ENVIRONMENTAL IMPACT OF LOW FREQUENCY ELECTROMAGNETIC FIELDS PRODUCED BY ELECTRIC POWER INSTALLATIONS

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***Abstract**: Low frequency fields produced by electric power installations are unavoidable and they occur in the neighbourhood of any of them. The preponderance of one of the component (electric or magnetic) depends on the operation regime of installation. The field level assessment could be performed by mean of calculus and measurements. The effects of these fields to other installations could be also determinate and many of reducing methods "at source" or at potential "victim" (shielding methods) are now known as classical. Unfortunately the effects on living being are not yet precisely evaluated. On this subject more knowledge is available for particular cases, generally for high level of field strengths. National and international standards recommend certain limits for human exposure and stipulate, with more or less rigorousness, procedures for exposure limits evaluation. The paper describes the particularities of low frequency fields produced by electric power installations and comments the measuring procedures used to verify the compliance with exposure limits proposed by European directives or recommendations. Also, the power frequency magnetic field strength nearby soil under bus bars in a typical Romanian substation was computed and influence of superposed bus bars systems was estimated.*

Keywords: electric power installation, low frequency field, public exposure, professional exposure.

1. Introduction

Power industry constitutes an important source of pollution for the environment. The most known and visible effects are due to emissions produced by fossil fuels burning. An invisible and chemical undetectable component of pollution and therefore long time ignored is the electromagnetic one.

Operating of any electric power installation is carried out by occurrence and persistence of electric and magnetic fields with operative (intentional) role and it is unavoidable associated with non-intentional field emissions. In the case of a.c. installations, the emitted fields have also sinusoidal components, depending on power frequency variation in time. These radiated emissions represent a source of electromagnetic pollution for environment.

The overhead lines and air insulated substations are responsible for occurrence of power frequency electric field due to applied voltage and having as

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sources the electrical charges existent on conductors. Consequently these fields occur even if the lines are in open-end operation regime. In case that the line is loaded it will occur variable magnetic fields beside the electric field.

At power frequency, only the currents through conductors represent sources for magnetic field, the component due to electric field variation being negligible. Cables with conductive shields or buried cables produce only magnetic fields: in this case the cable screen or the earth shields the electric field.

For conductive structures (including living being which can be considered, as a rule, electrolyte solutions) the electric field represent a source of current, while the variable magnetic field acts as a source of voltage. In both cases the final effect of exposure in these fields is the occurrence of currents in the circuits of other neighboring installations or living beings. Then, the fields produced by electric power installations can disturb the operation of other equipment and constitute a potential threat for human or other living being health.

2. Characteristics of low frequency fields produced by electric power installations

In the previous chapter were highlighted the differences (referring to their sources) between low frequency electric and magnetic fields. The features of these fields depend essentially on equipment or installation type: triphase line (single or double circuit), monophase line (as example, for electrical traction), substation, transformer, etc. Present paper refers only at power frequency fields produced in the vicinity of a.c. installations. As it is well known at power frequency the two fields can be calculate separately, no interactions between them occur due to cuasistationary regime.

In order to calculate the electric field produced by overhead lines, there are applied methods known from electrostatics. In this case the presence of conductive soil is eliminated by introduction of the real conductor's images related to earth surface. Then the medium is homogenized and the direct method can be applied: in one point the field is the result of charges existing on real conductors and on their images related to surface of soil too.

Magnetic field calculation is carrying out neglecting the influence of soil because it has no magnetic properties. In fact, in this case, the soil reaction as a shield is neglected, because the penetration depth at power frequency is very large (about 700 m, for a soil with a conductivity of about 100 Ωm). Consequently, the power frequency magnetic field produced by an overhead line is calculated considering only the currents through line conductors and superposing their effects. In the case of cables with shields or conductive sheds the induced currents in these structures most be taken into consideration (these currents depend of material characteristics of shields and their end connexions to earth). The shield-induced current always diminishes the surrounding magnetic field strength of the cable.

