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On the relation between radiated and conducted RF emission tests

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Abstract
This paper deals with the RF emission from small electronic products with a single (mains) cable in the frequency range from 30 to 230 MHz. Because it is important to have EMC assessments in an early stage of the product development, there is a need for simple, low-cost test methods that can be applied in the design lab. A workbench set-up, as described in IEC 61000-4-6, which is primarily intended for RF immunity testing, is also suitable for conducted RF emission testing. The relation between conducted and radiated test results is discussed and special attention is paid to systematic measurement uncertainties that may occur in both set-ups. A simple theoretical relation is derived, which corresponds well to the relation obtained from measurements, provided that the resonance effects in the radiated set-up are suppressed, e.g. by applying a common mode termination impedance to the cable.

1 Introduction.

In this paper we would like to discuss the measurement of RF emissions from small electronic products with a single cable (i.e. mains) in the frequency range from 30 to 230 MHz. In order to reach compliance with the EMC standards at a minimum of cost, it is useful to include some kind of EMC assessment in the early phases of the product's development, so that the designers receive fast feedback on any changes that they make in their design. The standard radiated RF emission test procedure described in CISPR22 is not suitable for this purpose, because it is too costly and too time-consuming. A workbench test set-up as described in standard IEC 61000-4-6, primarily intended for conducted RF immunity testing using a reference plane and coupling/decoupling networks (CDNs), is much more appropriate and can easily be installed in a design lab. It has been reported by several authors, e.g. [1] and [2], that the radiation characteristics of small electronic systems are determined mainly by the cables which are connected to such a system. This means that, in particular for products with a single cable, it must be possible to find a relation between the electric field strength measured according to CISPR22 and the common mode current measured via a CDN in the conducted test set-up.

We will take 230 MHz as the upper frequency of our considerations for the following reasons. The conducted test set-up and corresponding measurement equipment of IEC 61000-4-6 are defined up to 230 MHz. CISPR22 has a 7 dB relaxation of the limits above 230 MHz, and the products that we are aiming at have never posed any difficulties above this frequency.

Usually, EMC tests are not very accurate. A set-up itself may have systematic errors (e.g. up to ± 4 dB) and the layout of cables may add several dBs of uncertainties due to resonance effects. If we want to find a translation curve relating two different test methods, we should therefore try to eliminate the systematic errors, in particular resonance effects, otherwise we could easily end up with more than 20 dB of uncertainty in the translation curve. Numerical and analytical models for the test methods can be applied to support the measured results and to find a suitable curve for translating the conducted test results into CISPR22 limits.

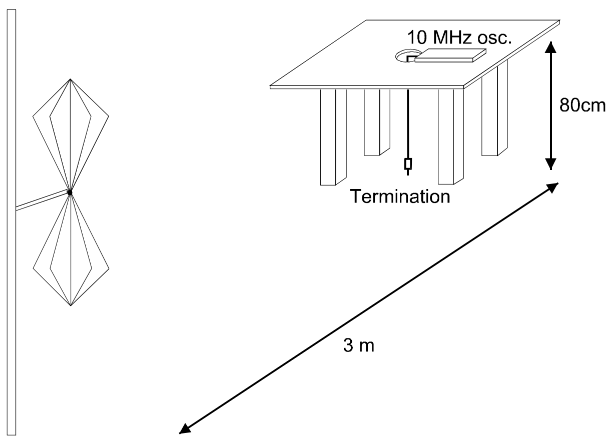

Figure 1. Open area test site (OATS)

The paper is arranged as follows:
First a short description will be given of the open area test site and the semi-anechoic room, which serve as the reference sites for CISPR22. It will be demonstrated

that the common mode termination impedance near the ground plane has a strong influence (about 15 dB) on the measured electric field strength due to resonance effects on the mains cable.
A conducted set-up for measuring the common mode current on the cable and possible causes of systematic errors will be discussed in section 3.
In comparing the measured field strength and the measured common mode current it turns out that a smooth translation curve can be obtained if in the radiated set-up a CM termination is chosen such that the VSWR on the cable remains low (section 4). This fact can be confirmed via numerical analysis (section 5) and even by means of a simple analytical model of the radiated set-up (see appendix). These theoretical considerations lead to a simple translation curve that can be applied in the design lab during workbench testing.

