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Evaluation of uncertainty of electric and magnetic field measurement and calculation results in the vicinity of transmission overhead power lines

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ABSTRACT
The paper is related to the assessment of exposure of the general public to extremely low-frequency electromagnetic fields in the vicinity of transmission overhead power lines, based on measurements and calculations of electric and magnetic fields. The uncertainty of electric field strength and magnetic flux density measurement and calculation results is evaluated for a typical 220 kV overhead power line. The most influential uncertainty components and the expanded uncertainties are analysed in detail. Measurement results obtained with two different electromagnetic field analysers are compared with calculation results. Compliance between these results is verified using the E_n number and ζ value. The analysis confirms the validity of both the obtained results and the evaluated expanded uncertainties. The study demonstrates that measurement and calculation uncertainties must be properly considered when assessing compliance with exposure limits. The presented methodology provides reliable results and is particularly important for the accurate evaluation of public exposure to electromagnetic fields, and for demonstrating compliance with the prescribed reference levels.

Section: RESEARCH PAPER

Keywords: overhead power line; measurement; calculation; electric field; magnetic field

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1. INTRODUCTION

The topic of the paper is related to measurements and calculations of electric field strength and magnetic flux density in the vicinity of transmission overhead power lines [1]–[3]. The results of electric and magnetic field measurements and calculations are significant for the assessment of exposure of the general public living in the vicinity of these power lines. When the assessment of exposure of the general public is based on measurements and/or calculations, the uncertainty of the results has to be taken into account when giving the conclusion about the compliance of the field levels with the reference levels prescribed by national or international legislation [4]–[6]. The uncertainty evaluation is particularly important when the obtained results of electric and/or magnetic field are close to the prescribed reference level. The analysis of measurement and calculation uncertainty is carried out for the results of electric and magnetic fields obtained in a real case of a 220 kV transmission overhead power line.

The measurements and calculations are usually carried out along the lateral profile located in the area where it is necessary to assess the exposure of the general public. The data related to power line geometry at the location of the lateral profile, including overhead power line conductor heights and their mutual distances, which are used for calculations, are also obtained by measurements. For that reason, these data have their uncertainty, which directly affects the calculation uncertainty [1]. The uncertainty components originating from voltage [2] and current measurements are also taken into account in the uncertainty budget related to calculation results.

The analysis of the uncertainty components, as well as the expanded uncertainty related to calculation results, are based on electric and magnetic field calculations and Monte Carlo simulations [7]–[13]. The measurements and calculations in the vicinity of the aforementioned 220 kV power line are performed in accordance with the relevant standards and guidelines [14]–[18]. For the selected example, the results obtained by electric and magnetic field calculations are compared with the measurement results, in order to ensure the validity of the obtained results. Ensuring the validity of testing results is a direct requirement of the standard [19]. According to [19], there are several ways to ensure the validity of the results, which, among others, include: the use of alternative instruments that are calibrated so as to give traceable results, functional verification of the measuring and test equipment, the use of reference standards, intermediate checks of the measuring equipment, repeating the testing by using the same or different methods, interlaboratory comparisons, etc. Comparing the results of measurements and calculations is a way of ensuring the validity of the results, based on the repetition of testing using different methods, in accordance with [19]. This way of ensuring the validity of the results is particularly suitable if it is not possible to perform measurements using two instruments in order to compare the results, or if the two instruments show results between which there is a significant deviation. The comparison of the results can be carried out on the site during each electric and magnetic field testing, which ensures continuous monitoring of the validity of the results, as well as checking of the measuring equipment in the period between two calibrations or two intermediate checks. The comparison of measurement and calculation results can also be carried out within interlaboratory comparisons [20], during which laboratories, in addition to measurements, can carry out electric and magnetic field calculations as well. If, as a part of an interlaboratory comparison, several laboratories conduct testing based on measurements, the calculation can be used as a method for determining the assigned value of the quantity that is the subject of the testing, i.e. value that is declared true value, and which the results obtained by measurements are compared with. In any case, it is necessary to add an expanded uncertainty to the results of measurements and calculations.

When evaluating the calculation uncertainty, the uncertainty components originating from the measurement of phase conductor heights, voltages, and currents were taken into account [1], [2], [21]. In the measurement uncertainty assessment, the error of the measuring system was taken into account as the most influential uncertainty component [22]–[24].

In Section 2, the measurement and calculation methods are presented. Section 3 presents the results of electric and magnetic fields obtained by measurements and calculations in the vicinity of the 220 kV overhead power line, as well as the evaluation of measurement and calculation uncertainty. In Section 4, the comparison of the results obtained by measurements and calculations is carried out.

