Influence of Termination Impedance on conducted Emissions in Automotive High Voltage Networks

M. Reuter[1*], S. Tenbohlen[1], W. Koehler[1]
[1] Institute of Power Transmission and High Voltage Technology (IEH), University of Stuttgart, Germany
[*] Martin.Reuter@ieh.uni-stuttgart.de

Abstract — **Changing the drive train of combustion engine cars from mechanical power transmission to an electric traction network for electric driven vehicles (EV) is a challenge for the EMC performance of the entire system. To reduce electromagnetic interferences, the electric high voltage (HV) traction system consists of entirely shielded housings and cables. In lack of alternatives recent component level EMC measurement methodologies for low voltage (LV) systems are also used for novel HV components. These methods have been developed for automotive LV harnesses, which consist of multiple bundled unshielded single wires. In contrast HV networks are manufactured of coaxially shielded cables and this change in network topology is not considered in EMC testing yet.**

This contribution investigates the effect of changed network topologies within HV systems on component level EMC tests. Therefore the recent state of art in component level testing is presented and the differences of LV and HV network topologies are discussed. An adaption of the component level test setup for HV components is introduced and a minimized HV system investigated. Results of a case study on an inverter for a hybrid car are presented and the impact of the measurements in the design of HV systems will be discussed.

Keywords - HV-LISN, Termination of HV-Cables, Component Level EMC Test, Automotive High Voltage Networks, Conducted Emissions

I. INTRODUCTION

Beside battery capacity, the electric efficiency of the drive train is a major concern in the development of electric driven vehicles (EV). Power losses of semiconductor devices are small during their conducting or blocking state, but within the switching process their losses can raise up to 1 kW. To prevent overheating and for efficiency issues the slew rates of power semiconductors are raised to physical boundaries. Fast slew rates automatically result in switching currents within the radio frequency (RF) spectrum, which are able to disturb sensitive electronic devices. At the same time there is an increasing number of susceptible RF communication services, such as FM radio, GPS navigation and hands free mobile phone services, which might be disturbed by the drive train. Thus developing EV is also a new challenge to ensure the electromagnetic compatibility (EMC) of the miscellaneous electronic devices and the electric traction system. The disturbance potential of EV increases severely as power transmission and sensitive RF communication systems are situated close to each other [1]. Unintended electromagnetic interferences of novel traction power transmission networks have to be suppressed in the automotive environment to ensure reliable operation of susceptible or security relevant electronic devices. To determine the EMC performance of the entire system the electromagnetic emissions of particular components need to be measured. As the network topologies of HV and LV networks differ substantially, this contribution analyzes how the component level EMC test setup has to be adapted for realistic test results of automotive HV systems.

II. COMPONENT LEVEL EMC MEASUREMENT METHODOLOGY

In 1983 a method was developed to measure conducted emissions of automotive components [2]. A Line Impedance Stabilization Network (LISN) was presented providing mainly three functions: It emulates a vehicle LV power network with its input impedance, it supplies the device under test (DUT) with DC power and it provides an impedance matching network to the measurement system with a decoupling of ambient distortions.

This LISN was developed by impedance measurements at automotive LV networks having two conductors, battery plus (BP) and battery minus (BM). With minor changes the setup presented in [2] is standardized in CISPR 25 and currently represents the default component level EMC test setup (illustrated in Figure 1) [3].

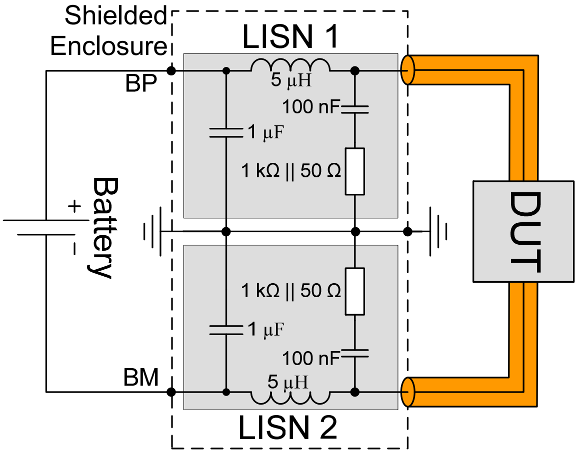

Figure 1. Electric equivalent circuit of EMC test setup according to CISPR 25 for HV components, using two LISNs [3]

Figure 1 shows the default component level EMC test setup, consisting of a power supply (battery) and a DUT. To emulate a vehicle situation each power line of the device is connected to a LISN. Although been developed for LV applications, this setup can easily be adapted for fully shielded HV systems. Therefore two LISNs are inserted into a shielded enclosure, connecting BP to one LISN, BM to the second and ground to the HV cable shields (dashed lines in Figure 1). With these adaptions the component level test setup according to CISPR 25 can be used for HV systems.

