

GUIDELINES FOR DETERMINATION AND EVALUATION OF LOW-FREQUENCY ELECTROMAGNETIC FIELDS OF HIGH-VOLTAGE POWER STATIONS

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Abstract: Enforcement of Directive 40/2004/EC binds the EU member countries to define their legislative proceedings on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields).

In this paper guidelines for determination and evaluation of low-frequency electromagnetic fields of high-voltage power stations are proposed. They are based on experiences gained with numerical calculations and measurements and are compliant with measurement practices and demands of international labor conventions and EU Directives.

Keywords: EM fields, Low-Frequency, Power Stations

1. INTRODUCTION

Presently applicable standards and technical recommendations give more or less general approaches to evaluation of electromagnetic field strength values regarding to exposure limit values for various environments. But none of them contains any particular method for determination of low-frequency electromagnetic fields of high-voltage power stations.

It is important to emphasize that employers must ensure investigations of electromagnetic fields inside their working areas at regular time intervals defined in articles 7 and 11 of *Directive 89/391/EEC*. The maximum time between two successive investigations is three years.

Since the most important element of these investigations are very complex measurements, measurement principles must be duly considered. Performing measurements is a highly demanding task involving knowledge of all influential parameters.

The most important is understanding of the measurement system. Assuring the possibility to repeat measurements in order to obtain the reproducible results of electromagnetic fields is also a prerequisite.

2. INVESTIGATION OF ELECTROMAGNETIC FIELDS INSIDE SWITCH YARDS

As foreseen by article 4 of *Directive 2004/40/EC* [2], employers must assure that the levels of electromagnetic fields to which workers are exposed are assessed and whenever applicable measured and/or calculated.

So far, there are no harmonised European standards available by CENELEC, covering the necessary assessments, measurements or calculations of electromagnetic fields to which workers are exposed.

As a result employers who are bound by the law to protect their workers from electromagnetic field effects are obliged to assure investigations on a scientifically confirmed basis.

In order to perform investigations of electromagnetic fields inside a power station, the next four approaches can be applied:

- measurements,
- calculations,
- assessment on the basis of emission levels provided by the equipment manufacturers, and
- combination of measurements and calculations.

In the following paragraphs, practical examples of the investigations are given.

2.1 Electromagnetic field measurements

Measurements inside aerial distributions power stations were made on the basis of our practical and theoretical experiences. Electromagnetic field measurements were conducted at 1 m above the ground level. The instrument used for this purpose met specifications of IEEE Std. 644 – 1994 standard [4].

Measured values reflect the actual power station operating state at the time of our measurements. It should be noted that these values don't define maximum possible exposure to electromagnetic fields in the working area.

Measurements themselves show conditions at a particular operating state of an investigated power station. In absence of case studies and if values of voltages and currents in a particular measurement period are not known, it is

impossible to thoroughly evaluate the electromagnetic field strength.

When investigating the electromagnetic field strength inside a power station with measurements, the following should be considered:

- measurement points should be selected at locations where the field strength is expected to be the highest,
- it is advisable to conduct measurements at locations where work inside power stations is likely to be performed,
- to avoid a systematic measurement error, it is advisable to pay attention to the micro location of the E – field and B – field sensor. Movement of the sensor for a few decimetres may change the electric or magnetic field values by more than 15%,
- the presence of the person performing the measurement should not affect the accuracy of the measured electric field strength by more than 3%.

In the following example, typical measured values of E – and B – field inside Slovenian aerial type distribution power stations are given as an example.

Minimum and maximum values of the electric field strength and magnetic flux density measured for 38% of the Slovenian distribution power stations are shown in Tables 1 and 2.

Table 1. Measured values of the electric field strength in Slovenian aerial type distribution power stations

| HV device | Measured values of E [V/m] | | |
|-----------------------|------------------------------|-------|---------|
| | Min | Max | Average |
| Disconnecter | 757 | 3.571 | 1.760 |
| Circuit-breaker | 307 | 4.303 | 1.498 |
| Current transformer | 535 | 4.767 | 806 |
| Voltage transformer | 401 | 4.542 | 858 |
| Local control cubicle | 390 | 3.563 | 1.167 |

Table 2. Measured values of the magnetic flux density in Slovenian aerial type distribution power stations

| HV device | Measured values of B [μ T] | | |
|-----------------------|-----------------------------------|-------|---------|
| | Min | Max | Average |
| Disconnecter | 0,78 | 15,01 | 4,21 |
| Circuit-breaker | 0,59 | 19,48 | 4,10 |
| Current transformer | 1,29 | 24,18 | 7,32 |
| Voltage transformer | 1,30 | 106,6 | 30,13 |
| Local control cubicle | 0,33 | 8,71 | 3,76 |

2.2 Calculation of the electromagnetic field

When an investigation of the electromagnetic field inside a power station is decided to be calculated, it is recommended to make a model containing elements affecting electric or magnetic field.

