Functional Safety Risks of Smart Power Devices due to EMI

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Abstract

An important prerequisite for the safe operation of vehicles is that all electronic control units (ECUs) installed in the vehicle meet the applicable standards for functional safety and for electromagnetic compatibility. Integrated circuits (ICs) that are used within these ECUs are therefore often tested according to functional safety and EMC standards, but in most cases this is done consecutively. Therefore, we developed an extended direct power injection (DPI) test setup to characterize the functional safety and the electromagnetic interference (EMI) behavior of ICs simultaneously. Based on the results, we show that EMI can have a significant influence on the IC's functional safety behavior.

1 Introduction

Automotive recall cases were becoming more frequent and for several years now, more vehicles are recalled each year than are newly registered. Some of the reasons for this are the ever shorter development cycles, the increasingly faster production, as well as the higher technical complexity. Almost every second recall today is related to problems with the electronic components in the vehicle. This is not surprising since modern vehicles contain sometimes more than 100 electronic control units (ECUs) including numerous ICs [1]. In 2014 alone, more than 60 million vehicles in the U.S. were sent back to the repair shop due to safety problems. Figure 1 shows the return rate

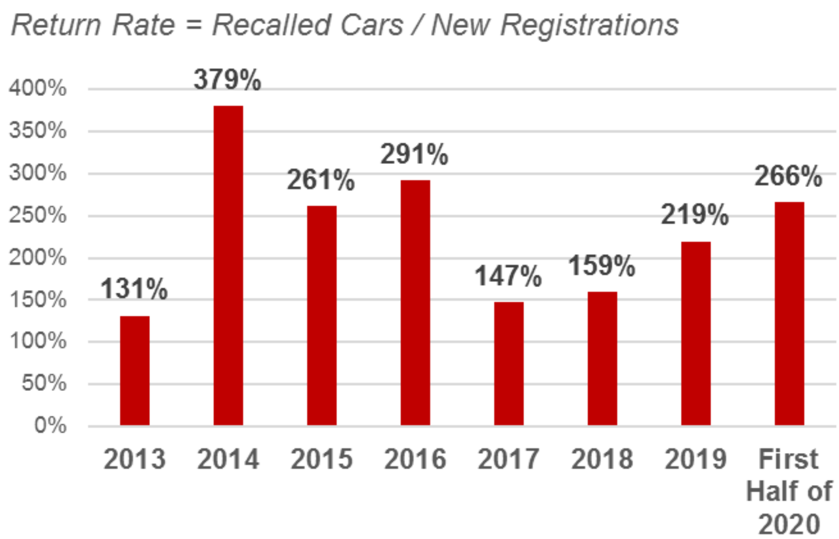


Figure 1: Return rate of vehicles

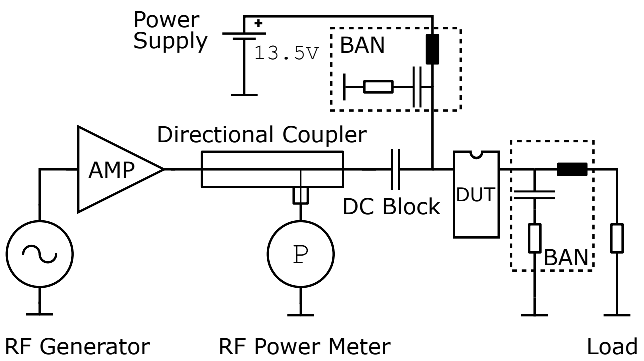
(recalled vehicles / new registrations) from 2013 to 2020 to further illustrate the importance of the need to develop more reliable and functionally safe vehicles in the future [2]. A very important property of all electronic systems is their electromagnetic compatibility (EMC). The compliance to EMC regulations is even more important for devices with safety functions, such as those used in the automotive sector to protect people. To make vehicles even safer in the future, mechanical switches and fuses, among other things, are increasingly being replaced by smart electronic components. Equipped with additional diagnostic and safety functions they are able to detect faults (e.g. short circuit, overtemperature, loss of ground,...) and react accordingly (e.g. disconnect a load or forward an error message to a control unit). The prerequisite for this, however, is that these safety functions also function satisfactorily in their electromagnetic environment and are not influenced by interference. In order to characterize the electromagnetic immunity behavior of ICs, several IC-level test methods are available. Currently, IC manufacturers test their products according the current versions of the applicable functional safety and EMC standards. But as described in [3] and [4] conventional immunity tests are not sufficient for functional safety. Why the conventional immunity tests are not sufficient has several reasons:

- Faults are completely ignored during tests and only perfectly working parts are tested
- The parts are not tested in real-life electromagnetic environments (only one EM phenomena at a time, injection of a interference signal into only one pin, etc.)
- Physical and climatic environment is completely ignored (i.e. EMC tests are usually performed at room temperature,...)

