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Experimental Characterization Methods for the Electromagnetic Emission of Inductive Wireless Power Circuits

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***Abstract*—Manufacturing electronic devices requires accordance to the electromagnetic compatibility requirements. Taking into account the growing importance of inductive wireless power transfer at higher frequencies, it is important that one can already early in the design process characterize the emissions. In this work, we describe the experimental methods which could be used for the characterization of as well conducted as radiated electromagnetic emissions of inductive wireless power circuits. We discuss the advantages and drawbacks of these methods and compare them with each other.**

***Index terms*—** Electromagnetic compatibility, electromagnetic emissions, wireless power transfer.

I. INTRODUCTION

The manufacturers of all electronic devices, including inductive wireless power transfer (IWPT) devices, are obligated to develop their products according to the electromagnetic compatibility (EMC) requirements. For the wireless charging of electric vehicles, a norm is being proposed [1]. But to date, no dedicated norms exist for the wireless power transfer of low power applications [2], which implies they have to meet the current EMC standards. A large class of IWPT applications functions at a low frequency (e.g., between 100 en 200 kHz for the charging of smartphones using the Qi-standard [3]). However, certain emerging applications use higher frequencies. A typical example is IWPT within biomedical implants which usually work within the industrial-scientific-medical (ISM) band of 13.56 MHz [4][5], although also other frequencies for the power transfer are used, e.g., 1.3 MHz in [6]. Another domain where the importance of IWPT is growing is within integrated circuits, be it as an off-chip discrete component, or a fully integrated component for e.g., powering the integrated circuit from a printed circuit board (PCB) [7], a chip-to-chip power transmission system [8], or an inductive inter-chip wireless superconnect [9]. Frequencies from 50 MHz to several GHz are reported [7][8][9][10]. These higher frequencies than the traditional wireless power transfer applications imply that IWPT circuits are preferably early in the design process characterized concerning electromagnetic (EM) emissions. In this work, we describe the experimental methods which could be used for the characterization of EM emissions of IWPT circuits. We discuss the advantages and drawbacks of these methods and compare them with each other.

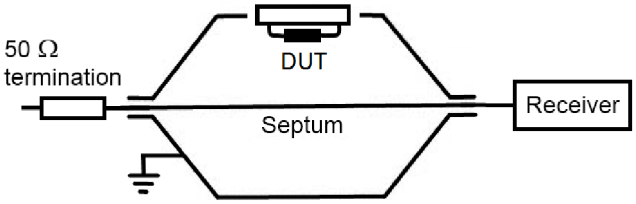

Fig. 1. The schematic cross section of a TEM-cell.

II. THE (G)TEM-CELL AND STRIPLINE METHOD

The first characterization method is the transverse electromagnetic (TEM) cell (Fig. 1), standardized in the document IEC 61967-2 [11]. The device under test (DUT) is connected to a PCB and is located on one side of the PCB. The other components are located on the other side. The PCB is used as one of the walls of the TEM-cell, with only the operating DUT within the cell. In the cell, a conducting septum can be found with a characteristic impedance of 50 Ω. It has two 50 Ω ports, one which is terminated with a 50 Ω load, and one which is connected to a frequency measurement receiver [12][13][14].

With the exterior of the TEM-cell grounded, one can in this way construct a rectangular waveguide that can support transverse electromagnetic wave propagation. The radiated emissions from the DUT can generate a TEM-wave in the cell that propagates to the receiver. Its power can be related to the power of the radiated emissions of the circuit.

A typical frequency range for standard TEM-cells is from 150 kHz to 1 GHz, although the cell can be modified for frequencies up to 2.5 GHz [15]. At higher frequencies, resonance phenomena appear by higher order modes of the electromagnetic wave, making the cell unsuitable. To overcome

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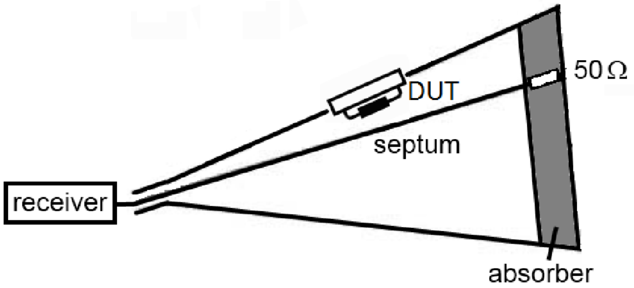

Fig. 2. The schematic cross section of a GTEM-cell.

this frequency limitation, the gigahertz-TEM (GTEM) was developed (Fig. 2). In essence, a GTEM-cell works similar to a TEM-cell, but by making the walls of the chamber divergent and adding an absorber wall at the end, the resonance phenomena at higher frequencies are suppressed, allowing measurements to frequencies up to 20 GHz.