III. COMPARISON OF AUTOMOTIVE HIGH AND LOW VOLTAGE NETWORK CHARACTERISTICS

The currently used component level EMC test setup emulates the input impedance of an automotive LV power network. But conducted emissions depend strongly on the load impedances of the disturbance sources within the tested device. Thus the component level setup according to CISPR 25 can only be used for HV systems if the input impedances of HV networks have similar characteristics as LV networks.

A. Comparison of Network Topologies

Nowadays automotive LV harnesses spread across the entire car. All electronic components are connected to this network, thus it is widely branched and its topology is close to stochastic. The LV network consists of several unshielded single wire cables bundled into one harness. The geometry of such a wiring harness is not continuous over its length and the distance to the next grounded structures is inconstant. In contrast automotive HV traction networks are rarely spread. They usually have just a couple of participating components as battery, inverter and possibly cooling solvent compressors. These networks typically consist of two shielded coaxial cables routed in parallel. As these cables have a constant geometry over their length, also the distance between conductor and grounded structure is constant (earthed cable shielding).

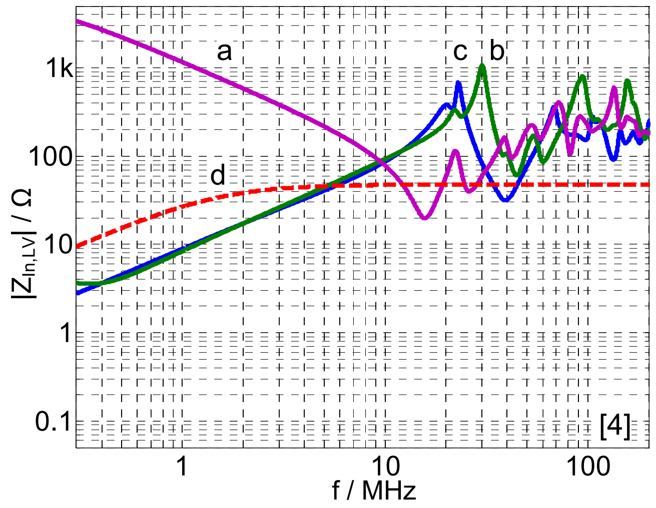

Figure 2. Input Impedances of different branches between battery and:
a) Open ended LV cable to wiper motor
b) Shortened LV cable to wiper motor
c) Shortened LV cable to front damper
d) LISN according to CISPR 25

B. Crosstalk and Q-factor of harness resonances

The unshielded cables of LV networks lay bundled in parallel close to each other. Therefore, these wires are closely coupled via mutual crosstalk. The line resonances of single wires are damped by transferring power through crosstalk to other lines [4]. All cables have minimum diameter that is needed for current transmission. Therefore the resistance of the single cables is quite high and consequentially the Q-factor of cable resonances is low. The whole LV networks harness is rather kind regarding single frequency resonances [4]. In contrast HV networks have to transmit high currents to a small number of attached components. Their conductor diameter is way larger than in LV networks and the shielding effectively prevents crosstalk between the lines. Thus line resonances of HV networks have a high Q-factor and cable resonances are hardly damped [5].

C. Distributed line elements and wave impedance

The characteristic or wave impedance of a transmission line is calculated as square root of series inductance divided by ground capacity of the line [6]. As LV networks are inconstant and stochastic in geometry over their extent, the distributed line elements are also not uniform over length. Thus the wave impedance of LV networks is inconstant over length and therefore impedance matching is not possible. As empirical rule the distributed line elements are supposed to be around $L_S \sim 1$ µH/m and $C_G \sim 100$ pF/m. HV cables have much larger wire diameters and the shielding is close to the conductor. The distributed line elements are constant over the length of the cable with values of $L_S \sim 100$ nH/m and $C_G \sim 500$ pF/m. These lines have a constant wave impedance of $Z_L = 10$ to 20 Ω, depending on cable diameter, geometry and permittivity of the applied insulation material [5].

D. Comparison of measured input impedances

Figure 2 and Figure 3 display measured input impedances of automotive LV and HV networks over frequency.

