Pre-Compliance Test Method for Radiated Emissions of Automotive Components Using Scattering Parameter Transfer Functions

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Abstract— **Radiated emission tests for automotive components according to CISPR 25 are used monitoring their electromagnetic compatibility. Due to parallelization of single work packages schedules are rather strict for component development and tests. Time for first EMC tests of prototypes and their delivery is getting short. Knowledge of EMC properties is important for the developer to initiate measures as soon as possible. An early estimation of radiated emission is directly connected to cost reduction. Hence, pre-compliance test methods become more and more important. This paper presents a pre-compliance measurement approach which is capable to predict the radiated emission with regard to the CISPR 25 standard. Site of operation of this prediction technique is the developer's laboratory setup without the need of an expensive semi anechoic chamber. The method uses the correlation of common mode currents on cable harnesses and the radiated field strength. Common mode currents on harnesses are assumed to dominate the radiated field in the frequency range up to 200 MHz. Common mode currents are measured with current probes. A recorded transfer function in combination with current probe measurements leads to an estimation of the radiated field. Transfer functions are obtained using scattering parameter measurements performed with a network analyzer. The transfer function will be described, analyzed and its applicability for field estimation will be shown by a case study.**

Keywords-CISPR 25; EMC; pre-compliance test; radiated emission; transfer function

I. INTRODUCTION

Electric automotive components require radiated emission tests according to CISPR 25 [1]. Nowadays, the schedules are rather strict during the development of an electrical component due to the parallelization of the single tasks. Therefore first prototypes of components are already delivered and tested by customers before measurements concerning their electromagnetic compatibility (EMC) performance have been carried out. From the equipment manufacturer's point of view an early knowledge of the component's EMC is an important matter regarding remedial measures like filter adaption, shielding or PCB layout changes. Hence, on-site pre-compliance measurement and fast analyzing methods are desired without the need of a semi anechoic chamber. This task demands a measurement method which can be applied on a laboratory setup and leads to a reliable estimation of radiated emissions during CISPR 25 radiation tests. Besides standard CISPR 25 measurements and complex simulations there are two fast methods being capable to predict radiated emissions. Those methods rely on the assumption that common mode currents on the component's cable harness are the main cause of electromagnetic emissions in the range of 0.15 to 200 MHz. In [2] the field domination of common mode currents for two parallel conductors is shown. Therefore, current probe measurements using a test receiver are the base for estimating radiated emissions.

The first method pursues an analytical approach which bases upon a Hertzian dipole model representing a cable harness and considering the geometry of the test setup, see [3], [4], [5], [6]. The second method employs a transfer function (TF) determined by measurements and bases on [7]. TFs include all aspects of the entire test setup like near field coupling of the antenna with the setup, anechoic chamber characteristics as well as the geometrical conditions of the test setup. Those aspects are difficult to implement in an analytical model. Herein, the advantage of the TF method can be found. A comparison of the analytical dipole model method and the transfer function method is presented in [8]

The creation of a TF can be performed either by using a test receiver and a signal generator or by using scattering parameter measurements performed by a network analyzer (NWA). The scattering parameter TF will be described and used in the frequency range from 30 to 200 MHz in horizontal polarization for a preliminary investigation. The TF in [7] requires multiple TFs and multiple current probe measurements as well as computed phase information. For a faster procedure without the need of phase information a measurement approach using only one current probe measurement will be presented.

Section II presents the principle and the generation of the TF via a NWA. A verification showing the correlation between electric field and common mode current using the gained TF as link will be presented. The influence of differential mode currents on the radiated emissions will be shown by the use of two parallel wires and a twisted pair cable configuration. The dependency of the TF on different impedance conditions for one setup will be investigated as well as the effect of filter elements. Section III shows a case study of the TF. Equipment under test (EUT) is a step-down switching regulator circuit.