Another method, which has similar advantages and disadvantages as the TEM-method, is the stripline method, standardized in the document IEC 61967-8 [11]. Here, the DUT is mounted on a PCB test board between an active conductor and the ground plane [16]. This method allows the measuring of the radiated emission in the frequency range of 150 kHz up to 3 GHz.

These methods for characterizing the emissions have several advantages:

- A TEM/GTEM/stripline measurement is simple to perform. Different circuits can be easily embedded and replaced on the test PCB.
- The setup and measurement itself can be done in a relative short time.
- The measurement itself does not significantly influence the currents within the DUT, which increases the reliability of the measurement.
- It is easy to relatively compare the emitted radiation from different circuit configurations.
- The measurement setup is relatively inexpensive, compared to for example an anechoic chamber.

The main disadvantages of these methods are:

- The radiation from horizontal currents only couple very weakly to a TEM-cell. Moreover, the exact location of the emitted radiation is unknown. You can only estimate the total power output of the DUT.
- Consequently, it is difficult to differentiate between the electric and magnetic fields, which severely limits the usefulness for the designer [17]. However, methods have been proposed to isolate the electric field coupling from the magnetic field coupling [18][19].
- Only the radiated emission is measured.
- Because the measurements are neither in the far or the very near field, the results may not accurately describe the near or far field radiated emission [12].

III. THE MAGNETIC PROBE AND SURFACE SCAN METHOD

One can determine the noise current leaving a wireless power circuit by measuring the magnetic field induced by a conductor with a magnetic loop probe. Indeed, according to Faradays law, the voltage induced at the probe is proportional to the magnetic field. This magnetic probe method is described in the standard IEC 61967-6 [11]. The main advantages are its low cost and simple implementation.

If one not only measures the noise current at one location, but one now scans the entire surface of the DUT with a magnetic loop probe, the magnetic field distribution can be determined, which can be linked to the current distribution. This surface scan can be done by mechanically moving a probe over the surface, either parallel or perpendicular to the DUT surface. We can also scan the surface with an electric field probe to determine the voltage distribution within the DUT. This is called the surface scan method and is described in the standard IEC 61967-3 [11].

The spatial resolution of the near surface scan is determined by the size of the used probe on the one hand, and the precision one can position the mechanical probe on the other hand [20]. Nowadays, resolutions of less than 1 μm are achievable [21].

Both the magnetic probe and surface scan characterization methods are useful over a frequency range from 150 kHz to 3 GHz [11][22].

The main advantages of the surface scan method are:

- Since the near magnetic field scan is a contactless measuring method, it can provide a lot of information about where currents are flowing within the circuit without significantly altering the currents within the device [12].
- The scan can be performed without building special circuit boards. Most wireless power circuits can be measured in the configuration they are intended to operate [12].
- The repeatability of the results can be guaranteed if the measurement probes are positioned accurately [13].

There are however several disadvantages linked to this characterization method [12]:

- The setup requires special equipment that is expensive and has limited uses.
- While the near surface scans accomplish good relative measurements, it is not straightforward to quantify the measured currents. Converting the magnetic field data to an absolute current requires a detailed knowledge of the geometries involved or the use of compensation techniques [23].
- The most important disadvantage of the surface scan is the time that is required to perform a complete scan at each relevant frequency. A thorough scan of the magnetic and electric field distribution can require several hours of measurement.
- The accuracy of the voltage distribution measurement is limited since no accurate, small and calibrated electric field probe exists.

TABLE 1
An overview of experimental EM emission methods.

