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A PROPOSED METHOD FOR QUANTIFYING UNCERTAINTY IN RF IMMUNITY TESTING DUE TO EUT PRESENCE

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Abstract—Throughout the performance of a RF immunity test according IEC 61000-4-3 there are several factors that should be taken into account to ensure the quality and to estimate the uncertainty associated to the results. One phenomenon that should be considered to calculate uncertainty is the disturbing effect produced by the EUT over the electric field generated within the calibrated uniform field area; nevertheless the mentioned effect is not easily quantifiable because the measuring process using additional antennas or field probes inside the semianechoic chamber could also alter the electric field distribution. An experimental method for quantifying the mentioned uncertainty contribution is presented. The method is based upon the fact that antenna-EUT coupling and reflection effects could be measured through changes in the input impedance of the field generation antenna. A validation procedure for the proposed method is also described. Hence, a relationship between the reflection coefficient at the antenna input port and the electric field strength is derived. The uncertainty contribution is calculated through the maximum relative change in the E-field intensity magnitude for the frequency range of 80–1000 MHz, considering the worst case for several EUT positions.

1. INTRODUCTION

In the execution of a RF immunity test according IEC 61000-4-3 inside a semianechoic chamber, the enclosure of the equipment under test (EUT) and other metallic parts can be coupled to the field generation antenna [1, 2], especially when the distance between EUT and the antenna is 3 m or less. This coupling implies changes in

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the imaginary part of antenna input impedance, and consequently, it changes the reflected and transmitted electromagnetic energy in the antenna port. The reflected electromagnetic energy over the EUT back to the transmit antenna also affect the magnitude of the electric field intensity applied to the EUT, that's the reason why, changes in the real part to the antenna input impedance are produced [3, 4]. Both, antenna-EUT coupling and reflected energy back to the transmit antenna, are represented in changes of the antenna input impedance and therefore introduce uncertainty in the magnitude of the electric field intensity effectively applied over the uniform field area (UFA) [5].

Changes in the total input impedance of transmit antenna implies relatively more o less reflected and transmitted power with respect to the data collected during the field calibration of the UFA according IEC 61000-4-3. This data is actually used during the test to generate the necessary power in the transmit antenna port to achieve a certain test severity level required by IEC 61000-4-3.

This document proposes a method to measure the uncertainty in the electric field magnitude over the UFA introduced due to EUT presence. The method is based on the direct measurement of antenna input impedance with and without presence of EUT over different position within the UFA defined by IEC 61000-4-3. Then the variation of the electric field magnitude is calculated in order to obtain the uncertainty contribution.

The main issues to measure directly the variations of the electric field within the UFA are: diffraction effects due to EUT presence would disturb the measured field, and that the use of measuring antennas or probes would alter the field distribution in the UFA.

All methods previously reported [2, 5] do not take into count the uncertainty due to dimensions of the EUT and the position over the test plane.

2. THEORETICAL JUSTIFICATION

In real antennas part of the energy applied to the input port is dissipated as heat due to finite conductive effects, and other portion of the energy is reflected back to the line due to impedance mismatch and the rest is radiated. It all depends on the relationship between line impedance and the antenna characteristic impedance. The real part of antenna impedance is called "Antenna Resistance" and the imaginary part "Antenna Reactance" [7]. The Antenna Resistance is the sum of radiation resistance and loss resistance. The radiation resistance is associated with the electromagnetic energy that is radiated into free space and the loss resistance is associated with the energy that is lost or dissipated as heat. The antenna reactance by definition does not produce any radiated energy and depends on its size in relation to the wavelength. This reactance could be quite influenced by mutual coupling with nearby objects [8, 9]. These facts should be considered when performing tests according IEC 61000-4-3, because the interaction EUT-Antenna affects the antenna impedance, and in consequence the magnitude of the E-field is generated in the UFA.