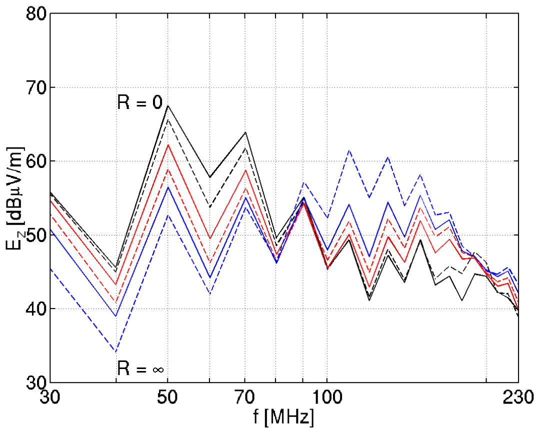

Figure 2. Spectrum of a 10 MHz oscillator measured in a SAR with various CM termination impedances.

2 The radiated RF emission test set-up

Standard radiated RF emission tests in the frequency range above 30 MHz are described in CISPR22. The method requires an open area test site (OATS) with a conducting ground plane and a test distance of 3 m or 10 m; see Figure 1. The device under test is placed on a turntable at 0.8 m above the ground plane. At each measurement frequency the turntable is rotated stepwise to cover the full 360°. The waves emitted by the device under test (DUT) can reach the receiving antenna via a direct path and an indirect path (reflection at the ground plane), so interference between the two waves may occur. This interference causes a reduction in the sensitivity of the set-up in certain frequency ranges, which can be overcome by scanning the height of the receiving antenna (between 1 and 4 m). The whole sequence is performed for horizontal and vertical polarisation of the receiving antenna, so the method becomes quite elaborate.
As an alternative to the open area site a semi-anechoic room (SAR) may be used. The requirement for both the OATS and the SAR is that the normalised site attenuation lies within ± 4 dB from the theoretical site attenuation. Since we wanted to use the SAR as a more accurate field strength measuring instrument (e.g. ± 2 dB), we have performed an additional calibration of this test set-up. Such a calibration is normally not used in EMC tests and the difference between actual and theoretical site attenuations is a generally accepted measurement uncertainty.
According to CISPR22 the mains cable should be plugged into a mains outlet in the ground plane, which means that the common mode termination impedance is undefined. It will be shown next that this common mode termination impedance is an important source of measurement uncertainty.

Influence of the CM termination impedance

In this section the influence of the common mode termination impedance on the RF emission, measured in a semi-anechoic room, will be investigated. We need a device under test (DUT) that offers sufficient field strength levels over the entire frequency range to enable good comparison with the conducted emission results later on. The applied DUT is a small box (15 cm x 8 cm x 2 cm), containing a crystal oscillator with a fundamental frequency of 10 MHz, positioned 80 cm above the ground plane. The receiving antenna is placed at a horizontal distance of 3 m, in vertical polarization and at 1 m height. Since the mains (adapter) cable does not yield sufficient emission levels, we will use the on-board battery supply and connect the signal output to a single vertical wire, which is connected to the ground plane via a termination resistor (see Figure 1).
Figure 2 shows the electric field strength measured for the following values of the termination resistor: 0 Ω, 50 Ω, 150 Ω, 300 Ω, 500 Ω and open circuit. Because discrete spectra are difficult to compare, the levels are shown at the harmonic frequencies only and connected by straight line sections.
A low CM impedance termination yields a systematic over-estimation of the field strength at frequencies between 30 and 80 MHz and an under-estimation between 100 and 200 MHz. A high impedance termination has the opposite effect. The influence of the termination is small above 200 MHz. The total variation in the curves is about 15 dB. Systematic errors of this kind could be reduced by choosing a common mode termination impedance that lowers the VSWR on the cable, as will be discussed later on.

3 The conducted RF emission test set-up

In the conducted test set-up the DUT is placed 10 cm above a large reference plane; see Figure 3. The signal output is connected via a single short cable to a CDN, which offers a common mode termination impedance of 150 Ω. The spectrum of the common mode current through the CDN test port is measured as a voltage over the 50 Ω input impedance of the spectrum analyzer. People who prefer the results in terms of terminal voltage should add 10 dB for the 50 / 150 Ω conversion.

