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Electromagnetic Field Measurements – Means of Verification

MICHAEL MANN, BERND GUTHEIL, JÖRG ZASTRAU, PAUL WEISS
Department of Electrical Engineering, Chair of High-Voltage Engineering and EMC
University of Kaiserslautern
P.O. Box 3049, 67653 Kaiserslautern
GERMANY

Abstract: - Repetitive measurements of the same object by varying teams are generally known as inter-laboratory tests. The results allow for a comparison of the measurement devices, the measurement procedures and the measuring teams. An inter-laboratory test of electromagnetic field measurements was conducted in order to ensure the comparability of the measurements. 17 participating teams determined the field strength at given measuring points. This paper presents the concept and design of the inter-laboratory test. The approach to a scientific evaluation and the most significant results are presented and discussed. Finally, an outlook to a inter-laboratory test of radar measurements is presented.

Key-Words: electro magnetic field measurement, inter laboratory test

1 Introduction

The revisable quality of the measurement procedure is the crucial factor to achieve good results of electromagnetic field measurements. In the field of safety at work, e.g. employees working at high-frequency (HF) transmitter stations entrust their life to the validity of electromagnetic field strength measurements. Solely measurements of adequate quality are able to put the evaluation of personal exposure on a firm basis. Reproducible measurements may create and convey credibility to the public. One of the fundamentals of credible measurements is a suitable Quality Assurance (QA) system being implemented at each testing facility. QA consists of the documentation of the employees' mandatory qualification and the adopted measures to sustain this qualification. The applied instruments of verification and measurement are to be revised by internal and external supervision at regular intervals with respect to precision, accuracy and representation of the metered values. The external evaluation of accuracy is verified by comparative inter-laboratory tests at best.

2 Intentions

Electromagnetic field measurements should be comparable despite the application of varying measuring instruments and measurement procedures. In a medium-term time frame, inter-laboratory tests of electromagnetic fields will become an inherent part of QA in the fields of safety at work and immission control. The national and international comparability of the measurements is ensured by trace to the national metrological standard. Accurate and thorough documentation additionally enhances the degree of transparency within country borders and beyond.

3 Implementation

The inter-laboratory test of electromagnetic field measurements is based on the concept of previous tests, e.g. immunity tests, resistance measurements or nuclide measurements. It is extended by the relevant characteristics of electromagnetic fields.

3.1 QA and traceability to national standard

The PTB (Physikalisch-Technische Bundesanstalt, federal physical-technical agency of Germany) as supervising metrological authority provides the national metrological standard for the international SI-unit-system at best measurement capability. The agency offers calibration service for custom or measurement standards. A calibration, which references measurement devices to the national metrological standard is referred to as "trace to national standard".

Tracing the magnetic field strength of electromagnetic fields seems trivial, as the value is measured in A/m where the fundamental units are meter and ampere.

In practice, the generation of the basic quantities of electromagnetic fields – electric (E) and magnetic field strength (H) and power flux density (S) respectively – requires a multitude of intermediate steps and leads via HF-specific measurement values. Due to the fact that HF-fields cannot be stored in terms of standard devices, they have to be producible at a "reference device" if required. In doing so, it is assumed that all of the relevant components of the reference device are traced by means of calibration and that the value to be determined is derived on the basis of the recorded data and the laws of physics.

3.2 Approach to an evaluation

The fundamental problem of designing an inter-laboratory test of electromagnetic field measurements is that the exact value of the electric field strength is unknown. Considering the transmitted power, the directivity of the antenna and the law of squared distance for regions free of reflection at far-field conditions, the electric field strength can be calculated as follows:

$$E_{\text{eff}} = \sqrt{\frac{P_0 \cdot Z_0 \cdot G_{\text{linear}}}{4 \cdot \pi \cdot r^2}} \qquad (1)$$

While P_0 designates the power of the transmitter, Z_0 is the characteristic impedance of free space. G_{linear} represents the accumulated gain of the antenna minus the attenuation of the cable and the horizontal and vertical attenuation, which can be determined from the Smith Chart. The distance between measuring point and the position of the antenna is referred to as r.