II. Transfer Function Method

A. Principle of Transfer Functions

The primary intention of the transfer function (TF) is to set up a ratio between a common mode current I_{CM} (stimulated by a source) on a default cable harness in a test environment and its radiated electric field strength E_{CM} measured by an antenna. The electric field component of differential mode currents is assumed to be zero [2]. The transfer function TF is given by

$$\boldsymbol{TF(f)} = \frac{\boldsymbol{E_{CM}(f)}}{\boldsymbol{I_{CM}(f)}} \tag{1}$$

By using one current probe measuring common mode currents I_{EUT} around a cable harness of an EUT's test setup in combination with the according TF a prediction of the radiated emission E_{pred} can be obtained by

$$\boldsymbol{E_{pred}(f)} = \boldsymbol{TF(f)} \cdot \boldsymbol{I_{EUT}(f)}. \tag{2}$$

The TF includes the common mode current distribution of the default cable harness. Precondition for the use of only one current probe measurement is the same current distribution for each frequency along the EUT's cable harness as during the TF generation. Different current amplitudes are considered in the TF due to the linear relation of current and electric field strength. Hence, for an exact field prediction the CISPR 25 test setup of the EUT has to be equal to the default cable harness setup of the TF generation or vice versa. This mainly implies the same geometrical setup, same load, source and cable impedances as well as grounding measures and common mode dominating parasitic effects.

B. Transfer Function Generation Using a Network Analyser

For the creation of a TF a default cable harness consisting of two parallel wires is set up according to CISPR 25 for component radiation tests. One end of the cable harness is loaded by either line impedance stabilization networks (LISN) or an adequate load corresponding to the EUT the TF is generated for. The other end is connected to Port 1 of a NWA acting as a broadband source. A current probe around the default cable harness at a certain position is connected to Port 2. The measurement antenna is connected to Port 3. Figure 1 shows a general block-diagram of the TF generation setup which has to be situated in a semi anechoic chamber. The 3-Port NWA measurement leads to a set of scattering parameters. The transfer function can be calculated by

$$\boldsymbol{TF(f)} = \frac{S_{31}(f)}{S_{21}(f)} \cdot \boldsymbol{AF(f)} \cdot \boldsymbol{Z_T(f)} \tag{3}$$

with the scattering parameters S_{21} and S_{31} (Port numeration according to Figure 1), the antenna factor $AF(f)$ and the transfer impedance Z_T of the current probe. Using the definition of scattering parameters and the wave U_{cbl}^{+} injected into the cable in combination with the received waves U_{probe}^{-} (received by the current probe) and U_{ant}^{-} (received by the antenna) as depicted in Figure 1 it can be shown that (3) equals (1).

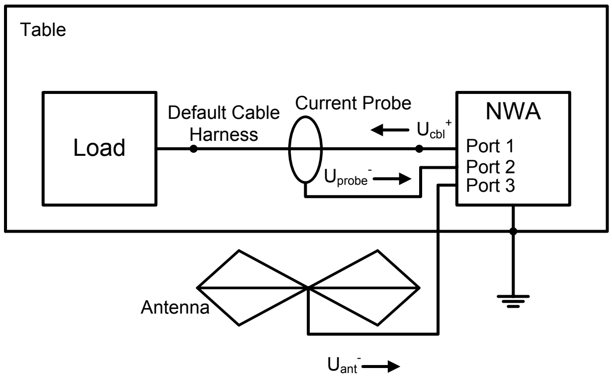

Figure 1. General block-diagram of the transfer function generation setup

$$\frac{S_{31}(f)}{S_{21}(f)} \cdot \boldsymbol{AF(f)} \cdot \boldsymbol{Z_T(f)} = \frac{\dfrac{U_{ant}^{-}}{U_{cbl}^{+}}}{\dfrac{U_{probe}^{-}}{U_{cbl}^{+}}} \cdot \boldsymbol{AF(f)} \cdot \boldsymbol{Z_T(f)} \tag{4}$$

$$\boldsymbol{E_{CM}(f)} = \boldsymbol{U_{ant}^{-}(f)} \cdot \boldsymbol{AF(f)} \tag{5}$$

$$\boldsymbol{I_{CM}(f)} = \frac{U_{probe}^{-}(f)}{Z_T(f)} \tag{6}$$

With (5) and (6) in (4) follows

$$\frac{U_{ant}^{-}}{U_{probe}^{-}} \cdot \boldsymbol{AF(f)} \cdot \boldsymbol{Z_T(f)} = \frac{E_{CM}(f)}{I_{CM}(f)} = \boldsymbol{TF(f)}. \tag{7}$$

C. Verification of the Applicability of the Transfer Function

The verification of the TF can be set up by two consecutive EMI test receiver measurements on the same test setup. The first one is a radiated emission measurement serving as reference. Therefore, the same test setup for the TF generation without the current probe is used. The measurement antenna is connected to the EMI test receiver. Port 1 of the NWA acts as EUT. The EMI test receiver delivers the reference field strength E_{ref}. For the second measurement the current probe is connected to the EMI test receiver and placed at the same position as it is for the TF generation. The obtained current I_{NWA} multiplied with the TF leads according to (2) to the predicted field strength E_{pred}. Figure 2 shows the described measurement setup.

