Abstract—On-board networks with different voltage levels are applied in vehicles equipped with an electrical drive system. Voltages in the range of several hundreds of volts are used in the traction (high-voltage; HV) network. Conventional electronic devices are connected to the low-voltage (LV) network. In the automotive industry, where HV components containing sensors, contactors and communication interfaces, etc., are used, both voltage levels are present. As a result, several coupling paths exist between the LV and the HV level which contribute decisively to the electromagnetic behavior of the complete vehicle. In order to obtain knowledge about the electromagnetic compatibility (EMC) characteristic as completely as possible during the component test, it is useful to extend the existing CISPR 25 test setups by measurement routines focusing on the HV/LV coupling behavior.

In the following, the investigation of the HV/LV coupling behavior of a complete HV vehicle system is shown. The measurement results are compared to those of a component test setup based on the CISPR 25 standard.

Keywords—high-voltage power train; EMC in hybrid electric vehicle; coupling between HV and LV power train; propagation of disturbances in HV power trains

I. INTRODUCTION

The electrical traction network is designed for the transmission of high power. In order to minimize losses, the voltage of the traction network is considerably larger than in conventional automotive systems. The power electronics of the power train work with small rise times. These steep voltage and current signals generated by the DC/AC inverter are a major source of EMC disturbances in the HV network [1],[2],[3]. Due to the high level of disturbance, several suppression measures become necessary. The shielding of the HV systems and components of the HV network is a widely used suppression measure, because the degree of efficiency is not reduced. Usually, the cable lengths between the inverter and the motor are also kept very short to limit the propagation of interferences. Consequently, a high level of shielding is achieved on the HV part of the electrical network. However, almost all HV components have interfaces to the LV network, which are used, for example, for control and communication lines. If there is only a little decoupling between the HV and the LV system, disturbances can propagate into the unshielded LV network. Thus, sensitive sensors in the LV system might be influenced in an impermissible way or limits might be exceeded during radiated emission tests [4],[5]. The diagram in Fig. 1 shows an impulse measured at one phase of the three-phase system between the motor and the inverter of the traction network [6] and the disturbance voltage at in LV system in the passenger compartment.

Fig. 1. Rising edge of an HV inverter signal and the disturbance voltage measured in the LV system simultaneously

II. MEASUREMENT AT A COMPLETE HV SYSTEM CONFIGURATION

The principal structure of the test setup is presented in Fig. 2. The system configuration consists of all HV components (cables and devices) of a fully electric-driven vehicle. The experimental setup includes the LV wiring harnesses and control devices which are necessary to set the HV components into operation. The advantages of the system configuration are the real conditions of the terminating impedances and the easy accessibility of the cable connections. A Controller Area Network (CAN) residual simulation is needed in order to control the HV devices.

Fig. 2. HV system configuration
During the measurement, an RF signal is fed into the HV system at a connector near the HV battery. Therefore, a special adapter (Fig. 3) was made which could be inserted easily. The adapter box provides blocking capacitors between the active conductors and the measuring ports which protect the RF measuring devices from DC voltages. Thus, it is possible to perform measurements in active operation modes. The adapter box itself is efficiently shielded. This ensures the continuity of the HV shield system. Simultaneously, the signal coupled into the LV system can be measured frequency-selectively at a wiring harness or a connection assembly. The measurement is performed with a vector network analyzer (VNA). A sufficient dynamic range can be achieved when an additional RF amplifier is used. The effective RF power fed into the HV system is measured with a directional coupler. The coupling can be carried out in Common Mode (galvanic coupling; CM) or in Differential Mode (inductive coupling; DM).

Fig. 3. Top and bottom view of the HV adapter box with DC blocking capacitors

A. Coupling of the interfering signal in CM, respectively DM

There are two DC blocking capacitors with a capacitance of 620 nF at the HV connection port, as shown in Fig. 4. The capacitance of one capacitor leads to a 3 dB cut-off frequency of about 5 kHz under consideration of the reference impedance of 50 \(\Omega\). A T-joint with a short circuit at its input is used for CM feeding. The RF characteristic of the capacitors should be very similar in order to achieve similar interfering voltages in both current paths. The RF signal generated by the VNA is amplified by 40 dB. The maximum output power of the amplifier is 40 dBm (10 W) at 50 \(\Omega\). The protection circuit between the amplifier and capacitors is needed because of the insulation monitoring system of the HV system generating a square wave signal with reference to the ground. The attenuator also protects the measuring devices from transient disturbances which occur if the HV contactor of the battery opens unexpectedly. This might happen if the interference immunity threshold of this system or component is exceeded.