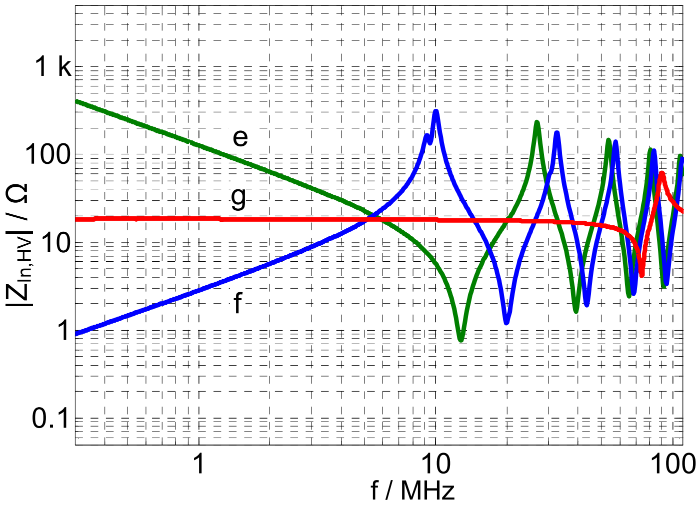

Figure 3. Impedances of automotive HV cables:
e) Open ended HV cable (ℓ = 3.3 m)
f) Shortened HV Cable (ℓ = 3.3 m)
g) Characteristic impedance (ℓ = 1 m)

978-1-4673-0717-8/12/$31.00 ©2012 IEEE

In Figure 2 the input impedance of different branches within the LV wiring harness of a car are shown [4]. As the input impedance of components generally is unknown and especially is not constant over time for switching semiconductor devices, the termination impedance of a LV harness branch is assumed to be in between open and short. In Figure 2 the input impedance of the same branch between battery and wiper motor are compared: once terminated with a short (a) versus an open ended termination (b). For comparison the input impedance of a LV branch shortened at the front damper also is displayed (c) [4]. The curves of Figure 2 show below 10 MHz capacitive behavior for the open ended branch and inductive characteristics for the shortened branches. More important is the impedance between 10 – 200 MHz, as it shows multiple resonances with low Q-factors. The input impedances are inconstant within a region of $Z_{IN,LV} = 30 – 800\ \Omega$ (28.5 dB). For LV networks low input impedances are critical, because conducted disturbances mainly consist of RF currents, due to the low operating voltage. The plotted input impedance of the LISN (d) describes the standardized worst case assumption of lowest cable harness input impedance.

Figure 3 shows the input impedances of a HV cable which is terminated with an open (e), short (f) and the cable's wave impedance (g) over frequency. Below 5 MHz it shows inductive behavior if shortened and capacitive for open ended termination, although with considerable lower values. Above 10 MHz sharp line resonances can be observed and the input impedances differ between $Z_{IN,HV} = 0.8 – 200\ \Omega$ (48 dB). The LISN input impedance is not the worst case estimation for HV cables. The wave impedance of the investigated cable is $Z_L = 18.5\ \Omega$. Thus terminating HV cables with a LISN results in a termination mismatch and in reflected radio frequency disturbances on the line.

E. Impact of line termination impedance

LV networks do not have a defined wave impedance and the LISN represents a worst case assumption for LV networks. Because the line resonances of single wires are damped by the rest of the harness, it is not necessary and not possible to terminate LV network transmission lines. In contrast, HV cables have high Q-factors of their line resonances, low crosstalk and defined wave impedances. These cables act as transmission lines and therefore need to be terminated with their characteristic impedance. Sharp line resonances may result in false measurement results if the cable's termination is mismatched.

IV. IMPEDANCE ADAPTION FILTER FOR LISN

To determine the disturbance potential of a component its conducted emissions on power and communication lines need to be measured. As the RF current and voltage emissions of disturbance sources strongly depend on their load impedance, it is important that the load situation on component level is as similar as possible to the EMC tests on vehicle level. At the line's resonance frequencies current and voltage on the line no longer depend linearly on the excitation power but are determined by impedance mismatch and the Q-factor of the resonance. The standing waves at cable resonance frequencies of a resonant structure as HV cables are only damped by its ohmic resistance. Due to the large diameter of the conductors their ohmic resistance is low. Line resonances can only be avoided by impedance match of the cable termination to the cable's wave impedance. This leads to the perception that the input impedance of the LISN has to be adapted to the wave impedance of the cable. The filter network shown in Figure 4 is able to match the termination impedance of a HV cable using a conventional LV LISN.

