EMI Coupling from Automotive Traction Systems

S. Weber, S. Guttowski, E. Hoene, W. John, H. Reichl
Fraunhofer Institute for Reliability and Microintegration
Gustav-Meyer-Allee 25, 13355 Berlin, Germany
E-mail: weber@izm.fraunhofer.de

Abstract— **Electric drive systems for vehicles are integrated into today's passenger cars by almost every car manufacturer. From the EMC point of view, the integration of electric drive systems into cars represents a substantial challenge. The conventional EMC procedures and techniques are not appropriate for the new components. In this paper, an electric drive system is investigated which is source of electromagnetic interference within a passenger car. A model for simulating coupling paths in the frequency domain, for standard cables as well as for shielded cables is developed and confirmed by measurements. The obtained results have been used to determine the acceptable noise level emitted by the power converter on the high-voltage cables of a drive system.**

Index Terms— **Power Electronics, Electric Vehicles, EMI Test Procedures, Limits, EMC, Modeling**

I. Introduction

The future drive concepts for passenger cars include an electric drive system either to reduce the fuel consumption or to build a zero-emission vehicle. Possible solutions are the hybrid car, the pure electric car and the fuel cell car.

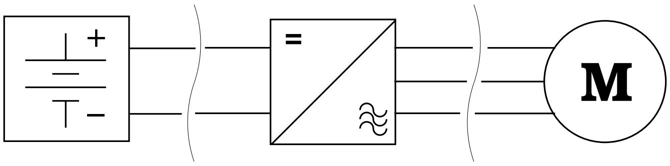

Fig. 1. Basic Structure of Electric Drive System

Figure 1 shows the basic structure of electric drive applications for vehicles. Electric power is provided by a battery or a fuel cell. They have the power converter and the electric motor in common. In fuel cell cars and in pure electric vehicles the power consumption of the power converter and the motor will be the same size. In hybrid cars, the electric drive system can be seized smaller since the main drive power is coming from the combustion engine. From the EMC point of view, the concepts can be treated similarly but they differ extremely from conventional automotive electrical components. The power converter is known to be a noise source due to fast switching transients. The integration of electric drive systems in today's cars represents a substantial challenge. The amount of power required by the electric drive, the power supply voltage of 300 or 900 V and the decentralized setup of the system within the car turn the electric drive system into a highly significant source of electromagnetic interference. In this paper, a detailed investigation of the spreading of EMI generated by the power converter is given. The power converter and the possible coupling paths between the noise source and the potential noise sink, the conventional electrical system of the car, are explored for this purpose. A model is developed to quantify electromagnetic noise emitted by the electrical drive system converter in the two possible configurations with and without shielded cables. This model is confirmed by measurements. The obtained results allow the determination of necessary filtering efforts and their discussion in terms of cost, weight and space.

II. Limits for a High-Voltage System

The limits required in the standards [1] have been developed for low-voltage components that are supplied by the power bus together with other components which might be very sensitive to electromagnetic interference, whereas the power converter's high power supply system is completely insulated because of the high voltage. For instance, the procedures and limits used to specify the conducted emissions by a car component given by the SAE standard [1] cannot be applied to the power converter, as the test procedures are not costumized for high-voltage supply systems with its specific topology. The small number of high-voltage components and the high levels of interference are reason for different conditions compared to conventional supply systems. Yet evaluating shielded cables the conventional test procedures do not help.

Using the conventional limits would lead to much higher effort in filtering than actually necessary. Therefore, a new approach to find appropriate emission limits for the high-voltage system is developed in this paper. These limits take into account the specific of the new components and they also are strict enough to ensure the electromagnetic compatibility of the whole system.

III. Noise Source Power Converter

The electric drive power converter has four terminals to spread EMI into the vehicle. First there is the high-voltage DC-bus connecting the power source. Then there is a three-phase-AC-bus connecting the motor to the power converter. The low-voltage power supply of a power converter and its control and sensor lines are additional interfaces to the car's conventional electrical system. Due to the fact that these interfaces connect the potential noise source and the possible noise sinks directly, they have to be designed carefully. But from the EMC point of view these interfaces can be treated like interfaces from conventional car components.