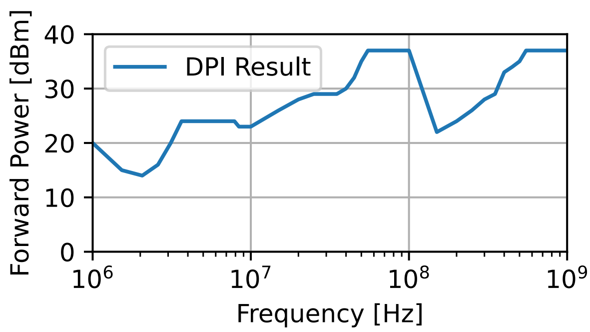
As described in [5], the performance of important safety functions of smart power devices such as e.g. correct overtemperature detection can be drastically reduced when the device is exposed to EMI. Based on these first investigations further case studies to compared the electromagnetic susceptibility of smart power devices in nominal state and in the fault state using a DPI test are described in this paper. Section 2 provides the background information of the used DPI methodology and section 3 explains the test strategy and the used test setup. Section 4 presents obtained test results and finally the analysis results are discussed and a conclusion is given.

2 DPI testing beyond nominal conditions

The DPI test to characterize the electromagnetic immunity of ICs is one of the most used test methods and is specified in the IEC-62132-4 standard [6]. The standard specifies the test setup that usually consists of a signal generator to create an interference signal, a high power amplifier to amplify the signal (e.g. up to a forward power of 37 dBm), a directional coupler and a coupling capacitor (usually a 6.8 nF MLCC capacitor) to directly inject the signal into specific pins of the IC which is referred here as device under test (DUT).



(a) DPI measurement setup



(b) DPI test result

Figure 2: DPI measurement setup to characterize the immunity of ICs

A basic test setup of such a DPI test is shown in Figure 2a. Normally one starts with the coupling of an interference signal at a start frequency (e.g. 1 MHz) and couple this via the coupling capacitor into one of the IC pins. At the same time, it is checked whether the DUT is influenced by the injected signal. The amplitude of the interference signal is increased stepwise until either the maximum amplitude of the forward power (e.g. 37 dBm for IC pins with direct connection to the cable harness) is reached or the DUT already shows an interference before. The same procedure is repeated for the next frequency step until the final frequency (e.g. 1 GHz) is reached. The final result provides a DPI characteristic (x-axis = frequency, y-axis = amplitude of the forward power), which shows at which frequencies the DUT reacts sensitively to an interference signal. An example of such a DPI result is shown in Figure 2b. For the investigations in this paper we used an automotive smart power high side switch as DUT. A typical block diagram of such a device is shown in Figure 3. Such intelligent power switches often have a range of diagnostic and safety features, such as protection against reverse polarity, electrostatic discharge, overtemperature and overcurrent. In the event of a fault, these functions help by, for example, opening the switch at the right time and thus interrupting the flow of current. They also pass on important fault information to the control unit.

