Measurement of Transient Pulses on High-Voltage Automotive Power Networks

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Abstract

Due to the high number of electronic devices and components in limited space, the Electromagnetic Compatibility (EMC) is an important issue in motor vehicles. In modern electrically powered cars high power has to be transmitted over the vehicle's electrical power system. This leads to enhanced requirements for the EMC as well as new methods for characterization of Electromagnetic Interferences (EMI) are necessary.
In this contribution a measuring system is described which can be used to measure transient voltage and current pulses on high-voltage power networks in normal driving conditions. The devices of the system are tested of its electrical characteristics and some measuring examples conduced at a hybrid car are shown.

1 Introduction

Compared to conventional automotive electrical systems in electrically driven cars the electrical network has especially to be designed for the transmission of higher power. Voltages in the range of 120 to 1100 V and high currents are important aspects particularly with regard to the EMC.

The electrical drive is controlled by power electronics. Steep voltage and current edges caused by switched power conductors, mainly IGBTs [1, 2], are a major source of disturbances which results in an increase of Electromagnetic Interference. On power supply lines of the electrical system the Electromagnetic Interferences can be conducted from the disturbing source to the disturbing sink. Dependent on the frequency of disturbance cables can also act as an antenna.
To get more detailed information about the origin and nature of the new disturbing sources and the relevant coupling mechanisms, it is necessary to investigate the electrical characteristics of the high-voltage power train and its components, especially in transient operational issues [3].

A huge EMI potential is represented by voltage and current pulses which have fast slew rates and appear on the high-voltage network.

In this paper the emphasis lies on a system for measuring DC- and AC- voltages, DC- and AC currents as well as transient interferences. The sensors of the measurement system can be applied at high-voltage cables and render a representation of voltage and current conditions at a certain place in the high-voltage network.

2 Design of the Measuring System

2.1 General view

The measuring system is spatially separated into two parts. The sensor components are installed in a shielded box which is placed in the engine compartment (**Figure 1**). The transmission of the measuring signals into the vehicle interior compartment is done by means of temperature resistant, coaxial 50 Ω-cables.

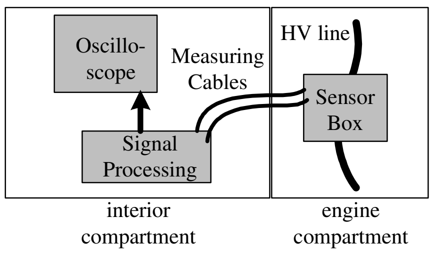


Figure 1 General view of the components of the measuring system

At the interior of the car the sensor signals are conditioned passively or actively and recorded by digital storage oscilloscopes (DSO). The power supply is provided by an independent DC-/AC converter connected to a lead storage battery.
The measuring system is designed for an on-board voltage of 130 V, currents can be measured up to 200 A. It is suitable for the frequency range from DC up to 40 MHz.

2.2 Measurement Sensors

2.2.1 Voltage Divider

In order to reduce EMI and of security reasons the high-voltage cables must be shielded. The high-voltage network is completely insulated from the car body (ground potential) the insulation resistance is electronically monitored.

The measurement is performed for both conductors of a high-voltage DC line by using a resistive voltage divider (**Figure 2**). The influence of the capacitance of the measuring cable can be minimized by a capacitive compensation (C_1, C_2). Because of the required length of 7 m the capacity of the measuring cable amounts 700 pF. This corresponds to a cable delay of 35 ns. The termination of the measuring cable with a Burch circuit (C_3, R_3) optimizes the distinctive frequency response of the system. The ratio of the divider is 100:1, its input resistance about 0.5 MΩ.