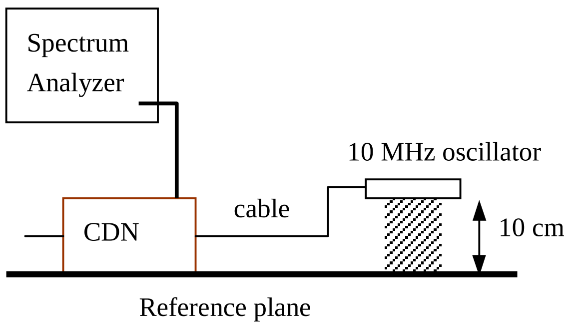

Figure 3. Conducted RF emission test set-up

Measurement uncertainties of the conducted set-up

The battery-powered 10 MHz oscillator was measured in a conducted test set-up according to IEC 61000-4-6. Because we want to compare the result with the results from the SAR measurements, the common mode current generated by the DUT was not measured on the mains wire but on the signal output. The output wire was connected to a CDN (type S1, where the 150 Ω coupling occurs via the shielding of a single coaxial wire).

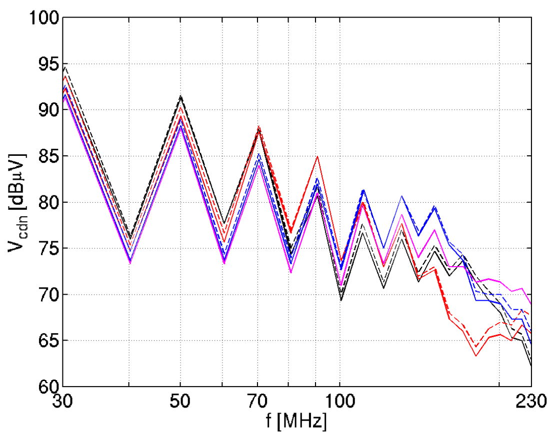

Figure 4. Variation in the spectrum measured at the CDN with a varying set-up geometry (see text).

Figure 4 shows the variations in the measured spectrum due to some geometry variations in the set-up:

- cable length was 10 cm, 25 cm or 1 m
- cable straight or meandering (only with 1 m length)
- height of DUT and cable was 5cm or 10 cm.

Below 100 MHz the variation in the results is less than 5 dB. At higher frequencies the set-up geometry becomes more important.

It can easily be shown that the variations in Figure 4 are of a systematic nature. Assume that the curve measured at 10 cm distance yields the "true" common mode current generated by the DUT and use this curve to normalize the other ones. The resulting curves are shown in Figure 5. Variations in the height of the DUT and the cable yield only small deviations (1 or 2 dB). They are caused by the fact that the common mode current itself will be slightly higher when the DUT is brought closer to the reference plane. Variations in cable length and routing are more severe. In particular folding or meandering of the cable should be avoided.

For accurate measurements at high frequencies either the cable length should be kept as short as possible or the characteristic impedance of the cable above the reference plane should be close to 150 Ω (i.e. the ratio of the cable height and its diameter should be about 3).

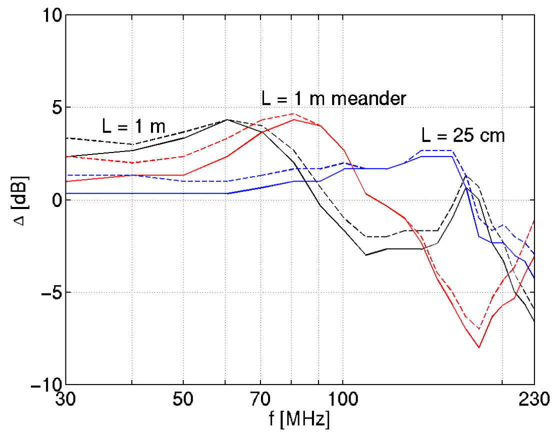

Figure 5. Variation in the spectrum measured at the CDN normalized to the result obtained at L = 10 cm. (solid curves: height = 10 cm solid, dashed curves: height = 5 cm)

The results shown in Figure 5 can be explained by means of transmission line theory. Consider a transmission line with a characteristic impedance Z_0, fed by a current source I_S and terminated in a load impedance Z_L. The ratio of the load current I_L with respect to the source current is given by

$$\frac{I_L}{I_S} = \frac{1}{\cos(\beta L) + j\sin(\beta L) Z_L / Z_0} \qquad (1)$$

If we relate the load current measured with a certain length of cable to the load current that would have been measured with zero length, we obtain curves as shown in Figure 6 for $Z_0/Z_L = 2$, L = 10 cm, 25 cm and 1 m. In this example the error with L = 10 cm remains within 2 dB.

