GUIDELINES FOR DETERMINATION AND EVALUATION OF LOW–FREQUENCY ELECTROMAGNETIC FIELDS IN WORKING AREAS INSIDE DISTRIBUTION 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).

However, present applicable standards and technical recommendations do not indicate any particular method for determination and evaluation of low–frequency electromagnetic fields in working areas.

In this paper guidelines for determination and evaluation of low–frequency electromagnetic fields in working areas inside distribution power stations are proposed. They are based on experiences gained with research calculations and measurements and are compliable with measurement practice and demands of international labour conventions, EU Directives and Slovenian legislation.

1. INTRODUCTION

As it is well known, discussions about the issues regarding electromagnetic fields have been on for decades worldwide. From the first steps, with which basics of understanding of electromagnetic fields were set up, an enormous progress has been made in the past twenty years.

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

The majority of the related European legislation has found its origin in *Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic, and Electromagnetic Fields (up to 300 GHz)* [1].

The focus of our researches is on electric and magnetic fields inside working areas of distribution power stations dealt with by the *Directive 2004/40/EC* [2].

The basic goal of the *Directive 2004/40/EC* [2] is to lay down minimum requirements for protection of workers from risks to their health and safety arising or likely to arise from exposure to electromagnetic fields (0 Hz to 300 GHz) during their work. Tables 1 and 2 of the annex to the *Directive* define exposure limit values and action values to taken as reference for evaluation of the electromagnetic field strength.

It is important to emphasize that any employer 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 investigations of the kind, whose most important dement are measurements are very complex, measurement principles must be duly considered. Performing measurements is a highly demanding task involving many kinds of knowledge. The most important is the knowledge of the measurement system. Assurance of the possibility of having measurements repeated to obtain the most significant results of electromagnetic fields is also a prerequisite.

Some of the basics ideas pursued in our development of the guidelines for determination and evaluation of low–frequency electromagnetic fields will be present below.

2. THEORETICAL BASICS

Low–frequency electromagnetic fields in linear substances, caused by harmonic changes in distribution of electric charges or currents, will be investigated.

If there are sources of time varying electromagnetic fields, with the angle speed of ω, present in homogeneous substances with linear characteristics, it is expected that all characteristic values of those fields will be changed with the same angle speed.

Analysis of these fields can be made with a model described with Maxwell equations. When analysing complex structures, characteristic for real conditions, complex equations can be met. Solving can be achieved by using numerical methods.

Electromagnetic fields are investigated at a distance much greater than the conductor diameter. Therefore it is possible to model all devices with short conductors or segments tangentially fitted to the actual course of conductors. The denser is the sectioning of each conductor the more precise is the calculation.

2.1 An approach to the calculation of the electric field strength

Our model for the calculation of the electrical field strength consists of two conductive straight segments (see Figure 2.1).

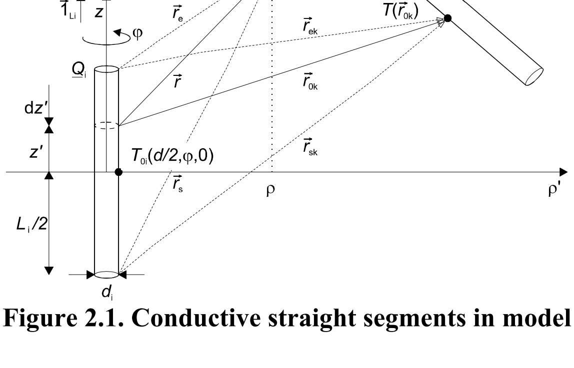

Figure 2.1. Conductive straight segments in model

The electric potential caused by charge $\underline{Q}_i$ in the general point of the model is described as a differential of this potential:

$$\mathrm{d}\underline{V}^{(i)}(T)=\frac{1}{4\pi\varepsilon_0}\frac{\underline{Q}_i}{L_i}\frac{1}{\sqrt{\rho^2+(z-z')^2}}\mathrm{d}z' \qquad 2.1$$