It is important to emphasize that calculated values of magnetic fields may significantly exceed operational values, especially in cases when the electromagnetic model does not reflect actual operational conditions or involve all relevant details.

Low-frequency electric and magnetic fields can be modelled using Maxwell equations. When analyzing complex structures, characteristic for real conditions, such models become extremely complicated and can only be solved using numerical methods.

When properties of installed equipment and materials, extensiveness of high-voltage power substation areas and goal of field assessment are to be taken into account, detailed numerical calculations often become too complex to be practically solved.

Knowing that assessment has to be made in areas where humans can be present and that the distance of these areas from field sources is always much greater than the conductor diameter, we can use a simplified calculation approach.

The basic idea is to model all devices with short conductors or segments tangentially fitted to the actual direction of conductors. The denser sectioning of each conductor provides more accurate calculation results. Nevertheless, it should not be forgotten that simplifying the usually complex electromagnetic structures leads to computation errors in the vicinity of electric and magnetic field sources.

The accuracy of the numerical tool used for modelling was analysed in a validation process conducted on simplified electromagnetic structures. Our analysis of the electromagnetic field design tool was made on a 400 kV power line and inside different types of 110 kV and 400 kV switchyards [3].

We developed an electromagnetic calculation model with which we investigated the highest theoretically possible electromagnetic field values of low-frequency electromagnetic fields for an aerial type of high-voltage power station. Our model was made on the basis of data from the design documentation (Figure 1).

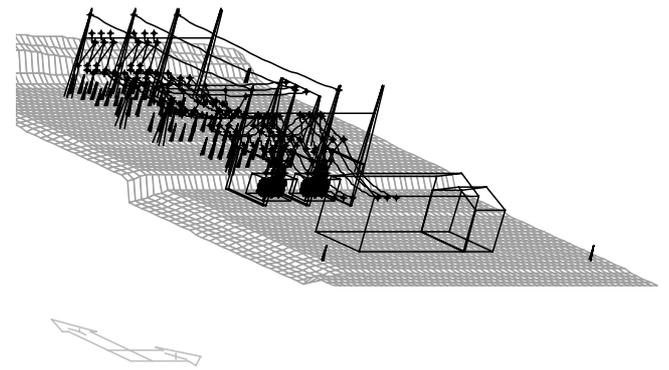


Figure 1. Electromagnetic calculation model of an aerial type of high-voltage power stations

Shown model consists of large number of short conductors, which are used for description of actual conductors and grounded poles in the switchyard.

In the model the following conditions should be satisfied:

- each conductor should be modelled separately,
- dividing conductors into segments shouldn't exceed eight segments when calculating the electric field strength in order to limit the time needed for determination of electric charges on each segment,
- high-voltage equipment should consist of an appropriate number of short conductors and conductive or ferromagnetic materials,
- distance between calculating points should be between 0,5 m and 1 m inside an aerial power station. A smaller distance may extend the calculation time beyond an acceptable limit without any useful effect.

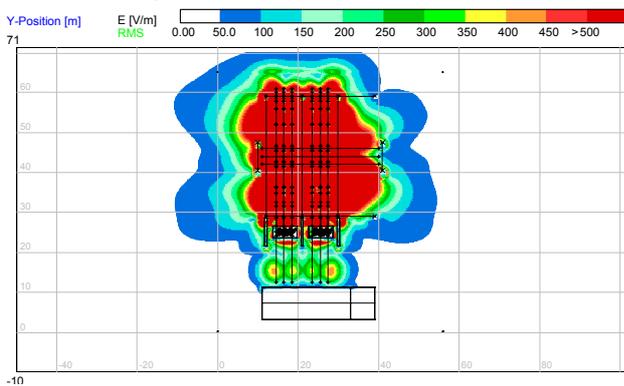


Figure 2. Calculated E – field values for an aerial type of high-voltage power station