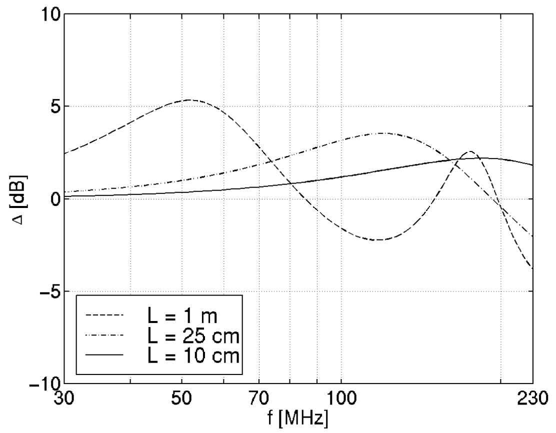

Figure 6. Error in measured common mode current for various cable lengths with $Z_0/Z_L = 2$.

Further uncertainties may be encountered in the common mode impedance of the CDNs themselves (see IEC

61000-4-6 for specifications). CDNs constructed for a restricted frequency range could have narrower tolerances than the ones that are intended for the full range from 150 kHz to 230 MHz.

4 Comparison of conducted and radiated test results

In the previous sections we have found the spectrum of the electric field strength E in the radiated set-up and the common mode current I_{cm} in the conducted set-up. If we normalize the E-field curves of Figure 2 to the common mode current corresponding to the curve with L = 10 cm from Figure 4 we obtain Figure 7, again for a set of termination resistors of 0 Ω, 50 Ω, 150 Ω, 300 Ω, 500 Ω and open circuit.

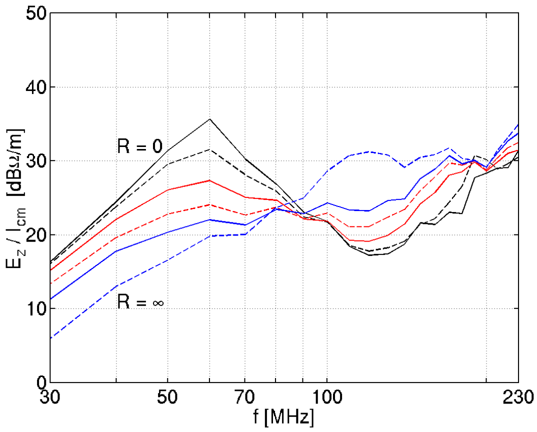

Figure 7. Relation of field strength E_z to common mode current I_{cm} for various termination resistances.

It is clear that the translation curve from conducted to radiated test results depends on the CM termination impedance used in the radiated set-up. An average translation curve is obtained with 150 Ω or 300 Ω. In practice we can of course not apply a resistive termination to the mains wire of a device under test. In our EMC test lab we have the following termination devices at our disposal: a LISN, various CDNs, an absorbing clamp (= MDS clamp) and an EM-clamp (= injection clamp). The measured frequency dependency of the CM impedance of these devices is shown in Figure 8. The CDNs and the EM-clamp are designed to have a CM impedance of 150 Ω (when terminated properly). A LISN is intended for the frequency range below 30 MHz. It shows a low CM impedance between 25 and 100 Ω for frequencies up to 100 MHz. The absorbing clamp has a rather high impedance below 60 MHz.

The radiated RF emission measurements for the small oscillator were repeated with four practical termination devices. The relation between the radiated and conducted test results is shown in Figure 9, where we recognize that the LISN gives a systematic over-estimation at frequencies between 30 and 80 MHz and an under-estimation between 100 and 180 MHz. Using the absorbing clamp has the opposite effect. A CDN gives a rather smooth translation curve between conducted and radiated test results. If the mains cable has a connector for which no CDN is available, the EM-clamp is a good alternative.