Potential $\underline{V}^{(i)}(T)$ is expressed with integration along the straight line:

$$\underline{V}^{(i)}(T)=\frac{1}{4\pi\varepsilon_0}\frac{\underline{Q}_i}{L_i}\int_{-\frac{L_i}{2}}^{\frac{L_i}{2}}\frac{1}{\sqrt{\rho^2+(z-z')^2}}\mathrm{d}z' = $$
$$=-\frac{1}{4\pi\varepsilon_0}\frac{\underline{Q}_i}{L_i}\ln\left[(z-z')+\sqrt{\rho^2+(z-z')^2}\right]_{-\frac{L_i}{2}}^{\frac{L_i}{2}} = \qquad 2.2$$
$$=\frac{1}{4\pi\varepsilon_0}\frac{\underline{Q}_i}{L_i}\ln\left[\frac{\left(z+\frac{L_i}{2}\right)+\sqrt{\rho^2+\left(z+\frac{L_i}{2}\right)^2}}{\left(z-\frac{L_i}{2}\right)+\sqrt{\rho^2+\left(z-\frac{L_i}{2}\right)^2}}\right].$$

Considering the direction of vector $\vec{1}_{Li}$ and marks in Figure 2.1 expression 2.2 can be derived into:

$$\underline{V}^{(i)}(T)=\frac{1}{4\pi\varepsilon_0}\frac{\underline{Q}_i}{L_i}\ln\left[\frac{\vec{1}_{Li}\cdot\vec{r}_s+|\vec{r}_s|}{\vec{1}_{Li}\cdot\vec{r}_e+|\vec{r}_e|}\right]. \qquad 2.3$$

When point $T=T(\vec{r})$ is moved into point $T_{0i}(d_i/2,\varphi,0)$, which is on the surface of the conductive straight segment with charge $\underline{Q}_i$, it is possible to determine potential contribution $\underline{V}_i^{(i)}$ on the surface of the straight segment as an effect of its own charge.

$$\underline{V}_i^{(i)}=\frac{1}{4\pi\varepsilon_0}\frac{\underline{Q}_i}{L_i}\ln\frac{4L_i}{d_i}. \qquad 2.4$$

If we move now the same point to the surface of another straight segment $T_{0k}=T(\vec{r}_{0k})$, of length L_k, the potential caused by charge $\underline{Q}_i$ in point T_{0k} is expressed as:

$$\underline{V}_k^{(i)}(T_{0k})=\frac{1}{4\pi\varepsilon_0}\frac{\underline{Q}_i}{L_i}\ln\left[\frac{\vec{1}_{Li}\cdot\vec{r}_{sk}+|\vec{r}_{sk}|}{\vec{1}_{Li}\cdot\vec{r}_{ek}+|\vec{r}_{ek}|}\right]. \qquad 2.5$$

For the reason of the mutuality, charge $\underline{Q}_i$ affects on potential $\underline{V}_k^{(i)}$ as charge $\underline{Q}_k$ affects on potential $\underline{V}_i^{(k)}$.

When defining expressions for any potential in the model, it is necessary to consider effects of the conductive ground (Figure 2.2).

When positions of all short conductors and charges on them are known the overall vector of the electric field strength is expressed as:

$$\underline{\vec{E}}(T)=\frac{1}{4\pi\varepsilon_0}\sum_{k=1}^{n}\frac{\underline{Q}_k}{L_k}\left(\frac{\vec{r}_{k+}}{|\vec{r}_{k+}|^3}-\frac{\vec{r}_{k-}}{|\vec{r}_{k-}|^3}\right). \qquad 2.6$$

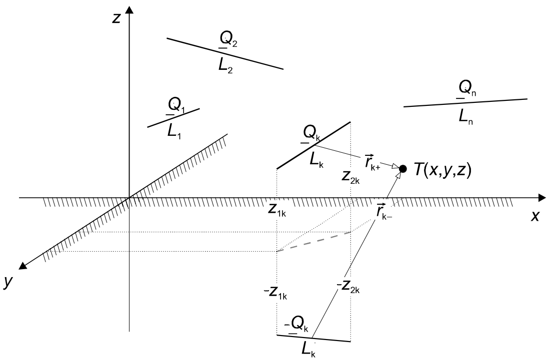

Figure 2.2. Conductive straight segments above the conductive ground

2.2 An approach to the calculation to the magnetic flux density

The shown principle used for expression of the electric field strength above conductive ground takes into consideration the ground effect on overall electric field strength vector. It is important to know if induced currents inside conductive ground have any important effect on overall magnetic field.

