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Characterization of the Susceptibility to EMI of a BMS IC for Electric Vehicles by Direct Power and Bulk Current Injection

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Abstract—In this letter the susceptibility to Electromagnetic Interference of a Battery Management System for Lithium-Ion and Lithium Polymer battery packs employed in emerging electric and hybrid electric vehicles is addressed. For this purpose, the susceptibility to EMI of a BMS front-end integrated circuit is experimentally assessed by the direct power injection and by the Bulk Current Injection method. Experimental results are shown and discussed to highlight different EMI-induced failure mechanisms.

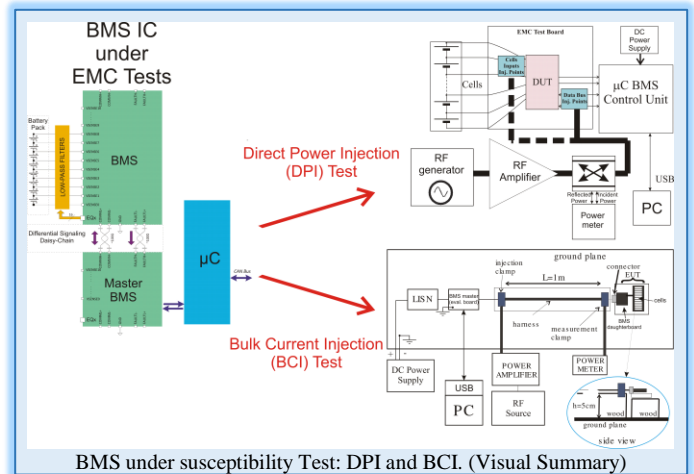
Index Terms—Battery Management System (BMS); Li-Ion Battery Pack; Electric Vehicles (EVs); Hybrid Electric Vehicles (HEVs); Direct Power Injection (DPI); Bulk Current Injection (BCI).

I. INTRODUCTION

Lithium-ion (Li-ion) and Lithium-Polymer (LiPo) battery packs for Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEV) can be damaged and give rise to severe hazards like fires and explosions in case of overdischarge, overcharge and/or operation at excessive temperature [1]-[3]. An electronic battery management system (BMS), which properly detects the onset of potentially critical conditions and takes the required actions in the charge/discharge phases is therefore mandatory for the safe operation of EVs and HEVs [1]-[3].

A BMS, as schematically depicted in Fig.1, typically includes several frontend modules, that acquire critical cell information like terminal voltages and temperatures, and an electronic control unit that runs specific control and management algorithms. Since Electromagnetic Interference (EMI) can be picked up by the long wires that connect BMS front-end ICs to each other, to the BMS control unit, to the terminals of the electrochemical cells and to the temperature sensors distributed over the whole battery pack [4]-[6], EMI-induced failures in the BMS unit are a major safety concern for emerging EVs and HEVs powered by batteries and have been therefore addressed in recent EMC literature [7]-[13].

In [10]-[11], different test setups intended to the simulation and to the experimental characterization of the susceptibility to EMI of a battery pack and its BMS are proposed. In [7], direct power injection tests have been performed on a BMS front-end IC and the measured RF leakage on the BMS cell inputs is compared with system-level simulations, whereas in [12]-[13] the susceptibility of a BMS front-end has been experimentally tested by Bulk Current Injection tests and



radiated immunity tests performed in compliance with ISO 11452-2 standard [14].

In this letter, the susceptibility to EMI of a new generation smart power BMS front-end IC, which is specifically intended for EV/HEV applications is experimentally investigated based on the results of Direct Power Injection (DPI) tests (IEC-62132-4 standard [15]-[16]) and Bulk Current Injection (BCI) tests performed in compliance with ISO 11452-4 [17]. Based on the measured results, the specific susceptibility level of the main IC pins and their different EMI-induced failure mechanisms are observed and compared. The effectiveness of filtering techniques, that can be adopted to enhance the immunity to

Take-Home Messages:

- The susceptibility to Electromagnetic Interference (EMI) of Battery Management Systems (BMS) units are a major threat to the safety of Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) powered by batteries
- DPI and BCI measurements results show that the BMS ICs can be susceptible to EMI superimposed on the cells and on Digital Data Link
- The susceptibility of Digital Data Links connecting BMS modules is particularly critical.
- The filtering recommended by the BMS IC datasheet is not effective in order to increase the overall EMI immunity.