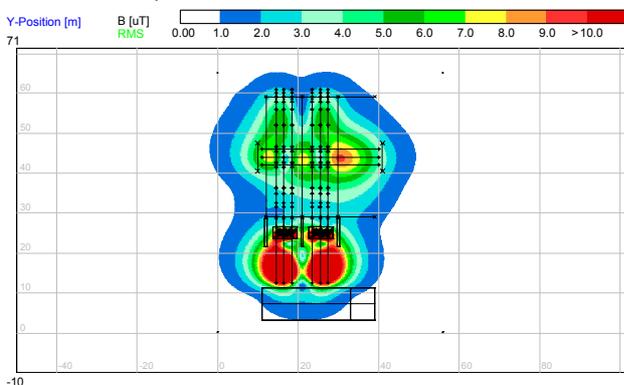


Figure 3. Calculated B – field values for an aerial type of high-voltage power station

2.3 Assessment on the basis of emission levels

Emission levels provided by the equipment manufacturer usually gives electromagnetic field values for specific individual equipment. It is well known that the major influence on combined E – field and B – field values is caused by connections of equipment into the network.

Therefore emission levels of the individual high-voltage equipment are not suitable for electromagnetic field assessments of complete power substations.

Those levels can nevertheless be used for assessments of electromagnetic fields caused by typical distribution transformer stations [5], which are met in urban areas (Figure 4).



Figure 4. Typical distribution transformer stations

2.4 Combination of measurements and calculations for the example power substation

In reality it is impossible to load high-voltage devices with their nominal values. Therefore, the model represents a useful tool for case studies allowing evaluation of theoretically possible maximum field strengths.

Computed results also show distribution of the electromagnetic field over the working area. This is very useful information enabling a reasonable reduction of the number of measurement points while providing more reliable results.

The combined approach avoids imperfections of measurements of the electromagnetic fields, which arises from actual power substation operating state and calculations of the electromagnetic fields or from simplifying the real electromagnetic structures in calculations.

Imperfections of the measured and calculated values that are not considering the combined approach are given in Tables 3 and 4.

Table 3. Measured and calculated maximum electric field strength values

| Area | Inside/In the vicinity | E [V/m] | |
|-------------------|------------------------|-----------|------------|
| | | Measured | Calculated |
| 110 kV switchyard | Line switch bay | 3.195 | 3.400 |
| | Transformer switch bay | 2.595 | 2.600 |
| Transformers | Transformer, 20 MVA | 990 | 1.200 |

Table 4. Measured and calculated maximum magnetic flux density values

| Area | Inside/In the vicinity | B [μ T] | |
|-------------------|------------------------|----------------|------------|
| | | Measured | Calculated |
| 110 kV switchyard | Line switch bay | 5,64 | 17 |
| | Transformer switch bay | 3,54 | 8 |
| Transformers | Transformer, 20 MVA | 4,40 | 14 |

Differences between measured and calculated E and B field values are caused because the measurements were performed at real operational state while the calculations were made at nominal operational state of power substation.

Size of calculating area, relevant details of real electromagnetic structure and the density of measurement points should be taken into account in the combined approach. Calculations used in the combined approach of electromagnetic field assessments should take into consideration actual operational state of equipment and conductors in power substations where measurements have been performed.

Measurements of E – field and B – field should be performed in adequate number of measurement points in order to have enough reconstruction points of electromagnetic field. Difference between inadequate and adequate combined approach is shown in the following two examples.

a) Inadequate combined approach

When model does not include enough relevant details and number of reconstruction points is not adequate differences between calculated and measured values are likely to appear.

Calculated values are graphically represented by coloured background while measured values are represented by coloured circles. When colours of the background and circles are the same, calculated values equals measured values. Results of the inadequate combined approach is shown in Figures 5 and 6.