To calculate power frequency fields produced by electric lines, usually are accepted the hypotheses that permit to solve the field problem such as plan-parallel one: the line is straight, infinitely long, located in an isotropic dielectric medium, distances between conductors and soil being constant and very large comparing to conductor's radius. In this case, the characteristics of field are the same in identical coordinate points located in parallel planes and all of these plans being perpendicular to long axis of line. A very rigorously approach, if it is justified, must consider non-homogeneities or discontinuities along the line. As an example, for overhead lines in vicinity of tower the fields are non-homogeneous, and in the span of line, the values of strengths are different because of sag of conductors.

In case of the triphase line, both electric and magnetic fields are, in perpendicular planes to the line, rotating fields (located in perpendicular planes to the line). This means that a rotating resultant vector describe an ellipse (the field have elliptical polarization) during a power frequency voltage or current cycle. In particular points located in the plane perpendicular to the line, the ellipse can degenerate to a circle or a straight line. The variation of the direction and the modulus of resultant field are due to the sinusoidal variation of quantities that represents the sources (electrical charges or currents) and the phase difference between them, considering all wires of system. The rotating sense of vector depends of system succession. Characteristic values of elliptic vector modulus (maximum and minimum) depend of observation point related to line, of phase's disposal and the magnitude of source quantities (voltage or current). The slope of ellipse axes is dependent only of the considered position of the point (position) in the plane perpendicular to line. In case of the overhead lines with nominal voltage greater than 110 kV, nearby the earth and due to relative large suspension distances involved, the field receives some interesting features which are taken into consideration for human exposure. Then, electric field becomes almost homogeneous and the significant component is the vertical one. Moreover, for distances between 0 m and 2 m no significant differences occur between field strengths. Monophase traction lines generate electric and magnetic fields with linear polarization (in a certain point, the field strength vector vary along a straight line with invariable direction in time).

Power frequency fields are generally difficult to be calculated in substations, because of their complex geometry and different parameters of equipments in operation. Under bus bars and far away from other primary circuits equipment, when their influence can be neglected, the field strength can be more simply calculate, if there are known the distances to earth of different bus bars and between the phases and also the system sequence and the sources parameters (voltages and currents).

Regarding low frequency fields produced by a triphase system in close proximity of soil it is well-known that a horizontal plane configuration is most disadvantageous. For substations this is the single adopted solution.

The instantaneous value of field strength vector, in a point M is given by following equation:

$$\overline{H}(M,t)=\overline{H}_{\mathrm{A}}(M,t)+\overline{H}_{\mathrm{B}}(M,t)+\overline{H}_{\mathrm{C}}(M,t)=\sqrt{2}I\ [\bar{e}_{\mathrm{A}}k_{\mathrm{A}}\sin\omega t+ \\ +\bar{e}_{\mathrm{B}}k_{\mathrm{B}}\sin(\omega t-2\pi/3)+\bar{e}_{\mathrm{C}}k_{\mathrm{C}}\sin(\omega t-4\pi/3)] \tag{1}$$

where $\bar{e}_A$, $\bar{e}_B$, $\bar{e}_C$ are versors of the three directions of field components due to each phase, and $k_{\mathrm{A}}, k_{\mathrm{B}}, k_{\mathrm{C}}$ are numerical coefficient reflecting the distance between source (phase conductor) and observation point, I – r.m.s. value of current and $H_{\mathrm{A}}, H_{\mathrm{B}}, H_{\mathrm{C}}$ – field strength due to each phase of system.

The resultant (three-dimensional/isotropic) r.m.s. value is determined performing an operation such as:

$$H_{\mathrm{res}}=\sqrt{H_x^2+H_y^2+H_z^2}\ , \tag{2}$$

where H_{x}, H_{y}, H_{z} are respective the r.m.s. values after each axis.

The computations performed for magnetic field strength, using the most frequently used clearances between phases and earth in Romanian substations drives to the following conclusions:

– the greatest values of magnetic field strength occur (for the same currents flowing in bus bars and for all their possible configurations) in substations with lowest nominal voltages because of reduced distances to the soil;
– for all voltage levels the greatest values was recorded under conductors sustained by equipment terminals;
– due to plane bus bars configurations (and without influences of another sources of current or conductive elements), the maximal values was recorded under mid-phase;
– for perpendicular crossings, the value of magnetic field strength near soil is practically given by inferior plane of bus bars.