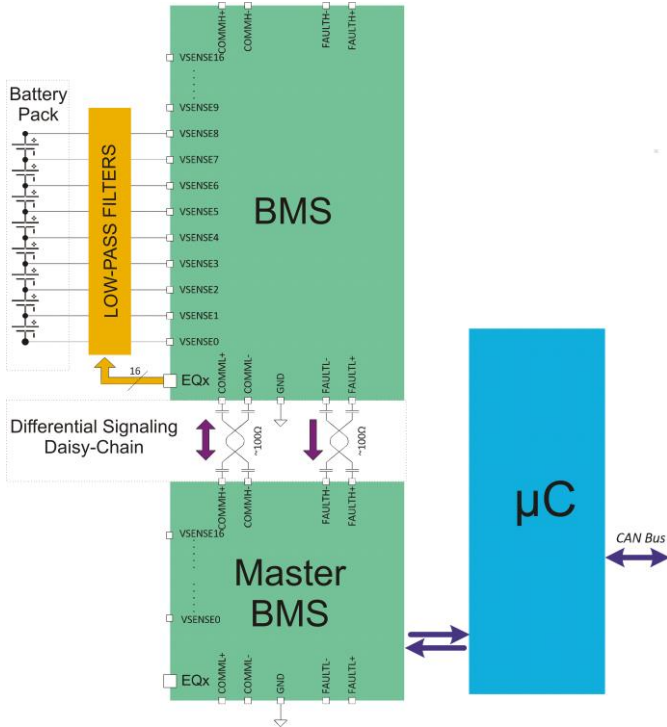


Fig. 1. Schematic the Battery Management System Processing Chain.

EMI of a BMS, is also discussed.

The letter is organized as follows: in Section II, the BMS IC considered in the Letter is introduced along with the printed circuit board (PCB) developed to perform EMC tests; then, in Section III, the test bench and the test procedure adopted for DPI [15] measurements are described and the results are reported in Section IV. The test setup for the BCI method [17] is described in Section V and the BCI test results are reported in Section VI. Based on both the DPI and BCI experimental results, the susceptibility to EMI of the BMS front-end IC considered in this study is discussed in Section VII and finally, in Section VIII, some concluding remarks are drawn.

II. BATTERY MANAGEMENT SYSTEM (BMS) IC

The commercial BMS front-end IC considered in this letter as a device under test is a smart power integrated circuit designed to monitor and perform passive charge equalization on up to 16 electrochemical cells connected in series and is connected to the master BMS unit by a capacitively coupled differential data link, which is also exploited to connect the IC to similar BMS ICs in a daisy chain structure, so that to monitor battery packs with more than 16 cells. Compared to previous generation BMS IC, this device handles a larger number of cells (16), includes a high-resolution (14bit) ADC resolution and features a high-speed (1Mb/s) data link, which make it intrinsically well suited to applications EV/HEV.

For each cell to be monitored there are two sense terminals: $VSENSE_N$ and $VSENSE_{N+1}$, and an equalization terminal EQ_N with N in the range from 0 to 16. The equalization terminal is intended to drive an external power transistor so that to perform passive charge equalization, i.e. to draw current from the most charged cells, so that to equalize the state of charge of the cells in the battery pack [18].

Although the BMS IC can simultaneously monitor up to 16 cells and more than 16 cells through a daisy-chain connection, a simple