2. METHODS

2.1. Measurements

The measurements were performed by using electromagnetic field analysers and isotropic probes for electric field strength and magnetic flux density measurements [14]. The probes ensure simultaneous measurements of all three spatial components of field vectors, based on which the instrument shows the resultant values of the field vectors.

Procedures for measurements of electric field strength and magnetic flux density in the vicinity of overhead power lines are given in [15]–[17].

The heights of the power line conductors at the location of the lateral profile where the measurements are carried out were measured with a laser rangefinder [1].

During the electric field strength and magnetic flux density measurements, the data on power line voltages and currents was provided by the electric power transmission company that owns the power line. The data is significant for the comparison of measured values with the values obtained by calculations.

2.2. Calculations

The calculations of electric field strength and magnetic flux density were based on a two-dimensional analysis using the method described in [1]–[3]. Electric field strength calculations were based on the method of image charges, while magnetic flux density calculations were based on the Biot–Savart law. The overhead power line was simulated by a set of infinitely long, straight-line phase conductors and ground wires. The conductors were parallel to each other and to the ground surface. The calculations in this paper were performed for the same points at which the measurements were carried out.

3. RESULTS OF ELECTRIC AND MAGNETIC FIELD MEASUREMENTS AND CALCULATIONS, AND UNCERTAINTY EVALUATION

3.1. Electric and magnetic field measurements and calculations

In the following text, an example of electric and magnetic field testing in the vicinity of the 220 kV overhead line is given, and a comparison of the results obtained by measurements and calculations is made. This example shows how the results of measurements and calculations can be used not only for internal control of the validity of the results, but also for conducting interlaboratory comparisons.

The towers on the analysed span of the 220 kV overhead power line are shown in Figure 1, and the location where the testing is performed is shown in Figure 2 and Figure 3.

In Figure 3, the point where the electric field strength was measured is marked as E_1, and the point where the magnetic flux

Figure 1. The towers on the analyzed span of the 220 kV overhead power line.

Figure 2. The location where the testing was conducted.

Figure 3. The location where the testing was conducted and the position of the measurement points E_1 and B_1.

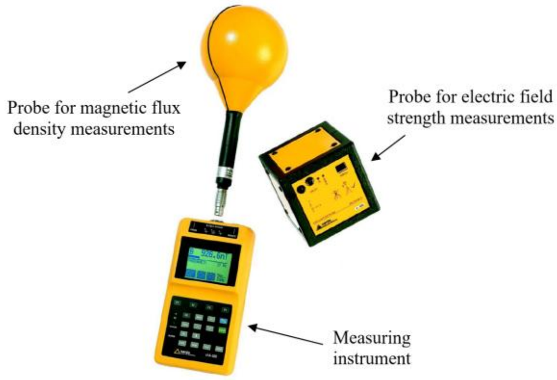

Figure 5. Measuring system 1.

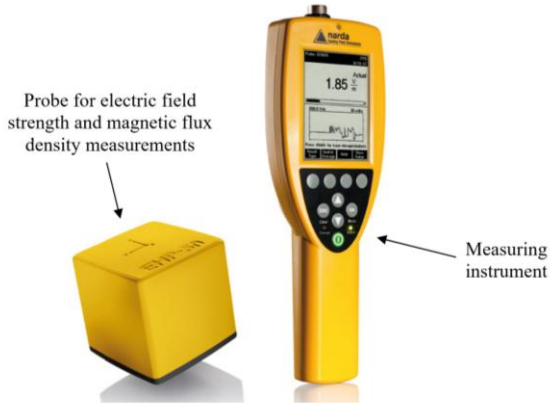

Figure 6. Measuring system 2.

density was measured is marked as B_1. The testing was conducted at a height of 1 m above the ground.

For conducting the testing, a location was chosen where the terrain can be considered flat, and where there were no objects that could cause electric field perturbation.

Figure 4 shows the geometry of the overhead line at the location of the lateral profile P, where the measurements are carried out.

Measurement point E_1 is located below the phase conductor corresponding to phase 8, at a distance of 8.5 m from the line axis ($x = -8.5$ m). Measurement point B_1 is located in the power line axis ($x = 0$ m), i.e. below the middle phase conductor (phase 4). During the measurements, it was decided that the measurement points should be located below the aforementioned phase conductors, in order to additionally reduce the error originating from their positioning along the lateral profile. Measurement point B_1 is located at the place where the highest value of magnetic flux density occurs along the lateral profile, while measurement point E_1 is located near the place where the highest value of the electric field strength occurs along the lateral profile.