Concerning mobile telephone base stations, the values of the calculated field strength are listed in Table 2. But the reflection and attenuation phenomena that will occur in practice will render the calculation of exact nominal values difficult while environmental conditions (e.g. ground conductivity, weather conditions) alter.

In principle, there are two methods of determining a best estimate of the nominal value: On the one hand, via direct trace to national standard, on the other hand via averaging a multitude of measured values after excluding outliers. Both procedures were applied in the context of the evaluation at hand.

To generate reference values, each point was repeatedly measured by a broadband measuring system traced to national standard, because solely broadband measuring devices can be traced to national standard at PTB. For the exclusion of outliers, a Grubbs' test with a confidence interval of 95 % was performed [1]. The averaging process did not weight the reference measurement in any way. The allocation of measured values to measuring teams used a randomised three-letter code.

Another estimate may be gained using a probe calibrated and traced to national standard. Calibration by a national metrological institute cannot ensure more accurate measurements because the measuring device itself consists of the same components as it did prior. This calibration allows for no more than an independent value of the best estimate.

One reference measurement cycle consists of the recording of 50 up to 350 individual values, each value measured over a time interval of 0.4 s up to 2 s. Up to seven measurement cycles (REF1-REF7) were completed at each measuring point. The arithmetic mean and the standard deviation were calculated for the recorded values of each measurement cycle. The subsequent calculation of the total uncertainty is based on these average values.

The participating teams were asked to write down the total uncertainty of each measured value. The uncertainty of the measuring teams is correlated with the total uncertainty of the reference values.

One basic approach of Quality Assurance may consist of limiting the total value of uncertainty. At Switzerland for example, the expanded measurement uncertainty is limited to ± 45 % (± 3.2 dB) for GSM mobile telephone base stations [2]. Defining such a limit requires thorough consideration with regard to the capabilities of the measurement devices and the signal to be measured. The expanded uncertainty of the national standard for the generation of an empty field adds up to ± 12 % (± 1 dB) for the given example (GTEM-cell, $f < 1$ GHz, cf. Table 1) – i.e. for most of the isotropic broadband measuring systems applied. Hence, it would be unrealistic to specify the total value of the expanded measurement uncertainty for a device calibrated by the standard to be lower than the uncertainty of the standard itself.

3.3 Uncertainties of reference values

Averaging the measured results of each team would provide a plausible basis of a reference value. An uncertainty of a reference measurement averaged over all of the participating teams would be less significant due to the diversity of measuring devices and would contradict the intention of the inter-laboratory test, i.e. a qualification of measurement procedures.

measuring point "sine wave 27 MHz"	
mean value	**2,289**
standard deviation of mean values	0,209
max (standard deviation of measuring cycles M1 up to M6)	0,069
linear regression	
relevant frequencies: f 1 [MHz]	26,971
extrapolated calibration factor of probe	
position PE [ ]	0,890
position PH [ ]	1,033
position PS [ ]	1,033
minimal calibration factor of probe [ ]	0,890
maximal calibration factor of probe [ ]	1,033
best estimate of calibration factor of probe [ ]	**0,962**
relative standard deviation of calibration factor of probe [± %]	**7,44%**
calibration field at PTB: relative standard deviation GTEM-cell (1 σ) [± %]	6%
mean values: maximal relative standard deviation [± %]	9,63%
relative standard deviation of reference value (1 σ) [± %]	13,57%
relative expanded measurement uncertainty of reference value (2 σ) [± %]	27,14%
relative expanded measurement uncertainty of reference value (2 σ) [± dB]	2,085
referece value: minimum [V/m]	1,603
reference value: best estimate [V/m]	**2,200**
reference value: maximum [V/m]	2,798

Table 1
EVALUATION OF REFERENCE MEASUREMENT ”SINE WAVE 27 MHZ“

In addition to the standard deviation of the mean values of the measurement cycles M1 up to M6, the maximum value of the standard deviation of each measurement cycle is calculated, see Table 1. The bound of ± 1 σ (coverage factor $k = 1$) of a Gaussian variable is referred to as standard uncertainty, the bound of ± 2 σ ($k = 2$) as expanded measurement uncertainty. The probability of a Gaussian variable being within the confidence interval is 95 % for a coverage factor of $k = 2$.