Contrary to the low-voltage interfaces, the connection to the power supply and the cables to the electric motor are high-power interfaces. These interfaces challenge the EMC compatible design of the system. The EMI generated by the power converter on its power terminals is characterized in [2]. Due to the fact that the main noise is known to be on the motor cables, these connections are either made to be as short as possible or the converter and the motor are integrated into a common casing. Therefore this paper mainly focuses on the high-voltage DC-bus although the model and the appropriate emission limits are also applicable to the motor cables. In the following the connections between the power converter and the power supply are considered.

IV. Coupling Paths

Starting from the theory of electromagnetic compatibility, the potential noise sink and the coupling paths have to be identified first. Integrating a new electric drive system into a vehicle, the noise sink to be protected against interference is the conventional electric system and its low-voltage devices such as the radio receiver. However the high-voltage system will be insulated and does not use the car body as return conductor like the low-voltage supply system does. As space for wiring harness is limited in modern cars, high-voltage and low-voltage cables are arranged closely to each other. Hence one important coupling path is crosstalk between the different lines. Besides crosstalk, the EMI radiated from the high-voltage cables into the vehicle is an issue to be addressed.

A. Crosstalk Analysis

For quantifying crosstalk, the underlying idea is to place the cables of the high power bus close to the cables of the low power bus. Figure 2 shows the setup chosen for the investigation. The setup is derived from the setup required for the conducted emission measurements according to standards [1]. The high-voltage bus cables – possibly shielded – are arranged in parallel to one line representing the low-voltage bus or any sensible signal line. The low-voltage line is connected to a line stabilizing network (LISN) on one side and to a component with worst-case impedance on the other side. Impedance of the input terminal of the component is supposed to be small for worst-case inspection. Values for worst-case inspection are mentioned in [3]. In case of signal lines input terminal impedance is high ohmic, at least $100\,\Omega$. Power input terminals are less ohmic, at least $0.1\,\Omega$. Based on this setup the impact of an electric drive system on the low-voltage electrical system of a passenger car can be quantified by measurement or simulation with lumped parameter models.

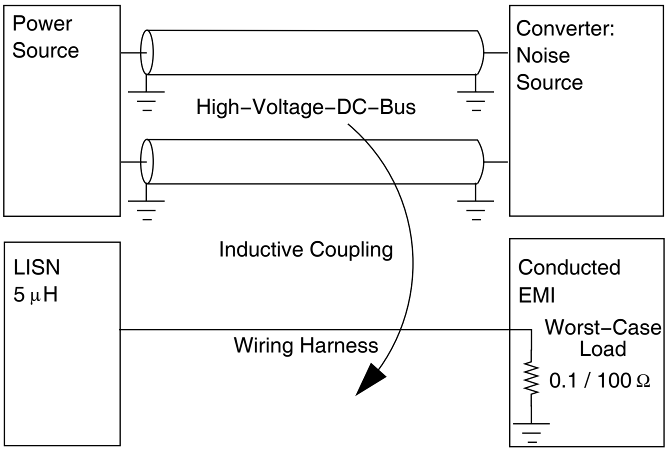

Fig. 2. Setup for Crosstalk to a Line Located 10 cm Beside the High-Voltage Bus

B. Radiated Electromagnetic Interference

In a quasi-static inspection of the radiated EMI, the lumped parameter model of the high-voltage bus can be used to determine the field strength at a distance of 1 m in the frequency range from 150 kHz to 30 MHz. Therefore the capacitances between the monopole antenna and the cables – respectively their shields – are calculated by 3D-FEM. Applying this model to a setup in a real car can be useful for predicting radiated EMI during the design phase of the system, as highest levels of conducted EMI occur in the frequency range up to 30 MHz. EMI radiated from the high-voltage bus has to fulfill the same standards as any other line connecting low-voltage components. As the conventional procedures can be used for EMC assessment of the high-voltage bus without changes, it is not further stressed in this paper.