For air insulated substations with nominal voltage up to 400 kV, using the notations in figure 1, respectively BB1 – plane of connexions sustained by equipment terminals (circuit breaker, disconnector etc.), BB2 – inferior bus bars plane and BB3 – superior (over crossing) bus bars plane, and considering the following conditions:

– aligned parallel configurations of over crossing bus bars systems and with the same distances between phases;
– identical r.m.s. values of currents through bus bars systems;
– the field strength values given by inferior system of bus bars (BB1 or BB2) represent the reference for comparison,

the calculated magnetic field strength at 1 m above the soil, compared to reference level is influenced by the superior bus bars system as follows:

- in case that only BB1 and BB2 bus bars planes exist and system sequence is identical, the presence of superior bus bars plane increase the field level at average values greater with about 17%, comparing to reference (field given only by BB1);
- in case that only BB2 and BB3 bus bars planes exist, the superior bus bars system increase the maximum values of field strength (comparing to reference, i.e. field given only by BB2) with about 45 %. The absolute field strength values reach to value that not exceeds 30% comparing to that given by only BB1 system.
- the transposition of phases for superior system reduces the field level at average values smaller with about 15 % comparing to reference levels if first (BB1 and BB2) bus bars systems exist and with about 40 % in the case of BB2 and BB3 systems.

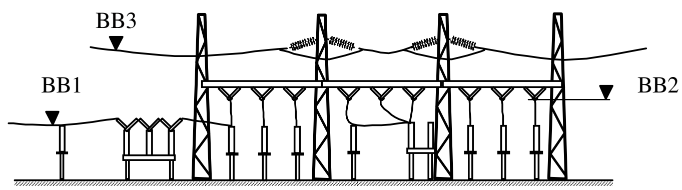

Fig. 1. Notations used to specify results of magnetic field computation in a substation: BB1 – the triphase connexions system sustained by equipment terminals; BB2 – the inferior bus bars system; BB3 – the superior bus bars system.

The reference values (computed considering only inferior system of bus bars in operation) are presented in Table 1.

Table 1

The computed maximal values (under mid-phase bus bars, at 1 m above soil) of magnetic field strength and magnetic flux density in a typical Romanian substation

U_n [kV]	Reference bus bars system	H [A/m/1kA]	B [μT/1kA]
110	BB1	67.0	53.2
	BB2	12.7	10.1
220	BB1	47.2	37.5
	BB2	10.2	8.1
400	BB1	35.3	28.0
	BB2	5.3	4.2

Because the voltages have variations in a limited range, the electric field strength under bus bars in an air insulated substation has also limited variations. Taking into consideration only the bus bar crossing which have the same voltage and situated perpendicular each to other, the results compared with strength field values given by inferior plane of bus bars (as reference) are [1] the following:

- larger values with about 20 % comparing to reference case, if the superior phase has the same name as the inferior one, below the field is estimated;
- smaller values with about 20 % comparing to reference case, if the superior phase has a different name as inferior one, below the field is estimated;

Measurements performed in a 400 kV Romanian substation point out that electric field strength does not excced 9 kV/m and remains under 2.7 kV/m in a substation having 110 kV nominal voltage. All these measurements were performed at 1 m above soil and in the middle of acces paths. For 400 kV, these values are slightly superior of those measured under overhead lines having the same voltage.

Fields strength could be performed in all above described cases using simplified hypothesis in order to facilitate calculation without adding unacceptable errors. The actual values of fields are still affected by a multitude of local conditions: the presence of conductive objects (including vegetation or soil irregularities) affects the values of electric field, while objects with magnetic and/or conductive properties influence the value of magnetic field.

3. Human exposure limits at low frequency electromagnetic fields

European Community members have, at the present time, recommendations regarding human exposure limits, without negative consequences to health, of significant parameters of electromagnetic fields with frequencies between 0 Hz and 300 GHz. There were elaborated different particular documents regarding public exposure and professional exposure. 2004/40/EC Parliament and European Council Directive [2] stipulate minimum requirements relating to professional exposure. These requirements become mandatory for Community members starting with 2008. This document stipulates the accepted limit values of electric and magnetic field strength, corresponding of specified frequencies ranges. Measures must be taken when these limits will exceed. It is also specified that these values were adopted considering only acute short-term effects scientifically proved. These limits are based on ICNIRP 7/99 Publication recommendations (ICNIRP – International Commission on Non-Ionizing Radiation Protection). Long-term exposure limits were not taken into consideration. Consequently, no limits of exposure time were attached to field strength limits.

