ELECTROMAGNETIC TEST ENVIRONMENTS ANALYSIS FOR EMI MEASUREMENTS

ANALISIS LINGKUNGAN UJI ELEKTROMAGNETIK UNTUK PENGUKURAN GANGGUAN GELOMBANG ELEKTROMANETIK

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ABSTRACT

This paper presents an analysis and review of different electromagnetic (EM) test environments for Electromagnetic Interference (EMI) measurements to verify its advantages or disadvantages and to obtain the correlation between those environments, namely: semi-anechoic chamber (SAC), fully anechoic room (FAR), classical reverberation chamber (RC) and vibrating intrinsic reverberation chamber (VIRC). The first analysis is based on literature studies from previous research by analyzing four key parameters: power-to-electric field ratio, the frequency range, equipment under test (EUT) size, and on-site measurement applicability. In order to verify their correlation, further investigation was done by radiated emission (RE) measurement of dummy EUT, simple monopole, in those environments. The literature study concluded that each test environment has advantages and drawbacks concerning some aforementioned evaluation. The existing SAC environment showed more established technique, but expensive and time-consuming. However, despite the small limitation on susceptibility and dwell time, RC, in particular VIRC, delivers potential and promising technique, with statistically good E-field uniformity, more time-efficient and on-site measurement applicability. The radiated emission simulation and measurement results of monopole antenna confirmed their correlation and the E-field strength graph showed a considerably similar pattern, except for frequency range 1.6 to 2 GHz where null radiation pattern occurs for some azimuth angle.

Keywords: electromagnetic test method, EM environments, test analysis, EMI measurements, EMC.

ABSTRAK

Paper ini menyajikan kajian dan analisis dari beberapa lingkungan pengujian elektromagnetik untuk pengukuran gangguan elektromagnetik untuk mengetahui kelebihan dan kekurangan masing-masing serta untuk mendapatkan korelasi antara lingkungan EM tersebut, yaitu: semi-anechoic chamber (SAC), fully anechoic chamber (FAR), reverberation chamber (RC) klasik dan vibrating reverberation chamber (VIRC). Analisis pertama dilakukan berdasarkan kajian litatur dari penelitian-penelitian sebelumnya dengan menganalisis empat (4) aspek penting, yaitu : perbandingan daya terhadap kuat medan elektrik, rentang frekuensi pengukuran, ukuran objek uji dan aplikasi untuk pengukuran on-site. Analisis lanjutan dilakukan dalam rangka verifikasi dengan melakukan pengukuran radiasi emisi EM dari benda uji sederhana, antenna monopol, pada empat lingkungan EM yang berbeda tersebut. Berdasarkan analisis empat parameter tersebut, kajian literatur menyimpulkan bahwa setiap lingkungan EM mempunyai kelebihan dan kekurangan masing-masing. Lingkungan EM AC menunjukkan teknik dan pengukuran yang telah lama dipakai dan teruji, tetapi membutuhkan biaya yang mahal dan waktu pengukuran yang lama. Di lain pihak, dengan keterbatasan pengujian ketahanan elektromagnetik dan dwell-time, RC secara khusus VIRC menunjukkan potensi dan teknik yang menjanjikan, dengan teknik pengolahan statistik homogenitas medan listrik yang baik, waktu pengukuran lebih cepat dan dapat dilakukan pengukuran/pengujian on-site. Hasil simulasi dan pengukuran antenna monopole di empat lingkungan EM yg berbeda, grafik kuat medan listrik menunjukkan adanya kemiripan kurva dan korelasi antara standard EM tersebut, kecuali pada rentang frekuensi 1,6 sampai 2 GHz di mana terjadi null pola radiasi pada beberapa sudut azimuth.