The adaption filter network shown in Figure 4 allows a broadband impedance matching to cables with wave impedances in a range of 0 – 50 Ω. The network consists of a series inductor of $L_S = 100$ nH and an RC element to ground. The RC element consists of a matching resistor and a 130 nF capacitor to prevent DC losses. Because this network is intended for a wide range of HV cable impedances it consists of a trim potentiometer (0 – 500 Ω).

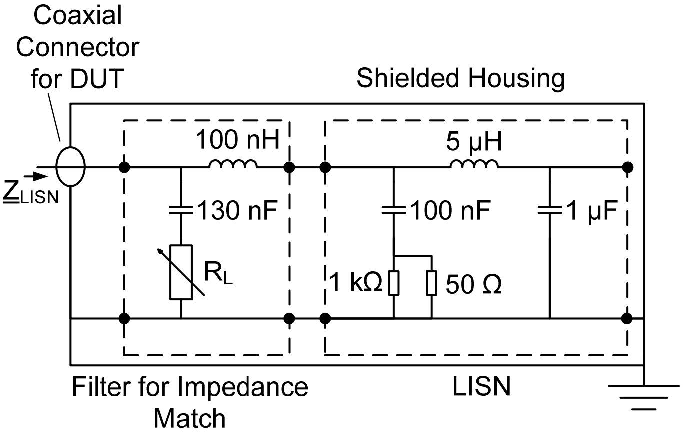

Figure 4. Electric equivalent circuit of LV LISN with input impedance matching filter network.

Figure 5 shows the input impedance of the entire structure with and without filter as standardized in CISPR 25. It starts at low frequencies with a value of ~ 8 Ω, then increases to a constant value of $Z_{LISN} = 50\ \Omega \pm 10\ \%$ between 5 - 110 MHz. The filter decreases the input impedance of the LISN structure to values of the attached HV cable. In Figure 2 the input impedance for an example value of $Z_{LISN} = 20\ \Omega$ is shown. It shows similar frequency characteristics, just at lower impedance values.

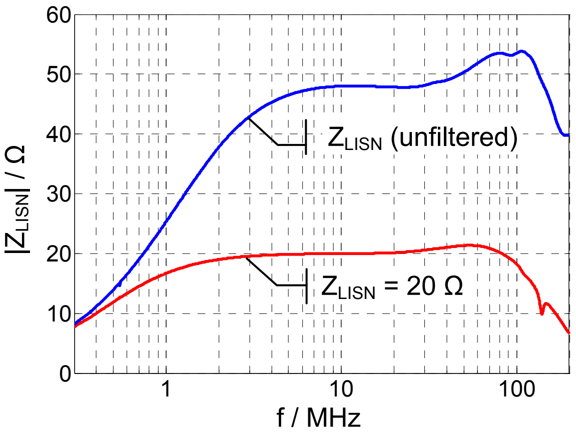

Figure 5. Input impedance of LISN with impedance matching filter set to $Z_{LISN} = 20\ \Omega$ and without filter according to CISPR 25.

Figure 6 shows the input impedance of a common HV cable ($\ell = 3.3$ m) terminated with variable input impedance LISN. It is measured using a Vector Network Analyzer (VNA). The wave impedance of the applied cable has been determined to $Z_L = 18.5\ \Omega$ [5]. A transmission line begins to behave as wave guide if $\ell > {}^{\lambda}/_{10}$, thus a HV cable of that length above a frequency of $f \approx 5\ MHz$ [5]. As the input impedance of the filtered LISN has a constant value within the region of 5 – 110 MHz this value is further used as notation of the adapted LISN input impedance setting.

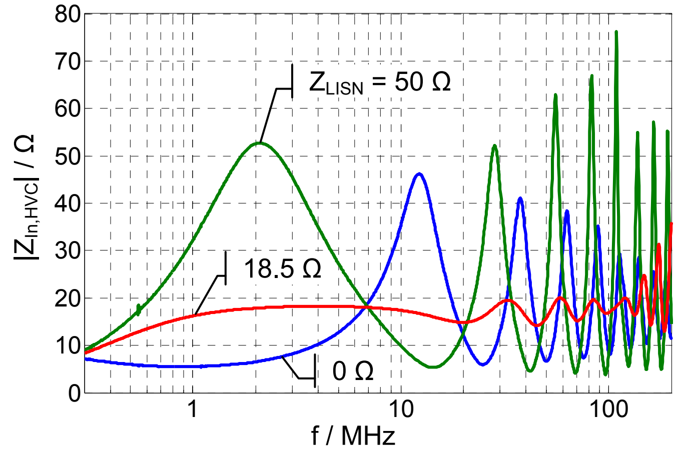

Figure 6. Input impedance of HV cable terminated with variable input impedance LISN set to values of $Z_{LISN} = [50, 18.5, 0]\ \Omega$.