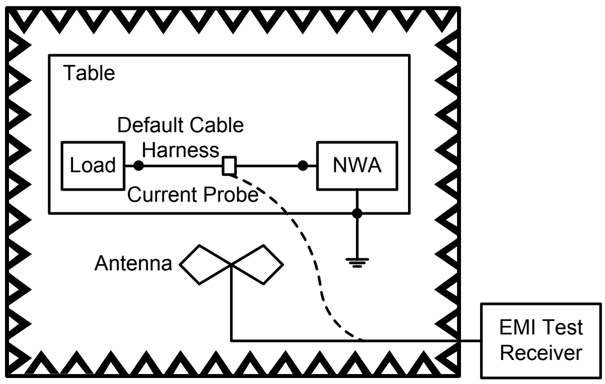

Figure 2. Test setup for verification purpose in a semi anechoic chamber

Figure 3 shows the comparison of E_{pred} and E_{ref} of a 1 m long two wire harness loaded with LISNs. The similarity of both curves is significant despite few deviations smaller 5 dB. Hence, the expected applicability of the TF method for equal setups during the TF generation and the verification measurement is proven. The accuracy of the verification is sufficient for a pre-compliance test method.

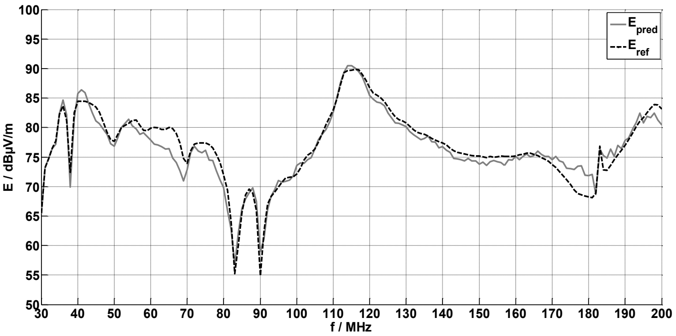

Figure 3. Comparison of the predicted field E_{pred} and the reference field E_{ref}

Deviations between the reference and the predicted radiated emission curve are caused by measurement uncertainties of the NWA and the EMI test receiver. Further reasons are different measurement cables and lengths for the TF generation and the EMI test receiver measurements. The NWA is placed on the measurement table inside the semi anechoic chamber. In contrast the EMI test receiver is situated outside the chamber, hence a change in the measurement setup.

D. Influence of Differential Mode Current on Radiated Emissions

A precondition of the applicability of the transfer function is a field dominating common mode current on the cable harness. Therefore two test setups with different cable harnesses will be compared considering their radiated emissions and common mode currents showing a minor effect of the differential mode current for the used setup. The test setups are similar to the one in Figure 2. The first one consists of two 1 m long parallel wires. The second one is a twisted pair cable. It consists of 1 m of the same type of wire as the first cable harness. Due to the twisted pair geometry field components excited by differential mode currents will be considerably smaller (almost zero) than the two wire configuration. The load is a 100 Ω resistor. As EUT a battery powered broadband impulse generator is used replacing the NWA and placed insulated 5 cm over the table.

Figure 4 shows the measured common mode currents in the middle of the cables and Figure 5 the measured electric field strength of the 2 wire and the twisted pair configuration. As can be seen in Figure 4 the common mode current of both setups is equal from 30 to 95 MHz. From 95 to 145 MHz simultaneous changes in the common mode currents and the field strengths can be observed for both setups. Hence in the region of 30 to 145 MHz the influence of the differential mode current on the field strength can be neglected as well from 180 to 200 MHz. Only in the region from 145 to 180 MHz some deviation between the electric field strength $E_{2\,wires}$ and $E_{twisted\,pair}$ occur. This effect is caused by slight differences between the test setups. Overall, differential mode currents have a minimal influence on radiated emissions in this setup.

