EMC Issues in Cars with Electric Drives

S. Guttowski, S. Weber, E. Hoene, W. John, H. Reichl

Fraunhofer Institute for Reliability and Microintegration
Gustav-Meyer-Allee 25, 13355 Berlin, Germany
email stephan.guttowski@izm.fraunhofer.de

Abstract

From the EMC point of view, the integration of electric drive systems into today's cars represents a substantial challenge. The electric drive system is a new component consisting of a high-voltage power source, a frequency converter, an electric motor and shielded or unshielded high-power cables. Treating this new electric drive system or its components as a conventional automotive component in terms of EMI test procedures and emission limits would lead to substantial incompatibility problems. In this paper the EMC issues related to the integration of an electric drive system into a conventional passenger car are investigated. The components of the drive system have been analyzed being either noise sources or part of the coupling path within the new electrical system of the car. The obtained results can also be used to determine the acceptable noise levels on a high voltage bus of an electric drive system.

Keywords

Power Electronics, EMC, Electric Vehicles, EMI Test Procedures, Modeling

INTRODUCTION

From the EMC point of view, the integration of electric drive systems into today's cars represents a substantial challenge. Due to the strict EMC requirements within the automotive environment resonant converter topologies or even multilevel inverters have been explored to be advantageous for electric vehicle drives [1-3]. However, the first commercial applications are equipped with a conventional hard switching power converter that will be discussed in this paper.

The future drive concepts for passenger cars include an electric drive system either to reduce the fuel consumption or to build up a zero-emission vehicle. Possible solutions are the hybrid car, the pure electric car and the fuel cell car which are shown in Figure 1 [4].

Although the ideas for the power supply differ in each of these cases, the drive concepts are very similar from the viewpoint of Electromagnetic Compatibility (EMC). But they differ extremely from conventional automotive electrical system components.

The power required by the electric drive is much higher than the power demand of the whole electric system in today´s conventional cars. The voltage in the high-voltage bus can be as high as 900 V. Therefore, conventional test procedures are not appropriate for such components due to size, weight, power and emitted noise.
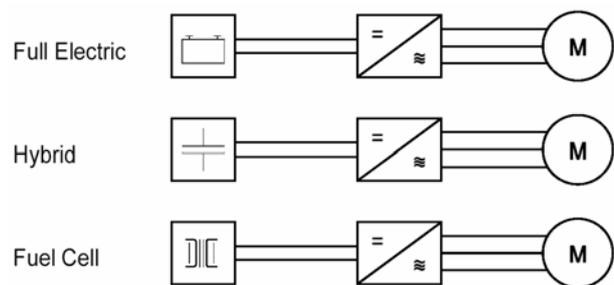

Figure 1: Electric Drive System Configurations for Passenger Cars

On the other hand, the components are not connected to the car's conventional electrical system by lines. The electric drive components are running on the HV-Bus which is made as a completely insulated power supply network. Moreover, the cables of the HV-Bus are often shielded. However, existing EMC requirements for conventional electrical system components do not take the shielding of cables into account [5]. Treating this new electric drive system or its components as a conventional automotive component in terms of EMC test procedures would lead to substantial incompatibility problems. Additionally, the effort for filtering would be unreasonable high.

Therefore, a new approach has to be developed in order to find appropriate emission limits for the electric drive components. These limits have to take the specific of the new components into account and they also have to be strict enough to ensure the electromagnetic compatibility of the whole system [6].

In this paper such an approach is described consisting of

1. an analysis of the main components of an electric drive system being either the noise source or part of the coupling path within the new electrical system of the car,

2. a determination of the coupling paths existing between the new electrical drive components and the conventional electrical system,

3. an adaptation of the EMC requirements of the conventional electrical system to the new electrical drive components using the coupling models.

Exemplarily shown in this paper, a new approach makes it possible to specify maximum interference levels on the high voltage bus. The knowledge available about modeling power electronic systems to be a noise source is adapted to answer the question how much noise is acceptable within a certain electrical environment [7].