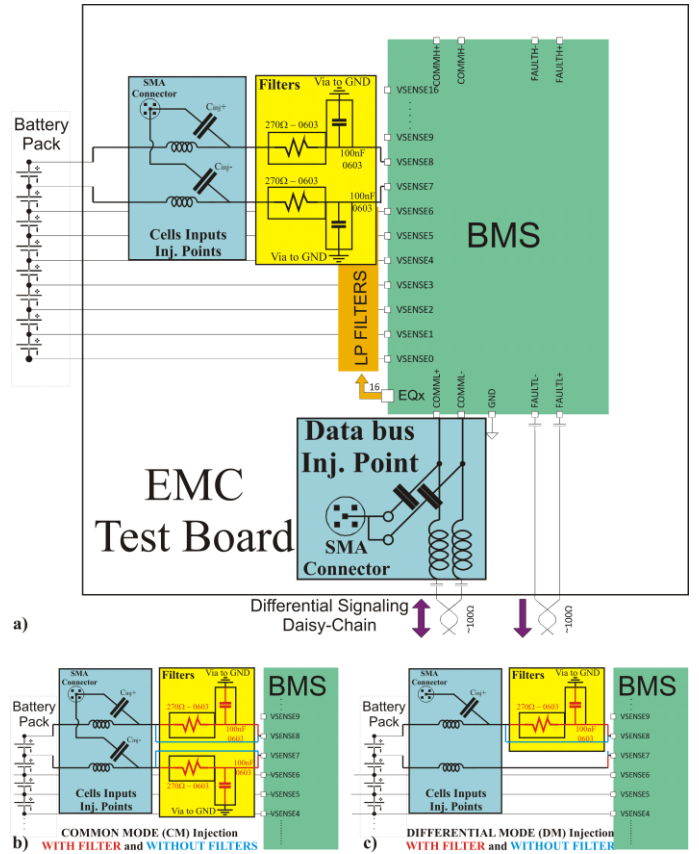


Fig. 2. a) Schematic of the BMS IC Test Board with the injection points considered for DPI tests; b) Sketch of common-mode (CM) Injection scheme with and without filters; c) Sketch of differential-mode (DM) Injection scheme with and without filter.

BMS structure monitoring 8 cells (the minimum number of cells required for proper operation) has been considered in the EMC tests presented in this work (see Fig. 1). The inputs corresponding to the top six cells of the BMS IC (not used), have been tied to the top cell of the stack, as recommended by the manufacturer.

A. DPI Test Bench

The immunity to EMI of the BMS IC in Fig.2 has been tested by the DPI setup in Fig.3. Here, the device under test (DUT) is operated from a 24 V power supply obtained from the battery pack, including eight pairs of series-connected commercial NiCd cells mounted on a separate board and tied to the DUT cell monitoring inputs by a devoted wiring including specific automotive connectors. The LC injection network connected as shown in Fig.2a provides a direct RF coupling to the BMS IC, whereas the RF source is connected to the microcontroller unit through an higher impedance, resulting from the series connection of the inductor of the injection network and of a common-mode choke connected at the control unit side of the communication link, as recommended by the BMS IC manufacturer. The differential digital communication lines of the DUT are connected to an evaluation board of the BMS master device that is in turn connected to a PC via an USB link. Such an evaluation board includes a BMS IC identical to the one mounted on the EMC test board, that is connected to it via its COMMH differential line and that is interfaced to the USB port via an USB dongle.

The operation of the EMC board is monitored and controlled by the

PC connected to the USB by a specific demo software provided by the manufacturer. In particular, the values of the cell voltages acquired by the DUT can be monitored and communication failures are reported on the application window of the PC.

An RF source connected to a 10 W RF power amplifier operating in the 1 MHz - 2 GHz bandwidth is employed to perform continuous wave (CW) RF power injection. The output of the power amplifier is fed to the injection points of the EMC test board via a coaxial cable. Injection points have been included so that to superimpose RFI:

- on the cell voltage monitoring lines connected to the 8th cell of the stack (both differential and common mode injection);
- on the COMML lines of the differential digital link connecting the EMC test board with the master BMS device.

III. DIRECT POWER INJECTION TESTS

A. DPI Injection Points

The susceptibility to EMI of the BMS IC included in the EMC test board has been tested by the DPI method by injecting RF power on the inputs corresponding to the cells to be monitored and on the differential communication bus, as depicted in Fig.2. In particular,