2.1. RF Immunity Test According the IEC 61000-4-3 Standard

The IEC 61000-4-3 standard is applicable to the immunity requirements of electrical and electronic equipment to radiated electromagnetic fields. It establishes test levels and the required test procedures. This requires radiated RF field generated by an antenna in a shielded anechoic enclosure using a precalibrated field, swept from 80 MHz to 1000 MHz with the step size not exceeding 1% previous frequency and dwell time sufficient to allow the equipment under test (EUT) to respond [10]. As shown in the Figure 1, the equipment under test is placed on the 0.8 m high wooden table (for table top devices) with its front face in the same plane as the UFA that was previously calibrated. Both the antenna position and the uniform area are fixed

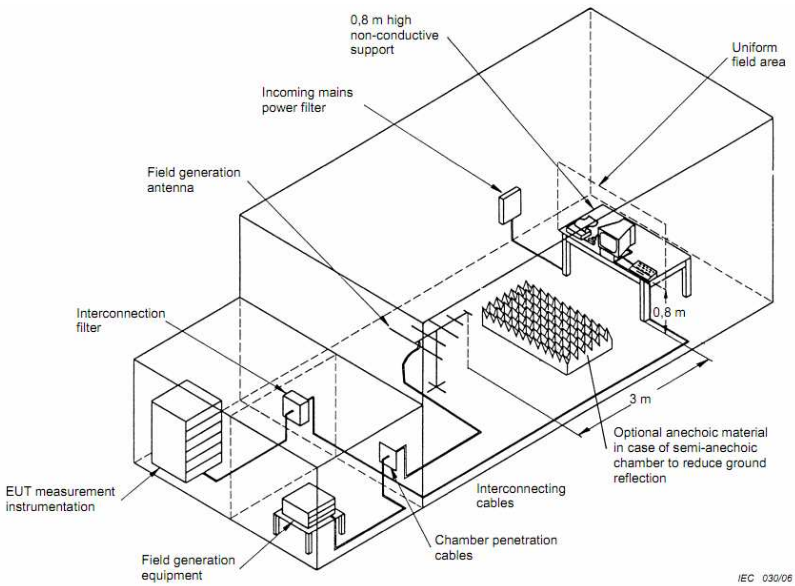


Figure 1. Example of a suitable setup for RF immunity testing [10].

with respect to the chamber. The standard requires at least 1 m of connected cable length to be exposed to the field, and recommends the use of ferrite chokes to decouple longer cables. The equipment under test is rotated on the table so that each of its four sides, and the top and bottom if it may be used in any orientation, face the antenna in turn, and are coplanar with the uniform area. For each orientation, two sweeps are performed across the frequency range, one in each antenna polarization. Severity levels are unmodulated and have to be 1, 3 or 10 V/m. The actual applied signals are modulated to 80% with a 1 kHz sine wave.

2.2. Uncertainty for RF Immunity Testing

The measurement is done over the hypothetical test field strength (without an EUT) within the UFA selected according to the field calibration process. To calculate the uncertainty budget for RF Immunity test, it should be taken into account several technical contributions, such as, field probe linearity, field probe anisotropy, field probe frequency interpolation error, power amplifier short and long term stability, power amplifier compression, stability and drift of signal generator, antenna location and absorber placement, mismatch between power meters and directional couplers, mismatch between antenna and power amplifiers, and the coupling between antenna and EUT [11].

While it is true that each laboratory have to select the most important contribution components to be included in their uncertainty budget calculation, on the basis of its particular circumstances, it is also a fact that there are some common elements in the uncertainty budgets for RF immunity test according IEC 61000-4-3 that have been reported. Some examples of uncertainty budgets for RF immunity test according IEC 61000-4-3 could be found in [5, 6, 11]. In all of them, it is considered that the influence of the EUT-Antenna interaction plays an important role and in consequence it should be determined. What is still not well defined is a method to simultaneously quantify the uncertainties due to EUT-Antenna coupling and reflections due to the EUT presence in the UFA.

2.3. Method Previously Reported

According to [2] "Uncertainties of immunity measurement" — Schaffner Guide, three methods are exposed to calculate the uncertainties due to antenna-EUT coupling: the antenna-antenna coupling method, the antenna-image coupling method and the antenna-ground plane coupling method.

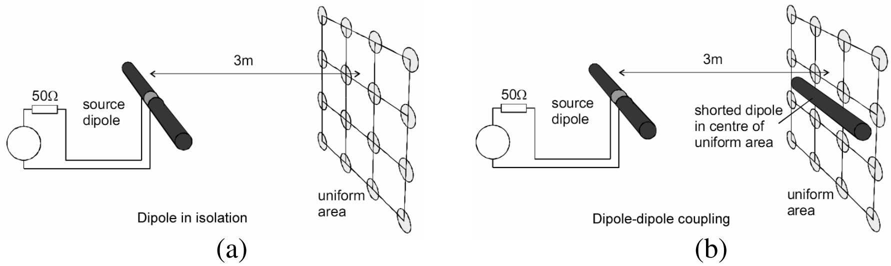


Figure 2. Geometry of modeled coupling. (a) Free Space. (b) Simulation of EUT-antenna coupling [2].

