Comparison of Active Levelling and Pre-Calibrating/Substitution Method for Radiated Immunity Testing of Large Equipment

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***Abstract*— Radiated susceptibility tests have originally been performed using the so-called leveling method: a field strength sensor is put in front or on top of the equipment under test and the power towards the antenna is changed until the required level is achieved. Since computers became available for controlling test equipment the pre-calibration, or substitution, method became more popular. From a metrology point of view this is also a standard method but the leveling method is still preferred in some standards. The advantages and disadvantages of the methods are described in terms of the testing of very large equipment. Measurements were carried out with large and small equipment and the result shows that the methods are applicable for different purposes; Active leveling is more suitable for small EUT in closer distance while the pre-calibration is the established and preferred method for large equipment.**

Keywords- radiated susceptibility tests, radiated immunity test, active levelling, pre-calibration, substitution, MIL-STD, AECTP, IEC 61000-4-3, Large Equipment

I. INTRODUCTION

Radiated susceptibility tests for Electromagnetic Interference (EMI) assessment, to achieve Electromagnetic Compatibility (EMC), have been developed many decades ago. The most well-known standard is the MIL-STD 461G [1], which is based on MIL-STD 461 [2]. Other standards for professional equipment are often a (national) derivative [3] [4]. E.g. the RTCA/DO-160 [5] for airborne equipment is derived from the MIL-STD. On the other hand for civil equipment the standard method is IEC 61000-4-3 [6], which was developed around 1990, based on IEC 801-3 [7], stimulated by the introduction of the European EMC Directive 89/336/EEC [8].

Historically, EMC has been an important concern for military [9]. EMI requirements were driven by military usage and EMC efforts were conducted by the military and a few industries. Before 1970, the factual review of available radio-frequency (RF) technologies shows that during this time the majority of electronics were developed by and for the military (with exception for AM/FM radio and TV), largely due to the limited application and high costs of this equipment [10]. This is now completely reversed. For the past four decades, starting with the emergence of the microprocessor in the mid 70s, commercial application began to take the lead of technology development and the consumer market has grown rapidly. This caused EMI problems to also show up in the civil environment and EMC standards to develop for this environment, resulting in the European EMC Directive 89/336/EEC, now 2014/30/EU [11] and the IEC 61000 series of standards. The MIL-STD uses the leveling technique up to 40 GHz, and alternatively the pre-calibration (or substitution) method above 1 GHz for radiated immunity tests. There is no difference for large or small equipment. The IEC 61000-4-3 [6] is using the pre-calibration method for a 1.5 m by 1.5 m area. But large industrial installations could be much larger.

Research has been performed like uncertainty of radiated immunity, sensor calibration and the effect of sensor position on the RS103 method [12], but no research on the effect of large reflecting equipment on the measured field strength has been published. In the development of IEC 61000-4-39 [13], we recognize similar discussions, where national committees comment on the setup based on estimation and engineering judgement. On the other hand, when discussing the leveling against pre-calibration, people feel confident with the technique they use. In the latest version of the NATO AECTP 500 standard both techniques have therefore been allowed for testing although the technique used for qualification shall be described in the test report [4]. To evaluate and provide suggestions for best practices, we performed measurements and compared the results of the leveling method and the pre-calibration (or substitution) method, for large, and small equipment. Active leveling and pre-calibration tests have been performed where the forward power, reflected power and electric field strengths have been measured. The objective is to provide a better understanding to why and when the methods are different and for which conditions, where the focus is on the size of the Equipment Under Test (EUT). As additional measurement, we also included the calculable method into the research, which is sometimes used in industry as an alternative method.

