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Considerations about the measurement of electromagnetic emissions

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Abstract. The main goal of the paper is to present procedures and analysis of the measurement that must be performed and the compulsory results to obtain compliance with conducted and radiated electromagnetic emissions.

After the introductory section which outlines generalities related to electromagnetic compatibility (EMC), the second section focuses on the dichotomy between near-field and far-field, present in two important zones where electromagnetic phenomena are totally different, which however are not well enough highlighted in the specific EMC standards.

The third section is devoted to emission measurements that must be performed in different electromagnetic environments and for different types of equipment depicted in the specific standards in force. As an example, the case of electromagnetic emissions produced by a household gas thermal power unit is presented.

Key words. Electromagnetic compatibility, near/far field, conducted/radiated emissions measurement.

1. Introduction

According to the standard IEC 60050-161, the International Electrotechnical Vocabulary, Chapter 161: "Electromagnetic compatibility, EMC, is the ability of an equipment or system to function satisfactorily in its electromagnetic environment (immunity), without introducing intolerable electromagnetic disturbances to anything in that electromagnetic environment (interference)" [1].

In most electromagnetic compatibility problems, the equipment involved in the above definition, is both aggressor and victim of the electromagnetic environment. When an equipment acts in its environment as an aggressor, it conducts or radiates electromagnetic energy strong enough to interfere with another equipment. In this case one is confronted with electromagnetic interference or emission. If it acts as a victim, it malfunctions due to the interference with another equipment or due to the existing fields in its environment. In this last case one is confronted with electromagnetic immunity or rather with an electromagnetic susceptibility issue [2]. Electromagnetic susceptibility is simply the lack of immunity and represents the inability of a device, equipment, or system to perform without degradation in the presence of an electromagnetic disturbance.

However, it must be said that "victims" are not always completely innocent either. That is why a poor EMC design of equipment and installations can make them very aggressive with the electromagnetic ambient, determining themselves harmful emissions.

There is a multitude of phenomena related to electromagnetic emissions. Conduction phenomena at low frequency (harmonics, voltage fluctuations, short voltage interruptions, voltage asymmetry, network frequency variation, low frequency induced voltages, etc.) and high frequency (induced voltages and currents, impulses and transient oscillations), low frequency radiation (magnetic and electric fields) and high frequency (electromagnetic fields, continuous or transient waves and electrostatic discharges), electrostatic discharge (ESD), lightning (LEMP) and nuclear (NEMP) pulses, all represent some of the concerns in nowadays electromagnetic compatibility [3].

Unfortunately, neither standards and in many cases nor specific literature clearly depicts the difference between near field radiation and far field radiation, both being lumped in the same category of radiated emissions, which tends readily to lead to confusion.

2. Near-field versus Far-field

DC sources cause connected loads to move with a constant drift speed and for this reason they produce only reactive fields that store capacitive and/or inductive energy, which, however, in the presence of other circuits, can transfer energy through capacitive or inductive couplings.

On the other hand, AC sources accelerate connected loads by producing both reactive and radiated fields. In general, radiation increases with the frequency and the length of the radiating element. The radiation is usually negligible when the radiating elements are much shorter than the wavelength.

There are therefore two basic types of electromagnetic fields, storage fields and radiated fields, the main distinction between the two being that the first one stores energy in the vicinity of a source, and the last one propagates energy through space.

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Storage fields can only exist in the vicinity (a few wavelengths) of conducting structures. Moreover, these fields disappear when their sources disappear or are disconnected. In contrast, radiated fields propagate (theoretically infinitely in a non-dissipative medium), continuing to exist even when their sources have already disappeared [4].

Storage fields can be only static, purely electric, and magnetic, or a combination of the two (fixed electric charges and/or permanent magnets). But for a field to transmit energy, it must necessarily be an electromagnetic one. The condition that two independent fields, electric and magnetic, coexist in the same region of space is an insufficient one. They must be the mutually related components of an electromagnetic field, with the direction of movement given by the Poynting vector $\overline{S} = \overline{E} \mathrm{x} \overline{H}$ (energy transmission or radiation vector).