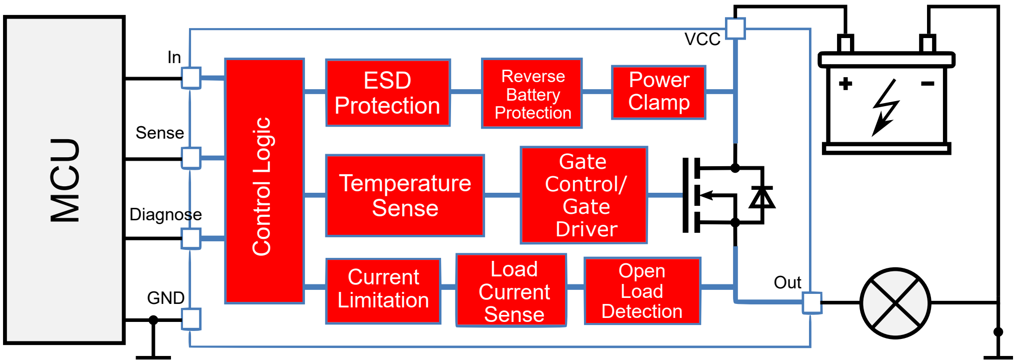


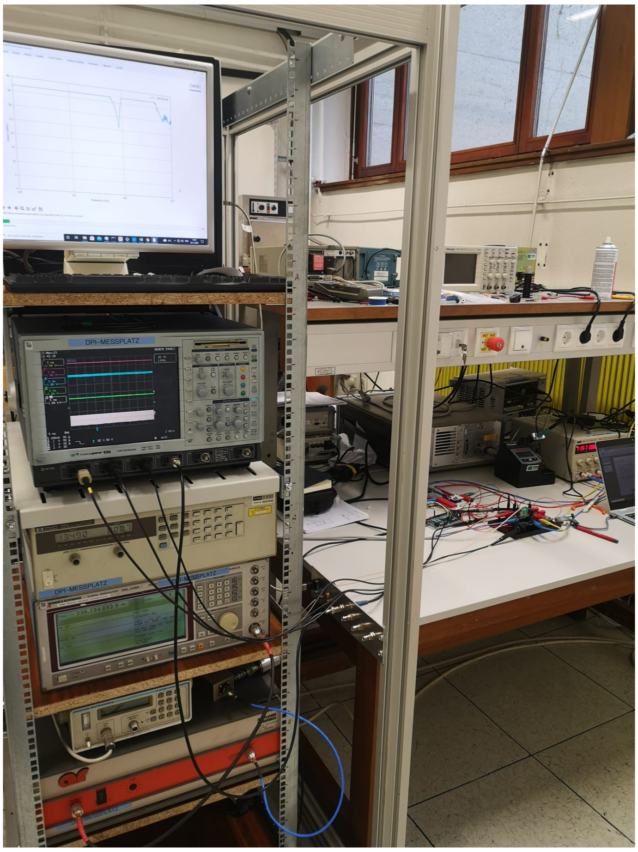
Figure 3: Typical block diagram of a smart power high side switch

The device used for the investigations has two pins, the power supply (VCC) and the output pin (Out), which are usually directly connected to the vehicle's wiring harness. Therefore, a broadband artificial network (BAN) is used in the DPI test setup to simulate the impedance of the cable and serve as a decoupling network for the interfering signal. The main function of such a switch is primarily just to switch on and off a load (e.g. a DC motor or a lamp). This can be done permanently or in pulse width modulation (PWM) mode. Monitoring the electromagnetic immunity of the DUT in only such operating states (ON, OFF, PWM) is quite simple and is often done with the aid of an oscilloscope using simple monitoring criteria, e.g., mask tests of output signals. According to the information in the IEC 62132 standard "Any function inside an IC can be affected even if it is not connected to the pin under test. Therefore, the operation mode(s) of the IC shall be chosen in a way that all functions of the IC are used during the test." This means that for the rather simple IC used, very extensive monitoring of the various operating states is necessary to find out whether one of the numerous diagnostic and safety functions can be influenced by an interference signal.

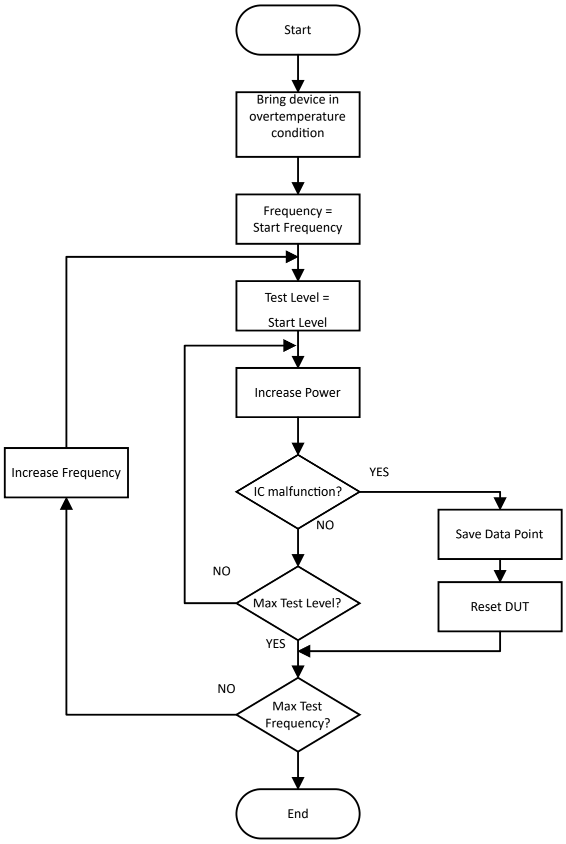
3 Test strategy for future immunity testing