EMC BEHAVIOR OF THE ELECTRIC DRIVE

The main components of the new electric drive for automotive applications are the electric motor, the power converter, the power supply and the lines connecting the components. Each of these components acts as a path for electromagnetic emissions. The power converter is known to be the main source of EMI. So the components of the drive system have to be analyzed being either noise source or part of the coupling path within the car's new electrical system.

Power Converters

Power electronic systems are known to be the main source of electromagnetic interferences within electric drive systems. The high speed switching device, e.g. the insulated gate bipolar transistors (IGBT), is the noise source which has to be modeled. A method to calculate the generated EMI of power electronic devices with changing pulse patterns is introduced in [8]. Most available physics-based models of semiconductor switches are not developed for high frequency calculations. For this reason, a simplified description of the noise source is derived.
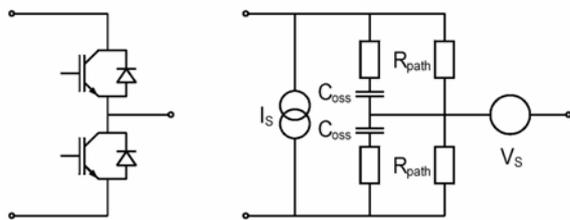

Figure 2: Half Bridge and its Equivalent Circuit to Predict EMI

Figure 2 shows the equivalent circuit to predict EMI of a high power density inverter. The current source I_S models the current flowing into the half bridge. This current represents the source of differential mode interferences. The task of the voltage source U_S is to model the output voltage which is the source of common mode interferences. Validity of these simplifications is proven in [8], thus the results can be used for further investigations.

Electric Motor

Another crucial factor for an accurate EMI analysis is the representation of the electric motor in the EMI frequency range. The way noise currents flow inside the machine does not necessarily have to be determined. In fact, it is more important to know the impedance of the electric motor as a part of the noise path and how this impedance varies as a function of frequency.

For several years now, research has been done on the electric motor and its impedance considering electromagnetic noise in power electronic systems. The high-frequency representation of the motor impedance depends on the electric motor principle and not on the drive application. Since the electric motors used in electric vehicles are common ac machines, the high-frequency representations developed for other applications than electric drives can be used for EMI predictions in electric vehicles.
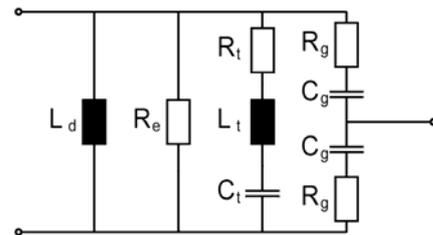

Figure 3: Per-phase Representation of the AC Motor

Figure 3 shows a high-frequency per-phase representation of an ac motor that has been proposed for overvoltage analysis by Moreira [9]. The parameter C_g represents the winding-to-ground capacitance. The parameter R_g is added in the circuit to represent the dissipative effects that exist in the motor frame resistance. The circuit formed by the parameters R_t, L_t and C_t is related to the winding turn-to-turn capacitance. The parameter R_e is responsible to account for the losses introduced by eddy current inside the magnetic core. The parameter L_d represents the leakage inductance of the machine winding. The methodology for the parameter estimation can be found in [9].

Traction Battery

The battery providing power to the converter is a main part of the path for EMI. Therefore, the battery behavior within the high frequency range needs to be determined.
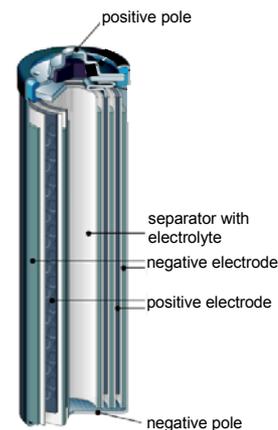

Figure 4: Structure of Cylindrical NiMH Battery

The basic structure of a battery consists of two electrodes and an electrolyte embedded in a mechanical separator. In cylindrical batteries the electrodes are rolled (Figure 4),

while they are laminated in prismatic batteries. The RF-properties result from the current path through this structure. Figure 5 demonstrates the current flow for two electrodes via the electrolyte.