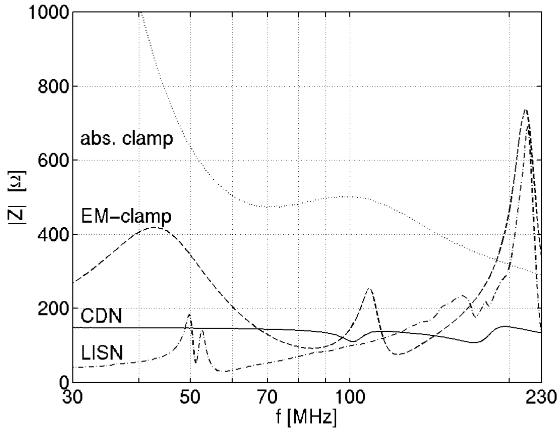

Figure 8. Measured common mode impedance of practical termination devices.

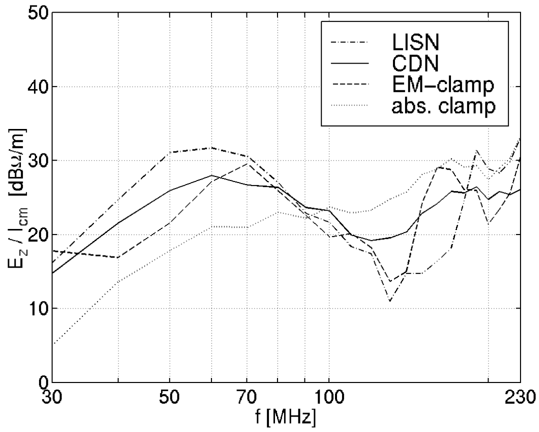

Figure 9. Relation of field strength to common mode current for practical termination devices.

So, applying an appropriate termination device in the radiated test set-up can reduce the uncertainties due to resonance effects on the mains cable and improve the agreement with conducted measurements.

5 Numerical model of the radiated test set-up

In order to gain more insight into the relation between the measured electric field strength and the measured common mode current shown in Figure 7 and Figure 9, a numerical analysis has been carried out, using the antenna software package EMIR [3]. In the model an equivalent voltage source is placed between the vertical wire and the DUT, which is modelled as a rectangular conducting plate. The resulting vertical electric field strength E_z at 3 m distance, normalized to the current at the DUT output port, is shown in Figure 10 for various values of the CM termination resistor (0 Ω, 50 Ω, 150 Ω, 300 Ω, 500 Ω and open circuit).

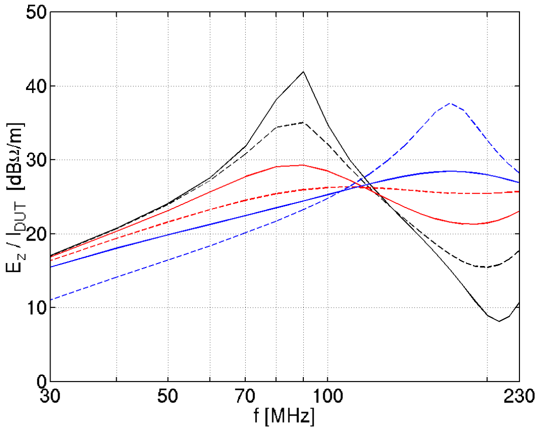

Figure 10. Relation between field strength and current obtained by numerical modelling.

The calculated results shown in Figure 10 are quite similar to the measured results of Figure 7. Again, we find a smooth translation curve for moderate values of the termination impedance (in this example 300 Ω yields the best curve).

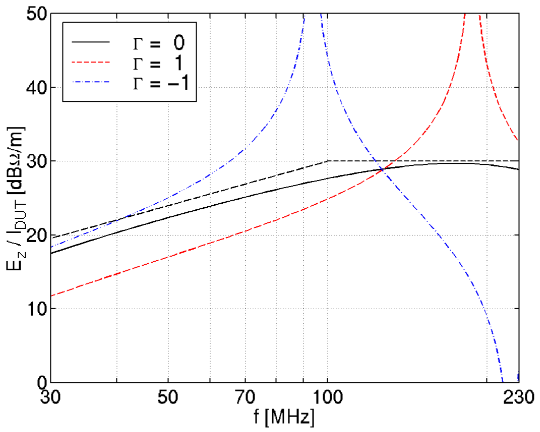

Figure 11. Relation between E_z and I_{DUT} obtained with equation (5), using h = 0.8 m, d = 3 m, s = 1 m. Straight lines are an asymptotic boundary curve