Kata Kunci: *metode pengujian elektromagnetik, lingkungan elektromagnetik, analisis pengujian, pengukuran gangguan Elektromagnetik, EMC*

1. INTRODUCTION

The deployment of electronic products in everyday life is significantly increasing the number of electromagnetic (EM) emission sources due to the improvement of tele-communication technology. For example, the amount of wireless communication is growing rapidly (e.g., Wi-Fi, Bluetooth, 4G, and 5G technologies, wireless sensor networks (WSN), radar, smart cities concept and more). These sources are becoming more compound and, in many cases, these products emit a lot of unwanted signals to one another. Moreover, the electronic devices that are evolving towards higher frequencies, smaller designs with limited electromagnetic compatibility (EMC) measurements, and lower power levels of operation resulting in the complexity of electromagnetic pollution. Electro-magnetic emissions in such environments can easily be the cause of much electromagnetic interference (EMI). EMC is defined as "the ability of the equipment, subsystem, or system to share the electromagnetic spectrum and perform at the same time its desired function without unacceptable degradation from or to the environment in which it exists." (Paul, 2006)

Today's electronic devices must be designed to be acceptably compatible with other electronic products. A key aspect of proper electronic design and optimization is EMI or EMC testing[1] based on EMC standards, i.e.: IEC 61000-4-3 (Commission, 2006) for mostly susceptibility test and depending on the electrical product class/family, i.e.: industrial-scientific-measurement equipment (CISPR 11, 2005), automotive (CISPR 25, 2014), ITE equipment (CISPR 22, 2005), household equipment (CISPR 14-2, 2015), etc, for radiated emission (RE) or radiated susceptibility (RS) test. The different existing test methods have been developed from classic concepts and techniques, such as free space EM environment. Many EMC test laboratories are commonly applying these conventional EMC tests (and relying on them) inside a semi-anechoic chamber (SAC), both for radiated emission (RE) and radiated susceptibility (RS) testing (Dwi Mandaris, 2020).

The conventional AC technique has been used for many decades. It is the most popular and the most established method for testing the compliance of

[1] Actually, we should call it EMI testing, but in common language people talk about EMC testing

equipment due to EM interference, but it requires expensive facilities and time consuming (Evangelia, 2020). On the other hand, RC has also been generating interest among researchers and engineers over the past decade as an alternative test method, as it reduces testing time and is more cost-efficient (Dwi Mandaris, Vogt-Ardatjew, Zaher Mahfouz, Suthau, & Leferink, 2018). Previous studies have compared RE test results between different test sites (F. Leferink, Hilverda, Boerle, & van Etten, 2003)(Hilverda, Leferink, Boerle, & van Etten, 2002)(Wilson, 2004)(Wilson, Holloway, & Koepke, 2004) to examine the applicability of different sites for performing EM measurements and showed the results were not satisfied yet. Therefore, further research is required to confirm and validate the applicability of different test environments for different EUTs and to increase their interchangeability, so test results from different sites can be correlated.

In order to examine different test environments, this paper discussed on reviewing and analyzing the correlation between EMI test standards in the different test sites (SAC, FAR, RC and VIRC), while TEM cell is out of this paper scope. Moreover, this research was verified by radiated electromagnetic field measurements of simple dummy EUTs, monopole antennas, as a reference and well-known radiation pattern in different test sites/ environments, by investigating the transfer function of E-Field.

2. ELECTROMAGNETIC TEST ENVIRONMENT

Regarding the field generation principle or EM signal detection method inside the EM chamber, EM measurement test environment basically can be subtracted into 3 different based environments (Morgan, 2011), namely; Anechoic Chamber (AC) including Semi-Anechoic chamber (SAC) and Fully Anechoic Room (FAR), the strip line EM like structure or Transverse Electromagnetic (TEM) or Gigahertz Transverse Electromagnetic (GTEM) and Reverberation Chamber (RC), including classical RC and Vibrating Intrinsic Reverberation Chamber.

Anechoic Chamber (AC)

The measurement principle of the AC environment is the line of sight (LOS) which only a single propagation path exists between two points, therefore the field can be analyzed in a deterministic way. If a reflection exists, like open area test sites (OATS) the two waves interfere with each other depending on the phase, amplitude, polarization, and direction of propagation. The analytical description of such a field is only possible if all the parameters are known and AC provides this solution.

AC can be divided into SAC and FAR. They are a half-space chamber or fully space chamber and utilizing the antennas either as detecting sensor or transmitting transducer. SAC is a shielded enclosure with absorbers mounted on the walls and ceiling.

Because the SAC has also a reflecting floor as a reference plane, it is comparable to an OATS. However, the typical disadvantages of the OATS, the influence of the weather and ambient signals, are not applicable for a SAC. Figure 1 is shown the geometry of the SAC.