Hoene has presented a new approach to model the battery regarding its dense packaging of electrodes and the direction of the current flow as solid conductor [10].
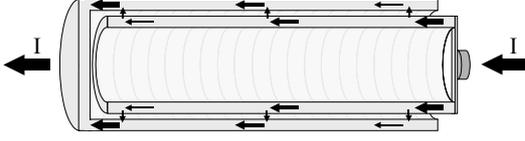

Figure 5: Current Path Through Battery

By using a homogeneous material instead of the electrode structure, properties like the internal and the external inductance or the skin effect can be predicted easily. Then the material properties of the homogeneous conductor have to emulate the material mixture from electrodes and electrolyte.

Figure 6 shows the behavior model for a single battery cell in the EMC frequency range. The model is parameterized and proved by impedance measurements on battery cells.

The model consists of the internal inductance and resistance (L_{int} and R_{int}), which both depend on the frequency due to the skin effect. Furthermore, the external inductance is represented by L_{ex}; the resistance of contacts by R_c. C_e models the capacitance between the electrodes and R_{ch} and V_{ch} which give a simplified description of the chemical processes.
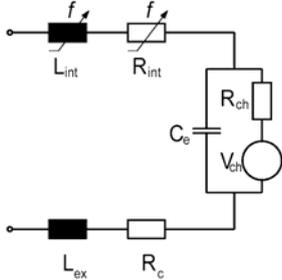

Figure 6: Equivalent Circuit to Model Rf-Characteristics of Batteries in Regarded Frequency Range

If necessary, they can be replaced by a more detailed low frequency model.

The internal DC resistance is given by the cross section A and the length l of the battery and the conductivity σ_{eff} of the homogeneous equivalent material (all in SI units).

$$R_{int,DC} = \frac{l}{\sigma_{eff} * A} \quad [\Omega] \tag{1}$$

To calculate the frequency dependent resistance, the skin effect formula for round conductors is used where f is the frequency, μ_0 the absolute permeability, $\mu_{r,eff}$ the relative permeability of the homogenous equivalent material and r the radius of the battery.

$$R_{int,Skin} = \sqrt{\frac{f * \mu_0 * \mu_{r,eff}}{4\pi * r^2 * \sigma_{eff}}} *1 \quad [\Omega] \tag{2}$$

A correction factor is added for prismatic batteries to take into account the influence of the battery's shape. The formulas for low and high frequency behavior are joined by a formula which is not physically but empirically proven:

$$R_{int} = \sqrt{R_{int,DC}^2 + R_{int,Skin}^2} \quad [\Omega] \tag{3}$$

The internal inductance for round conductors is divided into a DC (4) and a frequency dependent part (5).

$$L_{int,DC} = \frac{\mu_0\mu_{r,eff}}{8 * \pi} *1 \quad [H] \tag{4}$$

$$L_{int,HF} = \sqrt{\frac{\mu_0 * \mu_{r,eff}}{16 * \pi^3 * r^2 * \sigma_{eff} * f}} *1 \quad [H] \tag{5}$$

The total internal inductance is calculated by (6).

$$L_{int} = \frac{1}{\sqrt{\frac{1}{L_{int,DC}^2} + \frac{1}{L_{int,Skin}^2}}} \quad [H] \tag{6}$$

The external magnetic field strongly depends on the shape and the distance of the return path of the current. In [11], formulas are given to calculate the inductance for standard geometries of conductors. Regarding the batteries as solid conductors, these formulas can be applied to the geometry implemented in a specific battery. The contact resistance R_C is also parameterized according to the specific setup.
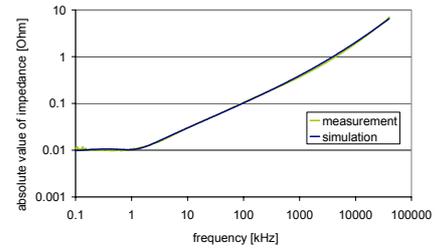

