EMI in Electric Vehicles

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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.*

Introduction

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.

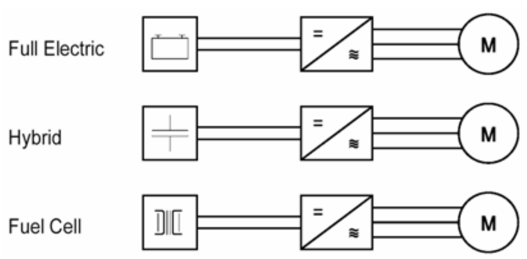

Figure 1: Electric Drive System Configurations for Passenger Cars

Although the ideas for the power supply differ in each of these cases, the drives 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.

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 an completely insolated 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. Treating this new electric drive system or its components as a conventional automotive component in terms of EMC test procedures and emission limits would lead to substantial incompatibility problems. Additionally, the effort for filtering would be unreasonable high [1].

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 [2].

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.

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 [3]. 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.

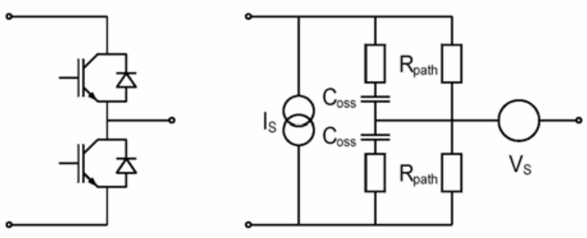

Figure 2: Half Bridge and its equivalent Circuit to predict EMI

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 [3], 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 application than electric drives can be used for EMI predictions in electric vehicles.

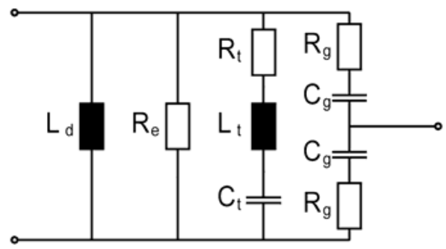

Figure 3: Per-phase representation of the ac motor

Figure 3 shows a high-frequency per-phase representation of an ac motor that has been proposed for overvoltage analysis by Moreira [4]. 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 [4].

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.

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 prosmatic batteries. The RF-properties result from the current path through this structure. Figure 5 demonstrates the current flow for two electrodes via the electrolyte.

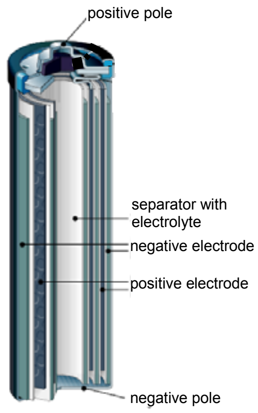

Figure 4: Structure of cylindrical NiMH battery

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 [5].

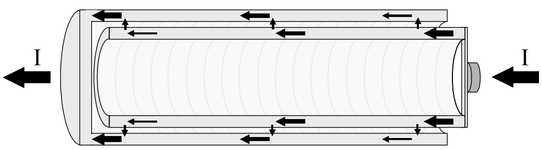

Figure 5: Current path through battery

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.

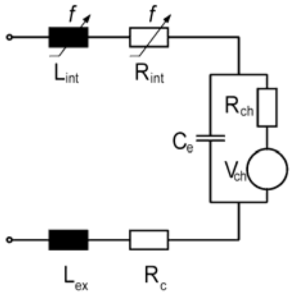

Figure 6: Equivalent circuit to model Rf-characteristics of batteries in regarded frequency range

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

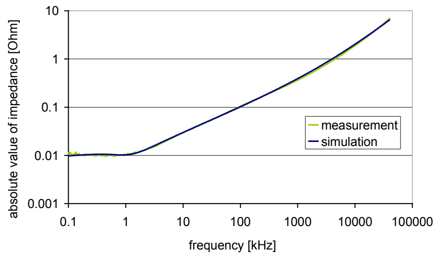

Figure 7: Absolute value of battery impedance

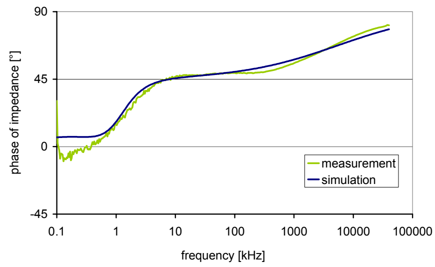

Figure 8: Phase of battery impedance

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 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. 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.