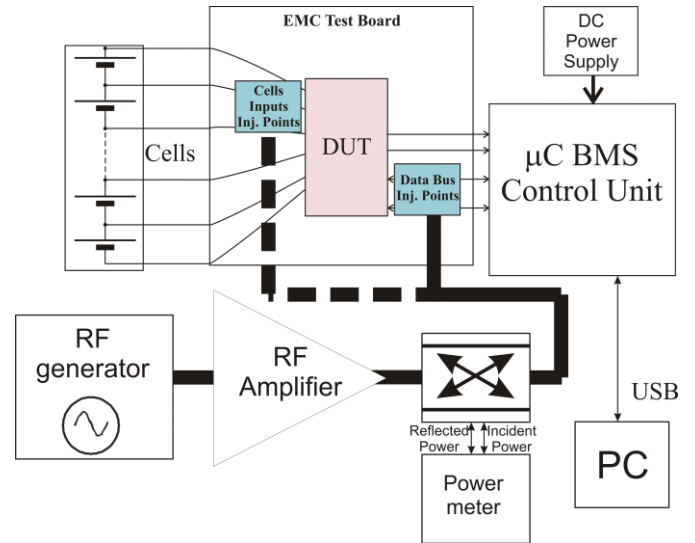
- two LC injection networks, with $L = 6 \mu\text{H}$ and $C = 6.8 \text{ nF}$ have been included to inject RF power on either one (differential injection, Fig. 2c) or both (common-mode injection, Fig.2b) the cell voltage monitoring terminals of the top cell in the stack (eighth cell);
- two LC injection networks, with $L = 3 \mu\text{H}$ and $C = 100 \text{ pF}$ have been included to inject RF power on either one (differential injection) or both (common-mode injection) the differential digital communication lines COMML+ and COMML-. These are intended to establish a digital communication between the test board and the master BMS unit. The values of inductance and capacitance have been chosen considering the maximum capacitive load that can be driven by the digital transceiver.

B. DPI Test Procedure

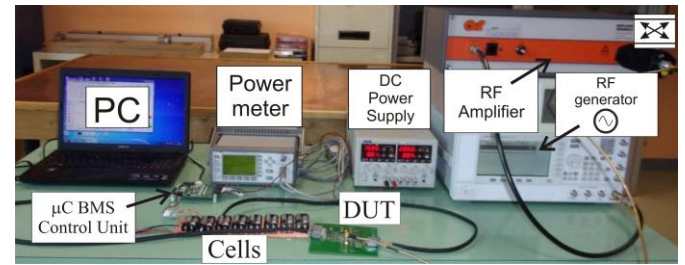
During DPI tests, the DUT is operated from the PC to periodically acquire the voltages of all the cells in the battery pack. The acquired data are then retrieved from the demo application window and manually checked during the DPI test with and without EMI injection. Based on the cell voltage readings and/or on the communication failure flags of the demo application, an EMI-induced failure is recorded if one of the following conditions occurs:

- 1) a transmission error is detected (CRC failure and/or communication timeout);
- 2) an EMI-induced offset in the cell voltages acquired with RF injection exceeding an error threshold V_T is detected. Taking into account of the accuracy level that is required to safely manage Li-ion cells and of the declared maximum error of the IC, an error threshold $V_T = 10 \text{ mV}$ is considered.

Based on the above failure criteria, DPI tests have been performed for each test frequency in the 1 MHz - 2 GHz bandwidth¹ by increasing the injected RF incident power until a failure is detected. The minimum RF incident power giving rise to the failure is then annotated as the DPI immunity level at the test frequency. If no failure is detected at the



a)



b)

Fig. 3. Direct Power Injection (DPI) Test Bench: a) sketch and b) photo.

maximum test incident power $P_{\text{max}} = 37 \text{ dBm}$; no immunity level indication is reported.

IV. DPI EXPERIMENTAL RESULTS

The results of DPI tests performed on the cell voltage monitoring inputs and on the COMML bus are reported in the following.

A. Cell Inputs Injection

The immunity level of the DUT undergoing DPI on the cell input injection point of Fig.2 is first considered. To this purpose, two different DPI excitations have been compared: differential (DM) excitation, performed by connecting only one injection capacitor to the signal terminal of the SMA connector in Fig.2, and common-mode (CM) excitation, performed by connecting both the injection capacitors to the SMA signal line. Both the tests have been repeated without RC input filters (i.e., using 0Ω 0603 SMD resistors and not mounting the filter capacitors) and with the 270Ω - 100 nF differential filters, as reported in Fig. 2, connected between the cell input terminals prescribed by the manufacturer.