2.3.1. Antenna-Antenna Coupling Method

This method assumes that in many situations the EUT acts as a secondary coupled antenna, and computes the electric field strength on the UFA produced by an 80 MHz tuned, half-wave dipole with and without (free space) a similar shorted dipole placed 3 m away in parallel, as its shown in Figure 2. The source antenna was supplied from a 50 Ω voltage source. To compute the electromagnetic fields, was used Numerical Electromagnetic Code and specific codes based on method of moments [12].

This method is by no means representative of the phenomenon of interaction EUT-antenna during a RF immunity test. The limitations of this method are: it is just a numerical calculation of a very simplified model of the phenomena that did not take into account the effect of the reflections from the EUT nor the coupling between the source antenna and shielded room (anechoic chamber), the calculation of the coupling only occurs at the lowest frequency and the field generating antennas recommended by the IEC 61000-4-3 standard are Biconical antenna, Log-periodic antenna, Horn antenna and double ridge waveguide antenna while in the simulation it was used a half-wave dipole which is not recommended for this type of test, the position of the coupled dipole never was varied to know how this parameters change.

2.3.2. Antenna-Image Coupling Method

This method is also based upon numerical calculation of the electric field intensity that intends to model the antenna-EUT coupling phenomena using an 80 MHz tuned half-wave dipole placed 3 m from a conducting metal sheet of infinite extent. Then the fields are calculated on UFA produced by the tuned half-wave dipole with and without the conductive ground plane of infinite extend. In this situation the coupling occurs between the source antenna and its image in the metal sheet, this image being located 6 m from the source antenna. Although the image is 3 m further away than the coupled antenna in the previous method, the current in the image is identical to that in the source antenna. In this case, it was also used Numerical Electromagnetic Code. The component of the total field that lies in the plane of the sheet is zero (boundary condition), but it is the field due to the source antenna that is of interest not the total field created by the source and its image [12].

In the same way as the Antenna-Antenna Coupling Method, the Antenna-Image Coupling Method is not appropriate to predict and measure the effect of the EUT presence in neither the field uniformity nor its magnitude. It should be noticed that both Antenna-Antenna Coupling Method and the Antenna-Image Coupling Method leads to different results.

2.3.3. Antenna-Ground Plane Coupling Method

A 90 MHz tuned, half-wave dipole with balun was measured over the frequency range 80–200 MHz over a ground plane on an open area test site. The antenna was first placed 4 m above the ground plane and oriented in vertical polarization to simulate the free-space (empty chamber) situation. It is known that there is only small coupling to the ground plane in this situation. It was then mounted 3 m above the ground plane in horizontal polarization to simulate the presence of a large metal EUT as is shown in — see Figure 3.

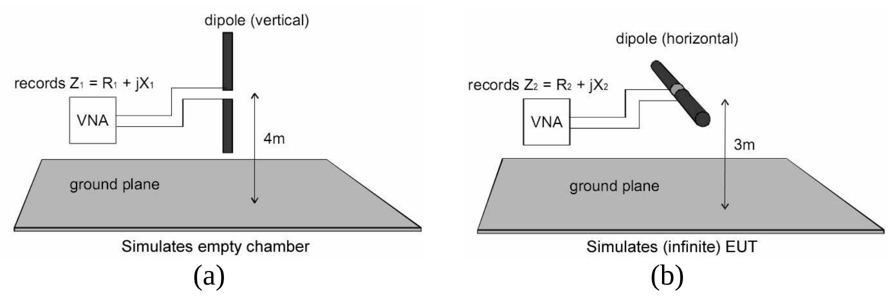


Figure 3. Geometry of antenna-ground plane experimental method. (a) Free space. (b) Simulation of EUT-antenna coupling [2].

Fairly obviously, fields cannot be measured, and as an alternative the change in the antenna input current amplitude was determined. Since the 50 Ω source was the same for both orientations it was only necessary to measure the antenna input impedance, Z_{in}, with a VNA.

From the measured values of $Z_{in} = R_{in} + jX_{in}$ in the two arrangements it is possible to determine the change in antenna current in decibels. Since the field from the source is directly proportional to the current this gives the change in electric field in decibels.

The problems with this method are: first of all an "infinite" ground plane is not a good representation of an EUT because the maximum EUT size is restricted by the UFA, so the coupling and reflection effects are not whatsoever equal, and once again the source antenna used is not the recommended one by the standard to perform the RF immunity test.