Table 1 exemplifies the evaluation of the reference measurement for the measuring point "sine wave 27 MHz". The „standard deviation of mean values" represents the uncertainties resulting from inaccurate positioning of the measurement device at repetitive measuring cycles, in short: repetition accuracy. Each measuring cycle is considered to be stochastically independent. Instable transmitters may fluctuate at various periods. If a transmitter fluctuates at a period that is long in comparison to the duration of a measuring cycle, the resulting uncertainty is represented by the standard deviation of mean values. The standard deviation of the measuring cycle will increase, if the transmitter has a period of fluctuation, which is very short compared to the duration of a measuring cycle. Any noise of the measurement devices and transmitters is represented by the uncertainty of the measuring cycles. The uncertainty of mean values is not correlated with the uncertainty of measuring cycles. Hence, the standard deviations are to be added by the root-sum-square (RSS) method.

This circumstance is evident in Table 1: The maximum standard deviation of each measuring cycle constitutes ± 0.069 V/m for the measuring point "sine wave 27 MHz"; a fraction of the maximum standard deviation of the measuring cycles. The transmitter is considered to be comparatively stable, the total uncertainty is mainly constituted by the repetition accuracy of the measuring cycles.

Vice versa, the standard deviation of mean values (± 4.36 V/m) is 40 % of the maximum standard deviation of the measuring cycle (± 10.68 V/m) in case of the diathermy device in PWM mode (see Section 4.2). The total uncertainty is primarily caused by the instability of the transmitter.

Another cause of uncertainty is the anisotropy of the electromagnetic field probe. The calibration certificates of the reference measurement device provide calibration factors, which were extrapolated to the emitted frequencies by linear regression. The application of an isotropic field probe renders the allocation of the detected field strength to a certain frequency or a certain direction impossible. Thus, the calibration factors are calculated for each emitted frequency and each direction. The best estimate of the calibration factor is centred between the minimum and maximum value of the extrapolated calibration factors. The difference between best estimate and extreme values represents the uncertainty ($k = 1$) of the calibration factor at the current measuring point.

The total value of the standard deviation is obtained by geometrical addition (i.e. RSS) of the previously discussed values [5]. The best estimate of the reference field strength can be determined by multiplying the mean value with the best estimate of the calibration factor.

3.4 Discussion of the statistical evaluation

Some inter-laboratory tests employ an evaluation of the results of the participating teams by applying the E_N-value [4]. The E_N-Value of a measurement is determined as follows:

$$\left|E_N\right| = \left|\frac{X_{lab} - X_{ref}}{\sqrt{U_{lab}^2 + U_{ref}^2}}\right| \tag{2}$$

X_{lab} indicates the measured value of a team, X_{ref} the reference value, U_{lab} the uncertainty of the team, U_{ref} the uncertainty of the reference measurement at a given measuring point.

The E_N-value does not allow for conclusions in terms of accuracy or the quality of the teams among one another. For $E_N \leq 1$, the measured results are assessed to be credible, for $E_N \geq 1$, the results are regarded as questionable. The level of credibility decreases with the increase of the E_N-value.

If the measured value of a fictive measurement device was constantly set to $X_{lab} = 0$, and the uncertainty was $U_{lab} = \infty$, then the E_N-value would be $|E_N| = 0$ solely due to the high uncertainty. So, a team may produce good results by choosing a high uncertainty value U_{lab} .

An alternative evaluation may apply the z-Score [6], which can be calculated using Equation (3):

$$z = \left|\frac{X_{lab} - X_{ref}}{\sigma_{ref}}\right| \tag{3}$$

X_{lab} indicates the measured value of a team, X_{ref} the reference value, σ_{ref} the standard deviation of the reference measurement at a given measuring point. σ_{ref} represents an achievable value of uncertainty.