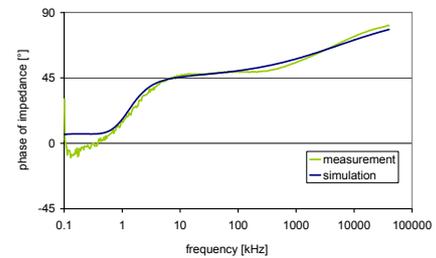**Figure 7: Absolute Value of Battery Impedance**

Figure 8: Phase of Battery Impedance

Figure 7 shows the measured and simulated absolute value of the impedance of a cylindrical NiMH-Cell with 3.3 cm diameter and 37 cm length, while Figure 8 shows the meas-

measured and simulated phase. The simulations match the measured data and therefore validate the proposed simplifications. So the way to describe the traction battery as a part of the noise path is appropriate for EMI prediction and advanced mitigation development.

Shielded and Unshielded Cables

The cables of the high-voltage bus connecting the power converter with the motor and the power supply have to be taken into account to describe the new electric drive system.

Due to the ratio between the size of the power converter and the frequency of the EMI, power electronic applications emit the noise mainly through their lines. That's why the cables for the high-voltage bus are so important during the design process of an electrically driven vehicle.

Usually the connection between converter and motor is kept very short to gain better results in terms of volume and EMC. Restrictions regarding the space available within the car demand cables for the connection to the power supply. From the EMC point of view, there are high-voltage lines within the system carrying the supply voltage as high as 900V.

The main question during the design process is to find out if shielded cables are necessary or not. In general, shielding can reduce the mitigations to ensure EMC within the system, but drawbacks are higher costs and reduced flexibility, which causes problems for the assembling. Regarding EMC criteria, the best solution would be a common shielding of both high-voltage bus lines. Such a solution would even aggravate the problem since the cooling conditions deteriorate, and therefore the size of the cable has to increase. In turn, that means higher costs and lower flexibility.

The tradeoff between shielded cables and EMI mitigations can only be found for specific applications. Research as presented in this paper, can provide guidelines for the decisions.

COUPLING PATHS

The new electric drive system consists of several components which are connected to the new high-voltage bus only. Integrating the 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. Existing requirements such as those for EMC aim to the compatibility within the conventional electrical system. In order to ensure compatibility within the new system, the connections between the conventional system and the new components have to be analyzed. 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. 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.

Coupling Path Modeling

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.
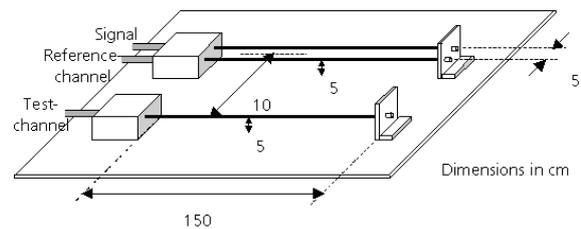

Figure 9: Layout for Inductive Coupling Modeling

The setup is derived from the setup required for the conducted emission measurements according to the SAE standards. 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 [12]. 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. 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.

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 9. In order to determine crosstalk, an inphase test signal is injected into both cables by a Gain-Phase Analyzer (HP4194A). The resulting signal is measured on a third line, representing the low-voltage electric supply system or any sensitive signal line.

The shielded cables are modeled by the lumped parameter line element model shown in Figure 10. It consists of the inductance LC for the inner conductor, LS 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 [11, 13] as well as the capacitance C_S between the cable shield and the ground plane. Resistances of the shield and the inner con-

ductor 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. [14]
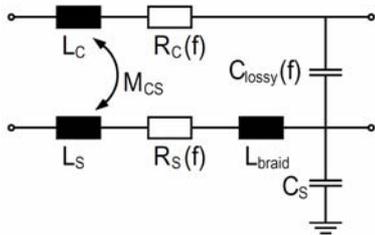