2.4. The Proposed Method

This method is based upon the fact that the electric field distribution over UFA is perturbed due to changes in the antenna input impedance caused by the presence of the EUT and its position within the UFA, making this E-field variation an uncertainty contribution component that should be quantified. Considering that the EUT could be placed anywhere within the 1.5×1.5 m UFA and that the signal frequency is swept from 80 MHz to 1 GHz, the changes in the antenna input impedance caused by the variation in reflection coefficient depends on the EUT position and the particular electromagnetic behavior of the test arrangement for a specific frequency.

The IEC 61000-4-3 standard establishes the procedure to calibrate field uniformity over the UFA [8]. Basically, the entire plane is subdivided in nine 0.5×0.5 m zones, forming a 16 point grid over which the field probe measures the electric field. Hence a conductive reflective plate (0.7 mm thick aluminum plate) of 0.5×0.5 was selected as the representation of a typical size EUT.

The proposed method consists in the measurement of reflection coefficient, Γ, with and without the conductive reflective plate emulating the EUT presence. It is possible to compute Γ through the measurement of the antenna input impedance, Z_A, using (1), where Z_0 is the characteristic impedance of the transmission line [13]. It is also feasible to compute the magnitude of the reflection coefficient using the $VSWR$ at the antenna input port (1). Measuring Z_A using a Vector Network Analyzer instead of the more conventional and simple $VSWR$ measurement obtained by power sensors, has several advantages among which are: the ability to observe separately the effect of coupling (changes of the antenna admittance) and the effect of reflections (changes in the antenna resistance), allow to increase the measurement speed, diminish the measurement noise, and reduce errors due to intermediate elements such as directional couplers. However, any of the above measurement techniques could be used taking into account the measurement capabilities of each laboratory.

$$|\Gamma| = \left|\frac{Z_A - Z_0}{Z_A + Z_0}\right| = \frac{VSWR - 1}{VSWR + 1} \tag{1}$$

In this experiment, when the reflection coefficient is measured without the reflective plate, Γ_0, the results provide information about the normal input impedance of the transmit antenna inside the semianechoic chamber. The second part consist on the placement of the reflective plate over nine different positions of the UFA, as is explained later, and in each position measuring the modified input impedance of the transmit antenna in order to quantify the reflection coefficients due to coupling and reflected energy, Γ_{EUT}. In that sense, there is a quantifiable relationship between the E field variation and Γ_{EUT} and Γ_0 that it is derived from the Friss' formula [14]. Therefore the theoretical electric field in far field zone, E, is expressed in terms of the distance R, the transmitted power, P_t, and the gain of the transmission antenna, G_t, as shown in (2).

$$E = \frac{\sqrt{30 G_t P_t}}{R} \tag{2}$$

In the same way, the transmitted and the incident power, P_i, are related by,

$$P_t = P_i \left(1 - |\Gamma|^2\right) \tag{3}$$

Substituting (3) into (2), results in the following equation,

$$E = \frac{\sqrt{30 G_t P_i}}{R} \sqrt{1 - |\Gamma|^2} \tag{4}$$

Assuming that the incident power at the antenna input port is fixed, the difference between the electric field strength generated in the center of the UFA with and without the EUT presence, ΔE, is expressed by,

$$\Delta E = |E_{EUT} - E_0| = \frac{\sqrt{30 G_t P_i}}{R} \left[\sqrt{1 - |\Gamma_{EUT}|^2} - \sqrt{1 - |\Gamma_0|^2}\right] \tag{5}$$

Then, the relative change in the E-field within the UFA due to EUT presence, ΔE_r, is,

$$\Delta E_r(\%) = 100 \cdot \left|\frac{E_{EUT} - E_0}{E_0}\right| = 100 \cdot \left|\frac{\sqrt{1 - |\Gamma_{EUT}|^2} - \sqrt{1 - |\Gamma_0|^2}}{\sqrt{1 - |\Gamma_0|^2}}\right| \tag{6}$$

Consequently, expressing (6) in decibels,

$$\Delta E_r(\text{dB}) = 20 \log \left(1 + \frac{\Delta E_r(\%)}{100}\right) \tag{7}$$

It must be noticed that since ΔE_r depends on frequency, f, location of the reflective plate within the UFA, l, chamber characteristics and type of the transmit antenna, the uncertainty contribution associated will also be different for each test site. In this work the uncertainty contribution corresponding to the relative change in the E-field within the UFA, u_{EUT}, was calculated taking the worst case approach, considering it as the maximum value of ΔE_r within the whole frequency range for each one of the reflective plate positions.