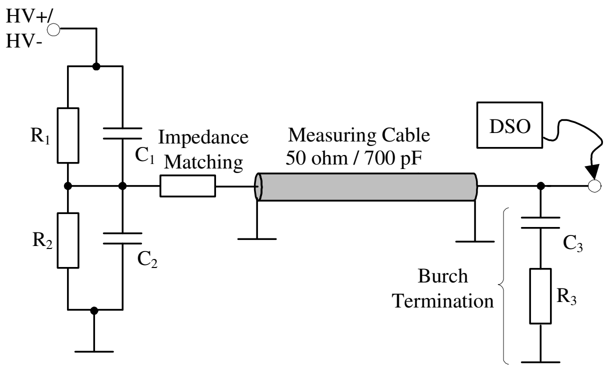


Figure 2 Capacitive compensated voltage divider

The divider arrangement is simulated in LTSpice. For this purpose a pulse source with an internal resistance of 50 Ω and a rise time of 1 ns is placed at the high-voltage input. The test probe of the oscilloscope is replaced by a discrete circuit with a capacitive part (10 pF) and a resistive part (1 MΩ). The cut-off frequency is reached at 70 MHz (**Figure 3**).

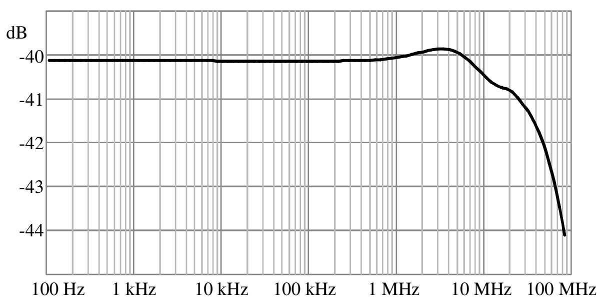


Figure 3 Frequency response of the capacitive compensated voltage divider

On the circuit board of the measuring box the divider is built-up with SMD components. The Burch termination is placed in a separate HF-enclosure which can be plugged in at the oscilloscope directly.

The step response of the complete assembled system is tested with a 50 Ω pulse generator achieving a rise time of 5 ns. According to the dimension of its components the amplitude is reduced by a factor of 100.

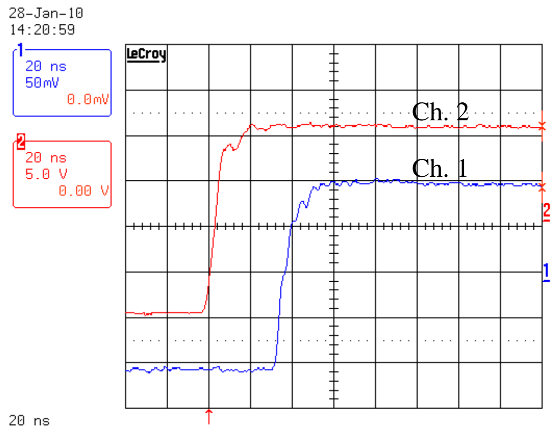
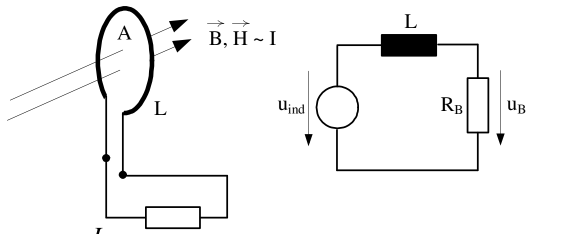


Figure 4 Input signal of the divider (Ch. 2) and step response of the divider (Ch. 1)

2.2.2 Rogowski sensor

For the measurement of transient currents a special Rogowski sensor was developed. It consists of a screened, toroidal winding on a plastic core. The function is based on the induction principle and Maxwell equations [4]: the voltage induced in the loop is proportional to the rate of change of the magnetic flux penetrating the screened loop. Due to the time constant and the proportionality between magnetic field and current this arrangement can be used as a differential current sensor (**Figure 4**).



$$\tau_{loop} = \frac{L}{R_B} \qquad u_{ind} = -A \cdot \frac{dB}{dt} = \mu_0 A \cdot \frac{dH}{dt}$$

Figure 4 Inductive loop and its equivalent circuit diagram

The time constant respectively the cutoff frequency of the wounded conductor loop results from its self-inductance (L) and the resistive load (R_B) terminating the circuit. The frequency response increases linearly until the cutoff frequency is reached. Above the cutoff frequency the inducted voltage remains constant because of the self-integrated behaviour of the loop (**Figure 5**).