In the EMC terminology these connections are the coupling paths. Based on the reasonable assumption that the new components operate on an isolated high-voltage bus, there are only two possibilities for coupling paths within the car. First, the components connecting both systems for power transmission can form a coupling path as well. Secondly, the cables lying in parallel with the wiring harness of the conventional low-voltage system can form an inductive coupling path. The first possibility depends on the components used for a special application. Therefore, requirements such as for a maximum of the transfer impedance of the components can be put forward.

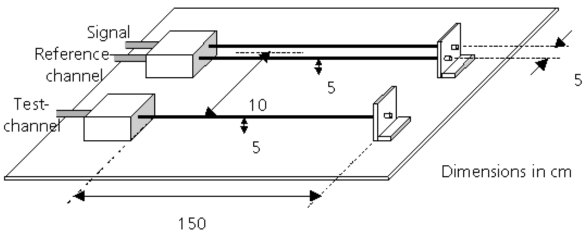

Figure 9: Layout for inductive coupling Modeling

However the inductive coupling of lines within the car is unavoidable. High-voltage and low-voltage bus are arranged closely to each other because of the limited space for harness available in modern cars. This coupling path needs to be modeled in order to calculate the effects of noise currents at the high-voltage on the low-voltage bus. Based on this model, emission limits can be found for the high-voltage bus avoiding interferences which exceed the EMC requirements for the low-voltage bus due to the inductive coupling.

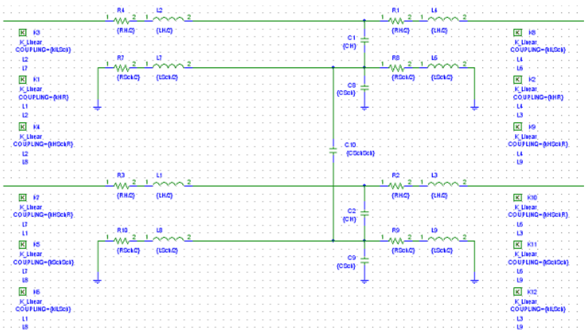

Figure 10: Lumped parameter model for the high-voltage bus

Figure 9 shows the setup chosen for the inductive coupling modeling. The high-voltage bus cables (in the back) were arranged in parallel to one line representing the low-voltage bus (in front). This setup has been derived from the setup required for the conducted emission measurements

Figure 10 shows the lumped parameter model that has been presented by Weber for the high-voltage cable. The method to determine the parameter resistance, inductance and capacitance per unit length can be found in [6] as well.

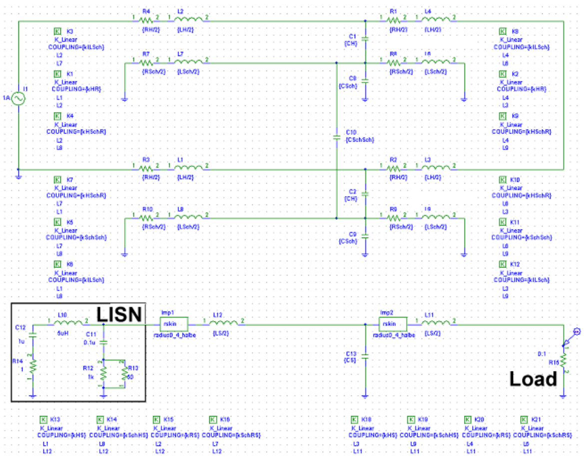

Figure 11: Lumped parameter model for the inductive coupling

Based on the model given in Figure 10, lumped parameter models for the coupling paths were developed. Figure 11 shows the model for the inductive coupling according to the setup given in Figure 9.

