments leading to construction of cable systems are typically political decisions, environmental and technical issues (e.g. not enough space for overhead line corridor in urban areas). Since the knowledge of behavior of long EHV cable systems and their impact on system is limited, such cables are often equipped with extensive measurement system and are subjects of ongoing research (e.g. Randstad 380 kV Zuidring in the Netherlands).

Only 27% of the EHV cables are XLPE cables, which is the consequence of late introduction of XLPE cables for this voltage level. The market development, as well as the numbers for lower voltage ranges (e.g. 47 % share of XLPE for range 110-219 kV) suggest that the share of XLPE cables will be increasing. New data on cable usage in transmission grids will likely be available around 2018, as similar study to CIGRE TB 338 was conducted also in 1996 (CIGRE TB 110 [4]). Even though noticeable increase in EHV cable usage is expected, such systems remain an expensive technical challenge.

2. Hygienic Limits

The installation of cables brings the issue of limits for induced current density, magnetic and electric fields in the surroundings of the cable line. General limits are given by directive 2004/40/EC of the European Parliament and the Council [8] which was implemented to the Czech Republic legal system as well. The hygienic limits regulating the usage of EHV cables in the

Czech Republic are specified by regulation no. 1/2008 col. from 12th December 2007 [6].

Three quantities are used for evaluation of ill-effect of non-ionizing radiation to human body for installations of EHV cables – so-called modified induced current density, magnetic flux density and electric field strength. The induced current is given by parameters of magnetic and electric fields; the exact equations for calculation of the current density the regulation no. 1/2008 col. [6] does not contain. The regulation gives the requirements for referential values of magnetic flux density and electric field strength of various frequencies for two categories of persons (public and staff). The referential levels are valid for field which is not deformed by presence of persons in the examined area. In case of strongly inhomogeneous field in the considered area, referential value is compared to average field intensity across area corresponding to the position of spine or head of the exposed person, or to the value in the geometric center of the area.

The maximal allowed value of the modified induced current density J_{mod} cannot be exceeded at any moment of time. The recalculated value for frequency 50 Hz is limited to 10 mA/m^2 for employees and 2 mA/m^2 for the public; both values are for the central nervous system. The limiting value depends also on the affected part of the body. The central nervous system is the most sensitive to affection; the limiting values for the rest of the body are 5 times higher. According to regulation no. 1/2008 subsequently amended regulation no. 106/2010 col. the modified current density J_{mod}, is defined as current flowing vertically through 100 mm^2 area divided by this area, which is modified by filter with frequency characteristic described in the regulation. [6]

For European network (frequency 50 Hz) the maximal limits for magnetic flux density and electric field strength for permanent exposition in rms values are shown in Tab. 1.

Table 1. Reference values for permanent exposition and frequency 50 Hz according to the regulation no. 1/2008 col. [6]

E_{rms} (kV/m)		B_{rms} (µT)	
staff	public	staff	public
10	5	500	100

2.1. The Usage of Limits for Magnetic Flux Density and Electric Field Strength

The limits given by the regulation no. 1/2008 col. are specific, but the comparison between maximal allowed electric field strength and magnetic flux density and maximal current density shows space for some flexibility. This conclusion is reached by applying the rules given by the regulation [6] and empirical experience [2]. It can be derived that the referential value of electric field strength 5 kV/m evokes current density only 1.39 mA/m^2, while the limit is 2 mA/m^2. To reach maximal current density the electric field would have to be 7.2 kV/m. Similarly, referential value for magnetic flux density 100 µT results to current density 0.82 mA/m^2, hence the magnetic flux density can reach up to 245 µT. The value of current density is given by magnetic and electric parts. Therefore the values 7.2 kV/m and 245 µT are usable only for cases where one of the fields is equal zero or can be neglected.

The hygienic limits impose boundaries for laying of the cables. The author designs the heights in which magnetic flux density are investigated: 0.2 m, 1 m and 1.5 m. The lowest value 0.2 m was specified for general public – persons with central nervous system positioned close to the ground (e.g. playing children), when the cables are laid down in publicly accessible areas. Therefore the measurement of magnetic field should be done in height of 20 cm and higher. According to the hygienic limits, referential value 100 µT should be kept. This value can be exceeded without violating limits for maximal current density.

3. The Possibilities of Magnetic Fields Reduction

The laying depth of the cable is given among others conditions, e.g. soil mechanical and thermal properties, also by limits of magnetic and electric fields. The electric field strength at the ground surface in case of cable placed under ground is limited and can be neglected. There are five possibilities to reduce magnetic fields:

- increase the depth of the cable trench,
- increase distance between cables,
- installation of ferromagnetic or conductive plates or loops,
- screen connection of cables' shields,
- phase sequence selection of cables.