Very often, the behavior of the IC in the undisturbed state is used as a reference to check whether the IC is affected by interference. Signals of the undisturbed IC are recorded and an error tolerance mask is created around them. During the DPI characterization, it is then observed whether the tolerance range is violated during the injection of the interference signal, which would be recorded as an error of the IC. Often the tolerance mask is defined by a deviation of e.g. $\pm 10\,\%$ of the signal in the undisturbed case. Such a tolerance window can be too wide for some functions and too narrow for others. In our opinion, not only signals of the undisturbed case should serve as reference for the monitoring criteria. Additionally, one should also consider the specifications given in the data sheet, such as timings, slew rates, voltage levels, etc. This makes it easier to ensure that an IC fully functions as intended in the event of interference.

In addition, monitoring all the safety functions should also be included during the DPI investigation. This is particularly important because additional interference can often occur when a functional fault occurs (e.g. short circuit). The immunity of the internal safety functions of the IC is therefore



(a) DPI measurement setup



(b) DPI measurement flow chart for overtemperature testing

Figure 4: Automated DPI measurement setup for overtemperature testing

particularly important. In order to keep the test effort within limits, an automatic test setup is required that can monitor the various parameters and adapt the test sequence to the requirements of the DUT with simple settings.

3.1 Automated test setup

To perform the immunity tests, we are developing a modular and flexible automated test setup. Since the test system is modular, it can very easily be equipped with additional devices to check various failure criteria. The actual measurement setup is shown in Figure 4a. This system makes it possible to perform DPI tests and define the failure criteria and adapt them to the DUT. Thus, the specifications from the data sheet can very easily be adopted as failure criteria, which are checked in the automatic measurement sequence. All monitored functions are evaluated during the test and at the end it can be determined exactly at which measuring point which criterion was violated.

An additional feature of our test system is the ability to heat the DUT. This allows us to test the immunity of the overtemperature protection function against EMI. Such an approach represents a first important step towards a combined functional safety and EMC assessment. Heating is provided by a heating block directly connected to an exposed solder pad on the bottom side of the PCB directly under the DUT.

4 DPI test: Nominal vs. overtemperature condition

We performed several DPI tests on different smart high side switches, where the interference signal was thereby coupled into their battery- or output pins. As an example of the variety of investigated switches, the results of a representative DUT are presented here. The Generic IC EMC Test Specification [7] requires high side switches to be tested in ON, OFF and PWM operation. These operation modes are later called nominal and are the three modes that are normally tested during a DPI characterization. We however, investigated the immunity behavior of the ICs also in additional operating conditions, but only the results in nominal and overtemperature conditions are discussed in the following chapter.

For our investigations, the DUT was configured with external components as proposed in its application note or data sheet and placed on a DPI test board, that was designed according to the guidelines specified in the IEC 62132 standard [6].

4.1 DPI test in nominal condition

Figure 5 shows the DPI test result of the DUT performed in one of its nominal conditions (i.e. ON mode). The blue line indicates the maximum forward power of the interfering signal at which the IC gets influenced and does not function as expected anymore. The two smaller diagrams represent the monitored signals during the DPI test at different frequency and power combinations. In this case two different signals were monitored; the output voltage (V_out) and the voltage at the sense pin (V_Sense). In nominal conditions the voltage at the sense pin represents the load current and in fault mode this pin is used to indicate a failure. The green areas in the diagrams show the tolerance ranges for the monitoring criteria. If a monitored signal leaves the green area, the behaviour of the IC is considered interfered by DPI.