Measurement results with z-Score ≤ 1 are considered to be good, 1 < z-Score ≤ 2 are regarded as satisfactory, 2 < z-Score ≤ 3 as questionable, z-Score > 3 as dubious. The inter-laboratory test is passed with a z-Score ≤ 2.

The z-Score of the participants is not influenced by the uncertainty value U_{lab} calculated by the respective team. In contrast to an evaluation via E_N-value, the teams can only influence their performance by putting effort into a minimization of the difference between the measured value X_{lab} and the reference value X_{ref} .

4 Results of the inter-laboratory test

measuring point	frequency	mean value	reference value	calculated value
	[MHz]	[V/m]	[V/m]	[V/m]
Sinus	27	2,34 ± 0,75	2,20 ± 0,60	-
Sinus	433	3,67 ± 0,57	3,94 ± 0,66	-
GSM far region	944 / 953	3,10 ± 1,50	3,10 ± 1,18	2,04
GSM near region	941 / 1853	17,83 ± 4,97	18,49 ± 6,20	17,42
UMTS	2167	2,12 ± 1,28	1,65 ± 0,53	1,63
diathermy CW	2450 ± 50	12,12 ± 5,10	12,46 ± 5,89	-
diathermy PWM	2450 ± 50	13,69 ± 13,54	13,37 ± 22,12	-
DECT	1892	0,29 ± 0,12	0,29 ± 0,27	-
Babyphone	434	0,24 ± 0,18	0,31 ± 0,35	-

Table 2
SUMMARY OF THE RESULTS

Table 2outlines the results of the evaluation. In the case of mobile base stations, the theoretical value is derived from data of the operating company.

4.1 UMTS

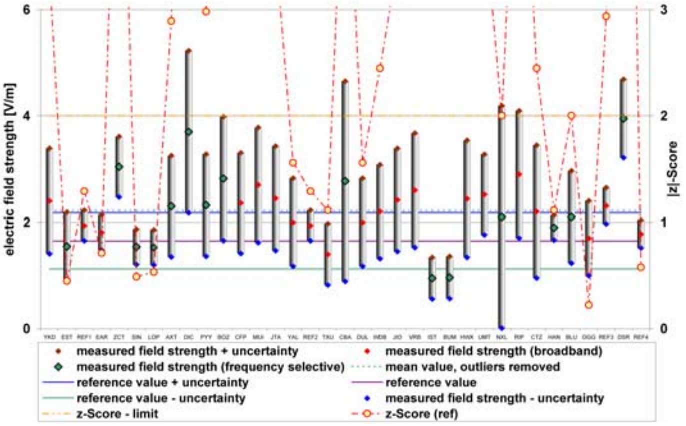

Fig. 1 Evaluation of the measuring point UMTS

The diagrams of the evaluation report show the measured values versus the team codes including the relevant uncertainty values in chronological order. The values identified as outliers were not incorporated for the calculation of the mean value. The results of the reference measurements were calculated without application of the frequency-dependent calibration factor. The average of the reference measurements was multiplied with the best estimate of the calibration factor to generate the reference value. This may lead to visible variations between the measured values of the reference probe and the averaged reference value.

Regarding compliance measurements with frequency-selective measurement devices, the request for a minimum resolution bandwidth of RBW ≥ 5 MHz is coupled with the request for choosing an appropriate detector envelope. According to regulations, the RMS detector has to be applied. Some teams presented results gained by consciously incorrect application of the Max-Peak detector. An overvaluation of twice the amount can be observed in Fig. 1 comparing the teams DIC (8th team from the left, Max-Peak) with AXT (9th team from the left, RMS), which leads to an increase in statistical spread.