Starting from Maxwell's equations, it is easy to arrive to the following expression:

$$-\int_V \left(\overline{E} \frac{\partial \overline{D}}{\partial t} + \overline{H} \frac{\partial \overline{B}}{\partial t} \right) dV = \int_V \overline{E}\,\overline{J} dV + \oint_A \left(\overline{E} \mathrm{x} \overline{H} \right) d\overline{A} \qquad (1)$$

or obviously

$$-\frac{\partial}{\partial t} \int_V \left(\frac{1}{2} \varepsilon E^2 + \frac{1}{2} \mu H^2 \right) dV = \\ = \int_V \frac{\overline{J}^2}{\sigma} dV - \int_V \overline{E}_i \overline{J} dV + \oint_A \left(\overline{E} \mathrm{x} \overline{H} \right) d\overline{A} \qquad (2)$$

which can be interpreted as a theorem of conservation of electromagnetic energy (the notations are notorious) [5].

The left-hand side of the relationship is nothing, but the unit time variation of the electromagnetic energy contained in volume V, i.e. the power density. The right-hand side of the relationship shows the quantities responsible for developing this power density. The first two terms are part of the energy balance used for low frequency, and the third one contains the Poynting vector, and represents the radiated power density.

Since the storage fields are always concentrated near the source, the usual term for their designation is that of near field. In contrast to storage fields, radiant fields initially "spread" over spherical surfaces of the same total energy. For this reason, radiated fields are often called far fields. Unfortunately, the term far field is sometimes also used to denote a very distant portion of a radiated field, where the radiation is approximately a plane wave.

Another major difference between stored and radiated fields is the way in which the source reacts when an object absorbs or displaces some of the energy contained in the field.

It is known that the propagation of radiated field energy is affected by absorption, reflection, or diffraction, however the introduction of a receiver in the field creates no effect over the source that produced it. On the other hand, moving or extracting energy from a nearby field will necessarily cause a reaction in the source that produced it. For this reason, storage fields are also called reactive fields. Furthermore, coupling a circuit in near-field not only picks up unwanted energy but also alters the operation of that circuit by extracting or redirecting stored energy into its nearby space.

The explanation of the fact that the reactive field (near-field) of an AC source is concentrated in the vicinity of the source, and the radiated field (far-field), extends its effects far from the source is mathematically straightforward.

The radiated power density of an electromagnetic field at the distance *r*, namely the third term of the right-hand side of eq. (2), can be represented by the following Maclaurin series [6]:

$$p_d = \frac{K_1}{r^2} + \frac{K_2}{r^3} + \frac{K_3}{r^4} + \ldots \qquad (3)$$

Imagining a sphere having the radius *r*, centered on the source, the total power passing through each of its surfaces can be calculated by multiplying the power density by its area:

$$P = \left(4\pi \cdot r^2 \right) \cdot p_d = 4\pi \left(K_1 + \frac{K_2}{r} + \frac{K_3}{r^2} + \ldots \right) \qquad (4)$$

The first term is a constant one, independent of *r*, being exclusively due to the field radiated by the source. The contribution of this term to the power (energy) value is constant, regardless of the size of the chosen sphere. As the radius of the sphere increases, the terms varying with the radius become negligible, which explains the reason why the radiated field is also called far-field.

Conversely, at very small distances (small values of *r*), the terms varying with the radius values become predominant, the constant term being this time negligible in relation to the variable ones. The sum of the distance-varying terms represents the power (energy) stored in the reactive field, and since they are dominant at small distances they represent near-field terms.

Fig. 1 presents the specific zones related to the electromagnetic fields generated by some source.

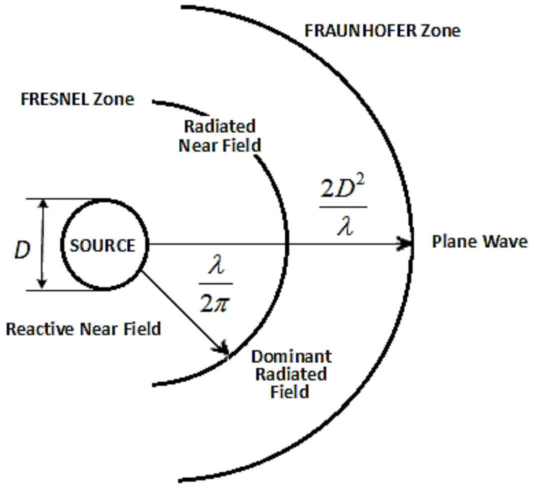


Fig.1 Zones of electromagnetic fields.