Figure 6 shows that the input impedance of the entire cable follows the termination impedance below 2 MHz, here the LISN input impedance. The first resonance of the mismatched cable (50 Ω and 0 Ω) occurs at 11 – 12 MHz, where the 50 Ω termination is transformed in an input impedance of ~ 5 Ω and the shortened end is transformed into ~ 45 Ω. Above this frequency regular impedance transformations can be observed. Only a termination of the HV cable with its wave impedance suppresses line resonances. The matched termination (18.5 Ω) shows a flat shape of the impedance curve. Slight mismatches appear in a frequency region of 30 -150 MHz. Above 150 MHz the impedance mismatch of the termination increases because of parasitic line inductivities within the adaption filter.

Figure 6 shows that using the presented filter network the termination match of HV cables is possible. It also proves that typical coaxial HV cables transform the termination impedance to the input according to transmission line theory above 10 - 20 MHz, only depending on length and wave impedance.

V. EFFECT OF TERMINATION IMPEDANCE ON CONDUCTED EMISSION TEST RESULTS

To show the influence of termination impedance on conducted emissions of HV components a minimum HV network representation is investigated. Figure 7 displays a simplified electric equivalent circuit diagram and Figure 8 shows a picture of the analyzed conducted emissions test setup. The setup consists of two parallel HV cables with a wave impedance of $Z_L = 18.5\ \Omega$. Both cables are excited in parallel with a broadband impulse generator (Schwarzbeck IGUF 2910) and terminated with two LISNs. The input impedance of these two LISNs can be varied as shown in section IV. The HV cables are routed 5 cm above a grounded, conductive plane as prescribed in CISPR 25 and have a length of $\ell = 3.3$ m.

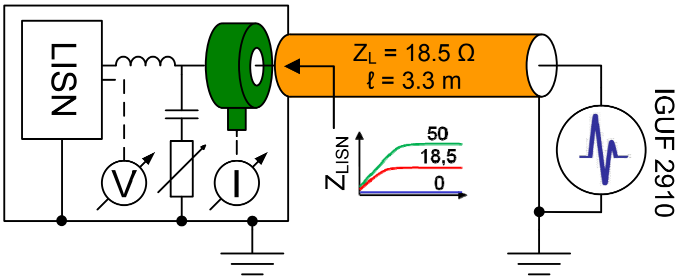

Figure 7. Simplified sktech of minimum test setup for conducted emission measurement of an impulse generator exciting a HV cable, which is terminated with variable input impedance LISN.

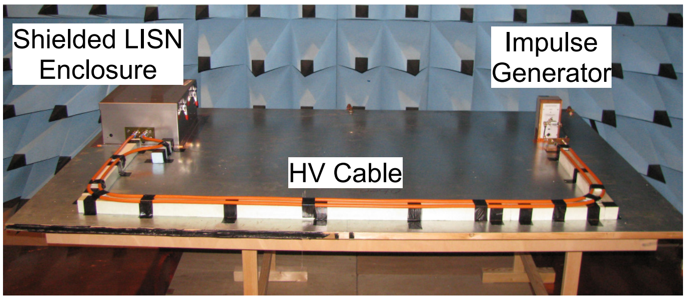

Figure 8. Picture of conducted emission test setup consisting of two parallel HV cables, excited with an impulse generator and terminated with variable input impedance LISNs.

A. *Influence of Termination Impedance on measured Disturbance Voltage at LISN*

The disturbance voltage at the LISNs is measured using an EMI test receiver (peak detector) according to CISPR 25. The disturbance voltage of the impulse generator is displayed in Figure 9 within a frequency range of 20 – 200 MHz.