$$u_{EUT} = \max\left(\Delta E_r(f,l)\right) \begin{cases} f \in [80, 1000]\,\text{MHz} \\ l \in \{1,2,3,4,5,6,7,8,9\} \end{cases} \tag{8}$$

3. EXPERIMENTAL SETUP AND PROCEDURE

3.1. Measurement the Relative Change in the E-field within the UFA Due to EUT Presence

The experiment consists in measuring the reflection coefficient at the antenna port with and without a reflective plate that serves as a representation of a EUT. The dimensions of the reflective plate were chosen to cover a grid of 0.5 m × 0.5 m within the semianechoic chamber UFA. The reflective plate was placed in nine (9) different positions,

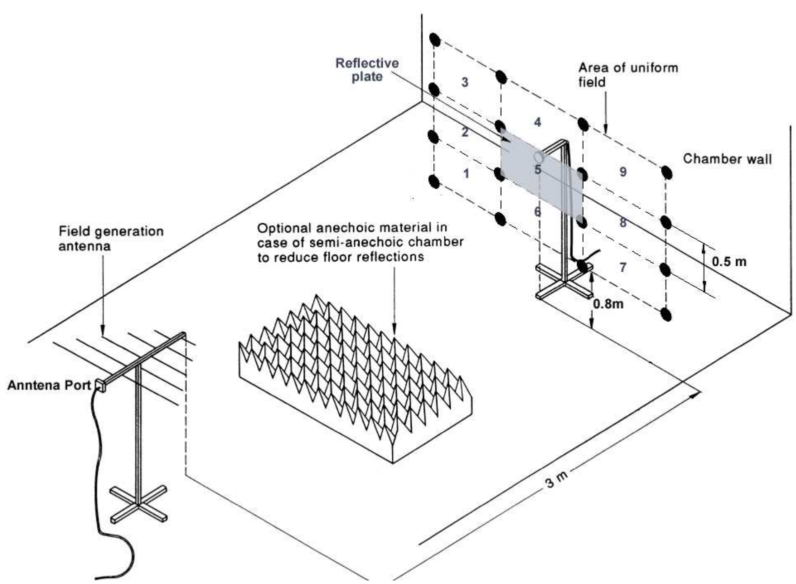


Figure 4. Experimental arrangement inside semi-anechoic chamber.

matching its vertices with the points where the electric field probe was placed for field calibration according to IEC 61000-4-3. A graphical representation of the experimental arrangement inside semianechoic chamber is shown in Figure 4.

The reflective plate was placed in each position because, from a theoretical standpoint, the EUT can be placed anywhere inside the UFA. Also, the size of the reflective plate is comparable to a typical size device that is tested in a 3 m semianechoic chamber, making the results realistic and representative. To hold the reflective plate, we used a plastic mast, of the same kind used to locate the isotropic electric field probe for field calibration. The measurements were performed all over the frequency band required by IEC 61000-4-3 (80 MHz to 1 GHz), in both antenna polarizations (vertical and horizontal), using a calibrated Vector Network Analyzer (VNA) placed outside the semianechoic chamber. In the presence of the reflective plate, the measurements were repeated for the nine selected positions with the reflective plate grounded and with reflective plate isolated. A Diagram of the measurement setup is shown in Figure 5.

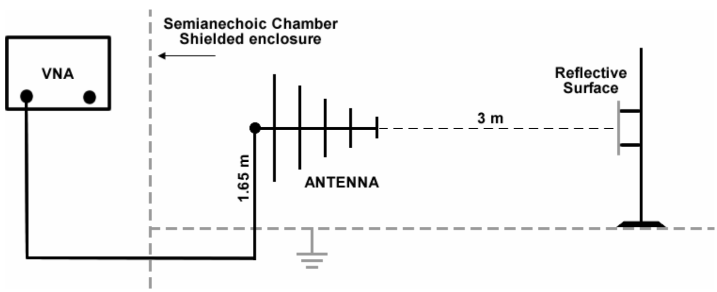


Figure 5. Diagram of the measurement setup.