The geometry of the near field lines is closely related to the structure of the source, usually presenting complicated shapes, while the geometry of the far fields becomes independent of the source, taking the form of spherical waves, which at sufficiently large distances become practically plane waves. In this zone, the impedance of the free space is given by the equality of the electric and magnetic components of the energy of the wave

$$\frac{B^2}{2\mu_0} = \frac{\varepsilon_0 E^2}{2} \rightarrow Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 120\pi = 377\ \Omega . \qquad (5)$$

The impedance of the free space is an essential parameter in the analysis of the coupling of an electromagnetic wave to another conducting structure or to a screen.

The zones depicted in Fig. 1 are quantitively quantified and named by analogy with optical physics. The plane wave region is the region in the far field region where the radiation can be approximated by a plane wave, zone called also the Fraunhofer zone, while all the other three zones together constitute the Fresnel zone. [7].

The zone where $r \approx \frac{\lambda}{2\pi}$, of about one-sixth of the wavelength, is the transition region between the near and far fields.

In the range $r \approx \left[\frac{\lambda}{2\pi}, \frac{2D^2}{\lambda}\right]$ one speaks about the far radiant field (according to the Rayleigh criterion). In this zone, the proportion of the energy stored in the field is much lower than the proportion of the radiated one.

Far-field waves maintain the wave impedance of the medium, being always electromagnetic, and circuits will absorb energy if they contain antenna-like elements.

Near-fields are usually dominated by one of the components, electric or magnetic, with inductively coupled energy having different characteristics.

High impedance circuits are particularly susceptible to interference from nearby electric fields while low impedance circuits are susceptible to interference from nearby magnetic fields.

Both near-field electromagnetic interference, which should rather be called induced interference, to differentiate it from far-field radiated interference, are frequency dependent. Energy in the near field is even strongly dependent on the frequency, the effects induced in a circuit being proportional to the speed of variation versus time of the magnetic field. Therefore near-field interference increases with the intensity of the magnetic field and with its frequency and decreases with the distance from the electromagnetic interference source [8].

However, for simplicity, and for practical reasons, regulations accredit the idea that radiated emissions are assumed to be predominant above the 30 MHz frequency, while conducted emissions are assumed to dominate the spectrum below 30 MHz.

The main reason is that usually above 30 MHz cables have resonant frequencies, which would lead to anomalies in measurement results. Beyond 30 MHz, one refers to radiated emissions.

3. Measurements and Discussions

To prevent malfunction due to electromagnetic interference, international regulatory bodies set limits of conducted and radiated emissions, limits that must be met by equipment placed on the market, such as consumer electronics, telecommunication systems, information technology systems, and medical equipment etc.

There are several organizations that provide emission limits for different equipment, such as:

- The International Electrotechnical Commission (IEC), a renowned regulatory body that sets generic EMC standards for equipment or systems in residential, industrial and commercial environments,
- CISPR (International Special Committee on Radio Interference) which regulates through basic, generic and product standards the emissions generated by electronic equipment,
- The Federal Communication Commission (FCC) and European Standards (EN), that drafts conducted emissions limits in industrial, scientific, communication, automotive, medical, and consumer devices.

If the equipment under test (EUT) falls within the allowable limits of the standards, the equipment is considered electromagnetic emissions compliant.

Apart from the above-mentioned regulatory bodies, in European countries are also popular the regulations issued by the European Committee for Electrotechnical Standardization (CENELEC), and the European Telecommunications Standards Institute (ETSI).

It worth mentioning that nowadays, three level regulations are in force:

- basic standards, which define measuring equipment, measurement methods and measurement and test uncertainty (e.g., CISPR 16 series)
- generic standards, which set limits through an interference model (e.g., IEC 61000-6 series and EN 50081 series for emissions and immunity)
- product and product-family standards, which provide both product specific requirements such as EUT operation and arrangement, measurement methods, measurement uncertainty and justified deviations from limits (e.g., CISPR 11, 12, 14, 15, 32).

Standards are updating continuously, mainly in terms of technology and in setting current limits.