The results of such DPI measurements are reported in Fig.4. All observed failures for DPI performed on the BMS IC inputs connected to the cells are related to offset in cell voltage readings exceeding 10 mV . It can be observed that the DPI immunity level of the DUT is higher than the 37 dBm test level for frequencies up to 10 MHz (except one failure reported at 1 MHz). At higher frequencies the measured

¹ The IEC 62132-4 frequency bandwidth (1MHz-1GHz) has been extended

to 2 GHz to include the 1.8 GHz frequency band, which is widely employed for wireless communications.

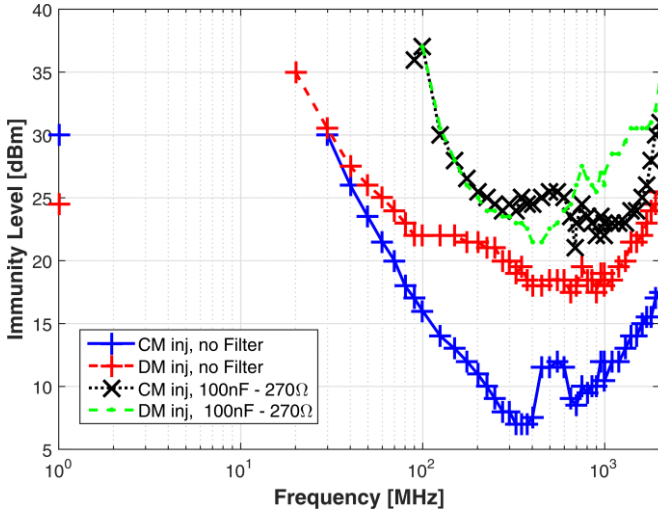


Fig. 4. DPI Immunity Test Results. DPI performed on the cells inputs: differential and common mode injection performed with and without the 270 Ω - 100nF input filter prescribed by the manufacturer.

immunity level for the unfiltered solution decreases with a slope of about 20 dB/dec reaching an immunity level as low as 5dBm for CM injection at a frequency of 300 MHz (a susceptibility level as low as 20dBm for DM injection at a frequency of 100 MHz), which slightly increases at higher frequencies. The immunity of the unfiltered IC is therefore lower for CM injection than for DM injection. On the basis of such results, EMI-induced failures do not seem to be specifically related to EMI superimposed onto the differential cell voltage to be acquired, but rather to mechanisms involving the CM RF voltage between each test pin and the IC reference (ground) voltage.

The results of DPI tests performed on a board including the 270 Ω - 100 nF differential filters prescribed by the manufacturer are rather similar for both CM and DM injection, with a minimum immunity level slightly higher than 20 dBm. A rather poor filtering effect (less than 5dB improvement) can be observed for DM injection above 200 MHz.

B. COMML Digital Inputs Injection

The immunity level of the DUT undergoing DPI on the COMML bus injection point of Fig.2 is first considered. In particular, differential (DM) excitation, performed injecting RFI on the COMML+ input only by a single 100 pF injection capacitor, and common-mode (CM) excitation, performed by injecting the same RF signal on both the COMML+ and the COMML- line by two identical 100 pF capacitors, have been performed and the results of such tests are reported in Fig.5. In commenting the DPI immunity level reported in Fig.5, it should be remarked that the LC injection networks, with $L = 3 \mu\text{H}$ and $C = 100\text{pF}$ and including a 100 Ω resistor in series with the inductor, that have been specifically designed considering the maximum driving capability of the digital drivers, introduce a high pass filtering effect from the RF input to the IC pin, with a cutoff frequency of about 50 MHz. As such, the actual RF injected voltage at lower frequencies is much less than the RF source incident voltage.

All observed failures for COMML DPI are related to timeout or errors in the cyclic redundancy code (CRC) check. The measured DPI immunity level is about 15 dBm for common mode injection and 20 dBm for differential injection in the bandwidth 50 MHz - 200 MHz.