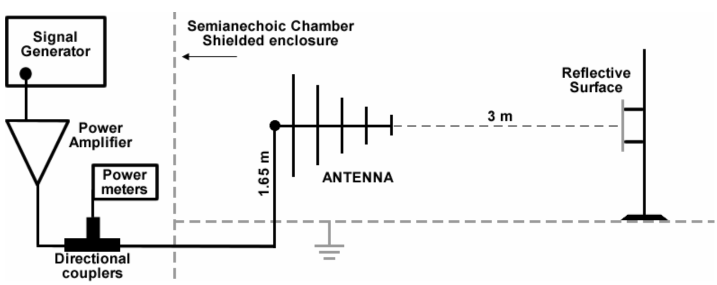


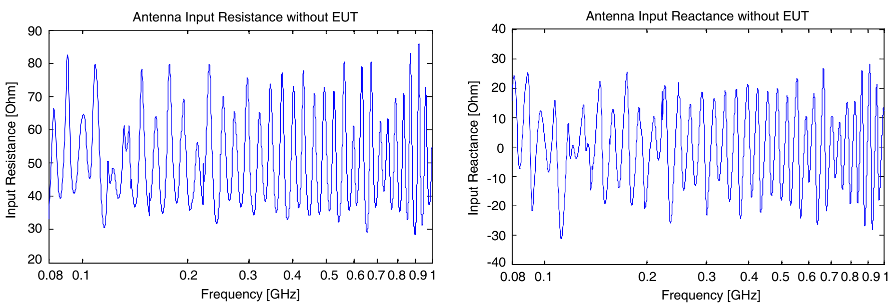
Figure 6. Diagram of validation setup.

3.2. Validation of the Measurements

The results were validated by measuring the reflected power and power delivered to the antenna input during the execution of a test according to IEC 61000-4-3, with and without the presence of the reflective plate in the nine (9) selected positions, using the power meters included in the IEC 61000-4-3 test system. A diagram of the validation setup is shown in Figure 6.

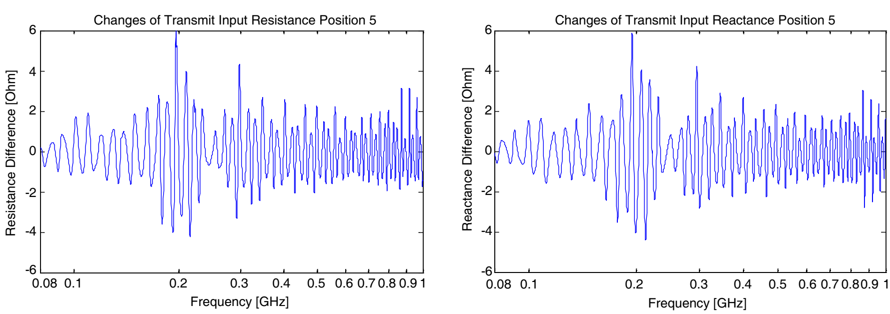
4. RESULTS

As explained before, the input impedance of the antenna (High Gain Log-Periodic R&S®HL046) was measured with and without the reflective plate. Figure 7(a) shows the real part of the impedance. As



(a) (b)

Figure 7. Antenna input impedance. (a) Resistance. (b) Reactance.



(a) (b)

Figure 8. Change in antenna input impedance for: Reflective plate in position 5, antenna horizontally polarized and with the reflective plate isolated. (a) Resistance. (b) Reactance.

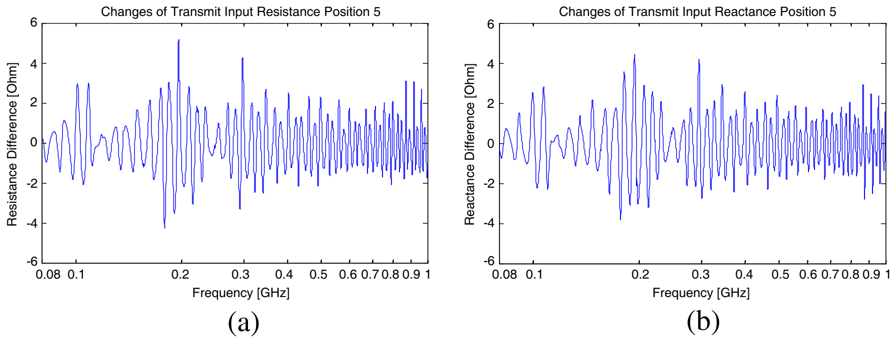


Figure 9. Change in antenna input impedance for: Reflective plate in position 5, antenna horizontally polarized and with the reflective plate grounded. (a) Resistance. (b) Reactance.

expected, the real part of the impedance of the antenna is designed to work close to $50\,\Omega$. Figure 7(b) shows the imaginary part of transmit antenna impedance. The following measurement results were taken with the antenna set in horizontal polarization; nevertheless the measurements were also performed for the vertical polarization case. The results of antenna input impedance measurements provide a benchmark for assessing changes in the input impedance, which in turn may be associated with, reflections on the EUT, EUT-antenna coupling and hence changes in the reflection coefficient.