The type of feeding can be changed to DM by using an injection probe. The injection probe induces a differential interference current between the active conductors.

B. Determination of the power fed into the device under test (DUT)

For the determination of an exact transfer function, it is necessary to know the effective RF power which is fed into the DUT. The reflected power cannot be detected by the internal directional coupler of the VNA due to the amplifier which is inserted in the feeding line previously to the DUT, according to Fig. 5. The reflection of the RF signal is caused by the impedance discontinuity between the feeding system with an impedance of 50 \(\Omega\) and the input impedance of the DUT. The reflection also depends on the way in which the signal is coupled into the HV system. Regarding a vehicle overall system, the effective impedance is defined by the characteristic impedance of the HV cables and the input impedances of the devices connected to the HV network. By using a directional coupler, the forward power and the reverse power can be measured separately and the effective power can be calculated from the difference between both quantities. Another advantage is that the frequency characteristic of the amplifier and the attenuation of the measuring cables, which are arranged previously to the power detection in the signal path, are automatically taken into account. Two separate S21 measurements have to be carried out to get the effective power fed into the DUT. The coupling factor of the measuring ports of the directional coupler with a very low insertion loss is 40 dB. This value is in the range of the gain of the amplifier to prevent any damage to the VNA input.

Fig. 4. Measurement setup for feeding CM and DM

Fig. 5. Determination of the RF power fed into the HV system

Due to the attenuation between the directional coupler and the injection location, the values measured have to be corrected according to the direction of travel of the signal. The attenuation of the measuring cables between the directional coupler and the VNA also has to be considered. Because of the relatively small lower cut-off frequency of the decoupling capacitors in comparison to the lowest measurement frequency, the influence of the capacitances can be neglected.
C. Decoupling in the LV network

The signal decoupling is carried out at a connector or at a wiring harness of the LV system. The decoupling can be carried out with coupling capacitance (galvanic decoupling) or with a current probe (inductive decoupling) [7]. If the measurement is performed in a complete vehicle system, vehicle antennas can also be used. By using the galvanic decoupling method, it has to be considered that the impedance of the LV system is influenced. If a current probe is used, the decoupling can be potentially freely performed at one or more (total current measurement) wires of the harness. If the transfer impedance of the current probe is sufficiently low, the feedback of the probe can be neglected.

In both cases of decoupling, a disturbance voltage, respectively a disturbance current, is measured and not the RF power in the LV system. The power used for the calculation of the transfer functions corresponds to power which is converted by the disturbance voltage or current in a 50 Ω system [8].

D. Transfer functions measured at the HV battery and the HV heater

At first, the signal decoupling was carried out at the LV wiring harness of the HV battery. The measurement of the total current was carried out at all wires of the harness simultaneously. The related diagrams are shown in Fig. 6. The coupling behavior was investigated in two different states of the system configuration. In the first state, the HV network is disconnected from the HV battery. Consequently, the RF power is only fed into the battery device and not into the whole HV system. In the second step, the whole HV system is regarded. In both states, the battery is in active operation mode. If the feeding is carried out in CM, the transfer functions measured are different for both configurations up to a frequency of 3.5 MHz. With an increasing frequency, both curves follow a very similar trend. The CM impedance of the HV network obviously has a low effect on the coupling behavior regarding the higher signal frequencies. The diagram also shows the transfer functions measured with feeding in DM at the same location. It can be seen that the curve of the transfer function is lower if the HV network is connected. In this configuration, the power fed into the system is split according to the particular impedances on the battery and the remaining network. Resonances occur due to longer cable lengths above frequencies of 1 MHz. The maxima of the curves are -60 dB in both configurations.