Figure 10: One of Ten Line Elements Modeling Power Cable

The comparison of simulation and measurement of crosstalk from the high-power cables to a single line is shown in Figure 11 for common mode currents on the shielded high-voltage system.
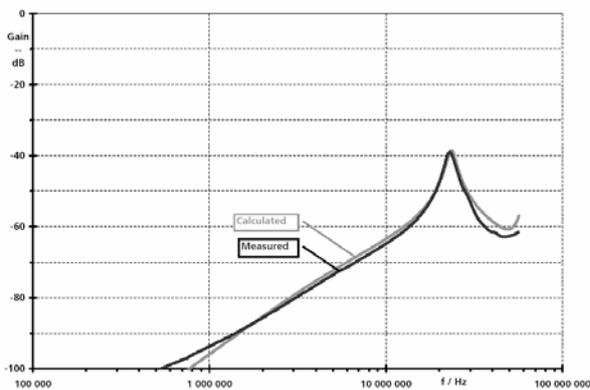

Figure 11: Measurement and Simulation of Crosstalk from Shielded Power Cable

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.

Based on the results of this work, the electromagnetic noise emitted by the electrical drive system converter can be quantified and possible measures can be developed. Since the two possible configurations with and without shielding can be compared, one of the main questions can be answered: whether or not shielded cables between the power converter and the power supply can replace the EMI filter. For both configurations, the remaining effort necessary for filtering can be determined and discussed in terms of cost, weight and space.

EMC REQUIREMENTS FOR A HIGH-VOLTAGE BUS

Based on the determined model of the coupling path, the limits for the high-voltage bus can be derived. The underlying idea is that the noise caused in the low-voltage system must not exceed the limits for this system. Therefore, the noise on the low-voltage bus can be taken directly from the EMC requirements for automotive components.
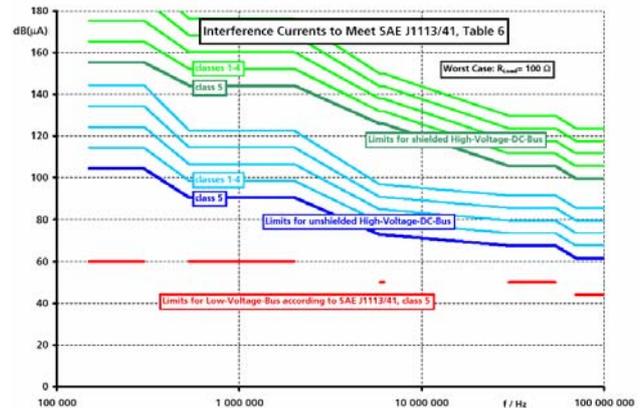

Figure 12: Limits for Interference Currents on the High-Voltage Bus to Meet Standards for Broadband Conducted Disturbances on Control/Signal Lines, Peak Values

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.
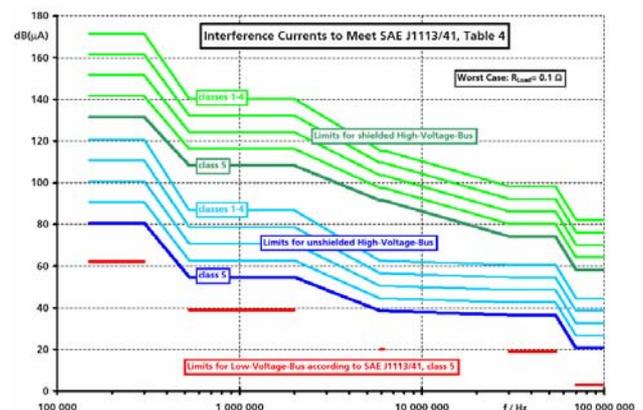

Figure 13: Limits for Interference Currents on the High-Voltage Bus to Meet Standards for Broadband Conducted Disturbances on Power Input Terminals, Peak Values

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 mm² cables of lengths from 0.5 m up to 2.2 m.

Figure 12 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 [5], Table 6) are met. For comparison the lowest limits (class 5) defined in the standards for signal lines are also pictured in Figure 12. 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 higher than standard limits. Interference currents on the shielded high-voltage bus can be another 37 dB higher than on the unshielded bus.