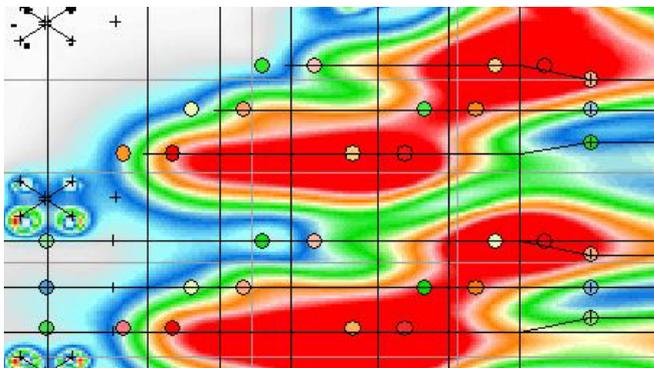


Figure 5. Part of inadequately calculated and measured E – field values

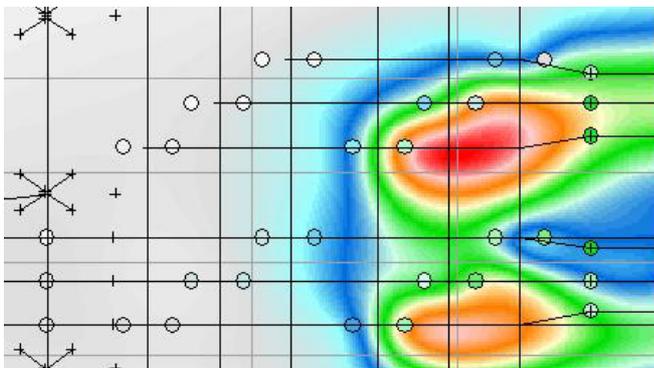


Figure 6. Part of inadequately calculated and measured B – field values

Differences between calculated and measured values of the electric field arises from imperfect calculating model. For example green and orange coloured circles are located under earthed metal construction of disconnector inside the switchyard.

Differences between magnetic field arises from variations of electric current. In the electric power system currents have been represented as average value of currents in the period of 15 minutes. Ironworks in the vicinity consumes major current load of measured power substation.

b) Adequate combined approach

The following example shows adequate combined approach of electromagnetic field assessment.

Investigation of electromagnetic field has been performed in such a way that an electromagnetic model has been build before measurements. Using calculated values measurement points have been defined.

Additional calculations of electric and magnetic filed values have been performed considering actual operational state in the time of measurements.

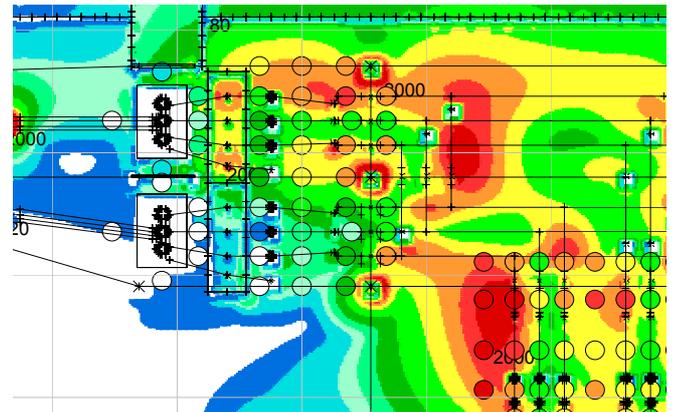


Figure 7. Part of adequately calculated and measured E – field values

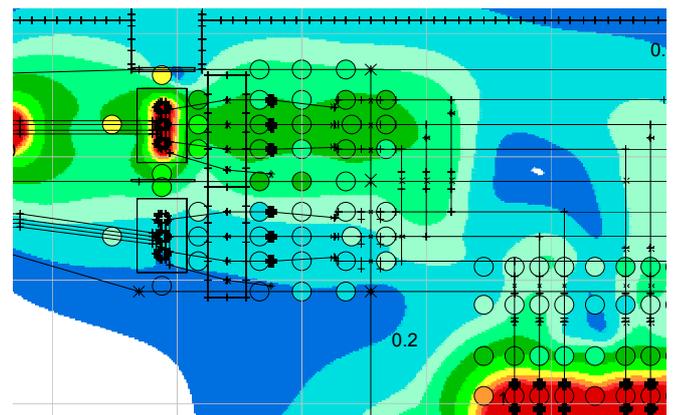


Figure 8. Part of adequately calculated and measured B – field values

Relatively good coincidence of calculated and measured values shown in Figures 7 and 8 gives confidence to use electromagnetic model in case studies necessary in the field investigation process.

3. CONCLUSION

Investigations of electromagnetic fields can be pretentious if their performers don't have sufficient knowledge of characteristics of electromagnetic fields. We therefore recommend making a calculation model for various types of power stations before making measurements in order to assure an appropriate selection of measurement points.

To fulfil requirements of occupational safety legislative acts, we recommend using an approach similar to the one presented above for evaluation of low-frequency electromagnetic fields of high-voltage power stations. Special care should be taken when working areas for different types of work are involved. For example, in the event of service intervention on high-voltage equipment, the electromagnetic field strength inside the working area affects only the neighbouring switch bays. On the other hand, when work is to be performed in the vicinity of operating equipment, it is necessary to take into account the highest possible load foreseen for the equipment installed.

We propose the presented guidelines to serve as a basis for uniformity and simplification of different types of investigations of electromagnetic field strength inside high-voltage power stations achieved at a reasonable cost. This is certainly a sufficiently strong argument to assure continuity of this kind of investigations and to avoid opposition of employers or their associations.

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