It is not feasible to lay the cables in deep trenches for economic and technical reasons. The shielding connection and configuration of cables have to be studied as suitable approaches to decrease magnitude of fields.

For long AC cables symmetrical cross-bonding connection of the screen is typically used. That means that cables' sheath are cyclically interrupted and screens are crossed in cable sections of the same length. In case the cable is operated at the nominal values, the current flows in the cable screen do not exceed 20 or 30 amperes. Magnetic fields are not reduced in this case and reach higher values than in the case of screens grounded at both ends of cables without cross-bonding, where the induced current in sheaths reaches approx. 40 % of core currents. However, since high screen currents lead to higher losses and reduced ampacity of the cable, symmetrical cross-bonding is the typical connection and it is used in the study case in following section.

Another way to reduce magnetic field is to set the sequence of phases in an optimal way. In case of one group of cables (L1 L2 L3) there is only one curve of magnetic flux density and the phase sequence has no influence on the curve. The situation differs completely when more cables per phase are used, which is studied in the following chapter.

4. Simulation

The goal of the simulation was to investigate limits and issues of full substitution of EHV overhead lines by cables with focus on hygienic limits for magnetic flux density and electric field strength, especially the impact of selection of phase sequence. Two cases were studied, a situation of cable line with two cable groups and case of doubled cable line (4 cable groups in total) with outage of one cable group of the EHV line.

The worst case scenario – limits for general public and central nervous system – is studied in both cases. As mentioned earlier, electric field strength on the ground surface level is negligible and therefore is neglected.

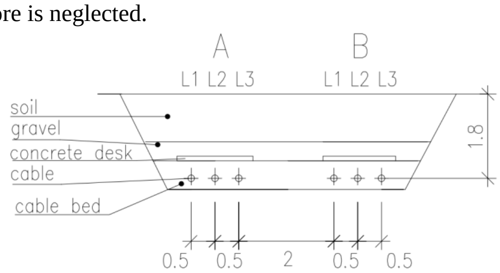

Fig. 1. The cable distribution in the trench

EHV cables carrying nominal current 1250 A with symmetrical cross-bonding is used in the study. The earth-cables which are able to reduce the magnetic flux density surrounding the cables by factor 0.7 to 0.9 (depending on position of cables) are not installed. Trenches were made by digging; their depth was determined in previous studies [2, 3, 7] and is 1.8 m. Simulation deals only with cables in the trench; transitions cable-overhead line or ground-air are not considered. The scheme of the trench and cable distribution there can be seen in Fig. 1.

The design of simulations and determination of their parameters were done by the main author. The simulations were processed by the program EMTP-ATP in company EGU - HV LABORATORY.

4.1. Phase Sequence Selection

The first case is focused on the situation with two cable groups; distances between cables are 0.5-0.5-2-0.5-0.5 m. For two cables per phase 6 basic combinations with different magnetic curves can be drafted, as shown in Tab. 2.

Table 2. Variations of phases

Phases	
123 - 123	123 – 132
123 - 312	123 – 213
123 - 231	123 - 321

The combinations which are mixing up the groups (e.g. 121-323) are not mentioned, as such designs lead to even higher values of magnetic flux density and hence there is no need to investigate them.

The resulting maximal values of induced current density and magnetic flux density for each combination are given in Tab. 3 where the best values were obtained for combination L1-L2-L3---L2-L1-L3. However, study by EGU – HV LABORATORY [7] showed that magnetic flux density would rise more rapidly at ground-air transition. Therefore the best combination is: L1-L2-L3---L1-L2-L3 which provides better results for transitions while maintaining comparable values for underground sections.

Curves of magnetic flux density at different height are presented in Fig. 2 for the best solution given by combination L1-L2-L3---L1-L2-L3 and in Fig. 3 for the worst solution for sequence L1-L2-L3---L3-L2-L1. The eminent influence of the phase sequence combination on magnetic flux density can be clearly observed in Fig. 4, where the best solution provides decrease of maximal value of magnetic flux density from 65 µT to 49.6 µT, compared to the worst solution. The comparison between both curves shows different shape of the curves as well.