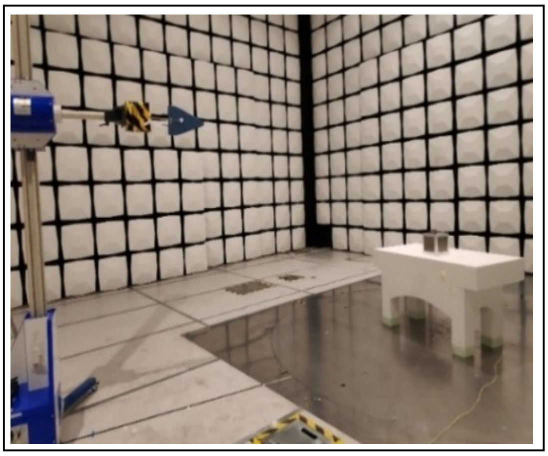

Figure 1. Semi anechoic chamber (SAC) test environment

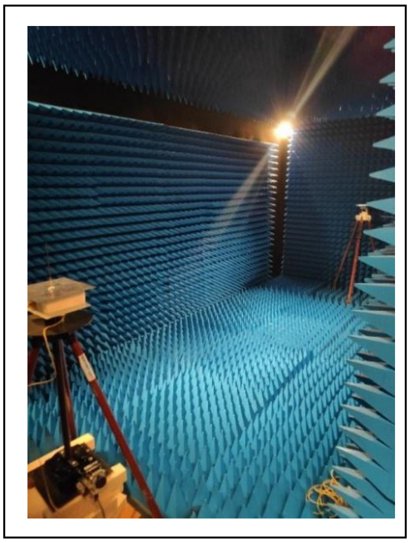

Figure 2. Fully anechoic room (FAR) test environment

The fully anechoic room or chamber is a shielded enclosure where the walls, ceiling, and floor have been covered with absorbing material. Therefore, this is a test site that provides a free space environment that replicating outer space. The geometry of the FAR is depicted in Figure 2.

GigaHertz Transverse Electromagnetic (GTEM) Cell

Figure 3. Gigahertz transverse electromagnetic (GTEM) Cell test environment

The GTEM cell is a coaxial line expanding pyramidally and having an impedance of 50 Ω. At its end, the line is terminated by a combination of termination resistors and RF absorbers designed and constructed to match the above-mentioned impedance. The EMC test method and procedure inside GTEM is based on IEC 61000-4-20 [ref]. Normally, the EUT was placed in the GTEM inside a structure and they were tested in 3 orthogonal positions (x, y, z) and 4 rotations for each one of these three positions, a total of 12 measurements for each EUT. The GTEM environment can be seen in Figure 3. Gigahertz transverse electromagnetic (GTEM) Cell test environment

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Reverberation Chamber (RC)

RC is an electrically large, highly conductive enclosed cavity or chamber (A. Hill, 2009). As opposed to deterministic free space methods such as anechoic chambers (AC), reverberation chambers utilize the multipath behavior of the field. They are designed and built to maximize the efficiency and effectivity of EMC/EMI testing in terms of measurement time, sensitivity, repeatability, and also costs. To satisfy those requirements and provide optimal results, RCs exploit the property to create strong resonances, which significantly increase the amplitude of the measured field, almost entirely overpowering the non-resonating components. The isotropy, statistical uniformity, and random polarization of the bouncing waves inside a perfect RC allow the measurements of statistics, such as the average, to be performed with reasonably high repeatability (Vogt-ardatjew, 2017).

The objective of a reverberation chamber is to generate anisotropic and statistically uniform test environment. This is conventionally accomplished by introducing a mechanical tuner into a shielded room. By rotating the tuner, the boundary conditions within the chamber are changed. Once the tuner has been moved to a sufficient number of positions the field at any given point is statistically uniform. The geometry of an RC is shown in

Figure **4**.