Thus, the new basic standard CISPR 16-1-1 series allows the transition to fast FFT-based EMI receivers for EMI compliance measurements, to new LISN requirements (phase tolerance ±11.5° in addition to magnitude tolerance of ±20%), to minimum 40 dB RF isolation between EUT/receiver and mains ports and to the evaluation procedure for radiated disturbance measurements, with the frequency range 200 MHz to 1, 6, 18 GHz, the step size ≤ 0.5% of max. frequency, the use of a small ≤ 40 cm biconical antenna to 1 GHz and of a transmit antenna as used for site validation above 1 GHz) [9].

As future work, an RMS-Average weighting detector will be incorporated in measurement procedures. It represents a valuable alternative to consecrated quasi-peak and average detectors. Its level versus frequency is situated between the levels of the average and quasi-peak detectors. From Fig. 2 one can also see that it exhibits a decreasing slope of 20 dB/decade up to a corner frequency of 10 Hz, after which its decreasing slope becomes only of 10 dB/decade.

Electromagnetic radiated and conducted emissions pre-compliance or compliance testing are usually performed using dedicated measurement receivers, optimized to perform EMC measurements, and having the following main features:

- high sensitivity, which allows signals to be discriminated by noise at levels well below standardized emission limits,
- greater resistance of input circuits to overload,
- high accuracy in amplitude and frequency.

Spectrum analyzers, much cheaper than EMC measurement receivers, are also widely used for rapid diagnosis, being suitable for visualizing frequencies and helping the interpretation of the nature of aggressive emissions.

In this experimental section, measurements are performed in compliance with the EMC standards EN 50081-1 as a generic standard, compatible to EN 55011/CISPR 11 as a product standard.

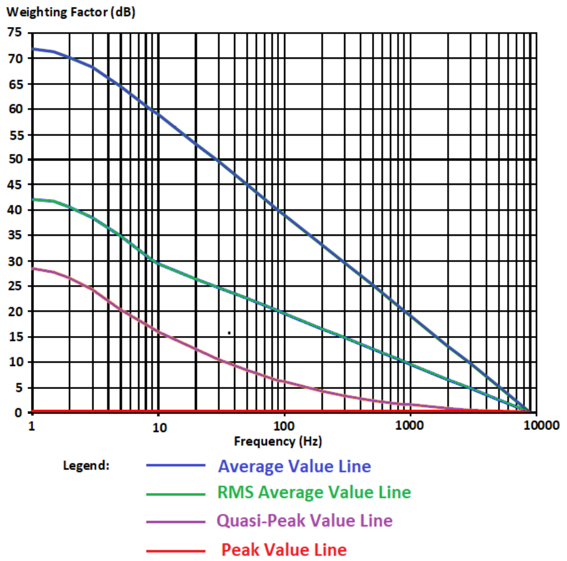


Fig. 2 RMS weighing detector compared to detectors in use.

The generic standard EN 50081-1, issued by CENELEC, deals with electromagnetic emissions in residential, commercial, and light industry environments [10].

The product standard EN 55011 is devoted to industrial, scientific, and medical electrical equipment and it operates in the frequency range 0 Hz to 400 GHz.

The standard EN 55011 separates equipment into two groups [11]:

- *Group 1 equipment:* contains all equipment in the scope of the standard, which is not classified as group 2 equipment,
- *Group 2 equipment* contains all equipment in which radio-frequency energy in the frequency range 9 kHz to 400 GHz is intentionally generated and used or only used locally, in the form of electromagnetic radiation, inductive and/or capacitive coupling, for the treatment of material, for inspection/analysis purposes, or for transfer of electromagnetic energy.

According to the intended use of equipment in an electromagnetic environment, they are divided into two classes:

- *Class A*: is equipment suitable for use in all locations other than those allocated in residential environments and those directly connected to a low voltage power supply network which supplies buildings used for domestic purposes.
- *Class B*: is equipment suitable for use in locations in residential environments and in establishments directly connected to a low voltage power supply network which supplies buildings used for domestic purposes.

As an experimental exemplification, in the following, the electromagnetic emission measurements, produced by one gas heating unit equipment (Group 2, Class B) will be analyzed.

Measurements are compliant with the generic standard EN 50081, respectively the product standard EN 55011 [12].

Fig. 3 presents the limits of conducted emissions at the mains terminal and radiated emissions at the distance of 10 m, according to the standard EN 55011.