The models presented in Figure 10 and 11 have been confirmed by measurements. Figure 12 shows one example for the comparison of simulation and measurements for one type of noise current, the common mode currents, in the high-voltage system. The results confirm the models found for the coupling path.

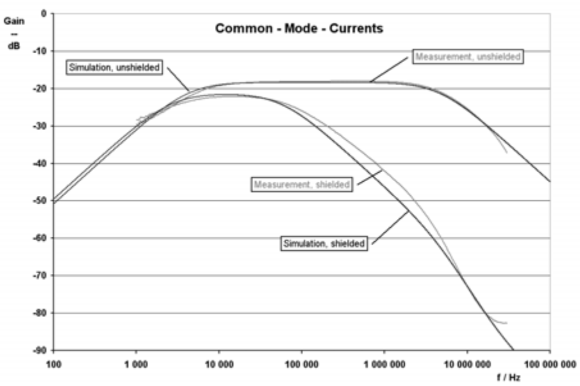

Figure 12: Comparison of measurement and simulation results

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. Based on these limits, the coupling model leads to the new limit lines for the high-voltage bus shown in Figure 13.

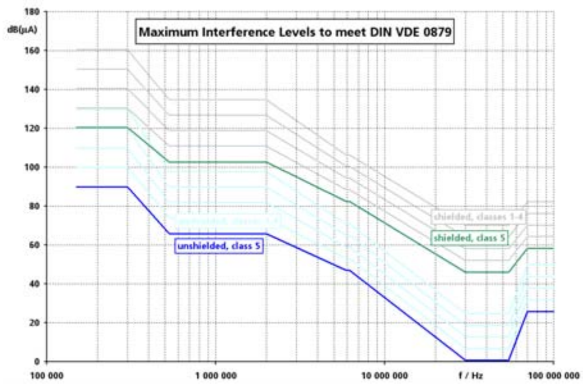

Figure 13: Acceptable noise levels on the High-Voltage bus

Similar to the EMC requirements for the low-voltage bus, the new limits can be defined for 5 different classes. These five classes can be seen in the Figure 13.

The limits are usable only for a certain set-up. Due to resonances on the cable, the characteristic of the set-up is mainly determined by the length of the cables. In this case, a length has been chosen considering requirements for EMC components measurements. Despite the fact that the set-up requirements of the standards have to be used for components measurements, the length of the high-voltage bus in real electric vehicles will change. So the resonances will move along the frequency axes. The authors aimed to show that the approach is feasible. Future work will lead to more general results.

Contrary to the conventional requirements, the new limits have to be put forward depending whether or not the cables are shielded. As Figure 13 shows, the noise on the high-voltage bus can be accepted to be 30 dB higher for shielded cables.

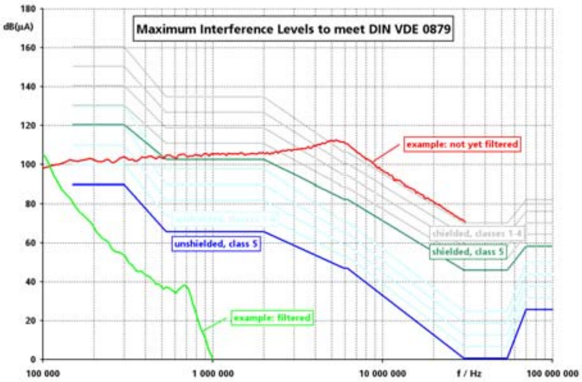

Figure 14: Applying the new limits to an power converter emissions

The results have been used for a real design decision in Figure 14. The decision refers to whether or not shielded cables are necessary and to the best compromise in cost. As Figure 14 shows, the class 5 limits where to meet in this case. As we can see in the results of the new approach, the configuration without any EMC filter would exceed the limits even with shielded cables. So EMC filters are necessary for both unshielded and shielded cables.

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.

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