Table 3. Maximal magnetic flux density at height 0.2 m up to ground and corresponding current density

Phases configuration	$\lvert B_{rms} \rvert$, (µT)	J_{rms}, (mA/m^2)
L1-L2-L3---L1-L2-L3	49.6	0.40
L1-L2-L3---L2-L3-L1	56.9	0.46
L1-L2-L3---L3-L1-L2	57.8	0.47
L1-L2-L3---L1-L3-L2	49.6	0.40
L1-L2-L3---L3-L2-L1	65	0.53
L1-L2-L3---L2-L1-L3	48.7	0.40

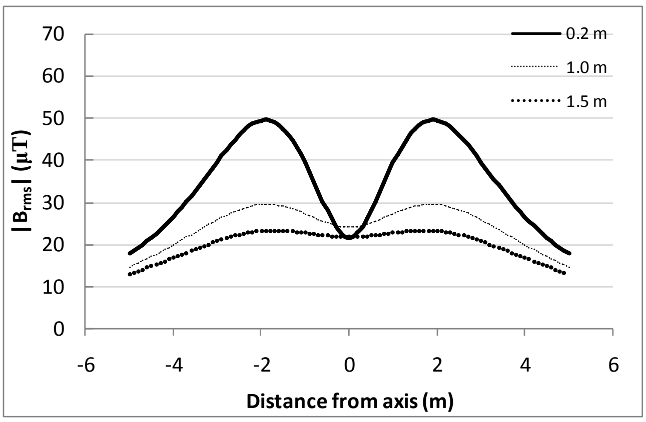

Fig. 2. Magnetic flux density distribution for the best combination

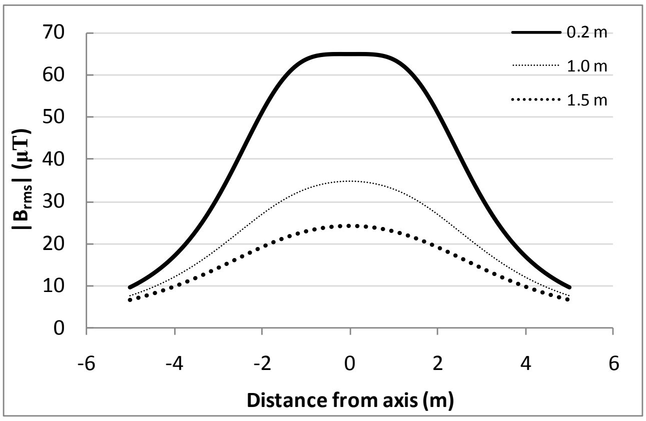

Fig. 3. Magnetic flux density distribution for the worst combination

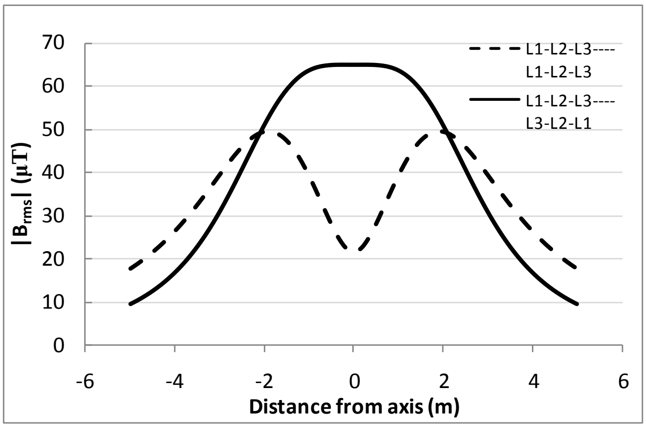

Fig. 4. Magnetic flux density distribution for the best and the worst combination at 0.2 m

4.2. The Cable Set Outage of EHV line

The design with four parallel cables per phase (each carrying current 1250 A) was simulated in order to demonstrate solution which maintains the transmission capacity of a replaced overhead corridor. The influence of outage of one of the inner cable sets of the corridor on magnetic flux density was investigated. Distances between cables are 0.5-0.5-2-0.5-0.5-9-0.5-0.5-2-0.5-0.5 m; phase sequence is L1-L2-L3---L1-L2-L3 L1-L2-L3---L1-L2-L3.

The resulting curves for normal operation and outage of one of the inner cable sets are shown in Fig. 5 and Fig. 6, respectively. The results show that the outage of one set of cables does not lead to increase of magnetic field density as in case of non-optimal phase sequence selection. Authors confirmed that this conclusion is also valid for outage of outer cable sets.