II. ACTIVE LEVELING

The radiated susceptibility or immunity test method based on leveling is using a generating antenna typically positioned

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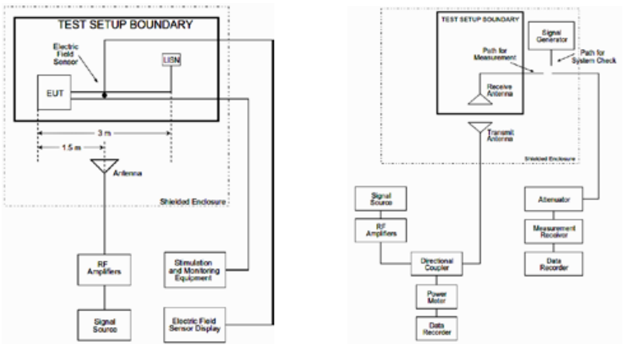
1 m or 3 m in front of the Equipment Under Test (EUT), as shown in Figure 1. . Tests are being performed in a frequency range from 10 kHz, but more often from 2 MHz, up to 40 GHz. Although there are comments on the fact that measurements are performed in the near field [14], this test setup replicates the EMI case: in military environments often antennas (or, more general, sources) are positioned very close to other equipment, and the test setup resembles this situation. Near field tests have been in use for many decades and proved to be a valid test to evaluate the risk of electromagnetic interference in many applications, such as ground based, land mobile, naval or aerospace applications.



(a) (b)

Figure 1. (a) AECTP 500 NRS02 Test equipment configuration [4], (b) Test and receive antenna procedure (1 to 40 GHz) [4]

Test levels are in the order of 10 V/m for sheltered environments, 50 V/m for exposed land based environments, 200 V/m for exposed naval environments, and up to 600 V/m for aerospace environments. The last two, 200 and 600 V/m, are field strengths next to high power high-frequency (HF) and ultra and super high frequency (VHF, SHF) transmit antennas and in the main beam of radar systems. As can be seen in Figure 1. , the field sensor is placed in front of the antenna and both of them are centered between the edges of the test setup below 200 MHz. On the other hand, above 200 MHz, the antenna and the field sensor are placed in a sufficient number of positions such that the entire width of each EUT enclosure and the first 35 cm of cables are within the 3 dB beam width of the antenna up to 1 GHz, 7 cm of cables above 1 GHz, where the EUT test setup boundary is less or equal than 3 meters. However, for EUT test setup boundaries larger than 3 meters, multiple electric field sensors are always required regardless of the test frequency range. The signal source is amplified to drive sufficient energy to the antenna. The electric (E) field sensor will receive and measure the signal until it reaches the required level stated in the standard. The reading of the display will show the electric field value based on the electric field sensor, placed within the EUT test boundary.

Above 1 GHz the pre-calibration method may be used as an alternative to the active leveling method. Therefore one field strength sensor, or a receive antenna, is put at the position where the EUT will be placed, and the power needed to generate the field strength is measured and stored. The electric field level is gradually increased until it reaches the applicable limit [4].

III. PRE-CALIBRATION

For commercial products radiated immunity tests are based on the pre-calibration method as described in IEC 61000-4-3 [6]. It usually is performed from 80 MHz to 1 GHz, although it can be extended up to 6 GHz. The electric field strength is 3 to 20 V/m, depending on the product application and environment. In this pre-calibration procedure the field strength has to be measured without the EUT being present. The IEC method requires a uniform field area (UFA) of 1.5 m x 1.5 m placed on a vertical measurement plane 3 m from the tip of the transmitting antenna. The field strength is measured at 16 points and at least 12 points shall fulfil the criteria. No clear description is given for large EUTs which are much bigger than this 1.5 x 1.5 m^2.

IV. EFFECT OF LARGE METAL OBJECT

If an electromagnetic field is radiating towards an infinitely large metallic plane then at the air-metal boundary a current will flow. Due to the continuity relation also an oppositely directed current will flow which will generate a field. This field will reduce the incident field from the antenna and the net effect is called Quasi Active Shielding (QAS) [15]. Consider the electric field generated by a short current carrying segment at a distance *r*:

$$\hat{E}_1 = j\frac{\hat{I}dl}{4\pi}\eta\beta\frac{e^{-j\beta r_1}}{r_1}$$

In Figure 2. due to the metal plane a current will be induced, resulting in a similar field $\hat{E}_2$, in opposite direction. The sum of the fields at some distance is then $\hat{E}_{net} = \hat{E}_1 - \hat{E}_2$

$$\hat{E}_{net} = j\frac{\hat{I}dl}{4\pi}\eta\beta\left(\frac{e^{-j\beta r_1}}{r_1} - \frac{e^{-j\beta r_2}}{r_2}\right)$$