The measurements performed at the LV wiring harness of the auxiliary heater are presented in Fig. 7. The HV PTC heater was operated in a passive mode or with a heating performance of 50%. The other HV components were connected to the network and in passive operation modes. The interesting frequency range is limited to 110 MHz in order to cover the range of radio services, especially the medium wave range and the FM range. The transfer functions measured show the dependence on the operation mode of the component. If the feeding is done in CM, respectively DM, then the coupling effect between the HV and the LV part is larger in the active operation mode.

The electric heater uses pulse width modulation and is a possible source of disturbance itself. In active operation modes, these disturbances can influence the measurement. The curve in Fig. 7 represents a zero measurement which is obtained by feeding into a 50 Ω termination resistance via the amplifier. The peak at about 500 kHz is a self-interference of the PTC. The measurement dynamic is slightly lower if the signal is coupled into the HV system because of the impedance mismatching between the measuring system and the HV system. The electric heater uses pulse width modulation and is a possible source of disturbance itself. In active operation modes, these disturbances can influence the measurement. The curve in Fig. 7 represents a zero measurement which is obtained by feeding into a 50 Ω termination resistance via the amplifier. The peak at about 500 kHz is a self-interference of the PTC. The measurement dynamic is slightly lower if the signal is coupled into the HV system because of the impedance mismatching between the measuring system and the HV system. The electric heater uses pulse width modulation and is a possible source of disturbance itself. In active operation modes, these disturbances can influence the measurement. The curve in Fig. 7 represents a zero measurement which is obtained by feeding into a 50 Ω termination resistance via the amplifier. The peak at about 500 kHz is a self-interference of the PTC. The measurement dynamic is slightly lower if the signal is coupled into the HV system because of the impedance mismatching between the measuring system and the HV system.
III. MEASUREMENT SETUP COMPONENT LEVEL

The EMC characteristic of conventional automotive components is usually tested according to the CISPR25 standard [9]. The standard describes established measurement setups for the test of conductive and radiated emissions. To investigate the comparability between measurements in complete vehicle systems or in system configurations and component measurements, the measurement method described is also used in a CISPR 25 test setup. The setup is illustrated in Fig. 8. HV cables and LV supply lines are terminated with line impedance stabilization networks (LISN). The HV LISNs are placed in a well shielded box to ensure the continuity of the HV shield system. The HV cables are assembled with connectors. This enables the use of the existing coupling adapters. The LV wiring harness of the DUT consists of two supply lines and two CAN lines which are terminated by an equivalent impedance.

![Fig. 8. Measurement setup according to the CISPR 25 standard](image)

The diagram in Fig. 9 shows the transfer functions of the HV PTC measured at the system configuration and the component measurement setup. A current probe was used in both cases for the signal decoupling. It can be seen that the curves measured are generally similar if the feeding is carried out in CM. The curve measured at the system configuration is characterized by more resonances. This can be explained with the branched topology of the HV network. Looking at the DM measurements, larger deviations can be identified. The differences of about 20 dB are caused by the different impedances between the active conductors (impedance between HV+ and HV-).

![Fig. 9. Comparison of system and component measurement setup](image)

IV. CONCLUSION

A measurement method using transfer function is presented for the investigation of propagation paths of EMC disturbances. It can be used for the characterization of the coupling behavior between the HV and the LV voltage level. The measurement is carried out by feeding RF signals of different frequencies into a HV port or a HV cable while the RF signal transmitted into the LV system is measured frequency-selectively at a LV interface of a cable harness. The signal coupling, respectively the signal decoupling, can be carried out with an inductive or capacitive coupling device or with the help of vehicle antennas. Measurement examples performed in a system configuration consisting of all HV components of an electric driven vehicle are presented. With knowledge of the transfer functions measured, critical components and operation states can be identified and effective suppression measures can be developed. Regarding complete HV systems, it is ensured that real conditions (terminating impedances) are taken into account. The existing standards have to be extended for the testing of components. The analysis of the HV/LV coupling characteristics at different setups performed is a contribution to the establishment of new EMC measurement procedures for automotive HV components.

REFERENCES