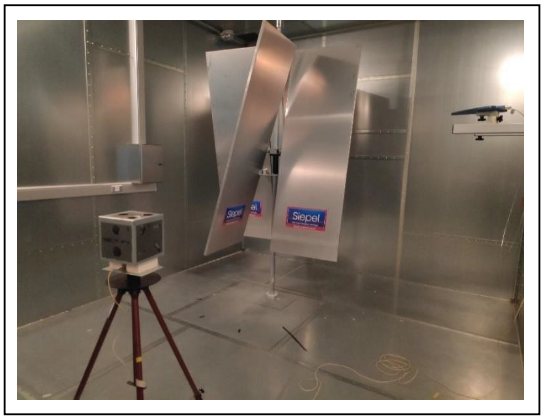

Figure 4. Classical reverberation chamber (RC) test environment

Figure 5. Vibrating intrinsic reverberation chamber (VIRC) test environment

The Vibrating Intrinsic Reverberation Chamber (VIRC) is a new type of reverberation chamber made of conductive fabric. By vibrating the walls, the field inside the VIRC is diffused and a statistically uniform electromagnetic field is created without the use of a mechanical rotating stirrer like classical one. The VIRC set up is depicted in Figure 5.

3. METHODOLOGY

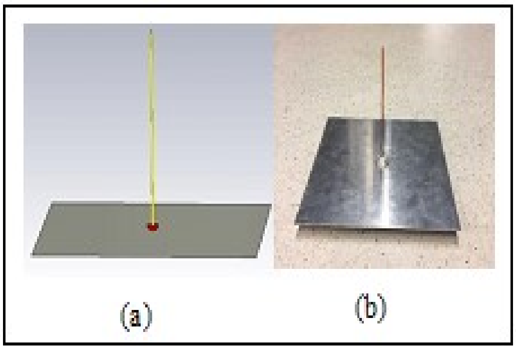

Figure 6. (a) Designed monopole antenna (b) Picture of monopole antenna

Two research methods and approaches have been applied in this section, literature-based and empirical (experiment) study. The first one is reviewed and analyzed some EM measurement environments by looking into four important parameters based on prior research. The next method is by experiment with dummy equipment under test (EUT) to verify the literature study.

In the simple measurement, the dummy EUT has been used. The EUT is a monopole antenna. It is used as a reference due to a well-known radiation pattern to show the correlation between the different environments. Additionally, this monopole also designed and simulated in 3D full-wave EM software. The simulated E-Field is then compared with the experiment results. The model of the monopole antenna can be seen in and it has length

15 cm and 2 mm in diameter and ground plane size is 20 cm × 20 cm.

Since the length of the monopole is 15 cm, the resonant first frequency should be at the frequency where this length is a quarter of the wavelength, meaning the resonance is approximate:

$$F_{resonance} = \frac{c}{0.15*4} = 500\ MHz \qquad [1]$$

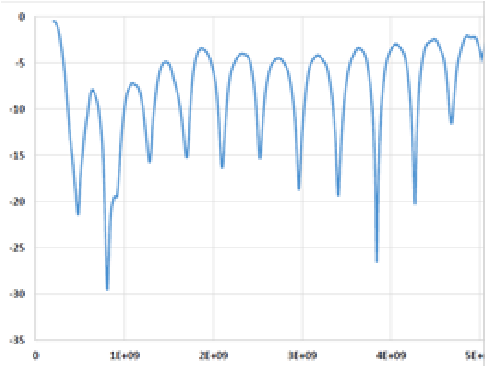

Figure 7. The coefficient reflection of monopole antenna

The next resonant frequencies will be approximately 1.5 GHz, 2.5 GHz, 3.5 GHz, and so on, while the anti-resonant frequencies will be at 1 GHz, 2 GHz, 3 GHz, and so on. These can be also seen in, which shows the S_{11} parameter of the monopole.

The measuring equipment consists of:

a. Receiver: A small LPDA antenna connected to the spectrum analyzer by a coaxial cable.

b. SPA with tracking generator (Anritsu MS2712E): This was configured in the two-port transmission measurement mode, so the transmitted signal was generated by tracking generator. The tracking generator's output power was approximately 0 dBm. The frequency range under test was from 400 MHz to 4 GHz with 551 frequency points.

c. The four test sites, FAR, SAC, RC, and VIRC are described in the previous subsections.

The monopole was connected to the spectrum analyzer (SPA) with an optical RF link (working frequency: 300 MHz to 3 GHz) to minimize the influence of this connection on the measurement results. All test methods and procedures follow the applicable international standard based on the EM environment.