With r_1=*r*-*d* and r_2=*r*+*d* where 2*d* being the distance between the current carrying segment and the metal plane. If *r*>>*d* then the net field strength becomes

$$\hat{E}_{net} = j\frac{\hat{I}dl}{4\pi}\eta\beta\frac{e^{-j\beta r}}{r}\left(e^{-j\beta d} - e^{-j\beta d}\right)$$

And the quasi active shielding (QAS) becomes

$$QAS = \left|\frac{E_1}{E_{net}}\right| = \left|\frac{1}{e^{j\beta d} - e^{-j\beta d}}\right| = \left|\frac{1}{2jsin(\beta d)}\right|$$

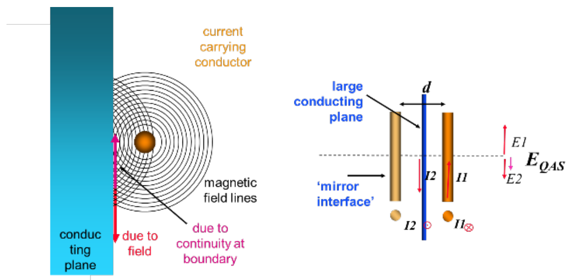


Figure 2. Active quasi shielding effect due to conducting plane nearby

So, if the EUT is nearby the sensor, it will affect the electric field strength reading in the sensor due to coupling between them, as shown in Figure 3.

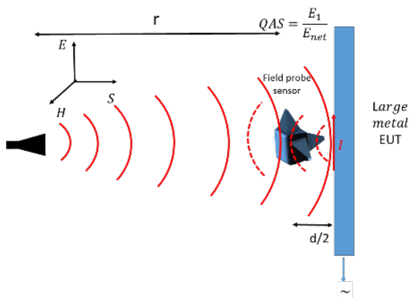


Figure 3. Coupling caused by induced current on large metal plate

In Figure 4. the reduction in field strength for the *x* and *y* directed antennas of the sensor theoretically is shown as function of the frequency. In case a sensor is placed on top of a metal EUT, as shown in Figure 5. , this effect will not occur, although the *y* directed sensor will be influenced by the enlarged virtual ground plane formed by the EUT.

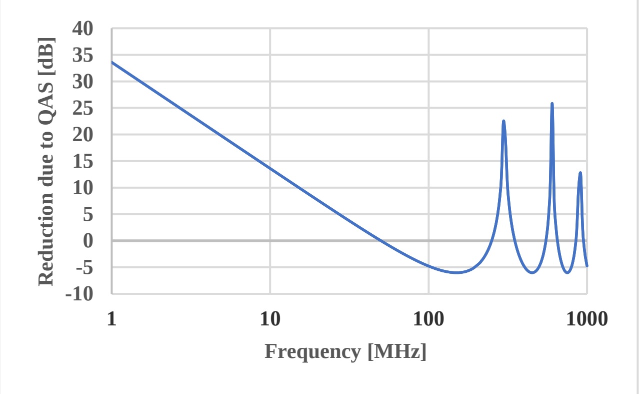


Figure 4. Reduction of E-Field strenght as function of frequency

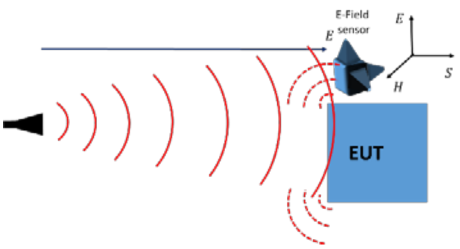


Figure 5. Effect of the field sensor on the top of EUT

The theoretical information given in this section may help to interpret and understand the experimental results more clearly presented in the next sections.

V. Influence of Vertical Grounded Wire

In particular if a large metal plate has an additional vertical ground wire, occuring effect will be worse as shown in the measurement and simulation results on Figure 6. to Figure 7. respectively. In pre-calibration method the presence of a vertical grounded wire above a conducting plane may cause a significant increase in electric field intensity when a vertically polarized electric field is applied. This setup may be necessary if the tested equipment is required to be grounded. This also confirms that large vertical metal plate or wire will influence the reading of E-field sensor if putted nearby. Some measurement and simulation were performed to prove this effect.