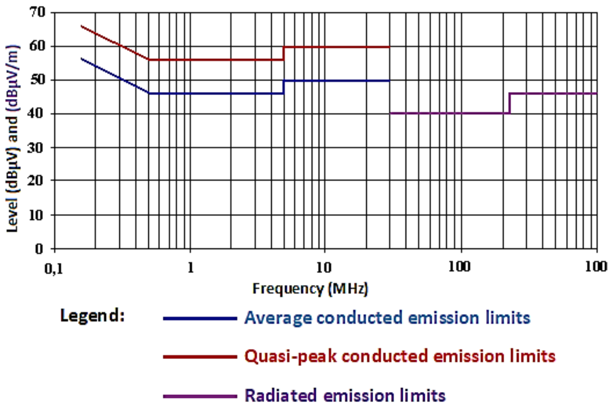


Fig. 3 Emission limits according to standard EN 55011.

Quasi-peak and average conducted emissions values must not exceed 60 dBμV, respectively 50 dBμV, in the frequency range 0.15-30 MHz, whilst quasi-peak radiated emissions values must not exceed 47 dBμV/m in the frequency range 230-1000 MHz.

A. *Conducted electromagnetic emissions*

In conducted emission phenomenon a certain portion of the electromagnetic energy produced by the equipment will be conducted onto the power supply cord.

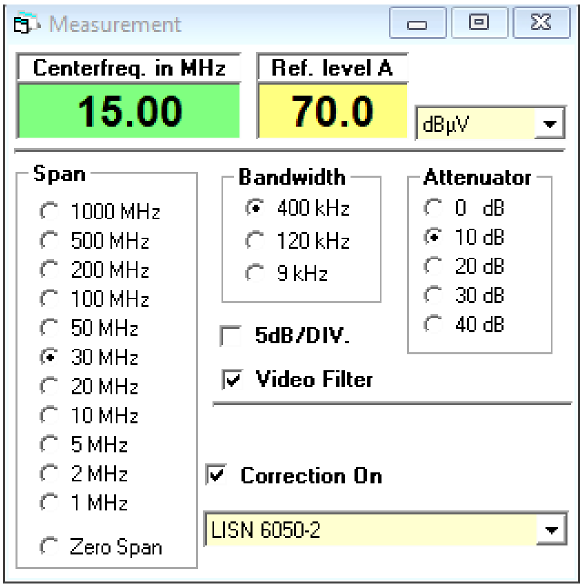
Equipment used for conducted emissions measurements is line impedance stabilization network (LISN), spectrum analyzer, RF cable, attenuator.

Conducted emission measurement parameters are presented in Fig. 4. One can see the 15 MHz central frequency of the 0-30 MHz measurement range. The reference level is evidently 70 dBμV and the attenuator is set at 10 dB according to the standard. For a better display resolution, the minimum bandwidth, namely 9 kHz, was chosen. The type of the line impedance stabilization network associated with the measuring equipment, LISN 6050-2, is also displayed.

In Fig. 5 the display mode parameters used for measurement are presented: the standard (EN 50081-1), the main values to be measured, namely the average and quasi-peak values.

Figs. 6 and 7 display the measurement results of conducted emissions produced by the equipment under test (EUT) in linear and logarithmic scales.

One can see that the EUT doesn't exceed the standard limits for the quasi-peak (60 dBμV- red line) and average value (50 dBμV- blue line). The actual maximum quasi-peak level of emissions is 38.2 dBμV occurring at the frequency of 11.157 MHz and the minimum average level is less than 16 dBμV in the end of the measurement range.



Centerfreq. in MHz: 15.00

Ref. level A: 70.0 dBμV

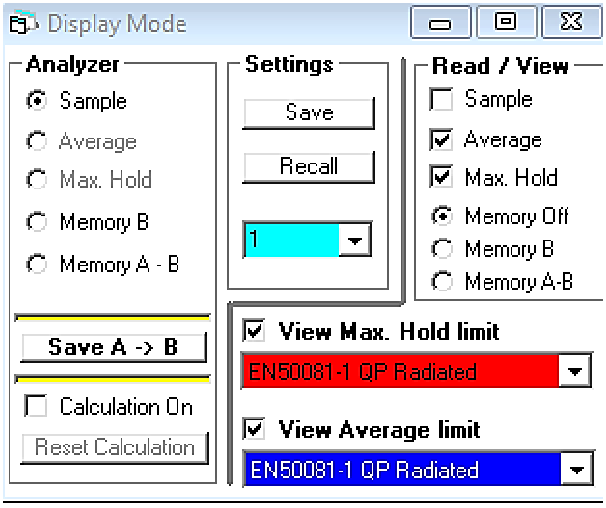
Span
○ 1000 MHz
○ 500 MHz
○ 200 MHz
○ 100 MHz
○ 50 MHz
● 30 MHz
○ 20 MHz
○ 10 MHz
○ 5 MHz
○ 2 MHz
○ 1 MHz
○ Zero Span