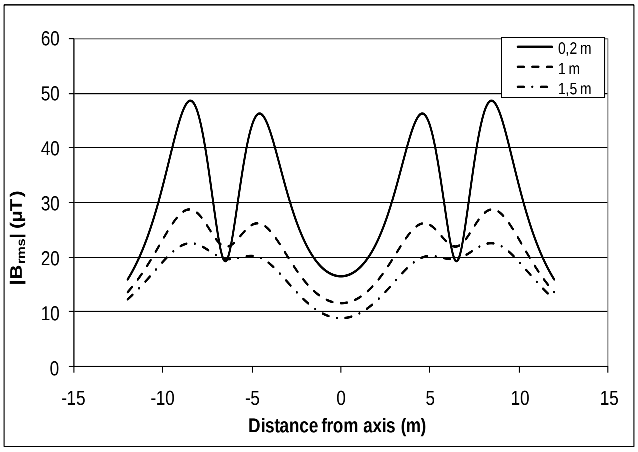

Fig. 5. Distribution of magnetic flux density for normal operation

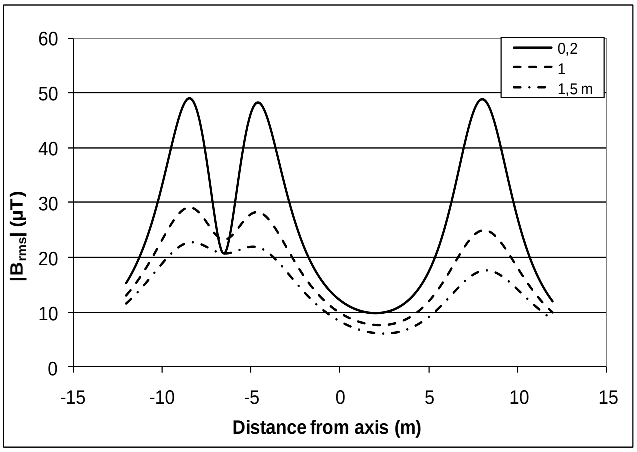

Fig. 6. Distribution of magnetic flux density with outage of one cable group

5. Conclusion

The article deals with hygienic standard for magnetic and electric fields and modified induced current density according to regulation of the Czech Republic no. 1/2008 col. and studies the influence of phase sequence on maximal magnetic flux density as well as the influence of outage of one of the cable sets for designs with multiple cables per phase.

The usage of EHV cables is still rare (0.5% of total EHV circuits length), especially due to high costs. Usage of cross-bonding for cable shield has no impact on magnetic flux density; deep trenches are not feasible for technical and economic reasons. Therefore the possibilities to reduce magnitude of magnetic field in the surroundings of the cable are limited to installation of earth-cables, ferromagnetic plates and to optimization of phase sequence (especially for installations with more than one cable per phase).

Magnetic flux density at height 0.2 m above ground (the height selected for public areas with public laying on the ground as the worst scenario from hygienic limits point of view) around cable line 2x1250 A (two cables per phase, 1250 A each) laid in depth 1.8 m was simulated for all reasonable phase sequences. Simulation results and further discussion suggest that the recommended phase sequence layout is L1-L2-L3---L1-L2-L3.

Magnetic flux density above cable line 4x1250 A (two cables per phase, 1250 A each, doubled cable line) laid in the same depth was simulated in case of outage of one of the cable groups for the best phase sequence L1-L2-L3---L1-L2-L3 L1-L2-L3---L1-L2-L3. The simulation results and further discussion suggest that the outage of one cable group has no negative impact on magnetic flux density from hygienic limits point of view.

Regulation sets limits for induced current density and referential values for electric and magnetic fields. Further investigation suggests some room for flexibility, especially while taking into account negligible electrical field's strength outside underground cables. Worst-case scenario for publically accessible area (current density limited to 2 mA/m^2 at all time) was studied.

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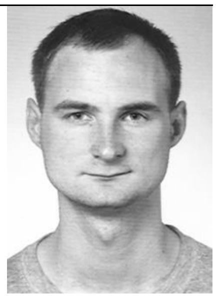
M.Sc. Martin Belatka
e-mail: xbelat01@stud.feec.vutbr.cz

Martin Belatka (1982) received his M.Sc. in Electrical Power Engineering from Brno University of Technology in 2006. He is Ph.D. student at the same university. He currently works for the Czech Transmission System Operator as a Specialist of Transmission System Network. His main fields of interest are overhead and cable transmission lines.

Ph.D. Martin Paar
e-mail: paar@feec.vutbr.cz



Martin Paar (1980) received his M.Sc. and Ph.D. in Electrical Power Engineering from Brno University of Technology in 2005 and 2009, respectively. He is currently an assistant professor at the same university. His main fields of interest are analysis, reliability and optimization of distribution network.

B.Sc. Przemyslaw Chodura
e-mail: p.chodura@student.tue.nl

Przemysław Chodura (1989) is a M.Sc. student of Sustainable Energy Technology at Eindhoven University of Technology since 2012. He obtained bachelor's degree in Power Electrical and Electronic Engineering at Brno University of Technology in 2012 and bachelor's degree in Marketing and Management at Silesian University in Opava in 2014. His research focuses on power transmission using HVDC technology.

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