The vertical wire with a length of 1.65 m was placed in the distance 1.5 m from the tip of the transmitting antenna. An isotropic field probe was 0.1 m beside the wire in different heights from 0.5 m to 1.8 m above the ground plane. For the measurement the pre-calibration with target electric field level 10 V/m was used. As the calibration was carried out in 16 discrete points, the electric field intensity was measured in every probe position without the presence of the wire to obtain the reference values. Than the vertical grounded wire was installed and electric field intensity was measured in the same points.

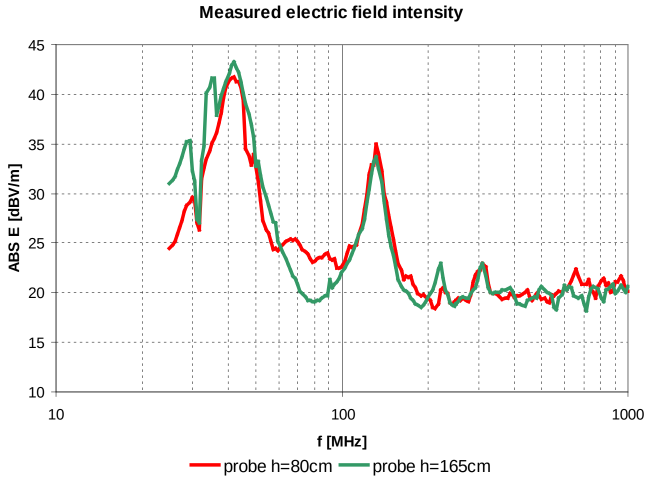


Figure 6. Measured field intensity at the vertical grounded wire

The measured results were normalized to compensate for the difference of the measured reference values and the target level 10 V/m. In Figure 6. , it can be seen that the increase in electric field intensity is up to 140 V/m and 60 V/m on the frequencies 42 MHz and 132 MHz respectively. It shows an increase of 23 dB at the first peak in the distance of 100 mm from the wire. This significant increase of the electric field is caused by the behavior of the grounded wire as a monopole antenna in resonance.

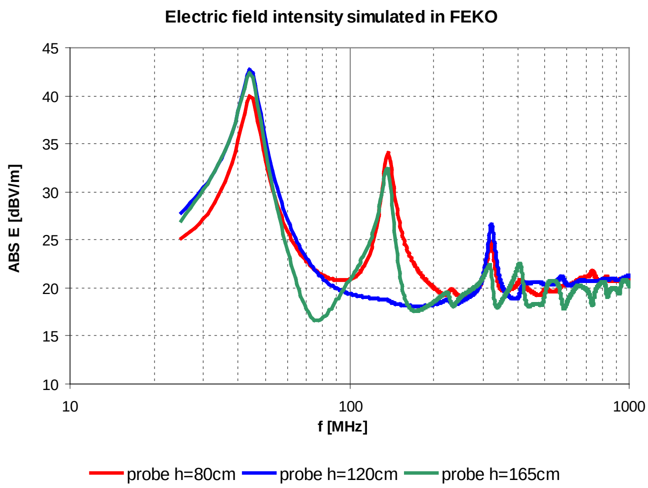


Figure 7. Simulated electric field at vertical grounded wire

The first peak is a product of the λ/4 resonance and the second one of the λ*3/4 resonance. Higher resonances (λ*5/4; λ*7/4;…) can be identified as well, but their magnitude is very low.

A set of simulations was done to verify the measurement results. The results shown in Figure 7. were obtained from the simulation for the same setup as the measurement. It reveals that the measurement and simulation results are in very good agreement. The simulation also shows that the value of E-field is highly dependent on the distance from the wire. As the current distribution on the wire in resonance is the dominant source of field in the area near the end of the wire, the equipment under test may be exposed to very high electric field intensity.

The effect described in this part may influence electromagnetic susceptibility test results of different kind of equipment requiring grounding during tests. E-field intensity may increase by 20 dB due to the presence of a ground wire. It also can explain some probable differences that may occur between the pre-calibration and leveling method using a field probe to set the target immunity level. As there is no EUT in the pre-calibration method during the calibration phase, the ground wire of the EUT will not affect the test results but it will be very effective in the active levelling method as the ground wire may be present close to the field sensor during the levelling stage.