The monitoring criteria for this test is defined by the undisturbed values of the monitoring signals and $\pm$ 10 % as allowed tolerances.

The overall minimum is located at 10 MHz at a power level of 24 dBm. A second local minimum is visible in the frequency range of 250 MHz at 29 dBm. For both discussed points, the voltage at the sense pin differed more than 10 % of the reference signal, which was a violation of the monitoring criterion.

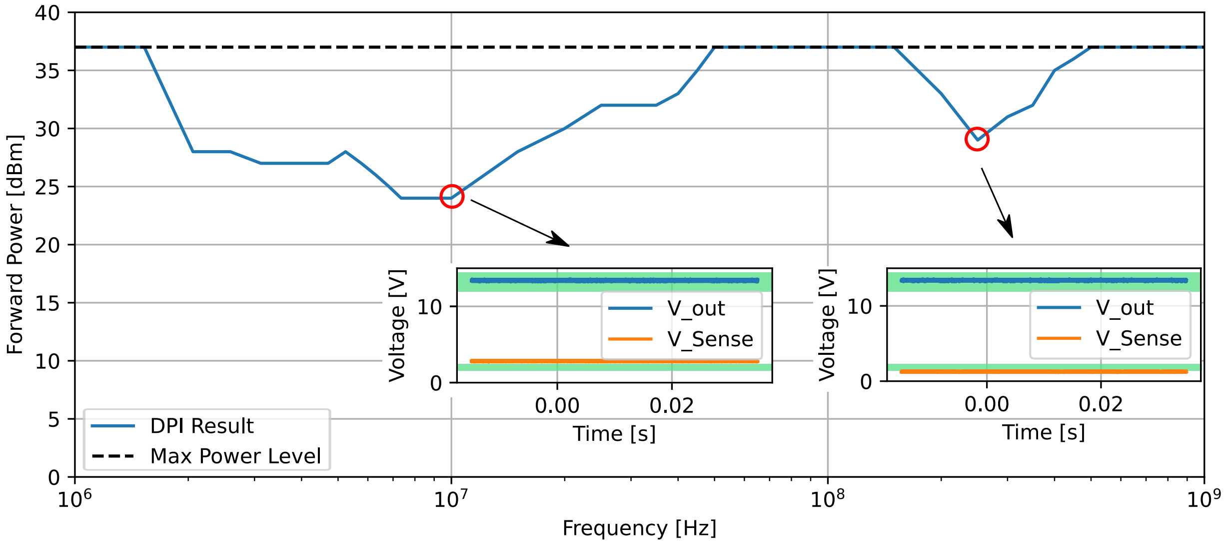


Figure 5: DPI result of the DUT operated in nominal condition (ON mode)

4.2 DPI test in overtemperature condition

This measurement was used to check whether the internal overtemperature detection, that should turn off the DUT in the event of an overtemperature, still works reliably when disturbances are present. For this purpose, the DUT was heated to a temperature at which it was in an overtemperature state and this temperature was maintained during the entire DPI measurement.

Figure 6 shows the corresponding DPI test result. The data sheet of the DUT specifies a minimum voltage level of 5 V the sense pin for the device detecting overtemperature. So, we used this parameter as a monitoring criterion for the following investigation. In addition to this, we also monitored the output signal. Since the switch is operated in overtemperature, its internal protection feature turns the switch off and the output voltage should remain at 0 V. As the data sheet does not give any information about the maximum output voltage in off-state, we considered it as a failure, if the output voltage is exceeding 2 V.