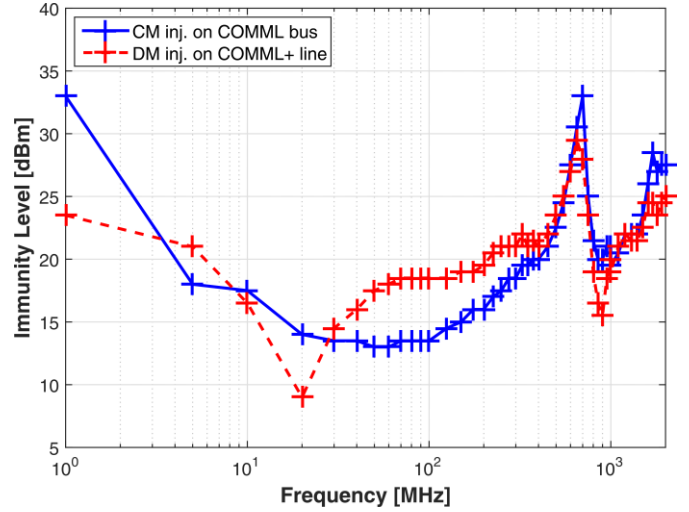


Fig. 5. DPI Immunity Test Results. DPI injection on the COMML bus: differential (injection on COMML+ only) and common-mode

The higher immunity level observed at higher frequency is likely to be related to the filtering effect of the injection network observed at lower frequency, whereas the measured immunity level at higher frequencies show immunity and susceptibility peaks related to resonances in the PCB traces and in the injection networks. It is worth noting that a lower immunity is observed at most frequencies for CM rather than from DM injection, which seems to be in contrast with the generally assumed higher immunity to CM interference of differential communication [19].

C. Discussion

Based on the results of DPI measurements, a significant susceptibility of the BMS front end IC to EMI injected on the battery inputs and on the communication line has been observed.

The introduction of RC filters on the cell inputs give rise to a substantial improvement in the immunity to CM disturbances (in the order of 15 dB), whereas the same filters are less effective to suppress DM interference (the actual improvement for the BMS system including the RC filters is only 5dB). For what concerns DPI on COMM lines a DPI immunity level lower than 13 dBm has been measured above 50 MHz for CM injection. A slightly better behavior has been reported for DM injection even though, in this case, a lower immunity peak of less than 10dBm has been reported. It is worth noting that unlike cells inputs, digital communication lines cannot be aggressively filtered in order to avoid unacceptable degradation of the digital signal to be transmitted. Based on the results discussed so far, it can be therefore concluded that the immunity level of the BMS IC is limited by the susceptibility of the digital communication lines.

V. BULK CURRENT INJECTION TESTS

In order to get more insight on the susceptibility of the differential communication line employed in the BMS IC at system level and to avoid the low-frequency bandwidth limitation related to the high-pass characteristics of the data bus DPI injection network discussed in the previous section, the susceptibility to EMI of the binary communication link has been tested by the BCI method, performed in compliance with ISO 11452-4 [17].

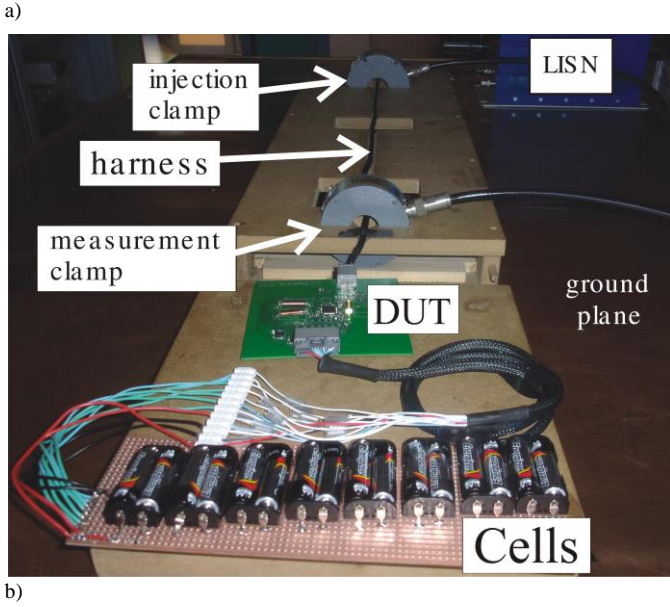
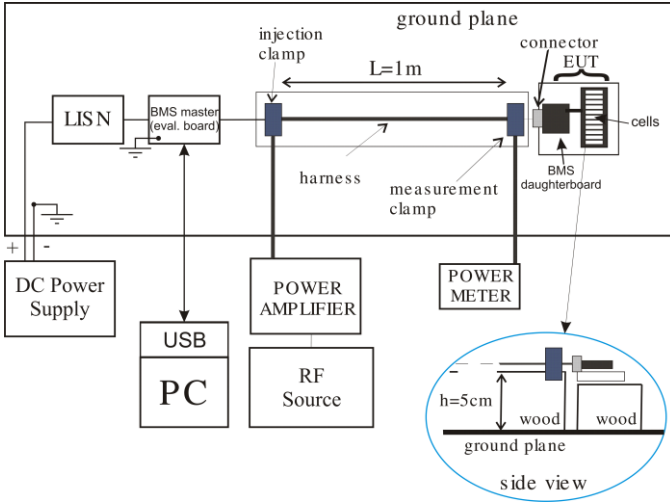