Similar to the previous section, this section may also help to interpret the reasons of discrepancies that arise in radiated immunity test results of EUTs which have ground wires.

VI. CALCULABLE METHOD

A third method is often denoted as calculable method. Suppliers of test systems are often calculating E-field using this method [19], by taking

$$E = \frac{\sqrt{30PG}}{R}$$

Where R is the distance, often assumed to be 3 m and 377 Ω as air impedance in far field region, P is the forward power and G is the gain. However, the gain is generally undefined for 3 m, for that reason it must be specially measured at 3 m for this purpose. For a popular high-power biconical antenna the power needed to generate 200 V/m at 3 m distance in the frequency range 50-100 MHz would be approximately 1100 W. For a popular bicon-log-periodic antenna it is stated that 10 W is needed at 3 m at 80 MHz for 10 V/m. In practice, these power levels appear to be an underestimate.

VII. EXPERIMENTAL SETUP

Active leveling and pre-calibration tests have been performed in three different laboratories; TUBITAK Turkey, INTA Spain, THALES Netherland. In addition to these methods, the calculable method was also studied at TUBITAK. The primary target of those measurements was to determine which method was more consistent with the standard method and more applicable to industrial environment. For that reason, only some measurement results are taken into account and the graph's format has been adjusted accordingly in order to show the effects of different EUT's and metallic surfaces on the E-field level.

We firstly experimentally investigated three different radiated immunity methods at TUBITAK from 80 MHz to 1 GHz; the standard field uniformity method, the active levelling method and the calculable method [16]. We compared them with each other on basis of applied forward powers and the effects created on a dummy EUT. As stressed earlier, the active levelling is the method in which the electrical field is actively established on the EUT by means of an electrical field sensor close to the EUT, as seen in Figure 8. without a pre-calibration and establishment of a field uniformity area. On the other hand, the calculable method completely relies on the theoretical calculation, the antenna gain and the antenna-EUT distance in order to calculate the electrical field value just on the EUT. In the calculable method, there is not a pre-calibration, a field uniformity area and an active field sensor.

Finally, the standard field uniformity method includes the 16-point field uniformity area which is pre-calibrated, generally at 3 m, prior to tests for the frequency range 80 MHz – 6 GHz, in accordance with IEC 61000-4-3 [6]. The EUT was placed inside this field uniformity area and a pre-calibrated field is applied to the EUT. In this standard method, while the field sensor is used in the calibration of the field uniformity area, it is only used for monitoring purposes in the test stage. In this research, we used metal boxes with receiving elements to simulate typical EUTs. The dummy EUT has an internal receiving small antenna which receives radiation through the slits on it. The other radiating element is a set of cables coming out from the slits and laid over the surface of the dummy EUT to simulate external cables of a typical actual EUT. The internal antenna and external cable configuration were connected to the same feeding point, an N connector, at the bottom of the metallic boxes. The internal antenna and external cables were connected to this N connector in parallel without any splitter and other components. One of the external cables was connected to the live point of the N connector and the other was connected to the metal case of the EUT to simulate the earth cable of an actual EUT.

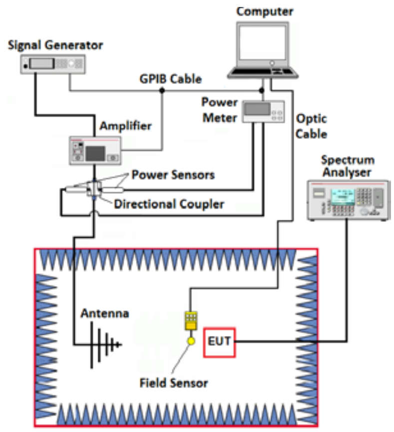


Figure 8. Active Leveling test set up [16]

During the research, two EUTs with different dimensions were used. In the measurements, the antennas were kept in fixed height at 1.7 m at standard and non-standard measurement distances. As the spatial field uniformity area was more uniform in horizontal polarization in the anechoic chamber, all the investigations were performed in the horizontal polarization. In each configuration, we recorded the forward power injected to the antenna, the displayed electrical field by the monitor sensor and the signal induced inside the EUT via the small receiving antenna and external receiving cables. As all the three methods aim for the same electrical field value on the EUT, the investigation of differences in forward powers injected to the antenna, displayed electrical field values on the electrical field sensor and the induced voltages inside the EUTs was the best way to compare the results of the three methods and to clearly show that the methods may yield different results despite the fact that all of them aim for the same electrical field target on the EUT.