Two measuring systems, marked as measuring system 1 and measuring system 2, were used to measure the electric field strength and magnetic flux density. These measuring systems are shown in Figure 5 and Figure 6.

Measurements of magnetic flux density performed at point B_1 by using the aforementioned two measuring systems were performed simultaneously, in order to ensure that the measurements were carried out under the same conditions, i.e. at the same overhead line load current. This way, the possibility of a deviation of the measurement results due to a change of the overhead power line load current is eliminated.

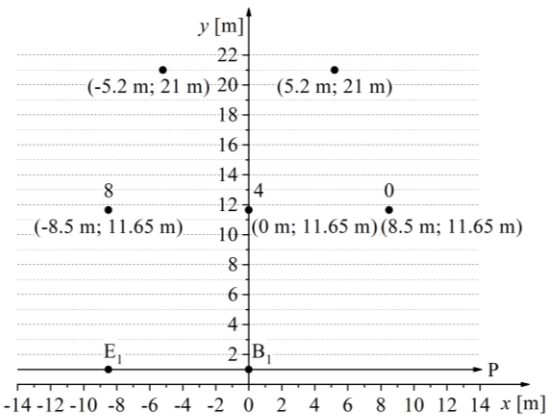

Figure 4. Geometry of the analysed 220 kV overhead line, with the position of measurement points E_1 and B_1.

Measurements of the electric field strength performed at point E_1 by using the aforementioned two measuring systems were carried out separately, in order to avoid the occurrence of electric field perturbation due to the proximity of the second measuring system. When measuring the electric field strength, the distance between the operator and the measuring probe was 10 m, in order to eliminate the measurement uncertainty component due to the presence of the operator [25], [26].

In the vicinity of the analysed overhead power line, there are two additional 220 kV lines: a closer single-circuit line and a more distant double-circuit line (Figure 2 and Figure 3). Considering the distances between these lines and the analysed one, as well as the fact that the closer single-circuit line was out of service at the time of measurements, it was concluded that the influence of these power lines on the measurement results at measurement points E_1 and B_1 is negligible, i.e. that the measured values of electric field strength (at measurement point E_1) and magnetic flux density (at measurement point B_1) originate exclusively from the analysed overhead power line.

Data on voltages and currents of the analysed overhead line at the time of electric field strength and magnetic flux density measurements were obtained from the authorized department of the owner of the overhead line and are shown in Table 1 and Table 2.

In Table 3, the results of electric field strength and magnetic flux density measurements and calculations are presented.

Table 1. Values of overhead power line voltages at the time of measurements carried out by using measuring systems 1 and 2.

Measuring system	U_0 in kV	U_4 in kV	U_8 in kV
1	130.20	129.83	129.62
2	130.39	130.04	129.74

Table 2. Values of overhead power line currents at the time of measurements carried out by using measuring systems 1 and 2.

Measuring system	I_0 in A	I_4 in A	I_8 in A
1 and 2	850.87	851.28	847.64

Table 3. Results of electric field strength and magnetic flux density measurements and calculations.

Measurement/calculation	E in kV/m	B in µT
Calculation	1.95	14.85
Measuring system 1	1.89	14.98
Measuring system 2	1.82	15.23

Based on the results shown in Table 1, it can be concluded that the power line voltage was very stable in the period of interest, which eliminated the possibility of deviation of the electric field strength measurement results obtained by measuring systems 1 and 2 due to the change of the overhead power line voltage. By calculating the electric field strength, in both cases, i.e. for both sets of voltage values from Table 1, the value of 1.95 kV/m was obtained.

In order to compare the results obtained by measurements and calculations and to ensure the validity of these results, it is necessary to calculate the uncertainty of measurements and calculations.

3.2. Evaluation of expanded uncertainty of electric field strength and magnetic flux density measurement results

During the calibration of both measuring systems, it was determined that the measurement error is within the range of ± 3 %, when measuring both electric field strength and magnetic flux density. When measuring the electric field strength, the distance between the operator and the measuring probe was 10 m, thus it is considered that the measurement uncertainty component which originates from the presence of the operator is negligible [25], [26]. It can also be assumed that the errors originating from the positioning of the measuring probes along all three axes are negligible, taking into account the way in which the positioning was performed. Before the testing, the height of the measuring probe was checked, and it was confirmed that it was 1 m in all cases. The measurement points were located directly under the phase conductors, and their positions were checked by measuring with a laser rangefinder and a measuring tape. Since the previously described measures were applied to eliminate the mentioned uncertainty components, an expanded measurement uncertainty of ± 3 % was adopted, which corresponds to the values obtained during the calibration of the measuring systems.