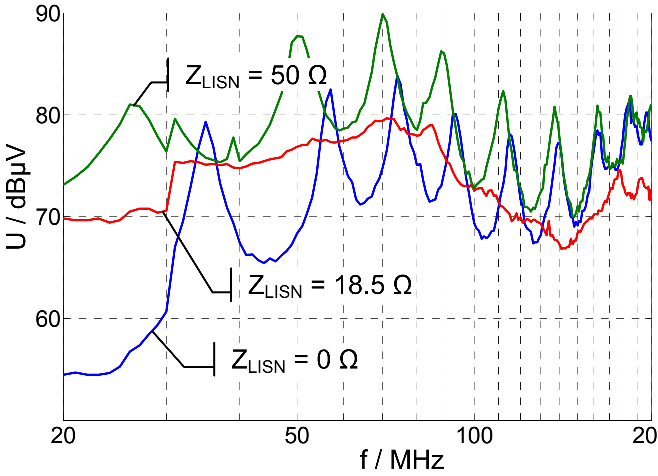

Figure 9. Measured disturbance voltages with LISN input impedances of $Z_{LISN} = [50, 18.5, 0]\ \Omega$.

The HV cables are terminated with different impedances as shown in Figure 6. Figure 9 shows the measured disturbance voltage on the line for the presented three termination impedances. The highest voltage values occur (with regular resonance enhancements) if the cables are terminated with the

978-1-4673-0717-8/12/$31.00 ©2012 IEEE

LISN input impedance of 50 Ω. Terminating the line with a capacitor (0 Ω) also results in regular resonances, but at lower voltage values. Only by terminating the line with its wave impedance (18.5 Ω) resonance enhancements of recorded disturbance voltages can be avoided. The difference in detected results of mismatched to matched termination impedance is around ± 15 dB. Even for the termination of 0 Ω the voltages at resonance enhancements exceeds the voltage values of the terminated line by 5 – 10 dB.

B. *Influence of Termination Impedance on Conducted RF Current Disturbances*

For radiated emissions the common mode disturbance current flowing on a line is essential [6]. Thus the current on the HV cable is measured with a Fischer F65-A current clamp and cable input impedances shown in Figure 6. The test results plotted in Figure 10 show the overall disturbance current measured in front of the line's termination as sketched in Figure 7.

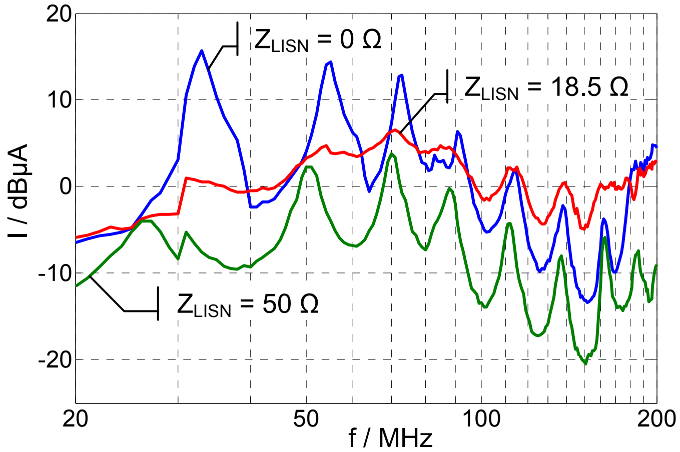

Figure 10. Measured disturbance current on HV cable with LISN input impedances of $Z_{LISN} = [50, 18.5, 0]$ Ω.

The curves displayed in Figure 10 show with increasing termination impedance decreasing current disturbances. Terminating the cable according to CISPR 25 ($Z_{LISN} = 50$ Ω) results in the lowest current values, but with regular resonance enhancements. Thus changing the cable length would result in changed resonance frequencies. A purely capacitive termination of the HV cable, in order to reduce conducted voltage emissions, yields in enhanced disturbance currents with regular resonances (0 Ω). Line resonances in current emissions can only be avoided using an impedance matched termination of the cable.

C. *Impact of Termination on Conducted Emissions*

For the measurement of conducted emissions of automotive HV components it is necessary to match the input impedance of used LISNs to avoid measurement errors resulting of cable resonances. Using the default test setup according to CISPR 25 results in frequent enhanced voltage values that may not occur in the vehicle or at different frequencies. Also the reduction of conducted voltages with a capacitor to ground (C_Y) enhances disturbance currents and does not damp line resonances. As the electromagnetic field is a direct result of common mode currents, the radiated emissions would also increase.

VI. CASE STUDY OF A HYBRID INVERTER

The HV network presented in section V is a minimum laboratory setup intended to verify line resonance effects of HV cables. Figure 11 shows a realistic HV component level test setup for a power converter in a hybrid driven car. It consists of two LISNs according to CISPR 25 in a shielded containment powering two HV cables. These are connected to the DUT, controlling an electric three phase synchronous machine (M). The power converter is also connected to the LV network represented by two LV LISNs. All power and communication lines are arranged in one harness of 3.3 m length, 5 cm above a conductive plane according to CISPR 25.