Fig. 6. Bulk Current Injection (BCI) Test Bench. a) Sketch and b) photo.

A. BCI Test Bench

The susceptibility to EMI of the COMM bus of the analyzed BMS system has been assessed by BCI measurements performed by the setup in Fig.6 in the bandwidth 1MHz-1GHz, following the ISO11452-4 standard [17]. In such a setup, a Li-ion battery pack including the EMC test board (a) and the BMS daughterboard have been considered as the equipment under test (EUT). In such an EUT, the BMS daughter-board is connected to a battery-pack emulator including 8 cells, which is analogous to the one employed for DPI tests described in Section IV, which also provides the power supply of the daughter-board. The whole EUT (battery pack with BMS daughterboard) is remotely grounded through the wiring harness and is placed at a 5 cm height over the test plane and at a distance of 5 cm from the monitoring clamp, in compliance with ISO 11452-4 standard [17].

The BMS daughter-board has been connected to the BMS evaluation board, here employed as a BMS master unit, via a 1m-long, two-wire harness, including the COMM bus differential lines.

The BMS evaluation board is connected to a PC via a serial-over-USB link, in order to control and monitor the operations of the BMS during the BCI tests. The BMS evaluation board is operated from a 16 V power supply provided by a DC power supply through a line impedance stabilization network (LISN) in compliance with ISO 11452-4 [17]. An injection clamp (F-130A-1 by FCC [20]) and a calibrated measurement clamp (F-51 by FCC [21]), have been placed along the wiring harness as shown in Fig.6 to perform BCI tests. The injection clamp is connected to the output of a 10 W RF power amplifier, whose input terminal is connected to a CW RF signal source, while the measurement clamp is connected to an RF power meter in order to measure the bulk current injected into the EUT. The power amplifier, the RF source and the RF power meter are located out of the test area.

B. BCI Susceptibility Tests

With reference to the setup in Fig. 4, BCI measurements in the bandwidth² 10 MHz - 400 MHz have been performed. To this purpose, for each test frequency, the injected BCI amplitude is increased up to a failure in the EUT operation is experienced or until the target BCI test current of 100mA and/or the maximum incident RF power deliverable by the amplifier is reached, (in case the latter is not sufficient to deliver the target 100mA test current). In the event of a failure, the failure injected bulk current measured by the power meter connected to the monitoring clamp is acquired and considered as the immunity level of the test PCB. If no failure is experienced at the test current, no failure value is reported. In case the target 100 mA test current is not reached, the test current delivered in correspondence of the maximum incident power of the amplifier is also reported for reference.

VI. BCI EXPERIMENTAL RESULTS

The results of BCI immunity tests on the COMM bus of the BMS system including the EMC test board are reported in Fig. 7. To this purpose, the BCI failure current is reported in the top plot in continuous line for frequencies at which a BCI failure has been reported. For those frequencies at which no BCI failure has been observed, the injected current, measured by the monitoring clamp in correspondence of the maximum test forward power (40 dBm) is reported in dashed line. In the bottom, the forward RF power applied to the injection clamp in correspondence of BCI failures is reported. A BCI failure level as low as 20 mA can be observed at 50 MHz and above 200 MHz. A higher EMI immunity has been observed at frequencies below 20 MHz, where no failures have been recorded at the maximum test power.