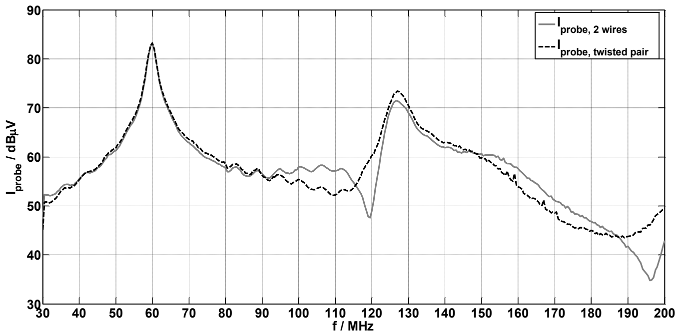

Figure 4. Common mode currents on the 2 wire and the twisted pair cable harness

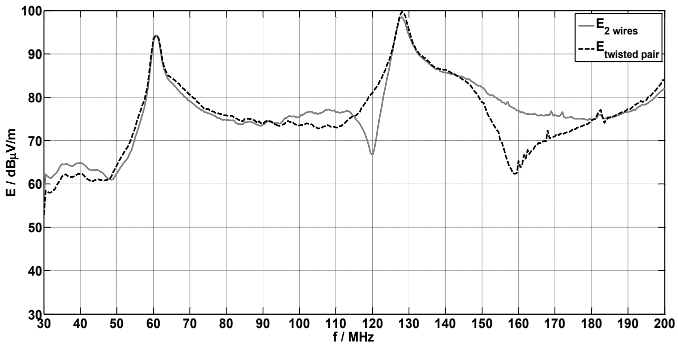

Figure 5. Electric field strength for the 2 wire and the twisted pair configuration

E. Impedance and Filter Analysis

The practical use of the method depends on the accuracy of one default transfer function although it is used for different EUTs and setups. Because the TF includes the common mode current distribution of the default cable harness, the current distribution of the EUT harness has to be the same. Changes in setup parameters will be investigated regarding their effect on the TF. Figure 6 shows electric parameters influencing the TF. Further parameters like current probe, antenna as well as different grounding and filter concepts are not depicted. The considered electric parameters are Z_{Load} and Z_{Source}. The 1 m long cable harness consisting of two wires and the parasitic capacitances will be kept constant. Z_{Source} of the NWA's Port1 (50 Ω) is changed by inserting series or parallel resistances. Additionally the effect on the prediction accuracy by insertion of filter elements will by shown.

1) Changes of Z_{Source}: By varying Z_{Source} from low to high resistive behaviour (Z_{Source} = 1 Ω, 50 Ω, 10 kΩ, 1 MΩ) with a constant Z_{Load} = 100 Ω it can be seen in Figure 7 that different Z_{Source} values do not have a significant effect on the TF. Deviations at lower frequencies are caused by the limited dynamic range of the NWA.

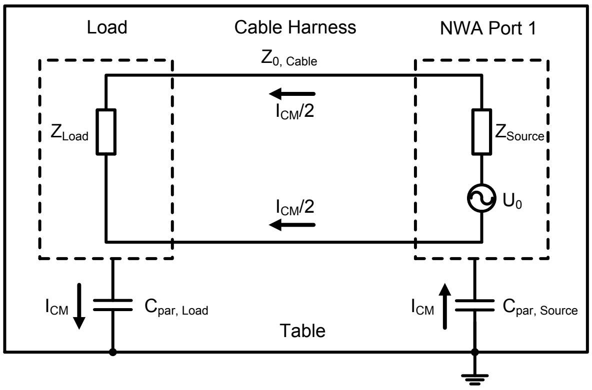

Figure 6: Electric parameters influencing the transfer function

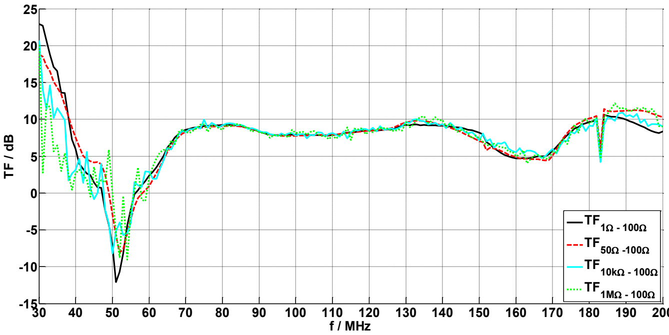

Figure 7: Transfer function TF with variable Z_{Source} and constant $Z_{Load} = 100\ \Omega$

2) Changes of Z_{Load}: By varying Z_{Load} from low to high resistive behaviour ($Z_{Load} = 1\ \Omega$, $50\ \Omega$, $10\ k\Omega$, $1\ M\Omega$) with a constant $Z_{Source} = 100\ \Omega$ in Figure 8 it can be seen, different Z_{Load} have an effect on the transfer function beginning at 120 MHz. This is due to a mode conversion from differential mode to common mode currents. Regarding different load impedances there is a need of different TFs.