To solve this problem, J.R. Carson and F. Pollaczek used the linear conductors method. The solution is in the analysis of magnetic field above the conductive ground and inside it.

Derivation of the related expression would exceed the allowed scope of this paper. What should be noted is that contribution of induced currents in the conductive ground at low–frequency magnetic field is insignificant.

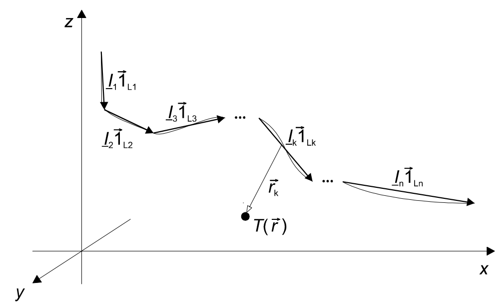

Figure 2.3. Modelling of the conductor with short segments

We can summarize that only currents in the conductors express magnetic flux density. Taking into regard Biot–Savart law, directions of currents and separation of conductor on short conductors (Figure 2.3) is expressed as:

$$\underline{\vec{B}}(T)=\frac{\mu_0}{4\pi}\sum_{k=1}^{n}\underline{I}_k L_k\vec{1}_{Lk}\times\frac{\vec{r}_k}{|\vec{r}_k|^3}. \qquad 2.7$$

3. INVESTIGATION OF ELECTRIC AND MAGNETIC FIELDS INSIDE SWITCHYARDS

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 by CENELEC available covering the necessary assessments, measurements and 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 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.

3.1 Calculation of the electromagnetic field

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

For this purpose example computations are made with commercially available electromagnetic field design tool.

As an example GIS 110/20 kV Power Station is modelled. The electromagnetic model consists of 2.804 short conductors with which all devices inside power station are represented. The following values are used for the currents:

- 110 kV line switch bay: 400 A,
- 110 kV line transformer bay: 210 A,
- Transformer primary core: 210 A,
- Transformer secondary core: 1155 A,
- 20 kV transformer switch bay: 1155 A,
- 20 kV line switch bay: 150 A.

The calculated values of the magnetic flux density are graphically presented in Figure 3.1.

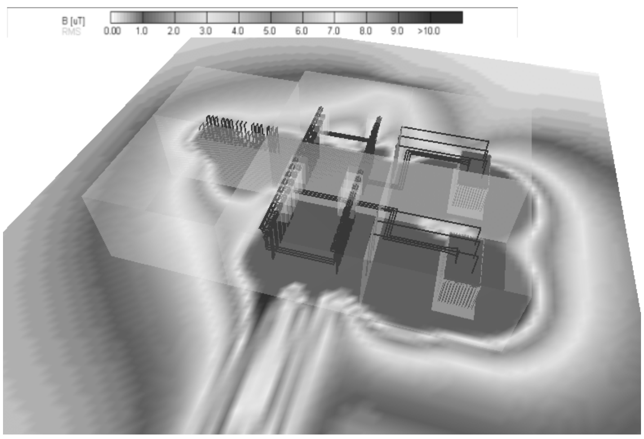

Figure 3.1. Magnetic flux density of a GIS 110/20 kV power station

Estimated values for various working areas are given in Table 3.1.

The accuracy of the tool used for modelling was analysed in a validation process conduced on a simplified electromagnetic structures.

Our analysis of the electromagnetic field design tool was made on a 400 kV power line and inside two different types of 400 kV switchyards [3].

The detected accuracy demonstrates that the difference between the computed and the measured values is some 25% for complex and below 10% for simple electromagnetic structures.