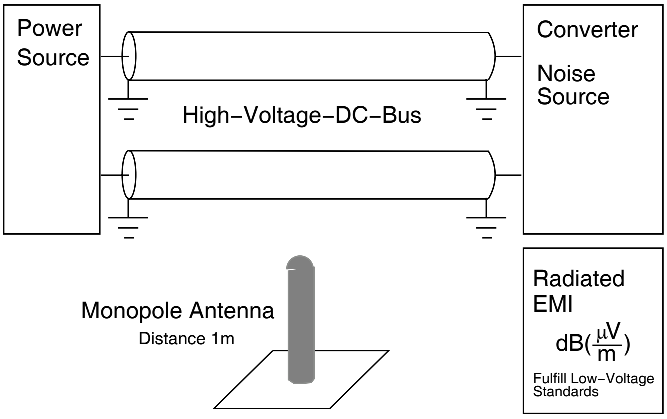

Fig. 3. Setup for Radiated EMI

V. Test Setup

As test setup two shielded cables with 70 mm^2 cross section of the inner conductor are chosen and assembled on a conducting ground plane as shown in Figure 4. In order to determine crosstalk, an inphase test signal is injected into both cables by a Gain-Phase Analyzer (HP4194A). The

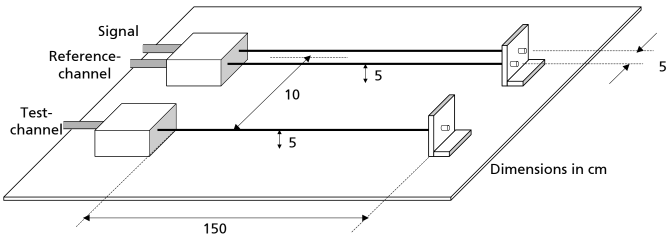

Fig. 4. Measurement Setup for Gain-Phase-Measurement with Networkanalyzer HP4194A

resulting signal is measured on a third line, representing the low-voltage electric supply system or any sensitive signal line.

The shielded cables are modelled by the lumped parameter line element model shown in Figure 5. It consists of the inductance L_C for the inner conductor, L_S for the inductance of the shield and the mutual inductance M_{CS} between both. They are calculated from geometrical dimensions with analytical formulas found in the literature [4,5] aswell as the capacitance C_S between the cable shield and the ground plane. Resistances of the shield and the inner conductor R_S and R_C depend on the frequency due to skin effect, which influences the shielding effect and the damping at resonance frequencies. Frequency dependent effects like diffusion and dielectric losses are of outstanding importance for the correct simulation of resonances in the coupling paths. That's why the described model is only suited for simulations in the frequency domain. An additional inductor L_{braid} on the braided shield which is not coupled to any other inductors, represents abating shielding effectiveness due to inductivity of the braid and its holes [6]. The investigated cable is 1.5 m long according to the setups defined in [1]. Its isolator shows a relative dielectric constant around $\epsilon_r = 4$. As the model has to be valid up to 100 MHz, where a wavelength of approximately 1.5 m appears, ten line elements of length less than $\frac{\lambda}{10}$ are used. Figure 6 shows the impedance of one high-voltage cable. The impedance calculated without dielectric losses differs clearly from measured values. Due to the fact that coupling and radiation of EMI from shielded cables is a problem mainly at occuring resonance frequencies, efforts are made to model dielectric losses correctly. This is particularly of importance for absolute values at resonance frequencies. The highest resonance frequencies of the power cable are also not correctly calculated if the decrease of the cable's capacitance with the frequency is not considered.