A second measurement setup was installed at non-standard and standard distances with the use of different EUT sizes at INTA [17]. These measurements were also performed in order to compare standard pre-calibration method based on IEC 61000-4-3 with levelling method at 1m on small (LxWxH, 18 cm x 20 cm x 8 cm), medium (LxWxH, 18 cm x 40 cm x 36 cm) and large (LxWxH, 80 cm x 60 cm x 135 cm) equipment in the frequency range 80 MHz – 1 GHz. Thereafter, we analyzed the data and showed the results for the power which was injected to the antenna and the electric field strength on the sensor inside the EUT. The result and target level are recorded for both the horizontal and vertical polarizations. (See Figure 9.)

The last setup was installed with the small and medium EUTs and the measurements were performed with the constant pre-calibrated electric field. During the testing the forward power and electric field reading were recorded.

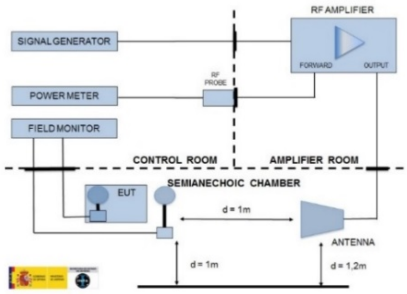
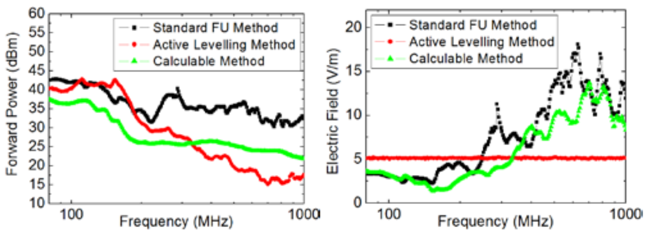


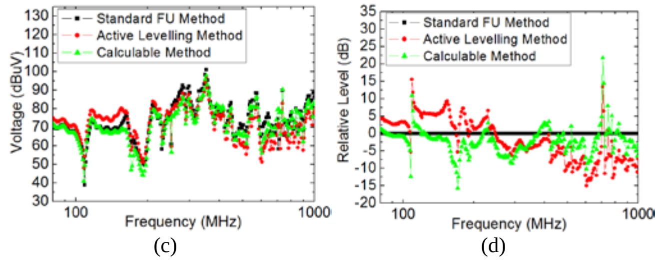
Figure 9. Test setup without pre-calibration at closer distance [17]

VIII. RESULT AND DISCUSSION

The comparison result of the active levelling method and calculable method at 1 m with the standard field uniformity method at 3 m, which was obtained at TUBITAK, are presented in Figure 10. and Figure 11.



(a) (b)

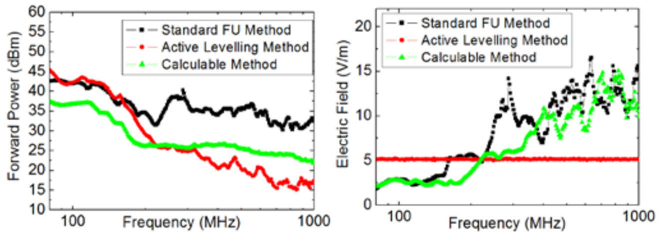


(c) (d)

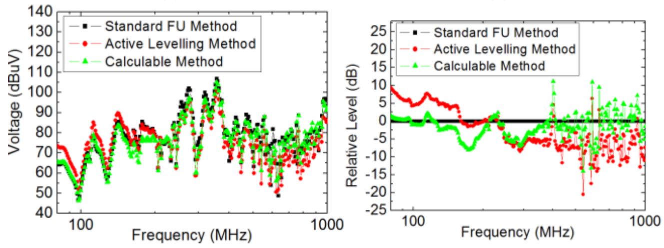
Figure 10. Comparison of alternative radiated immunity test methods at 1m with standard method at 3m (with small EUT) (a) injected power to antenna, (b) electrical field, (c) induced voltage inside EUT, (d) normalized induced voltage