The change in the antenna input impedance due to EUT presence was measured for each of the nine positions, shown in Figure 4, for both polarizations, with the reflective plate grounded and with the reflective plate isolated. As an example the results for position 5 are shown in Figures 8 and 9. The results show a maximum change in antenna input resistance and antenna input reactance of approximately $6\,\Omega$ near 200 MHz.

The Figure 10 shows the spatial average and the spatial maximum of relative electric field deviation. The average and the maximum were taken over all nine positions in each frequency, with the reflective plate isolated and with the reflective plate grounded. As shown in Figure 10, although there are differences in the Relative Electric Field Deviation measured with the antenna vertically polarized and horizontal polarized for frequencies below 200 MHz, these differences do not affect the contribution of uncertainty since the maximum of both curves are approximately equal to 0.32 dB. Figure 10 also shows that measurements made with the reflective plate grounded and isolated are not significantly different.

Figure 11 shows the expected correspondence of the $VSWR$ at

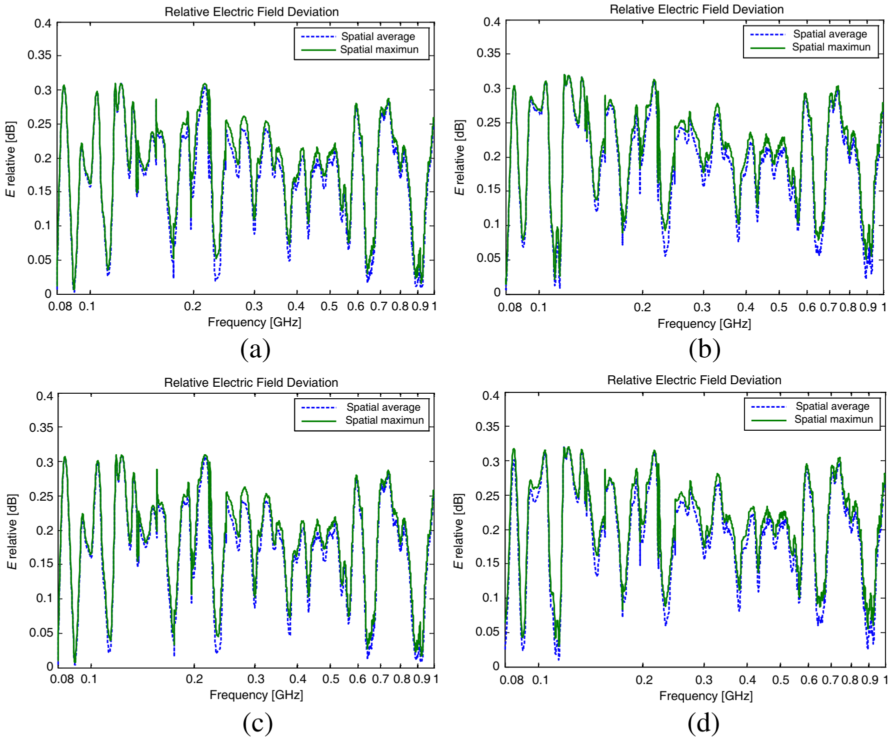


Figure 10. Relative electric field deviation. (a) Antenna horizontally polarized and reflective plate isolated. (b) Antenna vertically polarized and reflective plate isolated. (c) Antenna horizontally polarized and reflective plate grounded. (d) Antenna vertically polarized and reflective plate grounded.

antenna input port calculated through VNA measurement results and the data obtained using the validation setup (Figure 6). The difference between the $VSWR$ calculated using Z_A measurement results and the $VSWR$ measured directly by power sensors is explained by the fact that the signal generator and the power amplifier, used in the validation setup, introduce more noise and harmonics than the VNA, and also because of the error associated with the automatic gain control that maintain the antenna input power fixed. Therefore, the results obtained using the VNA show smoother frequency dependence than the results found using power sensors.

The procedure was repeated with the antenna placed for vertical polarization obtaining similar results to the previous case of horizontal polarization, showing the expected correspondence.