Method	**Frequency range**	**Emissions**	**Cost**	**Speed**	**Complexity**	**Scope**	**Required board**
TEM	150 kHz - 1 GHz	Radiated	Low	Fast	Low	Chip	Specified
GTEM	150 kHz - 20 GHz	Radiated	Low	Fast	Low	Chip	Specified
Stripline	150 kHz - 3 GHz	Radiated	Low	Fast	Low	Chip	Specified
Magnetic probe	150 kHz - 3 GHz	Conducted	Low	Medium	Low	Pin	Specified
Surface scan	150 kHz - 3 GHz	Radiated	High	Slow	High	Chip	Specified or generic
1 Ω / 150 Ω method	150 kHz - 1 GHz	Conducted	Medium	Medium	Medium	Pin	Specified
WBFC	200 MHz - 400 MHz	Conducted	Medium	Medium	Medium	Pin	Specified or generic

IV. THE 1 Ω / 150 Ω METHOD

The 1 Ω / 150 Ω method is used for the characterization of the current emissions leaving the circuit within the frequency range from 150 kHz up to 1 GHz. Two methods are described in the standard IEC 61967-4 [11][14]:

- The 1 Ω method which measures the direct radio frequency (RF) current of a single ground pin, using a 1 Ω resistive probe .
- The 150 Ω method which measures the RF voltage at an input/output pin, using a 150 Ω coupling network.

We refer to the standard IEC 61967-4 [11] and [14] for an overview of the standard setup of these methods.

The advantages of the method are [24]:

- The 1 Ω / 150 Ω method guarantees a high degree of repeatability and correlation of the measurements, due to the simple measurement setup.
- It provides a clear insight into the emission contributions of each single input and output.
- It gives a good indication of how well the device will perform in the final product concerning its electromagnetic compatibility.

The main disadvantage occurs when the wireless power circuit has a lot of pins. In practice, it is often too difficult to evaluate all of them. In that case, a selection of pins should be made to keep the measurement time reasonable, since the test boards must include for each pin supplementary resistance, capacitance as well as a high quality connector [12].

V. THE WORKBENCH FARADAY CAGE METHOD

The workbench Faraday cage method (WBFC) characterizes the conducted emission of a test object. The PCB with the DUT is placed inside a Faraday cage to avoid external influences (Fig. 3). All the functional connections, like power supplies, auxiliary equipment, wires,... are fed through filters, mounted on the wall of the Faraday cage, with high common-mode impedances [25]. The WBFC assumes that connected wires to the DUT become the dominant antennas, creating radiated RF emissions. The method supposes that the maximum conducted emission by a wire from the DUT can be estimated by replacing these antennas by a 150 Ω resistor. The voltage drop across this resistor is used as a measure for the RF emission. All wires from these filters are wrapped on ferrite ring cores to create impedances much higher than 150 Ω at the relevant frequencies [26]. The WBFC is standardized in the document IEC 61967-5 [11].

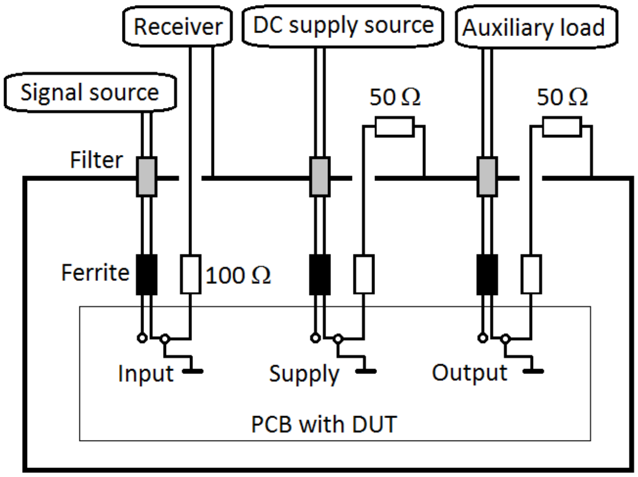

Fig. 3. Test setup for the WBFC.

The advantages of the WBFC are [11][26][27]:

- The measurement method has a high repeatability and is practical to use.
- The WBFC method can already in the early stage of the development give an idea of the radiated emission. Indeed, since the method is time efficient, it allows the designer to see relatively quickly the results of design adjustments.
- It does not require very expensive facilities.

The WBFC is a useful pre-compliance test for emission caused by common mode currents on wires from 200 to 400 MHz (depending on the PCB size). At very low frequencies, the method overestimates radiated emission. The main disadvantage of the method is that above 350 to 400 MHz, the field coupling or radiating from the PCB itself is dominating and the WBFC method is essentially not applicable [26].

VI. CONCLUSION

We compared the different experimental characterization methods that could be used for measuring the EM emission of inductive wireless power circuits. A recapitulatory overview can be found in Table 1. We emphasize that for measurements higher than 3 GHz, only the GTEM-method is useful. We notice the limited frequency range for the WBFC. Finally, we remark that the surface scan is an outlier due to the high cost, low speed and increased complexity. On the other hand, it leads to the most detailed overview of the emissions.

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