Bandwidth
● 400 kHz
○ 120 kHz
○ 9 kHz

Attenuator
○ 0 dB
● 10 dB
○ 20 dB
○ 30 dB
○ 40 dB

☐ 5dB/DIV.
☑ Video Filter
☑ Correction On
LISN 6050-2

Fig. 4 Conducted emission measurement parameters



Analyzer
● Sample
○ Average
○ Max. Hold
○ Memory B
○ Memory A - B

Settings
1

Read / View
☐ Sample
☑ Average
☑ Max. Hold
● Memory Off
○ Memory B
○ Memory A-B

☐ Calculation On

☑ View Max. Hold limit
EN50081-1 QP Radiated

☑ View Average limit
EN50081-1 QP Radiated

Fig. 5 Conducted emission display mode parameters

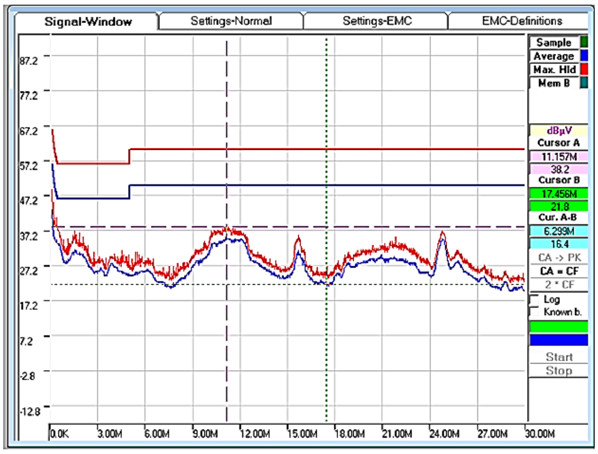


Fig. 6 Conducted emission measurement in linear scale

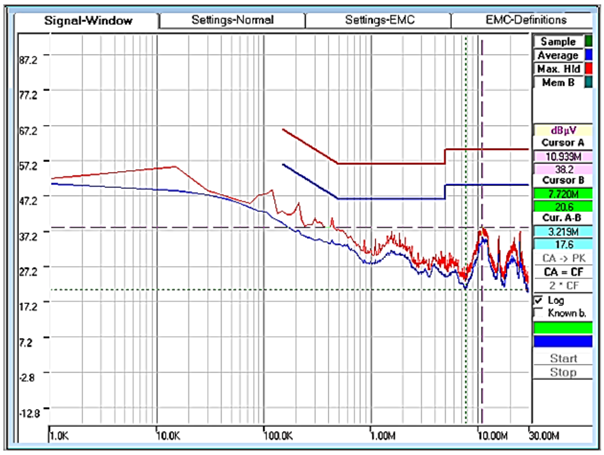


Fig. 7 Conducted emission measurement in logarithmic scale

Finally, one may conclude that the EUT is compliant according to the conducted emissions viewpoint.

B. *Radiated electromagnetic emissions*

Radiated emissions testing involves the measurement of the electromagnetic field intensity of the emissions produced unintentionally by the equipment into the air.

Equipment used for measuring radiated emissions is: TRILOG broadband test antenna, spectrum analyzer, coaxial test probe.