In particular, for RC or VIRC, the received power needs to be converted to total radiated power according to the relevant standard (Commission, 2011). Then by taking the antenna efficiency (η) factor for the receiving antenna (for log-periodic antennas, it is 0.75) and directivity (D) 0.64 for monopole, E-Field can be calculated as follows:

$$E\text{-}field\ (V/m) = g_{max}\sqrt{\frac{\eta_o D_{max} P_{total}}{4\pi}} \qquad [2]$$

where, $g_{max} = \frac{2}{r}$ in comparison with FAR and $\frac{1}{r}$ in comparison with SAC and r is measurement distance in the FAR/SAC.

4. RESULT AND DISCUSSION

Evaluation is based on four key aspects, as follows:

Power to Electric Field (E-Field) ratio

AC is typically used antennas as generating transducer or receiver. For instance, to achieve 10 V/m E-field strength, more than 100 Watt is required in generating side (Ott, 2009). Moreover, the required level depends on the operational environment. For instance, automotive and military equipment require up to 600 V/m and up to 200 V/m, respectively MIL-STD-461F, 1999). Although this is a common issue in the EMC world, very little literature exists. It is quite obvious that the key element is the antenna, which should give sufficient directivity in both planes (horizontal and vertical). On the other hand, the directivity should not be too much, as it will decrease the UFA. To improve our understanding and gain insight into the underlying properties of the antennas, a lot of measurements have been performed and supplemented with simulations. By analyzing both measurement and simulation results, the power needed by the antenna and the UFA were investigated (Frank Leferink, 1998b)(D. Mandaris & Leferink, 2017)(D. Mandaris, Moonen, Schuurmans, & Leferink, 2017).

However, this does not help to avoid the existing costly AC facilities with field absorbers. Another disadvantage when using antennas is the long test time, as a EUT has to be illuminated from all directions. A further essential problem is the size of the antenna. Theoretically, the antenna length is proportional to the longest wavelength, or lowest frequency of the band. In order to reach a minimum frequency of as low as 80 MHz, which is the default starting frequency for IEC-based standards, more than 1 m antenna size is required to make sure that the far-field region is reached (Balanis, 2005). Another issue is the vertical polarization when employing LPDA antennas (Frank Leferink, 1998a), as the tip of the dipole array is near to the metal floor, which causes coupling.

The second environment to develop a high E-field is the stripline or TEM cell-like structure (Frank Leferink, 1998c)(IEC 61000-4-20, 2006). The stripline TEM-like antenna technique was developed in 1971 and the rectangular, so-called Crawford cell was built for calibration purposes by the National Bureau of Standard (NBS)

(Crawford, 1974). After that, many kinds of TEM cell improvements were made and a comprehensive review of these TEM cell techniques can be found in (Frank Leferink, 1998b). This paper also proposes applying the new concept of the balanced stripline antenna and the results showed that, compared to the conventional antenna technique, the stripline required less power, gives better field uniformity (FU), and operates in a larger frequency range. The current state-of-the-art technique, well known and widely applied (IEC 61000-4-20, 2006), is GTEM as an alternative EMC test method. In terms of P2E, this is an interesting technique to develop a high E-field with moderate power. As mentioned in (Frank Leferink, 1998c), the power needed for the antenna to achieve 10 V/m is below 1 W. As a comparison, in a normal anechoic shielded enclosure, at least 100 W is needed to generate a field strength of 10 V/m over an area of 1.5 m × 1.5 m (Morgan, 2011). However, the TEM cell technique is not within the scope of this paper.

The last one is the RC technique. RC is an alternative test technique capable of creating high field strengths. The RC was introduced the first time in MIL-STD 1377. An RC is an electrically large, multimode, and highly reflective cavity or environment. Many publications on the RC can be found in the literature, for instance (Frank Leferink, 1998a)(Crawford & Koepke, 1986)(Hill, 1998)(Ramiro Serra, 2010). Some advantages of using the RC technique include:

a. A considerably large working volume compared to the total volume in the chamber (Ramiro Serra, 2010).
b. There are no disruptive ambient signals because RCs work in a screened environment.
c. RCs work in a relatively wide frequency range (F. Leferink, Boudenot, & van Etten, 2000).
d. When performing RE or susceptibility tests, the EUT directivity, position and/or orientation is irrelevant .
e. Particularly for RS testing, the RC technique requires much less power for generating a high field strength compared to the AC technique.