The measured BCI susceptibility levels observed in Fig.7 are rather poor and largely inadequate considering to the requirements of safety-critical automotive applications, where a BCI immunity level of 200 mA (or higher) is normally requested in the bandwidth from 1 MHz to 400 MHz.

A. Correlation Between DPI and BCI Test Results

Comparing the BCI and the DPI results, the DPI immunity level, for common mode injection, of about 15 dBm, which is reported in the 50 MHz - 300 MHz bandwidth and is equivalent to an RF peak open-

² The tests have been performed up to the maximum operating frequency of the RF amplifier and of the injection clamp (1 GHz). Nonetheless, the results obtained outside the 10 MHz - 400 MHz are just indicative [22].

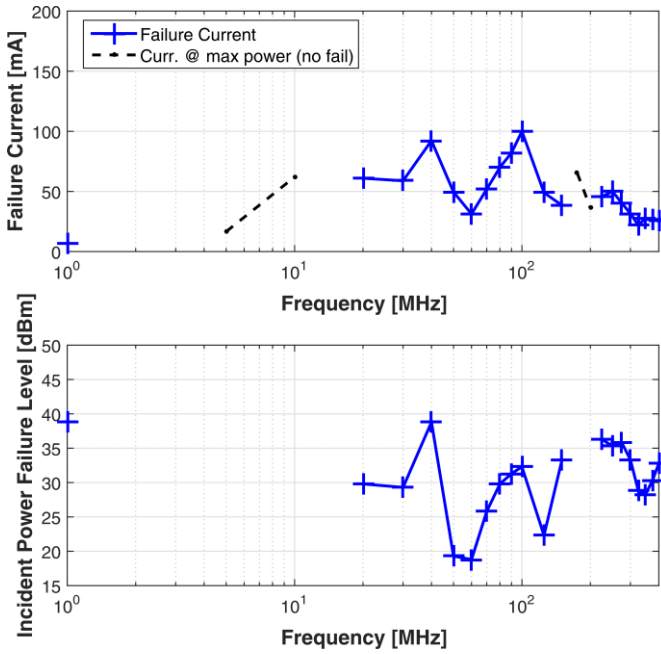


Fig. 7. BCI Immunity Test Results: EMC Test Board

circuit voltage at the injection pin $V = \sqrt{2R_G P}$ of about 3.5 V, where $R_G = 50 \Omega$ and P is the incident power, corresponds to a BCI immunity level oscillating between 20 mA and 60 mA with a mean value of about 40 mA in the same frequency range. Even though a rigorous correlation between the reported results is not possible because of the significant differences in the injection methods and in the experimental test setup, it can be observed that, in this frequency range, the ratio between the open-circuit DPI voltages at injection pins and injected BCI current resulting in a failure can be empirically expressed as:

$$Z = \frac{V_{DPI}}{I_{BCI}} \simeq 50 \Omega \div 150 \Omega$$

A correlation between BCI and DPI results is even more problematic for test frequencies out of the 50 MHz - 300 MHz range.

BCI tests highlight that the board is less susceptible to EMI even in the frequency range below 50 MHz, for which the results of DPI tests are not reliable due to the attenuation of the coupling network. At the same time, BCI results at higher frequencies, which are out of the frequency range prescribed by ISO 11452-4, can be questionable.

VII. CONCLUSION

The susceptibility to EMI of a BMS front-end IC targeting EV and HEV applications has been studied in this letter with reference to standard DPI tests, performed in compliance with IEC 62132-4, and BCI tests performed in compliance with ISO 11452-4 (closed-loop method).

Based on the measured results, it can be concluded that the BMS IC considered in this study is significantly susceptible to EMI and does not meet the EMC requirements for safety critical automotive systems. On the basis of DPI measurements, in particular, it has been highlighted that the BMS IC is extremely susceptible to EMI superimposed onto the digital communication lines, where a DPI

immunity level lower than 10 dBm has been measured at some frequencies.

Based on these results, the susceptibility to EMI of new generation BMS ICs is not improved compared to older designs and further research intended to address the susceptibility to EMI of BMS ICs is necessary.

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