The interference current limits to fulfill the requirements concerning interference voltage at the measurement port of the LISN [5], Table 4) are shown in Figure 13. 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 13. Again limits on the unshielded high-voltage bus are 18 dB higher than standard limits and limits for the shielded high-voltage bus can be another 37 dB higher than on the unshielded bus. Limits in Figure 13 are lower than limits in Figure 12. These limits allow the discussion of shielding versus filtering effort in terms of costs, weight and space.

CONCLUSION

The authors of this paper have presented the EMC issues related to the integration of an electric drive system into a conventional passenger car. The components of the drive system have been analyzed being either noise source or part of the coupling path. Simulation models have been created for EMI prediction as well as for the development of optimized mitigations. The results of this investigation can be used to determine the acceptable noise levels on a high voltage bus of an electric drive system.

The simulation results have been confirmed by measurements using components of an electric drive designed for a passenger car.

With these results, shielding and filtering measures can be verified and costs of the system can be optimized. Further research has to be carried out to model all relevant configurations.

REFERENCES

[1]   C. Chen, X. Xu, and D. M. Divan, "Conductive electromagnetic interference (EMI) noise evaluation for an actively clamped resonant DC link inverter (ACRDCLI) for electric vehicle (EV) traction drive applications," presented at Thirty-Second IAS Annual Meeting, IAS '97, 1997.

[2]   L. M. Tolbert, F. Z. Peng, and T. G. Habetler, "Multilevel inverters for electric vehicle applications," presented at Power Electronics in Transportation, 1998.

[3]   W. Dong, J.-Y. Choi, Y. Li, D. Boroyevich, F. C. Lee, J. Lai, and S. Hiti, "Comparative experimental evaluation of soft-switching inverter techniques for electric vehicle drive applications," presented at Industry Applications Conference, 2001.

[4]   G. Maggetto and J. Van Mierlo, "Electric and electric hybrid vehicle technology: a survey," in *Electric, Hybrid and Fuel Cell Vehicles, IEE Seminar*, 2000.

[5]   Society of Automotive Engineers., *SAE surface vehicle electromagnetic compatibility (EMC) standards manual*, 1997 ed. Warrendale, Pa.: Society of Automotive Engineers, 1997.

[6]   S. Guttowski, "EMV - Spezifikation als Meilenstein auf dem Weg zur Serienproduktion elektrisch angetriebener Straßenfahrzeuge," presented at EMV 2002, Düsseldorf, 2002.

[7]   C. Chen and X. Xu, "Modeling the conducted EMI emission of an electric vehicle (EV) traction drive," presented at IEEE International Symposium on Electromagnetic Compatibility, 1998.

[8]   E. Hoene, W. John, M. Michel, and H. Reichl, "Evaluation and Prediction of Conducted Electromagnetic Interference Generated by High Power Density Inverters," presented at European Conference on Power Electronics (EPE), 2001.

[9]   A. F. Moreira, T. A. Lipo, G. Venkataramanan, and S. Bernet, "High-frequency modeling for cable and induction motor overvoltage studies in long cable drives," *IEEE Transactions on Industry Applications,* vol. 38, pp. 1297-1306, 2002.

[10] E. Hoene, R. Saikly, S. Guttowski, W. John, and H. Reichl, "Rf-Properties of Automotive Traction Batteries," presented at 2003 IEEE International Symposium on Electromagnetic Compatibility, Istanbul, Turkey, 2003.

[11] C. S. Walker, *Capacitance, inductance, and crosstalk analysis*. Boston: Artech House, 1990.

[12] F. Broyde and E. Clavelier, "Designing Power-Line Filter for their Worst-Case Behaviour," presented at Int. Symposium on EMC, Zuerich, 1991.

[13] C. R. Paul, *Introduction to electromagnetic compatibility*. New York: Wiley, 1992.

[14] S.-P. Weber, S. Guttowski, E. Hoene, W. John, and H. Reichl, "EMI coupling from Automotive Traction System," presented at 2003 IEEE International Symposium on Electromagnetic Compatibility, Istanbul, Turkey, 2003.