Table 4 presents the results of the electric field strength and magnetic flux density measurements with their expanded uncertainties.

In Table 4, marks $U_{\mathrm{E_m}}$ and $U_{\mathrm{B_m}}$ correspond to expanded uncertainties of electric field strength and magnetic flux density measurement results, respectively.

Table 4. Results of the electric field strength and magnetic flux density measurements with their expanded uncertainties.

Measuring system	$E \pm U_{\mathrm{E}_m}$	$B \pm U_{\mathrm{B}_m}$
1	1.89 kV/m ± 3 % (1.83 kV/m to 1.95 kV/m)	14.98 µT ± 3 % (14.53 µT to 15.43 µT)
2	1.82 kV/m ± 3 % (1.77 kV/m to 1.87 kV/m)	15.23 µT ± 3 % (14.77 µT to 15.69 µT)

3.3. Evaluation of expanded uncertainty of electric field strength calculation results

The evaluation of the expanded uncertainty of the electric field strength calculation results was carried out in the way described in [1], [2], as well as by applying the Monte Carlo method.

The dominant components of the electric field strength calculation uncertainty are the components that come from the uncertainty of the phase conductor height measurement and the uncertainty of the voltage measurement.

As stated in Section 2.2, the calculations were based on a two-dimensional analysis, assuming a set of infinitely long, straight-line conductors parallel to each other and to the ground surface. Consequently, the influence of power line towers, nearby objects, and conductor sag was not taken into account. However, the measurement location was carefully selected to minimize these effects. The terrain below the line is almost flat, and point E_1 is located at a significant distance from both towers, thereby reducing the influence of the towers and minimizing the effect of conductor sag. The influence of conductor sag on the calculation results is analysed in detail in [27]. In addition, no objects that could perturb the electric field were present near point E_1, so this influence was considered negligible.

The component originating from the uncertainty of measuring the phase conductor heights was calculated in the way described in [1].

According to the method presented in [1], the calculations are performed for the adopted true values of overhead power line conductor heights, in order to obtain the true value of electric field strength (E_{t}) for the analyzed case. After that, the calculations are repeated taking into account the maximum error of height measurement (Δl_{v}), in order to obtain the value of electric field strength (E) when the laser rangefinder measures with the specified error.

On the basis of these results, percent error is calculated by using the following formula:

$$\delta_{\mathrm{E}} = \frac{E - E_{\mathrm{t}}}{E_{\mathrm{t}}} \cdot 100\ \% = \frac{E(h \pm \Delta l_{\mathrm{v}}) - E(h)}{E(h)} \cdot 100\ \%\,. \qquad (1)$$

It was adopted that the height measurement error is ± 0.4 m. The calculation showed that the true value of the electric field strength is 1.951 kV/m. When the height measurement error of ± 0.4 m is taken into account in the calculation, the results of the electric field strength calculation are in the range from 1.837 kV/m to 2.074 kV/m, i.e. in the range from 1.951 kV/m − 5.845 % to 1.951 kV/m + 6.335 %.

The component originating from the uncertainty of the voltage measurement is calculated in the way described in [2], for the case when the voltage measurement is performed with 0.2 accuracy class measuring transformers [28]–[30].

According to the method presented in [2], the calculations are performed for the adopted true values of overhead power line voltage, in order to obtain the true value of electric field strength

(E_t) for the analyzed case. After that, the calculations are repeated taking into account the measuring transformer error, in order to obtain the value of electric field strength (E) when the measuring transformer measures with the specified error.

On the basis of these results, percent error is calculated by using the following formula:

$$\delta_E = \frac{E - E_t}{E_t} \cdot 100\ \% \,. \qquad (2)$$

When the voltage measurement error of $\pm$ 0.2 % is taken into account in the calculation, the results of the electric field strength calculation are in the range from 1.945 kV/m to 1.957 kV/m, i.e. in the range from 1.951 kV/m − 0.299 % to 1.951 kV/m + 0.300 %.

If a rectangular probability distribution is adopted for both uncertainty components, the uncertainty budget of the electric field strength calculation results given in Table 5 is obtained.

When calculating the expanded uncertainty, the coverage factor of 2 was adopted, which corresponds to the level of confidence of 95.45 %, according to [7].