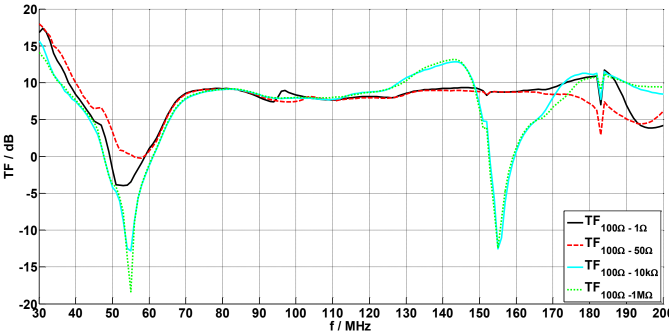

Figure 8: Transfer function TF with variable Z_{Load} and constant $Z_{Source} = 100\ \Omega$

3) Filter insertion: Using a verified default TF on a common mode current measurement of an EUT's test setup leads to an estimation of the radiated field if there are no changes in the setup. This should also be applicable if there are filters applied between cable harness and EUT. Figure 9 shows the predicted radiated field $E_{pred,\ CMC}$ of the setup in Figure 6 with a common mode choke between the 2 wire cable harness and the NWA in comparison to the measured field $E_{ref,\ CMC}$. Figure 10 shows the result with a Cy-Filter. The used TF does not include those filter elements. Both plots have similar curve shapes compared to their reference curves. Nevertheless, there are deviations grater than 10 dB. This are qualitative examples only. They provide an estimation of the radiated field but the accuracy depends strongley on the values of the filter elements and filter structure. Default transfer functions including filters can bring more accurate estimations. Disadvantage of this solution is a large number of TFs. Further examination concerning filters is needed.

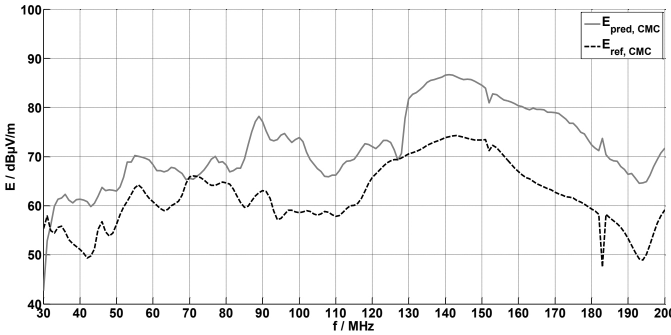

Figure 9: Comparison of the predicted field $E_{pred,\ CMC}$ calculated with a default transfer function and the reference measurement $E_{ref,\ CMC}$

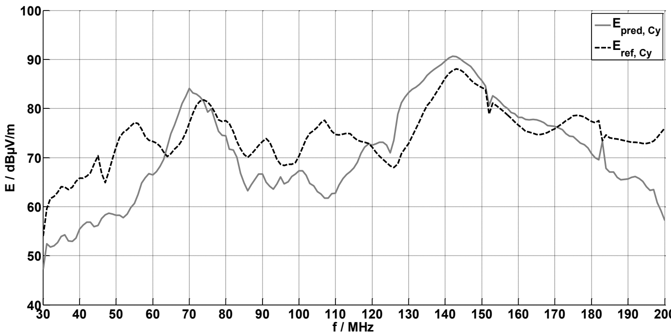

Figure 10: Comparison of the predicted field $E_{pred,\ Cy}$ calculated with a default transfer function and the reference measurement $E_{ref,\ Cy}$

III. Case Study

The used setup presented in section II is a minimum laboratory setup intended to verify the transfer function method and investigate impedance changes. A more realistic setup according to CISPR 25 consisting of a 12 V car battery, two LISNs and either a 1 m or 2 m long two wire cable harness is applied in this case study. The TF is generated as described in section II.B. Figure 11 shows the verification result of the TF according to section II.C for the 2 m harness setup. The 1 m harness is verified likewise. Both verifications have a positive result and allow the transfer function method for this more complex setup.