Table 3.1. Estimated maximum values of the magnetic flux density

Area	Next to	*B*
110 kV switchyard	Line switch bay	100 μT
	Transformer switch bay	10 μT
20 kV switchyard	Transformer switch unit	400 μT
	Connecting switch unit	400 μT
	Line switch unit	50 μT
Transformers	Transformer box door	30 μT

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. It is for those reasons that the calculated electromagnetic field values should be confirmed with measurements.

3.2 Electromagnetic field measurements

Electromagnetic field measurements were conducted at 1 m above the ground level. The instrument used for this purpose meets specifications of IEEE Std. 644 – 1994 standard [4].

Measurements inside aerial distributions power stations were made on the basis of our practical and theoretical experiences. The procedure was as follows:

- Inside 110 kV switchyards measurements are performed only for devices in one phase inside all switch bays,
- Measurement points are located:
  - Around the fence of 110 kV switchyards in characteristic points such as towers, circuit–breakers, disconnectors, etc.
  - In the middle between two high–voltage elements (circuit–breaker, current and voltage transformer, etc),
  - At maximally 1 m from power transformer under all high–voltage conductors and at middle of medium–voltage lines,
  - At 0,5 m and 1 m from switch units inside medium–voltage switchyards, in front of and behind them.

Maximum values measured inside the example power station are given in Tables 3.2 and 3.3.

Table 3.2. Measured maximum electric field strength values

Area	Inside/In the vicinity	*E*
110 kV switchyard	Line switch bay	3.195 V/m
	Transformer switch bay	2.595V/m
Transformers	Transformer, 20 MVA	990 V/m

Table 3.3. Measured maximum magnetic flux density values

Area	Inside/In the vicinity	*B*
110 kV switchyard	Line switch bay	5,64 μT
	Transformer switch bay	3,54 μT
Transformers	Transformer, 20 MVA	4,40 μT

The above 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.

3.3 Additional calculations for the measured electromagnetic fields

We develop an additional electromagnetic calculation model with which we investigated the highest theoretically possible electromagnetic field values in working areas.

In section 3.2, the measured values of an aerial type power station are given. Our model was made on the basis of data from the design documentation.

In the model we used the withstand voltage foreseen for built–in equipment, i.e.123 kV and the following current values:

- 110 kV line switch bay: 400 A,
- 110 kV transformer switch bay: 105 A,
- Transformer primary core: 105 A,
- Transformer secondary core: 576 A.

The calculated values of the electric field strength and magnetic flux density are graphically shown in Figures 3.2 and 3.3.

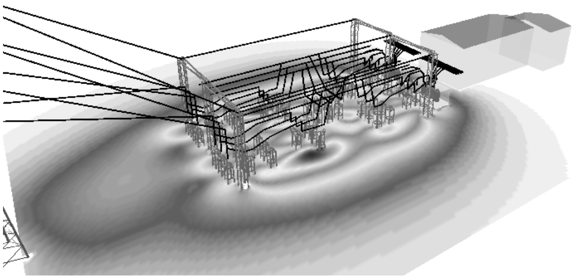

Figure 3.2. Electric field strength of an aerial 110/20 kV power station

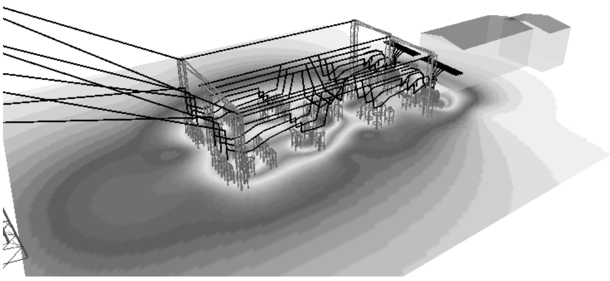

Figure 3.3. Magnetic flux density of an aerial 110/20 kV power station

The measured and the calculated values inside the example power station are given in Tables 3.4 and 3.5.