The current sensor is also suitable for frequencies lower than the cutoff frequency when the signal obtained from

the loop is integrated actively. For this purpose a broadband operational amplifier (OP) is used.
The time constant of the RC-circuit in the feedback branch of the integration circuit is selected in such a way that it corresponds to the constant of the conductor loop.
By using the operational amplifier the cutoff frequency of the arrangement is shifted downwards in a lower frequency range. The new critical frequency is determined by the resistive feedback path, active integration takes place between the frequencies f_1 and f_2.

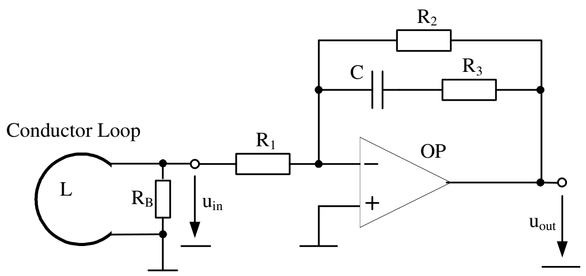
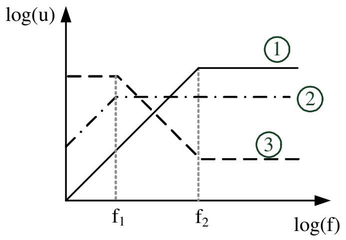


Figure 5 Circuit diagram of active integration



$$f_1 = \frac{1}{2\pi \cdot R_2 C}$$

$$f_2 = \frac{1}{2\pi \cdot R_3 C}$$

Figure 6 Frequency responses of the conductor loop (1), the active integrator (2) and its combination (3)

The practical structure of the current sensor consists of a PVC core which has several holes and a shielded cable short-circuited at its end. The shielding of the conductor loop keeps the coupling of electrical fields as small as possible. In order to prevent the induction of interference currents in the shielding, the braid is broken in the middle of the loop. A sufficient sensibility is achieved with four windings. The self-inductance of the current sensor amounts to 0.6 µH. Together with a resistive termination of 4.7 Ω this creates a time constant of 130 ns. The completed sensor is covered with a sheath of copper acting as electromagnetic shielding against the field of adjacent conductors.

Figure 7 View of sensor, the core of the high-voltage line is fitted through the centre hole

For further signal processing an active four-channel integrator device is designed. The components of the integrator module such as printed circuit board and a battery pack are placed in HF-enclosure. The signal ports are implemented as BNC connectors. The device comprises a low-battery indication for the bipolar power supply. The lower cutoff frequency is set at 15 Hz (f_1 in Figure 6).

Figure 8 4-Channel integration device

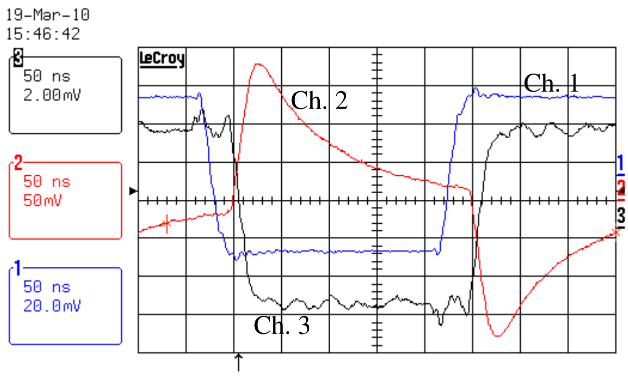


Figure 9 Step response of the conductor loop (Ch. 2), the sensor arrangement with the integrator device (Ch. 3) and an independent Pearson probe as reference (Ch. 1)

2.2.3 Hall effect current module

The measurement of DC and low frequency currents up to 200 kHz is done with commercial available current transducer modules. Its function is based on the closed loop hall effect [5]. The module is specified for currents having a maximum amplitude of 200 A, the current transmission ration is 1:2000. The measuring range can be changed easily by exchanging the shunt on the secondary side. For the operation a bipolar power supply provided by a DC/DC-converter in the measuring box is needed.