When the expanded uncertainty of the calculation results given in Table 5 is taken into account, it can be concluded that the calculation result is in the range from 1.82 kV/m to 2.09 kV/m, i.e. in the range from 1.951 kV/m − 6.76 % to 1.951 kV/m + 7.32 %.

In order to verify the obtained results, the calculation of the expanded uncertainty was repeated using the Monte Carlo method, where the number of iterations M was 10^4. In this way, M values of the electric field strength are calculated, and then their mean value E_{avg} and the standard deviation of the mean value σ are calculated. The range of values of $E_{avg} \pm 2\,\sigma$ corresponds to the probability of 95.45 %. The obtained results are shown in Table 6.

Based on the presented results, it can be concluded that the results obtained by two applied methods are complying when calculating the expanded uncertainty.

Table 5. Uncertainty budget of electric field strength calculation results obtained by the method described in [1], [2].

Measurement uncertainty component	Expanded uncertainty interval, %	Distribution	Divisor	Standard uncertainty interval, %
Uncertainty of phase conductor heights measurement	-5.85 to 6.34	Rectangular	1.73	-3.37 to 3.66
Uncertainty of voltage measurement	± 0.3	Rectangular	1.73	± 0.17
	Combined uncertainty interval:			-3.38 to 3.66
	Coverage factor:			2
	Expanded uncertainty interval:			-6.76 to 7.32

Table 6. Uncertainty budget of electric field strength calculation results obtained by the Monte Carlo method.

Measurement uncertainty component	E_{avg} kV/m	σ kV/m	σ %	$E_{avg} - 2\,\sigma \leq E \leq E_{avg} + 2\,\sigma$ kV/m
Uncertainty of phase conductor heights measurement and uncertainty of voltage measurement	1.95	0.069	3.55	$1.82 \leq E \leq 2.09$

3.4. Evaluation of expanded uncertainty of the magnetic flux density calculation results

The evaluation of the expanded uncertainty of the magnetic flux density calculation results was performed in the way described in [1], [2], as well as by applying the Monte Carlo method. The dominant components of the magnetic flux density calculation uncertainty are the components that come from the uncertainty of the phase conductor height measurement and the uncertainty of the current measurement. Point B_1 is located at a significant distance from the towers in order to minimize the influence of conductor sag [27].

The component originating from the uncertainty of the phase conductor height measurement was calculated in accordance with the methodology presented in [1]. The calculations are carried out for the adopted true values of conductor heights to obtain the true value of magnetic flux density (B_t). Then, the calculations are repeated taking into account the height measurement error to obtain the value of magnetic flux density (B), which corresponds to the case when the laser rangefinder measures with the specified error. The percent error is calculated using the following formula:

$$\delta_B = \frac{B - B_t}{B_t} \cdot 100\ \% = \frac{B(h \pm \Delta l_v) - B(h)}{B(h)} \cdot 100\ \% \,. \qquad (3)$$

The calculation showed that the true value of the magnetic flux density is 14.845 μT. When the height measurement error of $\pm$ 0.4 m is taken into account in the calculation, the results of the magnetic flux density calculation are in the range from 14.093 μT to 15.653 μT, i.e. in the range from 14.845 μT − 5.064 % to 14.845 μT + 5.444 %.

The component originating from the uncertainty of the current measurement is calculated in accordance with the procedure explained in Section 3.3, and the methodology presented in [2], applied to magnetic flux density, for the case when the current measurement is performed with 0.2 accuracy class measuring transformers [28], [31]. In this way, the true value of magnetic flux density (B_t) is obtained, as well as the value corresponding to the case when the measuring transformer error is taken into account (B). The percent error is calculated using the following formula:

$$\delta_B = \frac{B - B_t}{B_t} \cdot 100\ \% \,. \qquad (4)$$

When the current measurement error of $\pm$ 0.2 % is taken into account in the calculation, the results of the magnetic flux density calculation are in the range from 14.815 μT to 14.875 μT, i.e. in the range from 14.845 μT − 0.200 % to 14.845 μT + 0.200 %.

If a rectangular probability distribution is adopted for both uncertainty components, the uncertainty budget of the magnetic flux density calculation results given in Table 7 is obtained.

When the expanded uncertainty of the calculation results given in Table 7 is taken into account, it can be concluded that the calculation result is in the range from 13.98 μT to 15.78 μT, i.e. in the range from 14.845 μT − 5.86 % to 14.845 μT + 6.30 %.