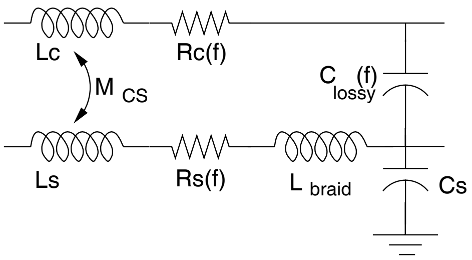

Fig. 5. One of Ten Line Elements Modeling Power Cable

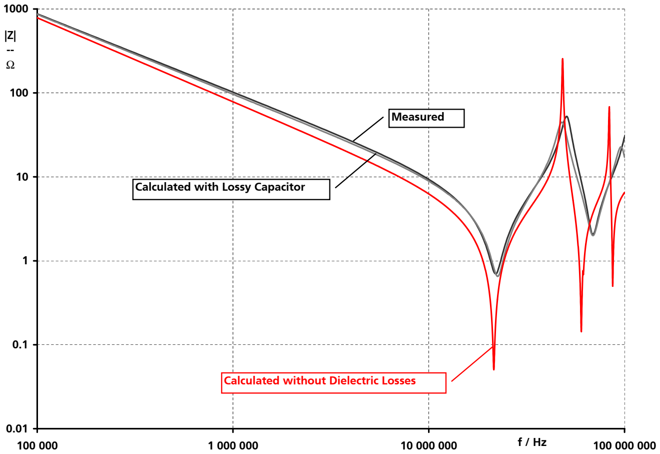

Fig. 6. Impedance of Shielded Power Cable of 1.5m Length

The comparison of simulation and measurement of crosstalk from the highpower cables to a single line is shown in Figure 7 for common mode currents on the shielded high-voltage system. The calculations match well with the measured data and therefore validate the model developed for the coupling path. Coupling values below −100 dB are ignored as measuring accuracy is not appropriate to resolve such high damping values. Above 30 MHz calculated coupling is little higher than measured levels. The coupling level at the resonance frequency around 23 MHz is predicted exactly with the developed frequency domain model.

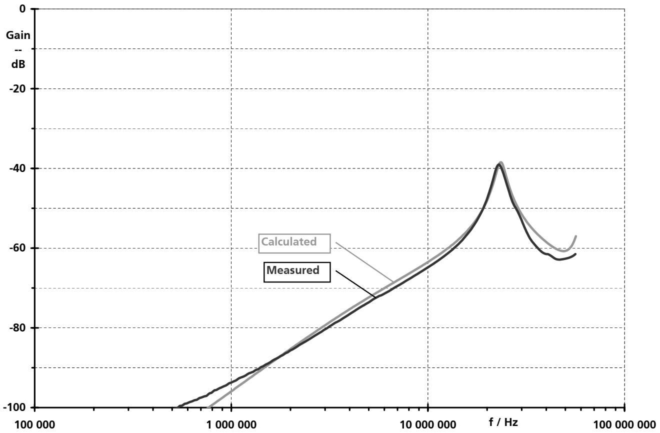

Fig. 7. Measurement and Simulation of Crosstalk from Shielded Power Cable

VI. DETERMINATION OF LIMITS FOR THE HIGH-VOLTAGE BUS

Based on the model of the power cable, the electromagnetic noise which is emitted by the electrical drive system converter and spread into the vehicle through the high-voltage bus, can be quantified and possible measures can be designed. The described model is used to calculate limits for interference currents on the high-voltage bus in

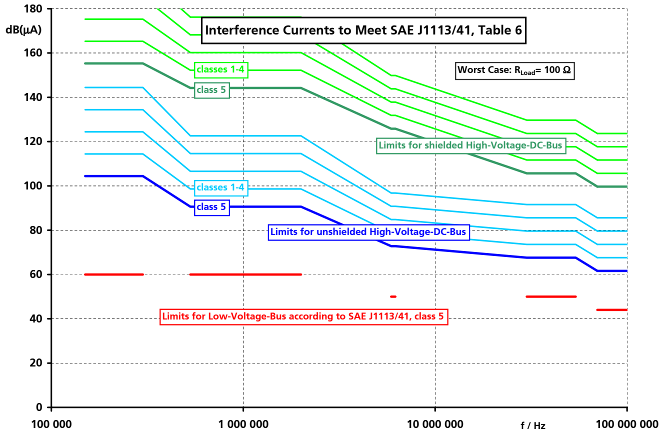

Fig. 8. Limits for Interference Currents on the High-Voltage Bus to Meet Standards for Broadband Conducted Disturbances on Control/Signal Lines, Peak Values

order to fulfill standards concerning the closely placed low-voltage wiring harness. The low-voltage line is connected to the LISN on one side and to a low-voltage component on the other side. Impedance of the input terminal of the component is supposed to be small for worst-case inspection. In case of signal lines, input terminal impedance is high ohmic, at least 100 Ω. Power input terminals are less ohmic, at least 0.1 Ω.

As maximum coupling occurs at resonance frequencies, the length of the cables has to be taken into account. In order to determine limits, the maximum coupling from cables of lengths from 0.5 m up to 2.2 m is calculated. The given values for current limits on power cables can be used for 70 mm^2 cables of lengths from 0.5 m up to 2.2 m.