Regarding public exposure, the limit values are specified in European Council 1999/519/EC Recommendation [3]. Accepted exposure limits at power frequency electric and magnetic field for two categories of individuals are presented in Table no.2. These values are based on admissible current densities (called "basic restrictions") in the head and trunk of human body at maximum values of $10mA/m^2$ for professional exposure and $2mA/m^2$ for public exposure.

"Basic restrictions" have attached measurable field parameters called "reference levels". If reference levels are not exceeded basic restrictions will be achieved.

1999/519/EC Recommendation specifies that possible long term (cumulative) effects were considered because a prudent security factor of 50 was adopted related to levels that produce acute effects.

Table 2

Exposure limits at power frequency fields stipulated by European directives or recommendations

Directive/ Recommendation	What regulate	Admissible limit of magnetic flux density, in air	Admissible limit of electric field strength, in air
2004/40/EC	Professional exposure	0.5 mT	10 kV/m
1999/519/EC	Public exposure	0.1 mT	5 kV/m

Regarding professional exposure, 2004/40/EC Directive specifies also limit values (based on current density as reference level) and measurable quantities – values that impose measures to be taken. The considerations concerning compliance with current density limits by mean of measurable parameters remain valid also for this case. But the compliance with the limits doesn't guarantee the lack of electromagnetic interferences or other effects to some prosthesis or metallic implants, pacemakers etc.

European regulations regarding exposure limits for individuals are very useful but measuring procedures, processing and interpretation of results are not specified within them. Because these electromagnetic fields are variable in time and space, some specifications are necessary, such as: number of measuring points and theirs space disposal, requirement regarding accuracy of measuring equipment, acceptable atmospheric conditions, results processing procedure if short time variations are recorded. All of these specifications are necessary in order to avoid inadequate interpretations.

At present time, at least for public exposure level evaluation the recommendations of standard draft IEC 62110 (106/108/CDV) – "Measurement procedures of electric and magnetic field levels generated by AC power systems with regard to human exposure" [4] can be applied. In conformity with this document, the exposure level represents the space average of field values along entire human body of an individual (positioned in the field) and the "maximum exposure limit" is the maximum level of these averages. In the case of non-homogeneous fields, the field level must be measured at three distances above soil level (0,5 m, 1 m and 1,5 m) or, inside buildings, above floor level. The exposure level will be the average of these three measurements. To compare with limits specified in [3] maximum exposure limit must be used.

Standard draft considers that an overall uncertainty (due to equipment, measuring procedure, atmospheric conditions etc.) of 10 % is acceptable. But even measuring equipment is adequate [5], the results can be seriously affected if atmospheric conditions are unfavorable (i.e. high humidity) or the operator does not respect the requirements of procedure. As an example, a measurement of electric field performed holding in hand the field probe or disposing it in a close proximity of operator will be seriously affected because conductive human body will distort the field. Also, the same type of measurements performed in high humidity conditions (greater than 60 %) will be affected by large positive errors increasing with relative humidity: these errors can reach even 500 % for a relative humidity of 90 % [6].

4. Conclusions

Power frequency electric and magnetic fields generate by electric power installations represent for the environment electromagnetic disturbances that must be limited. The mitigation methods are necessary in order to avoid interferences in surrounding weak current equipment and also unacceptable exposure of living being. Measuring procedures used to evaluate human exposure at low frequency field are defined but their application and processing of results are still not rigorously specified mainly in the case of standards that impose single exposure limits. The consequences could be an interpretation of measuring results in order to satisfy the interest of involved part: owner of source of field or organisation that represents the individuals. It is necessary that up to moment when requirements regarding professional exposure being mandatory a common procedure for measuring to be adopted for all factors involved in producing, transport and distribution of electric energy. On the other hand, the criterion of admissible limits of low frequency field strength must be considered even in the design phase.

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