The calculation of the expanded uncertainty was repeated using the Monte Carlo method, with the number of iterations M being 10^4. As a result of the calculation, M values of magnetic flux density are obtained, based on which their mean value B_{avg} and the standard deviation of the mean value σ are calculated. A range of values of $B_{avg} \pm 2\,\sigma$ corresponds to a probability of 95.45 %. The obtained results are shown in Table 8.

Table 7. Uncertainty budget of magnetic flux density calculation results obtained by the method described in [1], [2].

Measurement uncertainty component	Expanded uncertainty interval, %	Distribution	Divisor	Standard uncertainty interval, %
Uncertainty of phase conductor heights measurement	-5.06 to 5.44	Rectangular	1.73	-2.92 to 3.14
Uncertainty of current measurement	± 0.2	Rectangular	1.73	± 0.12
	Combined uncertainty interval:			-2.93 to 3.15
	Coverage factor:			2
	Expanded uncertainty interval:			-5.86 to 6.30

Table 8. Uncertainty budget of magnetic flux density calculation results obtained by the Monte Carlo method.

Measurement uncertainty component	B_{avg} µT	σ µT	σ %	$B_{avg} - 2\sigma \le B \le B_{avg} + 2\sigma$ µT
Uncertainty of phase conductor heights measurement and uncertainty of current measurement	14.85	0.45	3.04	$13.95 \le B \le 15.76$

The presented results confirm that there is a compliance between the two applied methods when calculating the expanded uncertainty.

4. COMPARISON OF THE RESULTS OBTAINED BY MEASUREMENTS AND CALCULATIONS

4.1. Comparative review of measurement and calculation results of electric field strength and magnetic flux density

Figure 7 and Figure 8 show a comparative review of the ranges of the electric field strength and magnetic flux density results obtained by measurements and calculations, with their expanded uncertainties taken into account. The uncertainty calculated in the way described in [1], [2] is adopted as the expanded uncertainty of the calculation results.

Based on the obtained results, it can be concluded that there is an overlap of the ranges of the electric field strength results obtained by calculations and measurements using measuring systems 1 and 2. The same conclusion applies to the values of magnetic flux density obtained by calculations and measurements using measuring systems 1 and 2.

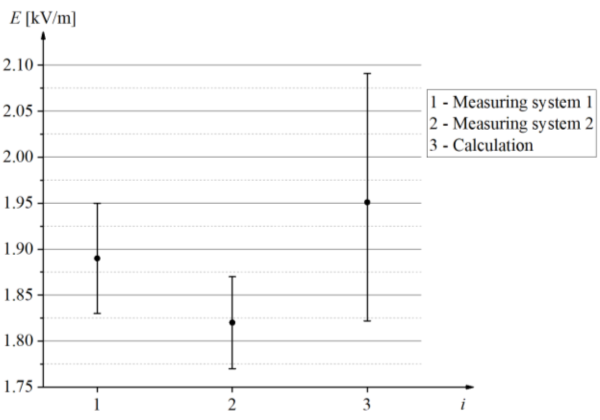

Figure 7. Electric field strength results obtained by measurements and calculations taking into account their expanded uncertainties.

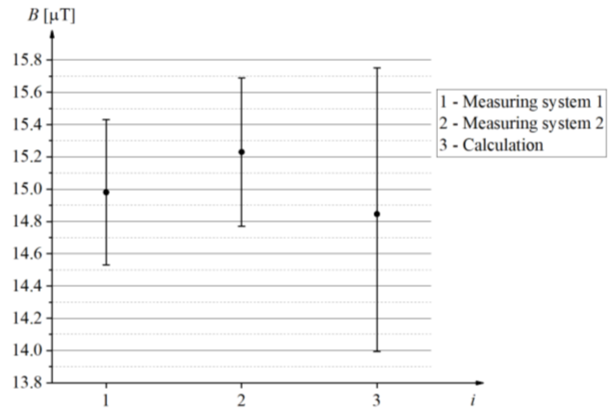

Figure 8. Magnetic flux density results obtained by measurements and calculations taking into account their expanded uncertainties.

Based on the presented results, it can be concluded that, in this way, the validity of the measurement and calculation results is ensured.

4.2. Evaluation of measurement and calculation results based on E_n number value

Standard [32] pertains to the conduct of interlaboratory comparisons and defines methods for evaluating the obtained results. One of the methods for evaluating the obtained results according to this standard is based on the calculation of the E_n number.