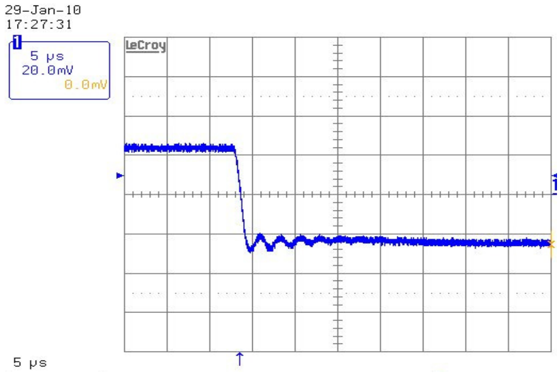
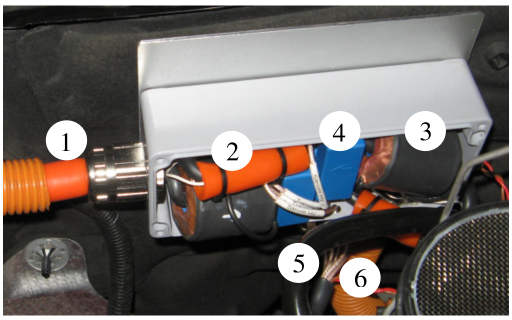


Figure 10 Step response of the Hall effect module on excitation with a pulse rise time of 1 µs

2.3 Installation in the hybrid vehicle

The measurement arrangement is installed in a vehicle with a mild hybrid system. It features an automatic start/stop function and during acceleration the combustion engine can be assisted by the electric drive. Under suitable conditions such as breaking procedures energy can be regained and used for charging the high-voltage battery. The hybrid system fed by a 130 V lithium ion battery provides an electrical power of 15 kW in addition to the combustion engine. For the large number of conventional electrical components an on-board system working with a voltage of 12 V is coupled by means of a DC/DC-Converter.

The first measurement box which contains the voltage dividers and current sensors is installed at the main DC line near the high-voltage battery. The shields of energy and measuring cables are contacted at the enclosure of the measurement box. The signal cables and the supply line are brought together in a braided hose and guided into the interior compartment.



1 line from HV-battery
2 voltage tap
3 Rogowski sensor
4 transducer module
5 measuring cables
6 further leading line

Figure 11 Measuring box installed in the motor compartment

3 Measurement examples performed on the vehicle

When the ignition is activated the voltage of the HV-network is 12 V. During the start procedure of the combustion motor a small voltage dip is visible after the on-board voltage of 130 V is reached. While the motor is running spikes appear in the voltage signal (**Figure 12**). The voltage between HV+ and HV- is calculated by subtraction of the voltage signals measured in reference to ground. The curve progressions of the currents show an oscillating characteristic. Due to the opposite orientation of the sensors the current in HV+ and the HV- core are measured with the same polarity.

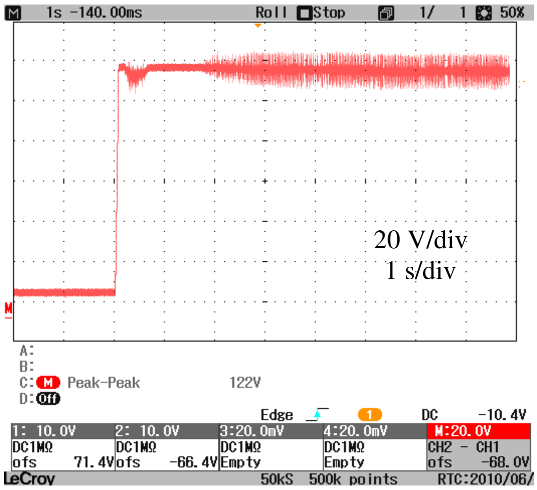


Figure 12 Voltage profile during the start procedure

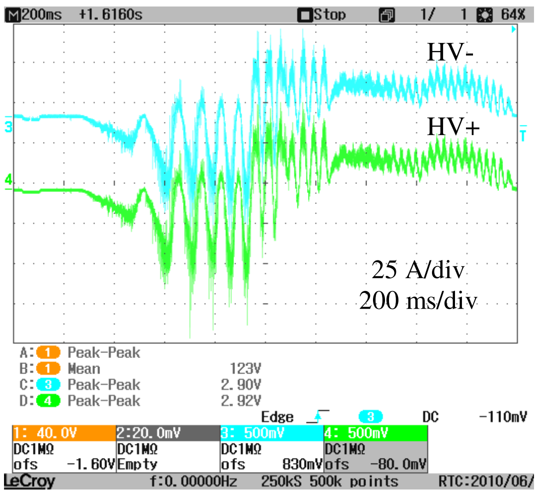


Figure 13 Current impulses during the starting procedure of the combustion engine