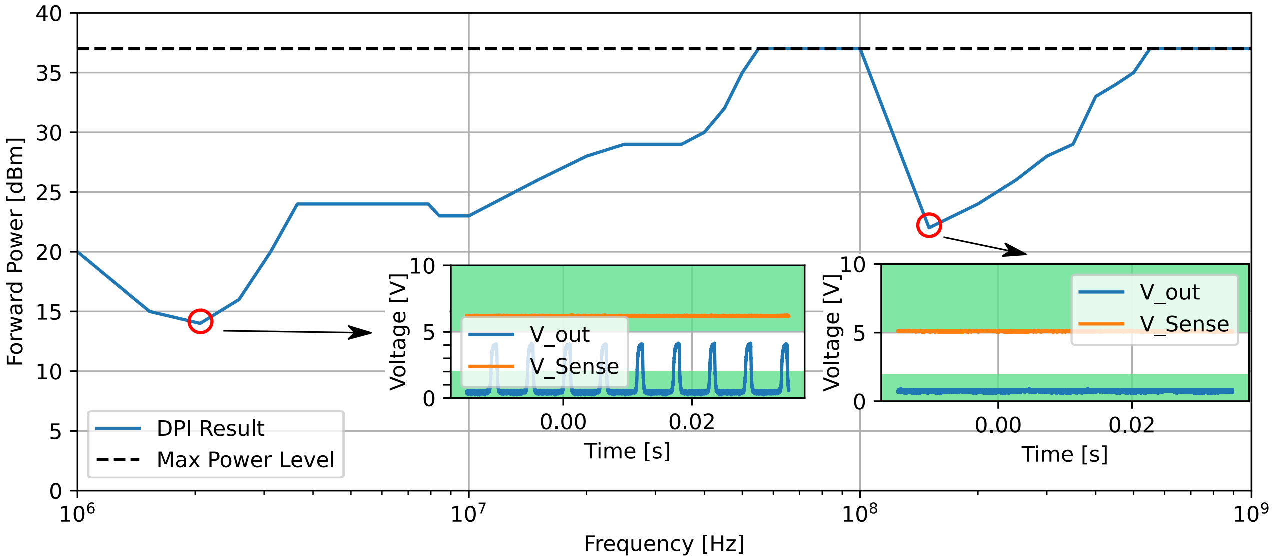


Figure 6: DPI result of the DUT operated in overtemperature condition

The DPI result shows that the overtemperature protection no longer works reliably in some frequency ranges even below a power level of 15 dBm. Especially, at the frequency level of 2 MHz only a forward power of 14 dBm is needed to disturb the overtemperature protection function. The voltage at the sense pin still indicates an overtemperature correctly, but at the output we measured a pulsed voltage with voltage peaks up to 4 V (output turns on). In the frequency range of 150 MHz we got another local minimum at 22 dBm in the DPI characteristic. At this measurement point the sense voltage is below 5 V which means that the overtemperature was no longer indicated correctly. With higher interference amplitudes, the behaviour becomes significantly worse, as the voltage at the sense pin falls far below 5 V.

Comparing the DPI tests in nominal and overtemperature condition, quite different results are obtained. To disturb the nominal operation of the IC, a forward power of 24 dBm was required in the most sensitive case. However, to deactivate the overtemperature protection, a forward power of 14 dBm was sufficient. The obtained test results are strongly dependent on the operating conditions. According to the Generic IC EMC Test Specification[7], the same device is even classified differently. I.e. if the test is performed in nominal conditions, the DUT would be a class 2 device, since the device withstands a minimum forward power of 24 dBm over the entire frequency range. However, if the overtemperature protection function is also tested, the device would not even be classified as class 1 (>18 dBm).

5 Outlook

Protection against overtemperature is a very important feature of automotive smart power devices. But, this is only one of many. Therefore, further studies on smart power devices to investigate their functional safety behavior under the influence of EMI are planned. For this purpose, the DPI test setup is to be further developed accordingly in order to also test the electromagnetic immunity of further built-in diagnostic functions (such as short-circuit detection, loss of GND, loss of load,...). Since DPI tests under "non-nominal" conditions are not yet specified in the Generic IC EMC Test Specification [7], it would be desirable if immunity tests under these conditions for ICs that are including functional safety features were also included here in future.

6 Conclusion

In this article, the investigation results of smart power high side switches regarding the immunity of their integrated functional safety features against EMI are shown. Since all functionalities of the switch that can be affected by the interference signal must also be tested during an immunity characterization at the IC level, a comprehensive test of the DUT was performed. For this purpose, one representative switch was tested according to IEC 62132-4 (DPI method) in different operation modes; nominal modes that are commonly used in standard DPI tests, and additionally fault modes to verify that important functional safety features are still working properly during the test. The performed DPI investigations have shown that an important built-in functional safety feature (overtemperature detection and protection) does not work satisfactorily in presence of an interference signal.

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