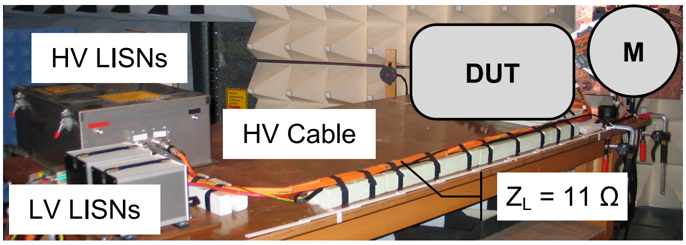

Figure 11. Component level EMC test setup for a HV component consisting of DUT, electric machine M, HV and LV networks each line terminated with a LISN.

Within the shielded compartment a printed circuit board is applied, that enables to vary the input impedance of the HV LISNs as described in section IV. The peak voltage on the HV lines at the LISNs connectors were measured using an EMI test receiver. As the used HV cables have a characteristic impedance of $Z_L = 11$ Ω, three input impedance values are investigated: $Z_{LISN} = 50$ Ω according to CISPR 25, impedance match $Z_{LISN} = 11$ Ω and a purely capacitive termination $Z_{LISN} = 0$ Ω. Figure 12 shows the measured disturbance voltage over frequency in a range of 20 – 200 MHz.

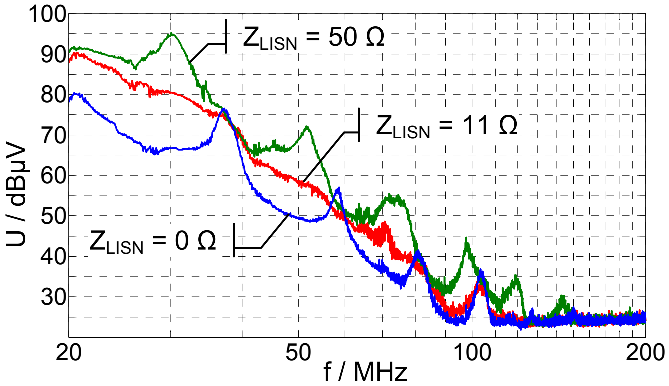

Figure 12. Measured disturbance voltages of the hybrid inverter on HV- with LISN input impedances $Z_{LISN} = [50, 11, 0]$ Ω.

The disturbance voltage measured according to CISPR 25 (50 Ω) shows regular resonance peaks in the test results of ~ 15 dB. These resonance enhancements cannot be observed if the cable is terminated with its wave impedance of $Z_L = 11$ Ω. A capacitive termination reduces the disturbance voltage at the end of the cable, except for the resonance frequencies, where voltage exaggerations of 3 – 6 dB occur (0 Ω).

VII. IMPACT ON EMC PERFORMANCE OF HV-SYSTEMS

There are two different areas that are affected by the presented results: The component level measurement methodology and the EMC design of HV systems. By adapting the LISN input impedance valid test results can be achieved, but a LISN is just an emulation of an automotive system. Thus the impedance matching adaption of the LISNs does not improve the EMC performance of HV systems.

A worst case scenario of mismatched input impedances on both sides of a HV cable could lead to reflected disturbances. In this case the line resonances could even amplify occurring conducted emissions and compromise filter effectiveness. Figure 13 shows the input impedance of an HV cable measured using a VNA ($\ell = 3.3$ m). If a cable acts as wave guide according to the transmission line theory, the termination impedance is transformed to a different value at the input of the line. The quotient of maximum to minimum value of that input impedance is an indicator for the amount of impedance mismatch.