For the case study the EUT is a step-down switching regulator circuit like used in car electronics powered over the LISNs by a car battery. It is floating 5 cm above the table. The setup for the 2 m cable harness is shown in Figure 12. In Figure 13 the corresponding block-diagram can be seen.

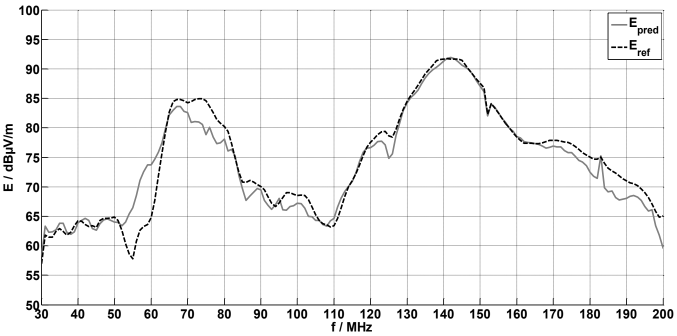

Figure 11: Verification measurement of the transfer function for the case study setup with 2 m cable harness

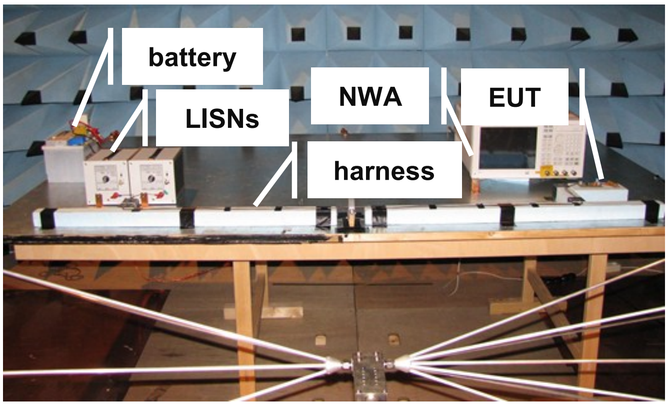

Figure 12: Test setup with battery, 2 LISNs, 2 m cable harness and EUT

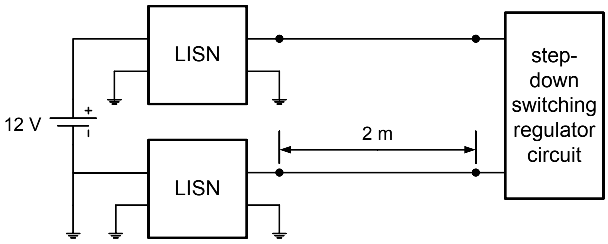

Figure 13: Block-diagram of the case study setup

Figure 14 presents the prediction result $E_{pred,\ step\ down,\ 1m}$ for the 1 m cable harness. The accuracy of the estimation compared to the reference measurement $E_{ref,\ step\ down,\ 1m}$ is better than 10 dB. Only around 72 MHz a deviation of 20 dB occurs.

As can be seen in Figure 15 the predicted emission $E_{pred,\ step\ down,\ 2m}$ has accuracy better than 5 dB between 30 and 50 MHz and between 85 and 185 MHz compared to the reference measurement $E_{ref,\ step\text{-}down.\ 2m}$. The rest of the spectrum exhibits a difference of up to 30 dB. Because of the 2 m length of the harness the TF method is more sensitive to changes in the setup.

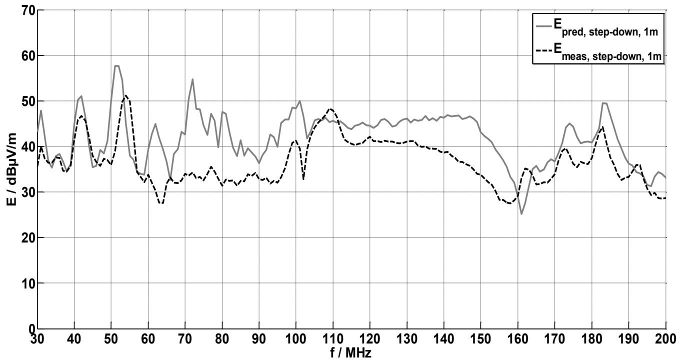

Figure 14: Comparison of the predicted field $E_{pred,\ step\text{-}down,\ 1m}$ and $E_{ref,\ step\text{-}down,\ 1m}$