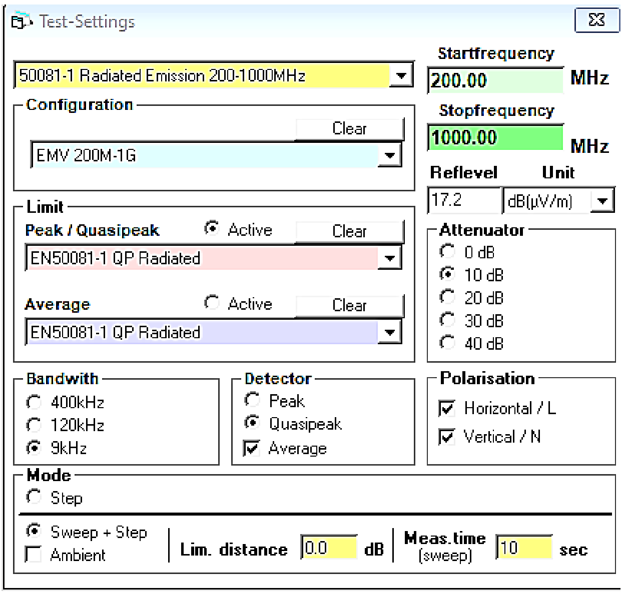
Radiated emission test settings are presented in Fig. 8.

The measurement range is 200-1000 MHz. The standard recommends the use of a 10 dB attenuator. Again, for a better resolution a 9 kHz bandwidth is chosen.

Both quasi-peak and average available detectors were activated along with both horizontal and vertical polarizations of the receiving antenna. The sweep was set to every ten seconds.

Figs. 9 displays the measurement results of radiated emissions generated by the equipment under test (EUT) at the distance of 10 m in linear scale.

The standard limit of 47 dBµV/m (the magenta line) for the quasi-peak value is displayed. The average limit value is not specified in the standard EN 55011.


Test-Settings

50081-1 Radiated Emission 200-1000MHz

Startfrequency: 200.00 MHz
Stopfrequency: 1000.00 MHz
Reflevel: 17.2
Unit: dB(µV/m)

Configuration
EMV 200M-1G

Limit
Peak / Quasipeak ● Active
EN50081-1 QP Radiated
Average ○ Active
EN50081-1 QP Radiated

Attenuator
○ 0 dB
● 10 dB
○ 20 dB
○ 30 dB
○ 40 dB

Bandwith
○ 400kHz
○ 120kHz
● 9kHz

Detector
○ Peak
● Quasipeak
☑ Average

Polarisation
☑ Horizontal / L
☑ Vertical / N

Mode
○ Step
● Sweep + Step
☐ Ambient

Lim. distance 0.0 dB
Meas.time (sweep) 10 sec

Fig. 8 Radiated emissions test settings

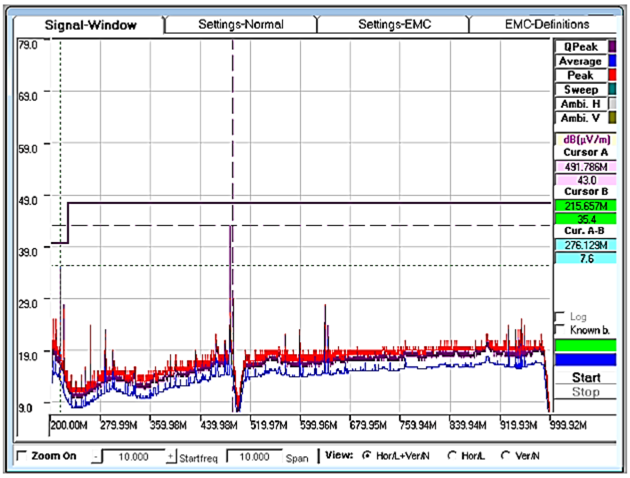


Fig. 9 Radiated emission test in linear scale

Again, the EUT doesn't exceed the standard limit, the maximum quasi-peak level of radiated emissions being 43 dBµV/m which occurs at the frequency of 492 MHz.

So, the EUT being compliant including in what regards radiated emissions limits, one may conclude that the EUT is overall compliant with standard electromagnetic emissions.

4. Conclusions

It is obvious from the sections of the body of the paper that the problem of assessing EMC compliance of a product is a vast one, both due to the relatively large number of standards to be covered and to the complexity of the required measurements that need to be included in every EMC test report. Also, EMC compliance assessment is time consuming and costly, therefore fitting the tests into the specific standards is a crucial issue, to not misrepresent the results.

In conclusion, it is almost compulsory that the assessment of the compliance with EMC requirements be a constant concern from the very early stage of any design. In this respect one mustn't neglect to carry out pre-compliance home rapid tests at various stages of the design, which obviously may lead to time and money savings.

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