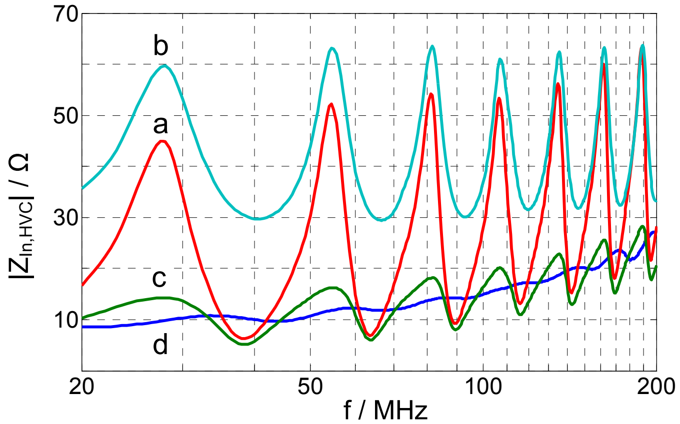

Figure 13. Measured input impedance of a HV cable with different line terminations on excitation and termination side of the cable ($Z_L = 18.5\ \Omega$):
(a) Both sided mismatch: $Z_{In} = 50\ \Omega$, $Z_T = 50\ \Omega$
(b) Attenuated mismatch: $Z_{In} = 50\ \Omega$, $Z_T = 50\ \Omega$, 3.8 dB
(c) Termination matched: $Z_{In} = 50\ \Omega$, $Z_T = 18.5\ \Omega$
(d) Both sided match: $Z_{In} = 18.5\ \Omega$, $Z_T = 18.5\ \Omega$

Curve (a) displays the measured input impedance of a HV cable with two sided termination impedance of 50 Ω. The measured input impedances of curve (a) are within a range of $Z_{In,HVC} = 7$ to $52.2\ \Omega$ (17.5 dB). If the line resonances are damped via termination matching the range width in the input impedances will be reduced.

One common approach to reduce impedance mismatch is the introduction of an attenuating device into the signal path. Although this is not applicable in HV systems the input impedance with introduction of a 3.8 dB-attenuator is measured and displayed in Figure 13 as curve (b). It shows a significant reduction of the input impedance range of $Z_{In,HVC} = 29.5$ to $64.5\ \Omega$ (6.8 dB). A single sided impedance match of the line (c) reduces the input impedance range of $Z_{In,HVC} = 6$ to $16.2\ \Omega$ (8.6 dB). It damps the observed line resonances not as effectively as the attenuating device, but it is applicable in an automotive HV filter. If the HV cable is terminated with its wave impedance on both sides (d) nearly no resonances in the input impedance are observable.

Subsequent HV filters should not only focus on decoupling of emissions, but also provide an impedance matched termination of attached HV cables. This effectively damps line resonances and standing waves, which can disturb nearby systems. In a branched automotive HV network each HV cable should be at least terminated at one end, as it is common technique in bus systems.

VIII. CONCLUSION AND OUTLOOK

The recently used component level EMC test setup as standardized in CISPR 25 for LV components is not applicable for HV components because of substantial differences in network input impedances. HV cables develop sharp resonances if the attached termination does not match their wave impedance. Thus impedance mismatches need to be avoided within the component level EMC test setup. Otherwise line resonances lead to falsified, exaggerated measurements. Test results may not be reproducible when the investigated device is mounted in its automotive environment. If cable lengths differ EMC countermeasures will become ineffective, because of shifted line resonance frequencies. The common LISN network should be adapted as shown in this contribution to achieve valid EMC test results of HV components.

Adapting the input impedance of the LISN for a component level EMC test does not affect the emissions of a HV system integrated in an electric driven vehicle. To avoid line resonances within an automotive HV network the applied cables should be terminated at least one sided. Common termination techniques of communication bus systems should also be implemented in HV networks. In the development of filters for HV networks impedance matched termination has to be considered. Traditional filter design using ground capacitors directly at the input results in reflected distortions because of too low termination impedance. Instead a RC termination can be implemented. Further investigation on filter design for HV components will focus on the effects of impedance matched termination within the filter structure.

REFERENCES

[1] S. Guttowski, S. Weber, E. Hoene, W. John, and H. Reichl, "EMC issues in cars with electric drives," in *IEEE International Symposium on Electromagnetic Compatibility*, Boston, 2003, pp. 777 - 782 vol.2.

[2] S. Yamamoto and O. Ozeki, "RF Conducted Noise Measurements of Automotive Electrical and Electronic Devices Using Artificial Network," in *IEEE Trans. Veh. Technol., vol. VT-32, no. 4.*, 1983, pp. 247 -253.

[3] I.E. Comission, "CISPR 25 Ed. 3: Radio disturbance characteristics for the protection of receivers used on board vehicles, boats and on devices – Limits and methods of measurement," 2008.

[4] H. Rebholz, *Modellierung leitungsgebundener Störgrößen in der Komponenten- und Fahrzeugmessung*, 1st ed. Stuttgart: Sierke Verlag, 2010.

[5] M. Reuter, S. Tenbohlen, W. Köhler, and A. Ludwig, "Impedance Analysis of Automotive High Voltage Networks for EMC Measurements," in *EMC Europe 2011*, York, UK, 2011, p. 6.

[6] C. Paul, *Introduction to Electromagnetic Compatibility*. New York: Wiley & Sons., 1983.