In the case of electric field strength, the E_n number is calculated using the following expression:

$$E_{n_i} = \frac{E_i - E_{ref}}{\sqrt{U_{E_i}^2 + U_{E_{ref}}^2}}, \quad (5)$$

where the marks denote the following:
E_i – the value of electric field strength obtained by testing;
E_{ref} – the assigned value of electric field strength (adopted reference/true value);
U_{E_i} – the expanded uncertainty of the result E_i;
$U_{E_{ref}}$ – the expanded uncertainty of the assigned value E_{ref}.

In the case of magnetic flux density, the E_n number is calculated using the following expression:

$$E_{n_i} = \frac{B_i - B_{ref}}{\sqrt{U_{B_i}^2 + U_{B_{ref}}^2}}, \quad (6)$$

where the marks denote the following:
B_i – the value of magnetic flux density obtained by testing;
B_{ref} – the assigned value of magnetic flux density (adopted reference/true value);
U_{B_i} – the expanded uncertainty of the result B_i;
$U_{B_{ref}}$ – the expanded uncertainty of the assigned value B_{ref}.

The criterion for the evaluation of results is as follows:
$|E_n| < 1$ – indicates satisfactory results and gives no warning;
$|E_n| > 1$ – indicates unsatisfactory results and triggers a signal for corrective action.

For the calculation of the absolute value of the E_n number, the measurement and calculation results with their expanded uncertainties given in Table 9 were used.

The result of the electric field strength calculation falls within the range of 1.82 kV/m to 2.09 kV/m, i.e. within the range of

Table 9. Results of electric field strength and magnetic flux density measurements and calculations with their expanded uncertainties.

Measurement/calculation result	$E \pm U_{\mathrm{E}}$	$B \pm U_{\mathrm{B}}$
Measuring system 1	1.89 kV/m ± 3 %	14.98 µT ± 3 %
Measuring system 2	1.82 kV/m ± 3 %	15.23 µT ± 3 %
Calculation	1.95 kV/m ± 7.2 %	14.85 µT ± 6.2 %

1.95 kV/m – 6.62 % to 1.95 kV/m + 7.18 %. For the purpose of simpler E_{n} number calculation, the calculation result is presented in further analyses as 1.95 kV/m ± 7.2 %, which yields a value range of 1.81 kV/m to 2.09 kV/m.

The result of the magnetic flux density calculation falls within the range of 13.99 µT to 15.76 µT, i.e., within the range of 14.85 µT – 5.74 % to 14.85 µT + 6.16 %. For the purpose of simpler E_n number calculation, the calculation result is presented in further analyses as 14.85 µT ± 6.2 %, which yields a value range of 13.93 µT to 15.77 µT.

If the results obtained by calculations are adopted as the assigned values for the electric field strength and magnetic flux density, the E_{n} number values given in Table 10 are obtained.

Table 11 presents the E_{n} number values corresponding to the case when the results obtained by measurements using measuring system 1 are adopted as the assigned values. The E_{n} number values corresponding to the case when the results obtained by measuring system 2 are adopted as the assigned values are given in Table 12.

Based on the results presented in Table 10 – Table 12, it is concluded that in all cases $|E_{\mathrm{n}}| < 1$, which means that the obtained results are correct and the expanded uncertainties of the measurement and calculation results have been properly determined. This conclusion is highly significant considering the fact that certain uncertainty components were not taken into account during the calculation of measurement and calculation uncertainties, such as uncertainties due to probe positioning, uncertainty arising from neglecting the actual shape of the conductor, and uncertainty due to voltage drops. The presented results confirm that the aforementioned omissions are justified in this specific case, since incorporating the mentioned uncertainty components would increase the expanded uncertainty while further decreasing the absolute value of the E_{n} number.

Table 10. Absolute values of E_{n} number calculated under the assumption that the values obtained by calculations are adopted as the assigned values.

Measurement result	Electric field strength	Magnetic flux density
Measuring system 1	0.40	0.13
Measuring system 2	0.86	0.37

Table 11. Absolute values of E_{n} number calculated under the assumption that the values obtained by using measuring system 1 are adopted as the assigned values.

Measurement/calculation result	Electric field strength	Magnetic flux density
Calculation	0.40	0.13
Measuring system 2	0.89	0.39

Table 12. Absolute values of E_{n} number calculated under the assumption that the values obtained by using measuring system 2 are adopted as the assigned values.

Measurement/calculation result	Electric field strength	Magnetic flux density
Calculation	0.86	0.37
Measuring system 1	0.89	0.39

4.3. Evaluation of measurement and calculation results based on ζ value

Another method for evaluating the obtained results according to standard [32] involves calculating the value of ζ.