As can be seen from Figure 10. , for the measurements with the dummy EUT, at first glance, it is easily noticeable in Figure 10. (a) for the smaller dummy EUT (0.125 m^3) that the required injected power to the antenna in the active levelling method exceeds the power required in the standard method at several lower frequencies due to the EUT presence, despite the fact that the antenna is 3 m away from the EUT in the standard method but 1 m away in the other methods.

The electrical fields on the field sensor severely changes due to the EUT presence for the standard and calculable methods. The curves in Figure 10. also reveal that the results of the standard and calculable methods are reasonably consistent but the active levelling method causes over-testing in lower frequencies and under-testing in higher frequencies in comparison with the standard method. In addition, we see in Figure 11. that the results did not change significantly for the larger dummy EUT (1 m^3).



(a) (b)



(c) (d)

Figure 11. Comparison of alternative radiated immunity test methods at 1m with standard method at 3m (with large EUT) (a) injected power to antenna (b) electrical field, (c) induced voltage inside EUT, (d) normalized induced voltage

The second measurement result series obtained at INTA are shown in Figure 12. To Figure 15. .Those graphs show the external electric field and incident power on the antenna for the small, medium and large EUTs and for both of the polarizations with the pre-calibration method according to EN61000-4-3 [6] at 1 meter distance and the active levelling method in the same distance.

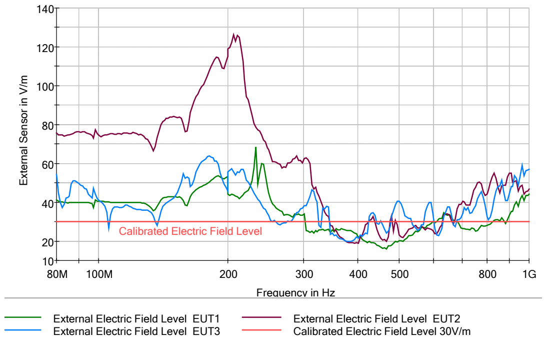


Figure 12. External E-Field level @ 30V/m – Comparison 3 EUTs – horizontal polarization

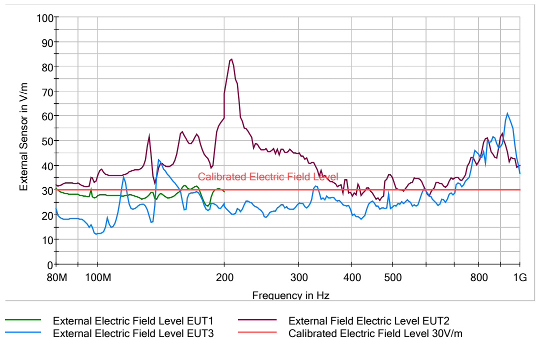


Figure 13. External E-Field level @ 30V/m – Comparison 3 EUTs – vertical polarization

The graphs shown in Figure 12. and Figure 13. are the results of the pre-calibrated 30 V/m E-field and the external E-fields under the presence of the three EUTs. The graph clearly shows that discrepancy is relatively high between them. The curve for the small EUT (EUT1) doesn't change as much as for medium size EUT. Obviously it occurred due to the coupling between the E-field sensor and the large metal plate nearby.

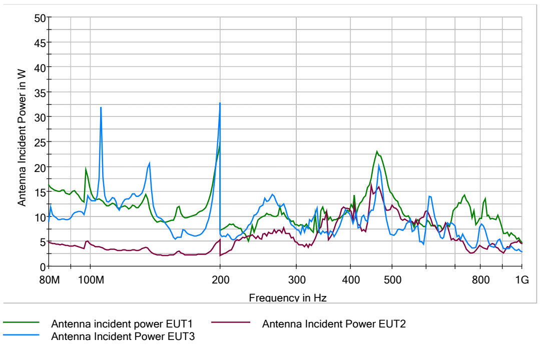


Figure 14. Comparison of incident power d=1m, @30 V/m – vertical polarization – EUT1

The comparison level of the incident power on the antenna given in Figure 14. and Figure 15. There are many fluctuations especially in the lower frequencies, which mean E-field strenght were significantly influenced by reflections thus more power was needed to maintain it. At the end it will result in overtesting or undertesting. This is caused by induced currents along the metal conductive surface which acts as active shielding and subsequently this phonemenon causes the return of electric fields and affects the reading of the field sensor.