The RC technique has attracted many researchers for several decades. A lot of effort has been put into improving the technique for many applications (Frank Leferink, 2010)(Wilson, Koepke, Ladbury, & Holloway, 2001)(Holloway et al., 2012)(van de Beek, Vogt-Ardatjew, Schipper, & Leferink, 2012), reviewed different types of RC and stirring strategies (R. Serra et al., 2017) and performance characteristic for different purposes. Currently, as an alternative method, the RC standard has been developed as a guide to carry out RE or susceptibility EMC testing (Commission, 2011). With respect to P2E, RC is the best. It is possible to generate very high E-field strength with a small amount of input power, for instance for RCs with 1.2 m^3, 1 W gives 100 V/m (Morgan, 2011). Furthermore, the RC also does not require expensive absorbers on the ceiling and walls of the chamber. The RC is a very promising technique because of its P2E ratio, and time-efficient.

The Size of Equipment Under Test (EUT)

Antennas are the default transducer inside an AC that illuminates any EUT size or receives the signal from the interference source. As long as the AC and its UFA are big enough for a very large EUT, the test can be done appropriately. However, as mentioned before, this sophisticated testing facility is very costly. Large EUTs, such as very large industrial equipment, large radar equipment, airplanes, and so on, need a very large capacity chamber. Transport to the EMC laboratory is also an issue. If this is not possible, testing has to be done on-site. Additionally, when testing large EUTs, the conductive metal plates of the EUT will disturb the E-field level, which results in over-stressing (testing) or under-stressing the EUT susceptibility level (D. Mandaris et al., 2016).

The size of the EUT is the main problem of the TEM cell technique. The geometry of the TEM or GTEM cells has the limitation of having a small test volume, as approximately one-third can be occupied as a working volume. The TEM and GTEM dimensions are also limited at higher frequencies due to multi-mode resonances. Due to the geometry of the GTEM, the working volume is relatively small compared to the GTEM dimension. Of course, it is possible to extend the size of the GTEM cell, but this would affect the need for input power (Morgan, 2011), while the GTEM would also be less usable at higher frequencies due to the presence of resonances.

Another type of screened room that varies between the TEM cell concept and the classical chamber is called dual-polarized broadband field generator (BFG), as described in (Andrew S. Podgorski, 1996). The idea was to use the existing chamber and place a stripline at both the horizontal and vertical polarization. This BFG and the balanced stripline antenna seem to be the best TEM cell-like structure so far, as it uses moderate power, has considerably good uniformity, and covers a broad frequency range. It can also be used to test large-size EUTs. However, this TEM version still has to be operated inside a big and costly AC.

Large EUTs can, however, be tested easily inside an RC. However, a larger EUT also means a bigger RC, which creates higher costs, especially when the RC is a big metallic box, like the classical one. However, there is another type of RC that is made from conductive fabrics: VIRC. It is simpler, lighter, and does not need extra space inside the laboratory; it can be folded and put away fast. Moreover, the most important advantage of the flexible structure of the VIRC is that it can be installed in-situ (Frank Leferink, 2010)(Frank Leferink, 2008b)(F. B. J. Leferink, Boerle, & Sogtoen, n.d.). The VIRC is operated by moving the walls, while a classical RC makes use of a stirrer or tuner. If the stirrer is rotated continuously, we call it a mode stirred chamber. In this case, the field variation over time is fast. The mode tuned technique makes use of discrete steps of a motor for rotating the tuner. In this case, the field is stable until the stirrer is moved to the next position. The mode stirred technique is much faster at measuring than the mode tuned technique, but for some applications where the equipment under test has a long dwell time, mode tuned is preferred. In this case, the tunable intrinsic reverberation chamber (TIRC) can be used (Frank Leferink, 2008a). This is a VIRC, but the walls are not moving or vibrating continuously. The walls can be moved using a stepper motor, or the modes can be changed using a conventional paddlewheel driven by a stepper motor. The fields can, therefore, be mode-tuned in a TIRC, instead of mode-stirred in a classical RC.

The Frequency Range

Looking at the operating frequency range, especially for the SAC, the lower frequency is a problem due to the near field effects and absorbers, which do not work very effectively. But the main problem at lower frequencies is that the size of the antenna is small to the wavelength and therefore has very low efficiency. In general, the lower the frequency, the bigger the antenna (D. Mandaris et al., 2017). At high frequencies, above a few GHz, the radiation pattern is much more complex, which makes it more difficult to achieve a good UFA.