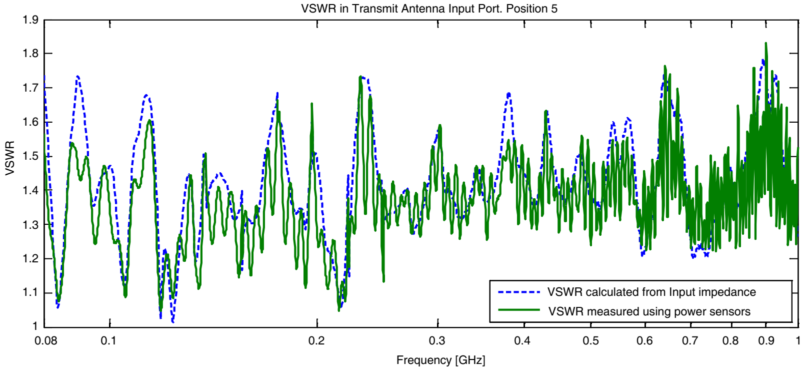


Figure 11. *VSWR* verification with the reflective plate in position 5, antenna horizontally polarized and reflective plate isolated.

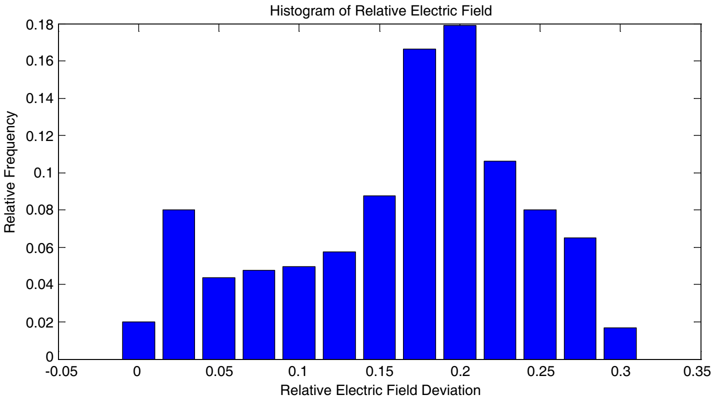


Figure 12. Histogram of relative electric field deviation, ΔE_r.

Applying the criteria defined in (8) the measurements and calculations show that the uncertainty contribution due to EUT presence in RF Immunity Testing according IEC 61000-4-3, for the particular case described in this paper, is 0.32 dB. That value should be reported in the uncertainty budget. To include this contribution to the uncertainty budget is necessary to know the distribution of data; however it is not possible to foresee the exact probability density function that best fits the phenomenon of field variations within the UFA due to interaction EUT-Antenna. The relative (statistical) frequency histogram of ΔE_r, shown in Figure 12, exhibits an asymmetric behavior, which does not correspond to a rectangular distribution as assumed in [6] nor to a triangular or normal distribution. Instead, a U-shaped distribution is more likely to be applicable [5]. Nevertheless, further research should be conducted to conclude on the use of this contribution within a budget of uncertainty. The relative frequency, shown in Figure 12, was calculated, dividing the number of measurement data points included in each bin normalized by total number of elements of the $\Delta E_r(f)$ vector.

5. CONCLUSIONS

The method proposed constitutes an experimental way to quantify the uncertainty by the presence of EUT due to Antenna-EUT coupling and reflected energy back to the source antenna on a semianechoic chamber. This method was performed, measuring antenna input impedance using a VNA and was validated through power sensor measurement using the complete measurement system corresponding to a test according IEC 61000-4-3 to ensure the results. The relative change of the electric field magnitude caused by the presence of the EUT has its maximum at 120 MHz, and represents a deviation of 0.32 dB for the worst case position. Hence the contribution associated to the uncertainty budget is 0.32 dB, which is not a depreciable quantity. Data show that ΔE_r has an asymmetrical distribution around its mean value, not corresponding to a rectangular, triangular or normal behavior. The experiments performed also show that the EUT presence by itself does not compromise the field uniformity. This could be explained as a consequence of the superposition principle of electromagnetic field theory, in which the main components of field are due to the antenna radiation, and the secondary components are consequence of the fields induced in the metallic parts of the EUT. Measurements made with the reflective plate grounded and isolated showed no significant difference. In the same way, measurements done with the antenna in vertical and horizontal polarization showed no significant differences. The method could also be useful to evaluate semianechoic chambers by comparing the electric field deviation within the UFA between them. The next investigation is to evaluate this method using different transmit antennas to know which one introduces a minor uncertainty due to the phenomenon explained in this work.

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