In the appendix a very simple analytical model is derived, based on the assumption of a sinusoidal current distribution on the vertical wire. Figure 11 shows some results of this analytical model for a pure traveling wave (Γ = 0) and for pure standing waves (Γ = ±1). In the case of a traveling wave the relation E_z/I_{DUT} has an almost constant level of 30 dBΩ/m for the frequency range from 100 to 230 MHz and it is approximately proportional to frequency from 30 to 100 MHz.
At 30 MHz the results obtained with the analytical and numerical models are in good agreement. Above 100 MHz there is about 4 dB difference. This is probably due to the fact that the real current distribution is not perfectly sinusoidal (and the analytical model does not include radiation losses).
So, if we define an asymptotic boundary curve, proportional to frequency between 30 and 100 MHz and constant at 30 dBΩ/m between 100 and 230 MHz (as indicated in Figure 11), we can use this curve to translate conducted measurement results into radiated results and still have some margin in practice.
The CISPR22 class B limit of 40 dBµV/m at 3 m distance can thus be translated into a common mode current limit of 10 dBµA or a terminal voltage of 54 dBµV in the range from 100 to 230 MHz. The limit is 10 dB higher at 30 MHz and varies linearly with the logarithm of the frequency between 30 and 100 MHz.

One more question has to be investigated. In this modelling section the electric field strength and the current at the DUT output have both been considered in the radiated set-up, whereas in the previous sections the common mode current was taken from measurements in the conducted set-up. Whether the common mode current on the mains cable is approximately the same in both set-ups depends on the size of the DUT and on the coupling mechanisms involved.
In both cases an RF signal is generated at the DUT. A common mode current can flow via the cable to the ground plane and the loop is closed via a capacitance from (part of) the DUT to the ground plane. If the coupling mechanism is voltage-driven, we have to consider the stray capacitance from the disturbing voltage node to the ground plane. This stray capacitance does not vary much for heights between 10 cm and 80 cm in the case of a PCB with a side length smaller than 10 cm (factor G_1 in [3]). If the side length is larger, there will be some difference in the stray capacitance between the two set-ups and the orientation (track up or down) will play a role.
In the case of a current-driven coupling mechanism we have to consider the total capacitance between the PCB and the environment. With a small PCB (10 cm square) the common mode current will be about 1.5 dB higher at 10 cm than at 80 cm height. With a large PCB (50 cm square) the difference will still be less than 6 dB.

Appendix Derivation of a simple analytical model

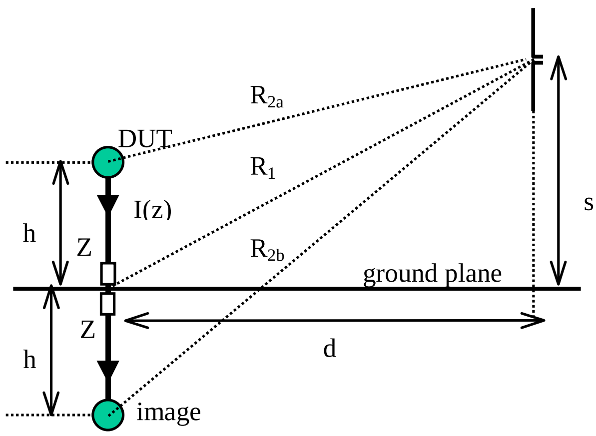

Figure 12. Geometry of the radiated set-up.

Assume that the device under test (DUT) is small with respect to the considered wavelengths, so only the mains wire yields a contribution to the radiated field. Suppose that the mains wire runs vertically (z-direction) and that the current distribution on this wire can be described by means of a sinusoidal distribution. In that case we can apply a general formula from antenna theory [4], which states that the electric field component in the z-direction due to such a wire segment can be written in terms of the current and its derivatives at the ends of the wire segment:

$$E_z = \frac{\eta_0}{4\pi}\left\{\frac{e^{-jkR_2}}{jkR_2}\left.\frac{dI}{dz}\right|_{z_2} + \frac{z_2 - z}{R_2}\left(1+\frac{1}{jkR_2}\right)\frac{e^{-jkR_2}}{jkR_2} I(z_2) + \right.$$
$$\left. -\frac{e^{-jkR_1}}{jkR_1}\left.\frac{dI}{dz}\right|_{z_1} - \frac{z_1 - z}{R_1}\left(1+\frac{1}{jkR_1}\right)\frac{e^{-jkR_1}}{jkR_1} I(z_1)\right\} \quad (2)$$

where $R_1 = \sqrt{d^2 + (z - z_1)^2}$ and $R_2 = \sqrt{d^2 + (z - z_2)^2}$ are the distances from the two end points of the wire segment to the observation point z at a horizontal distance d; see Figure 12.