In the case of electric field strength, the value of ζ is calculated based on the following expression:

$$\zeta_i = \frac{E_i - E_{\mathrm{ref}}}{\sqrt{u_{\mathrm{E}_i}^2 + u_{\mathrm{E}_{\mathrm{ref}}}^2}}, \tag{7}$$

where the marks denote the following:
$u_{E_{\mathrm{i}}}$ – combined standard uncertainty of the result E_{i};
$u_{E_{\mathrm{ref}}}$– standard uncertainty of the assigned value E_{ref}.

In the case of magnetic flux density, the value of ζ is calculated based on the following expression:

$$\zeta_i = \frac{B_i - B_{\mathrm{ref}}}{\sqrt{u_{\mathrm{B}_i}^2 + u_{\mathrm{B}_{\mathrm{ref}}}^2}}, \tag{8}$$

where the marks denote the following:
u_{B_i} – combined standard uncertainty of the result B_i;
$u_{\mathrm{B}_{\mathrm{ref}}}$– standard uncertainty of the assigned value B_{ref}.

The criterion for the evaluation of results is as follows:
$|\zeta| \leq 2$ – indicates satisfactory results and gives no warning;
$2 < |\zeta| < 3$ – indicates questionable results and triggers a warning signal;
$|\zeta| \geq 3$ – indicates unsatisfactory results and triggers a signal for corrective action.

For the calculation of the absolute value of ζ, the measurement and calculation results with their expanded uncertainties given in Table 9 were used. The standard uncertainties were calculated by dividing the corresponding expanded uncertainties by the coverage factor of 1.96.

The calculated absolute values of ζ related to the measurement and calculation results of electric field strength and magnetic flux density are given in Table 13 and Table 14.

The marks in Table 13 and Table 14 denote the following:
$E_{\mathrm{m}_1}, B_{\mathrm{m}_1}$ – values of electric field strength and magnetic flux density obtained by measurements using measuring system 1;

Table 13. Absolute values of ζ related to the electric field strength results obtained by measurements and calculations.

Measurement/ calculation result	$E_{\mathrm{ref}} = E_{\mathrm{c}}$	$E_{\mathrm{ref}} = E_{\mathrm{m}_1}$	$E_{\mathrm{ref}} = E_{\mathrm{m}_2}$
Measuring system 1	0.78	/	1.74
Measuring system 2	1.69	1.74	/
Calculation	/	0.78	1.69

Table 14. Absolute values of ζ related to the magnetic flux density results obtained by measurements and calculations.

Measurement/ calculation result	$B_{\mathrm{ref}} = B_{\mathrm{c}}$	$B_{\mathrm{ref}} = B_{\mathrm{m}_1}$	$B_{\mathrm{ref}} = B_{\mathrm{m}_2}$
Measuring system 1	0.25	/	0.76
Measuring system 2	0.72	0.76	/
Calculation	/	0.25	0.72

$E_{\mathrm{m}_2}, B_{\mathrm{m}_2}$ – values of electric field strength and magnetic flux density obtained by measurements using measuring system 2;
$E_\mathrm{c}, B_\mathrm{c}$ – values of electric field strength and magnetic flux density obtained by calculations.

Based on the presented results, it is concluded that in all cases $|\zeta| < 2$, which means that the obtained results are correct and that the expanded uncertainties of the measurement and calculation results have been properly determined.

5. CONCLUSION

The paper presents the evaluation of uncertainty of electric field strength and magnetic flux density measurement and calculation results in the vicinity of an overhead power line. The evaluation of uncertainty of these results is very important when it is necessary to compare the results with the prescribed reference levels, in order to provide the conclusion regarding the exposure of the general public to electromagnetic field. In these cases, the conclusion has to take into account the expanded uncertainty. The analysis is carried out for the real case of a 220 kV transmission overhead power line. For the selected example, the results obtained by electric and magnetic field calculations are compared with the measurement results and, in this way, the validity of the results is verified. The comparison of the results obtained by measurements and calculations with their expanded uncertainties confirms that the results obtained by using these two methods are complying. The methodology for the evaluation of the most relevant uncertainty components is demonstrated. It is shown how the comparison of the results obtained by measurements and calculations can be used for ensuring the validity of testing results, both during interlaboratory comparisons and for the purpose of intermediate checks within a certain testing laboratory. The results of electric field strength and magnetic flux density obtained by measurements and calculations in the vicinity of the analysed overhead power line, with their expanded uncertainties, do not exceed the reference levels of 5 kV/m and 100 μT, prescribed by the Recommendation 1999/519/EC.

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