Table 3.4. Measured and calculated maximum values of the electric field strength

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

Table 3.5. Measured and calculated maximum values of the magnetic flux density

Area	Inside/In the vicinity	*B*	
		Measured	Calculated
110 kV switchyard	Line switch bay	5,64 μT	17 μT
	Transformer switch bay	3,54 μT	8 μT
Transformers	Transformer, 20 MVA	4,40 μT	14 μT

A comparison of the measured and calculated magnetic flux density proves the importance of modelling. Only thorough case studies supported by an electromagnetic model give reliable basis for a credible evaluation of the highest possible expected field strength in working areas.

3.4 Recommendation for an investigation approach

In order to perform a thorough investigation of electromagnetic fields inside a power station, we recommend to build first an electromagnetic model with all its necessary details and after that perform measurements.

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

Computed results show also distribution of the electromagnetic field. This is very useful information enabling a reasonable reduction of the number of measurement points by means of which measurement faults at are minimized.

Most of the distribution power stations are built typically. They usually consist of line switch bays, transformer switch bays and connective switch bays. For such stations investigations can be made with a typical already existing model. But when power stations of an atypical design are dealt with, it is hardly possible to completely avoid building of an electromagnetic model.

4. INVESTIGATION FINDINGS

Tools used for modelling electromagnetic structures usually offer a limited possibility for considering all details that can affect the electric or magnetic field strength. Therefore, it is reasonable to analyse and evaluate the computation error that may occur and to define limitations of modelling tools.

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.

So the combined approach is the right solution. By applying it, it is possible to master the calculation and measurement uncertainty within acceptable limits, up to 20%.

When investigating the electromagnetic field strength inside a power station on the basis of the combined approach, i.e. with measurement and calculation, the following should be considered:

- Calculations:
  - Each conductor should be modelled separately.
  - Dividing conductors into segments shouldn't exceed eight segments when calculating the electrical field strength in order to limit the time needed for determination of electrical charges on each segment.

- High–voltage equipment should consist of an appropriate number of short conductors and conductive or ferromagnetic materials.
- Models of the transformer with core should take into consideration u_k.
- 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.

– Measurements:
  - Measurement points should be at locations where the field strength is expected to be 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 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%.

Minimal and maximal measured values of the electric field strength and magnetic flux density inside 17% of the Slovenian distribution power stations are shown in Tables 3.6 and 3.7.

Table 3.6. Measured values of the electric field strength in Slovenian aerial type distribution power stations

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

Table 3.7. Measured values of the magnetic flux density in Slovenian aerial type distribution power stations

HV device	Measured value of *B*		
	Min	Max	Average
Disconnector	0,78 μT	15,01 μT	4,21 μT
Circuit-breaker	0,59 μT	19,48 μT	4,10 μT
Current transformer	1,29 μT	24,18 μT	7,32 μT
Voltage transformer	1,30 μT	106,6 μT	30,13 μT
Local control cubicle	0,33 μT	8,71 μT	3,76 μT

Values of the investigated electromagnetic fields at 1 m above the ground level inside 110 kV switchyards of the analyzed Slovenian power stations don't exceed the following values:

– 5 kV/m for the electric field strength, representing 50% of the action value defined in *Directive* [2],
– 125 μT for the magnetic flux density, representing 25% of the action value defined in Directive [2].

With regard to characteristic values of low–frequency electromagnetic fields evaluated for 17% of the Slovenian distribution power stations, it is necessary to analyse the field strength at 2 m above the ground level as foreseen by Directive *40/2004/EC* [2].

5. CONCLUSION

Investigations of electromagnetic fields can be pretentious if their performers don't have sufficient knowledge of electromagnetic field characteristics. Therefore, we recommend to make a calculation model for various types of power stations before making measurements in order to assure an appropriate measurement principle.

To fulfil requirements of *Directive 40/2004/EC* [2], we recommend to use an approach similar to the present above for evaluation of low – frequency electromagnetic fields inside 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 present guidelines to serve as a basis for uniforming and simplifying different types of investigations of electromagnetic field strengths inside distribution power stations at a reasonable cost. This is certainly a sufficiently strong argument to assure continuity of this kind of investigations ant to avoid opposition of employers or their associations.

In Slovenia distribution operators strongly rely on results from the performed investigations of electromagnetic fields. They will be further discussed with the government in the process of preparation of new legal documents.

6. REFERENCES

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