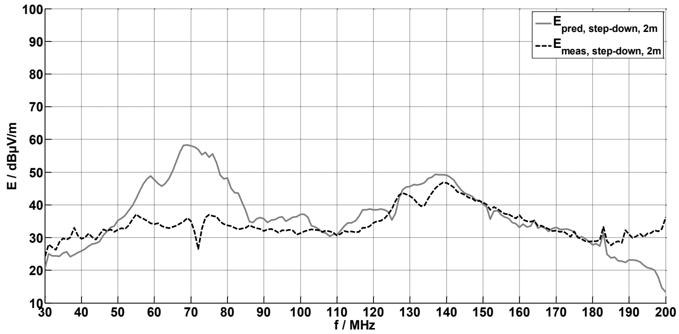

Figure 15: Comparison of the predicted field $E_{pred,\ step\text{-}down,\ 2m}$ and $E_{ref,\ step\text{-}down,\ 2m}$

The highest deviations between 50 and 85 MHz can be explained by analyzing common mode currents and electric field strengths. In Figure 16 dashed lines represent the measured common mode current and electric field strength during the TF generation excited by the NWA. Both current and field strength are contained in the TF. Solid lines represent the same parameters excited by the step-down switching regulator circuit. $E_{meas,\ NWA,\ 2m}$ compared to $E_{meas,\ step\text{-}down,\ 2m}$ exhibits a resonance rise between 50 and 85 MHz. This resonance rise is also present in the TF leading to the deviation between $E_{pred,\ step\ down,\ 2m}$ and $E_{ref,\ step\text{-}down.\ 2m}$.

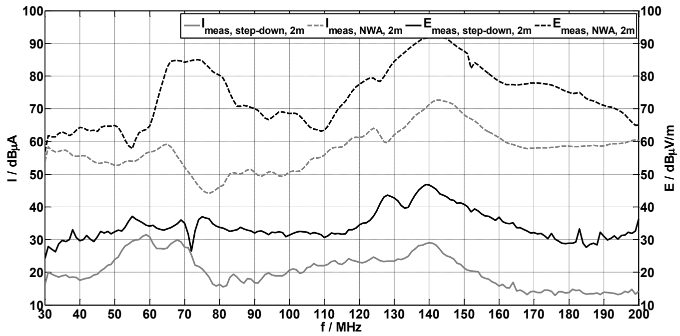

Figure 16: Comparison of step-down regulator and NWA common mode currents and electric field strengths for the 2 m cable harness

This case study shows the applicability of the transfer function method in certain accuracy limits. However, those limits cannot be globally defined. Therefore, each test setup configuration needs its own default TF for an exact estimation.

IV. CONCLUSION

This contribution presents a method for the prediction of radiated emissions according to the CISPR 25 standard for component tests. Using current probe measurements detecting common mode currents on a test setup's cable harness in combination with an appropriate transfer function can lead to a fast estimation of radiated emission. The method can be applied directly on a developer's laboratory setup with no need of an expensive semi anechoic chamber. Therefore this method is applicable with low effort during the development process.

A general description of the transfer function method is introduced. The generation of transfer functions with scattering parameter measurements and its appropriate verification with a deviation smaller than 5 dB are presented. As a result of common mode dependency influencing parameters are detected and analyzed. It is shown that differential mode current radiation can be neglected for the investigated test setup. Load impedances of the test setup have a direct effect. Hence, they have to be considered in terms of different transfer functions. Purely ohmic impedances of EUTs do not have an impact on the transfer function. Because the transfer function depends on common mode currents parasitic capacitances between load and table and between NWA and table will affect the transfer function. Those parasitic effects, different grounding and filter concepts are parameters with very high impact on the method which have to be analyzed further. A case study shows the applicability of the method for a step-down switching regulator circuit.

In summary the whole method depends on many parameters. If the transfer function setup and the later EUT test setup are equal very accurate estimation of radiated emission can be made. However, regarding this method as a pre-compliance test with demand of accuracy of ± 20 dB, boundary conditions and limits for transfer functions have to be found. One universal transfer function is not possible. With those conditions a set of different transfer functions can be generated. Depending on the EUT a suitable transfer function has to be chosen and applied for a reliable pre-compliance test.

Further studies have to be carried out concerning common mode impedances, grounding and filter concepts as well as different types of cable. The frequency range from 0.15 to 200 MHz and both antenna polarizations have to be checked. A test on a complex setup with a multi wire harness including bus systems, low voltage and high voltage components will be performed in addition.

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