The TEM cell can be used until the height of the septum becomes a half wavelength. The GTEM extended this range, although for higher frequencies multiple resonances occur due to coupling of the EUT with the septum, higher-order modes, the resonance, and in general, the GTEM is limited to a few GHz (IEC 61000-4-20, 2006).

The RC has a relatively wide test frequency range, starting from the lowest usable frequency defined by the point where statistical FU can be achieved. Using the VIRC is even better, as it also works at lower frequencies than classic mode-stirred RCs (Frank Leferink, 1998a)(F. Leferink et al., 2000). An RC starts when approximately 60 modes can be generated. Currently, the RC is alternatively can be used as an EMC test technique (Commission, 2011) which creates a P2E ratio and a large statistically uniform area of illumination and is much faster because of its isotropy (Dwi Mandaris, Vogt-Ardatjew, Suthau, & Leferink, 2018).

On-site EMI measurements

The last parameter is the capability of the EM test environment to be applied on-site testing. Both two environments (AC and GTEM) and classical RC can be neglected due to those techniques are permanent facilities and impossible to move outside the laboratory. The only possible EM environment which can be built on-site is VIRC (F. B. J. Leferink et al., n.d.)(F. B. J. Leferink, 2008)(Frank Leferink, Boerle, & Sogtoen, 2000). And this is the most essential advantage of VIRC in comparison with other EM environments for EMI measurement in a different application.

Measurement result

The last analysis is the experiment results.

Figure is shown the simulated maximum E-field strength in comparison with four different EM environment. The figure demonstrates the E-field strength as measured in four test environments and they have compared additionally with the simulation results. In the frequency band 1.6 to 2 GHz, the discrepancies between the FAR and RC or VIRC are obvious (up to 15 dB). This happens in cases where the monopole does not radiate well in that direction due to a zero in the radiation pattern. This range is actually where most probably the maximum emission occurred, which can’t be detected inside the FAR due to the under scanning plane (without height scan).

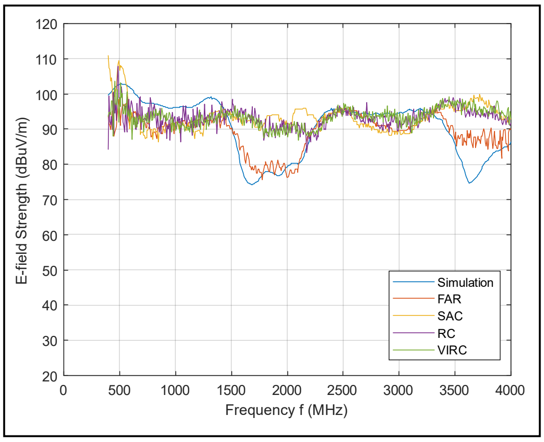

Figure 8. The simulated and experiment E-Field in different test environments (FAR, SAC, RC, and VIRC)

In case of an RC, VIRC, and SAC – where additional reflections with a different angle exist, caused by the conductive walls in of the RC and VIRC or the floor of the SAC – this energy is successfully directed to the receiving antenna. Apart from that, the rest frequency band, all the sites has a pretty similar pattern with simulation results with ±5 dB discrepancy except for frequency above 3.5 GHz. This happened most probably due to measuring system limitation where optical link fiber is not working properly above 3 GHz.

5. CONCLUSION

EMI / EMC test standard for EMI measurement has been reviewed based on four parameters. The conventional SAC and FAR methods are well-established techniques, a deterministic concept with directly E-field maximum detection, broadband test frequency range, available for big EUT, with some low-frequency problem but unavailability for in-situ testing. Additionally, some noticeable draw-backs are, it requires expensive facilities, absorbers, power amplifiers, and measuring systems and is time-consuming for EMI radiated testing to be able to capture all EM emissions for all possible directions. On the other hand, RC/VIRC test standard method as using statistical evaluation and total radiated power measurement, despite it has some disadvantages, like missing directivity, dwell time problems, this technique allows simpler test method, giving very high E-field, good UFA, available for big EUT and specifically on-site applicability for VIRC method. Measurement also shown a considerably similar pattern between those standard methods with small deviation, except for frequency between 1.6 to 2 GHz where the null of the radiation pattern occurs for some azimuth angle.

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