The interfering pulses which are produced by the IGBT converter are generated with a characteristic repetition frequency. By changing the time base a damped oscillation with a frequency of 18 MHz can be seen. At the same time there are superimposed pulses in the characteristic of the current, too.

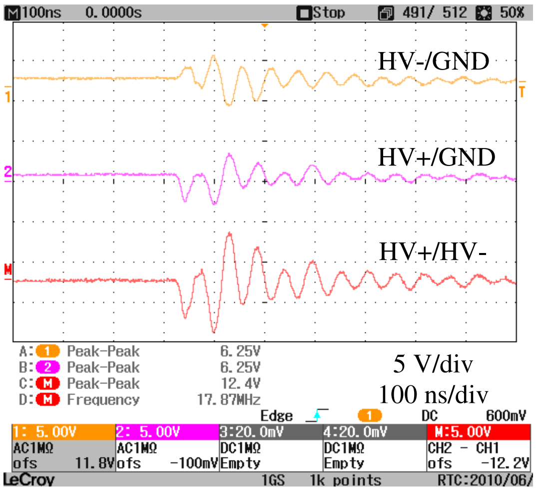


Figure 14 Voltage impulse with a frequency of 18 MHz (AC coupled)

Current impulses with high amplitudes can be measured when the electric drive is used to boost the torque or to recover braking energy. During these procedures peak currents up to 200 A occur for a few seconds.

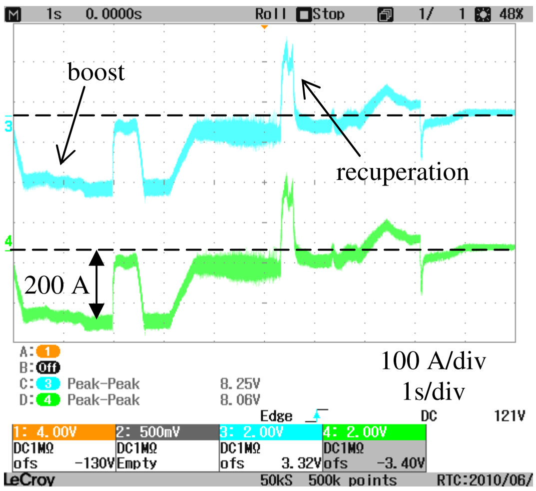


Figure 15 Current profile, during recuperation currents are pictured positive, negative current peaks indicate a recuperation procedure

4 Conclusions

The described measurement system can be used to investigate transient voltage and current signals on a high-voltage network in normal driving conditions. Measuring boxes with sensor arrangements are placed in the engine compartment, exactly at the position of the HV-cables where voltage and current relations or transient pulses are of interest. The sensor signals are analyzed in the time domain by digital oscilloscope. The components of the measuring system are tested for their electrical characteristic. Therefore the step response of the components is examined.

The measurement system is designed for frequencies from DC up to 40 MHz., currents up to 200 A and an on-board voltage of 130 V. In order to achieve a wide bandwidth there are used two different sensor types for the current detection and a special compensation circuit for the voltage divider.
The system is installed and applied in a car with a mild hybrid system. Several voltage and current profiles in different frequency ranges are demonstrated.

If several measuring boxes are installed at different locations near to the electrical HV components the voltage and current characteristics of the HV network can be measured completely. The measuring system can be used to characterize electromagnetic disturbances which are generated by components of the HV-network. The measurement results can also be used to estimate requirements that must be met by components of the HV power train in order to ensure a safe and reliable operation of the car.

5 References

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