$\eta_0 \approx 120\pi\,\Omega$ and $k = 2\pi/\lambda_0$ (for wave propagation in free space).

A sinusoidal current distribution on the mains wire can be written as

$$I(z) = I_0\left[\frac{e^{j\beta z} - \Gamma e^{-j\beta z}}{e^{j\beta h} - \Gamma e^{-j\beta h}}\right] \qquad (z > 0) \qquad (3)$$

where I_0 is the current at the DUT port (z = h) and $\beta = 2\pi/\lambda$ describes the wave propagation on the wire.

Γ relates the amplitudes of the waves in positive and negative z-directions. In transmission line theory this would correspond to the voltage reflection coefficient at z = 0. In this simple model it is not necessary to know the characteristic impedance Z_0 of the "vertical transmission line".

The effect of the ground plane can be included by assuming a current distribution on an image wire, which satisfies the requirement $I(-z) = I(z)$, or

$$I(z) = I_0\left[\frac{e^{-j\beta z} - \Gamma e^{j\beta z}}{e^{j\beta h} - \Gamma e^{-j\beta h}}\right] \qquad (z < 0) \qquad (4)$$

Equations (2), (3) and (4) can be combined in a straightforward manner to obtain the vertical component of the electric field at $z = s$.

Usually only the far field terms are of interest:

$$E_{z\_far} = \frac{-j\beta\eta_0 I_0}{4\pi}\left\{\frac{e^{j\beta h} + \Gamma e^{-j\beta h}}{e^{j\beta h} - \Gamma e^{-j\beta h}}\left(\frac{e^{-jkR_{2a}}}{jkR_{2a}} + \frac{e^{-jkR_{2b}}}{jkR_{2b}}\right) + \right.$$
$$\left. -\frac{2(1+\Gamma)}{e^{j\beta h} - \Gamma e^{-j\beta h}}\frac{e^{-jkR_1}}{jkR_1}\right\} \qquad (5)$$

where $R_{2a} = \sqrt{d^2 + (s-h)^2}$, $R_{2b} = \sqrt{d^2 + (s+h)^2}$ and $R_1 = \sqrt{d^2 + s^2}$.

In the case of near field conditions (with a measuring distance d = 3 m this occurs at f < 20 MHz) the following near field terms should be added:

$$E_{z\_near} = \frac{-\eta_0 I_0}{4\pi}\left\{\frac{h+s}{R_{2b}}\left(1+\frac{1}{jkR_{2b}}\right)\frac{e^{-jkR_{2b}}}{jkR_{2b}} + \right.$$
$$\left. + \frac{h-s}{R_{2a}}\left(1+\frac{1}{jkR_{2a}}\right)\frac{e^{-jkR_{2a}}}{jkR_{2a}}\right\} \qquad (6)$$

An example of the results is shown in Figure 11.

6 Conclusions

Radiated RF emission tests according to CISPR22 are not convenient for testing during the early phases of a design. The conducted test set-up described in IEC 61000-4-6 is more appropriate. For small devices with a single cable a theoretical relation between radiated and conducted RF emission test results can be found, which corresponds well to the measured relation, provided that the effects of resonances in the radiated set-up are suppressed, e.g. by applying a CM termination to the cable. The theoretically derived "ideal" translation curve yields sufficient margin to allow its application in less ideal practical situations.

We agree with Leuchtmann et al. [5] that it is not reasonable to state that the radiated method is the only reference, because then we would be forced to reproduce the systematic errors from the radiated set-up into the conducted method, or end up with unpractically large margins. However, we think that CDNs are more suitable than an MDS clamp in a design lab.

Further investigations should include statistical evaluation of a number of products of different sizes to check the validity of the "ideal" translation curve and find out how to proceed with products having more than one cable.

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