Figure 8 shows peak values of limits for interference currents on the shielded and the unshielded high-voltage bus so, that the current limits on a closely placed signal line as defined in the standards ([1], Table 6) are met. For comparison the lowest limits (class 5) defined in the standards for signal lines are also pictured in Figure 8. The limits on the high-voltage bus are pictured for all defined classes but the limits fulfilling class 5 requirements are emphasized. Limits on the unshielded high-voltage bus are 18 $dB(\mu A)$ higher than standard limits. Interference currents on the shielded high-voltage bus can be another 37 $dB(\mu A)$ higher than on the unshielded bus.

The interference current limits to fulfill the requirements concerning interference voltage at the measurement port of the LISN ([1], Table 4) are shown in Figure 9. For comparison, the lowest voltage limits (class 5) defined in the standards for power input terminals are also pictured converted to current limits on the low-voltage system according to Figure 2. Again limits on the unshielded high-voltage bus are 18 $dB(\mu A)$ higher than standard limits and limits for the shielded high-voltage bus can be another 37 $dB(\mu A)$ higher than on the unshielded bus. Limits in Figure 9 are lower than limits in Figure 8. These limits allow the discussion of shielding versus filtering effort in terms of costs, weight and space.

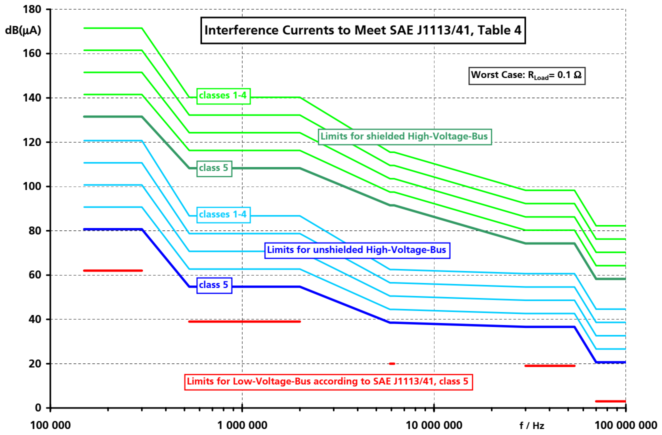

Fig. 9. Limits for Interference Currents on the High-Voltage Bus to Meet Standards for Broadband Conducted Disturbances on Power Input Terminals, Peak Values

VII. CONCLUSION

This paper gives a detailed investigation of the electric drive's power cables considered as a spreading path for electromagnetic interference generated by the power converter. For this purpose, the possible coupling paths between the noise source and the potential noise sinks, the components of the conventional low-voltage electrical system of the vehicle, are explored. A frequency domain lumped parameter model is found and confirmed by measurements. Based on the results of this work, limits for current interference levels on high-voltage supply systems are derived. The different limits for shielded and unshielded cables allow the discussion of shielding versus filtering efforts in terms of costs, weight and space.

REFERENCES

[1] SAE J 1113/41, *Limits and Methods of Measurements of Radio Disturbance Characteristics of Components and Modules for the Protection of Receivers on Board Vehicles,* SAE HS 3600, Warrendale, 1999

[2] Eckart Hoene et al., *Evaluation and Prediction of Conducted Electromagnetic Interference Generated by High Power Density Inverters,* EPE Conference, Graz, Schweiz, 2001

[3] Frédéric Broyde and Evelyne Clavelier, *Designing Power-Line Filter for their Worst-Case Behaviour,* Proc. Int. Symposium on EMC, Zuerich, S.583ff., 1991

[4] C.S.Walker, *Capacitance, Inductance and Crosstalk Analysis,* Artech House Inc., Norwood, 1990

[5] Clayton R. Paul, *Introduction to Electromagnetic Compatibility*, John Wiley & Sons, Inc., New York, 1992

[6] M.Tyni, *Transfer Impedance of Coaxial Cables with Braided Outer Conductors*, 3rd Wroclaw Symposium on EMC, 1976

Stefan-Peter Weber went to school in Regensburg, Germany and holds a degree as an electrical engineer of the Technische Universitaet Ilmenau. He is now working on his PhD Thesis at the Fraunhofer Institut fuer Zuverlaessigkeit und Mikrointegration in Berlin. His research field is the design of filters and shielding configurations in power electronic systems. He is father of a little boy named Paul.