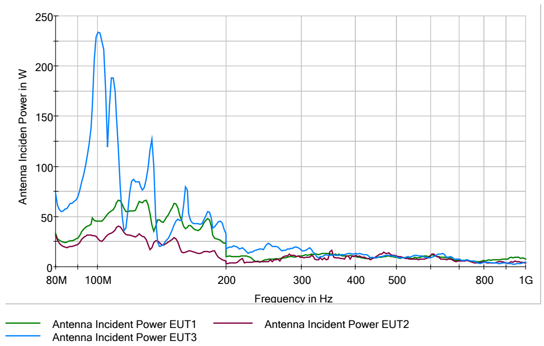


Figure 15. Comparison of incident power d=1m, @30 V/m – vertical polarization - EUT3

As seen in the figures from Figure 12. to Figure 15. in some frequency bands and polarization, there is a certain correlation between the leveling method (1 m) and pre-calibration method. But none of them can be considered as a result which can be perfectly correlated for both the polarizations and for any frequency range.

The final results are shown in Figure 16. and Figure 17. respectively. In Figure 16. the pre-calibration result is shown for the small EUT. The field strength was kept constant at the pre-calibration level of 100 V/m, and the forward power and the field strength in front of the EUT were measured.

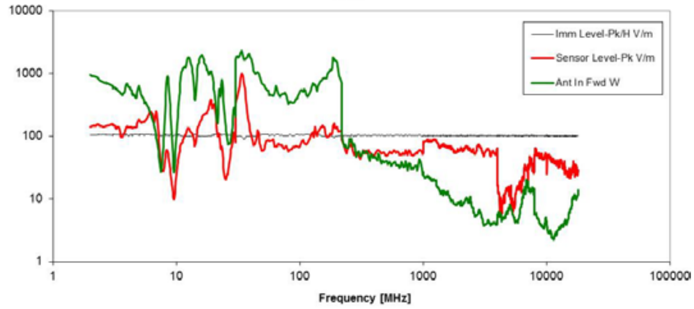


Figure 16. Sensor level and antenna forward power for small EUT

In Figure 17. the pre-calibration result is shown for the medium-sized EUT, for 200 V/m. The shape of the necessary forward power is comparable, but not the same because the test setups (and thus the pre-calibration setup) were different. The influence of the EUT on the recorded field strength is obvious.

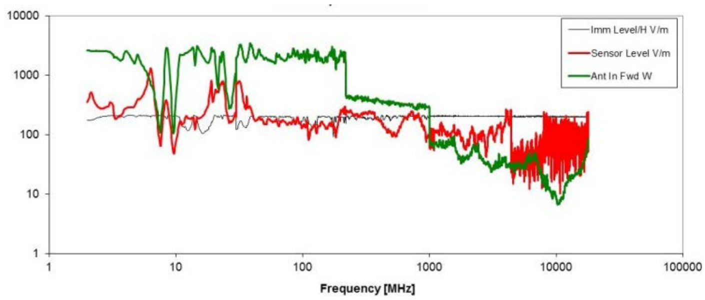


Figure 17. Sensor level and antenna forward power for medium size EUT

IX. CONCLUSION

Active leveling and pre-calibration field strength measurement techniques have been compared. It has been shown that those methods have their own advantages and drawbacks for different conditions. The leveling method does not need pre-calibration because only the sensor is placed at a certain position nearby the EUT, and the generated field is measured using the sensor at close distance. This method is suitable only for small EUT because the method is influenced by the level of the electric field near the EUT, causing large variation due to interaction with the EUT. This effect becomes more prominent for large EUT. The pre-calibration technique is beneficial to small as well as large EUT.

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