4.2 Diathermy device in PWM mode

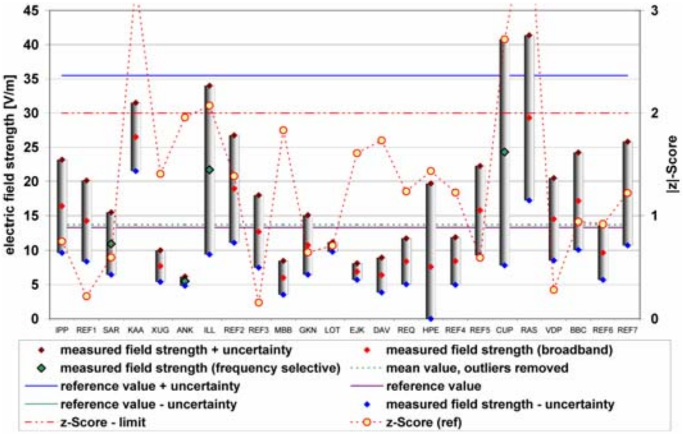

Fig. 2 Evaluation of the diathermy device in PWM mode

Fig. 2 represents the more or less statistical distribution of the measured values in an uncertainty bound of ± 165 %. The so-called "PWM mode" challenged the teams due to its instability. Should a measurement with a low uncertainty be imperative, extensive measurements at low metering time periods have to be conducted.

4.3 Babyphone

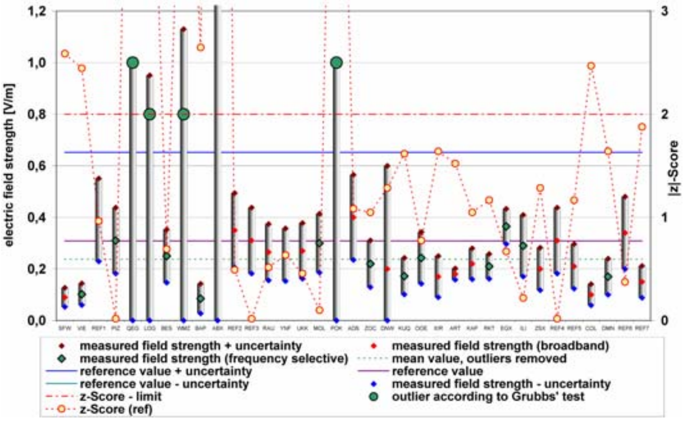

Fig. 3 Evaluation of the measuring point Babyphone

The "Babyphone" measuring point is of interest because the respective devices are subjected to public criticism in spite of having a relatively low power output. The results are not expected to be exact due to the inhomogeneity of the field, the inaccurate positioning of probes and the distance between probe and transmitter antenna of approximately 0.1 m. One can merely state that the field strength is below 0.6 V/m due to the noise floor of the reference probe.

5 Conclusion and outlook

The inter-laboratory test indicated that the measurement devices are generally capable of validating the compliance with legal limit values if the employees have the required know-how. Furthermore, a realistic estimation of the total uncertainty is essential considering the uncertainty of the measuring devices, the uncertainty of the sampling and the parameters of the transmitter. Considering the technological limits, the comparability between broadband and frequency-selective measurement devices is given. One should be aware of the limited capabilities of broadband measurement devices. CISPR 16-1 [3] specifies the compulsory application of frequency-selective measurements employing a Quasi-Peak detector at radio disturbance measurements close to the limit value of field strength. Isotropic measurement is more complex if frequency-selective devices are applied.

In general, the sensitivity of broadband devices is not sufficient for an accurate detection of commonplace field strength values in public areas. Broadband devices are hardly applicable to determine the field strength of complex signals (e.g. diathermy device in PWM mode).

Frequency-selective measurements permit the separation and identification of multiple transmitter stations. The field strength of multiple sources can be compared to the frequency-dependant limit values. Hence, the exposition can be assessed more accurately in comparison to broadband devices. Continuous QA can provide measurements of ample accuracy. Repetitive inter-laboratory tests constitute an essential part of adequate QA systems.

The experience gained by the inter-laboratory test described in this paper provided beneficial support for an inter-laboratory test of radar signals that took place in September 2005.

The course of action showed that the teams went to the time and effort of increasing the reproducibility of the measured results. Just as well, additional time was invested in order to calculate the uncertainty budget according to GUM [5] for each measuring point and test setup. So, the common purpose to enhance the credibility of measurements was achieved.

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