RFIP method: towards a better characterization of integrated circuits immunity

A.Ayed[1], T.Dubois[1], J-L.Levant[2], G.Duchamp[1]
[1] Laboratoire IMS, Université Bordeaux 1, 351 cours de la Libération – 33400 Talence, France
ala.ayed@ims-bordeaux.fr , tristan.dubois@ims-bordeaux.fr, genevieve.duchamp@ims-bordeaux.fr
[2] ATMEL Nantes SA, route de Gachet - 44306 Nantes, France – jean-luc.levant@atmel.com

***Abstract*— This paper presents an evolution of a conducted immunity measurement technique for integrated circuits: the Resistive RF Injection Probe (RFIP) test method. This method complements the Direct Power Injection (DPI) method by giving different immunity parameters (voltage, current, impedance, power). After a brief description of the method, immunity parameters computation is detailed and both RFIP probe and test bench are characterized. Immunity parameters calculation model is then verified by implementing a virtual test bench using simulation. Finally, RFIP immunity measurements on a microcontroller's embedded analog to digital converter (ADC) are carried out and compared to DPI and Vector Network Analyzer (VNA) results.**

***Index Terms*— integrated circuits, immunity measurement RFIP, DPI**

I. INTRODUCTION

Electronic components qualification goes through estimation of their electromagnetic compatibility in their functional environments before manufacturing and marketing processes. Due to continuous technological advances of integrated circuits, those have become more and more miniaturized and complex especially by mixing digital and analog functions inside the same chip which makes electromagnetic interference more likely able to spread and cause disturbances. This leads designers to seek for adequate measurement techniques allowing for emission and susceptibility limits quantification.

A set of immunity measurement techniques was proposed within the international electrotechnical commission project “IEC 62132” [1]. More specifically, IEC 62132-4 describes the Direct Power Injection (DPI) method [2] which is largely used as an integrated circuits conducted immunity measurement technique. This method consists in injecting a conducted radio frequency (RF) disturbance to one or several pins of an integrated circuit and allows determining the power above which the device under test (DUT) is considered to be disturbed according to a predefined susceptibility criterion.

Knowing the disturbance power is actually desired but does not suffice for ICs designers who wish to have further information on disturbance parameters such as voltage and current in order to harden their designs against harsh electromagnetic interference. In this context, some methods have been proposed as an alternative to the DPI method. High Frequency conducted Power injection (HFPI) [3] consists in injecting the disturbing RF signal using a special probe. This probe contains an RF voltmeter and an RF current-meter permitting voltage and current measurement after the application of a frequency-dependent correction procedure. The main drawback of this method is the fact it is proprietary which makes it less employed. Another method was also proposed: the Resistive RF Injection Probe (RFIP) method [4]. RFIP test bench is very similar to the DPI one and requires the use of a simpler probe compared to the HFPI to ensure the determination of different immunity parameters when the fault occurs, namely power, impedance, voltage and current.

In this paper, an evolution of the RFIP method is presented. The immunity parameters computation principle is explained as well as the different steps of the probe and test bench characterization. Measurement results of an analog to digital converter immunity will then be presented and compared to the DPI and VNA measurement results.

II. PRESENTATION OF THE METHOD

A. RFIP measurement principle

The principle of the RFIP measurement is comparable to the DPI in terms of the required test equipment. However, instead of injecting the Continuous Wave (CW) disturbing signal through a capacitor, it is rather injected through a known impedance value, Z_p. A differential voltage measurement across Z_p allows the determination of the different immunity parameters. In [4], two RF differential probes are connected to the scope in order to estimate the voltage drop V_p across Z_p. The proposed enhancement of the measurement test bench consists in recovering both voltages using two identical RF amplifier blocks, which lifts off the need to employ expensive differential probes. Thus, both RF amplifiers and Z_p constitute the RFIP probe used in this immunity measurement technique. “Fig.1” shows a picture of the RFIP probe.

In the next sections, the immunity parameters computation is showed along with the RFIP probe and test bench characterization.

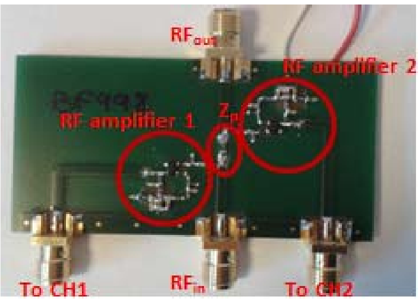

Figure 1. RFIP probe

B. *Immunity parameters calculation*

RFIP method consists in retrieving different immunity parameters of a device under test when the failure occurs by knowing both V_{ch1} and V_{ch2} voltages measured by a Digital Storage Oscilloscope (DSO). The computation of the voltage (V_{DUT}), current (I_{DUT}), and consequently impedance (Z_{DUT}) and power (P_{DUT}) relies on the network-parameter equations of the different test bench elements intervening during the measurement. Consequently, each component of the measurement set-up has to be characterized separately using vector network analyzer measurements in order to get its Scattering parameters (S parameters). Those are then converted to Z parameters using S- to- Z-parameter conversion formulas [6].

Given the voltage and the current at the input of each block (considered as a quadrupole), output voltage and current can be deduced using its Z parameters.

This computation is to be repeated as many times as we pass through a measurement set-up block starting from the DSO to the DUT pin to be tested as seen on “Fig.2”.

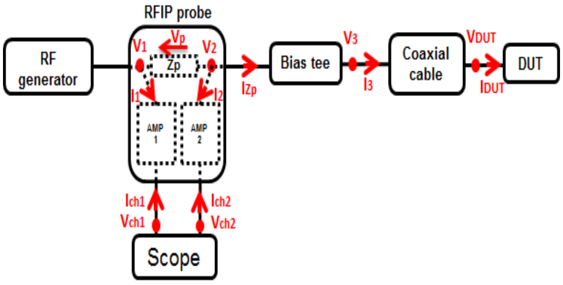

Figure 2. RFIP test bench block diagram

The RFIP probe and the DSO allow the estimation of V_{ch1} and V_{ch2} which form the elementary data-points of the immunity parameters calculation model. The bias tee plays the role of the DPI injection capacitor and is used to ensure decoupling between the bias DC voltage and the RF signal. The latter reaches the DUT up to the IC’s tested pin through a coaxial cable.

Having measured V_{ch1} and V_{ch2}, I_{ch1} and I_{ch2} can be deduced:

$$I_{ch1} = -V_{ch1} / Z0_1 \quad (1)$$

$$I_{ch2} = -V_{ch2} / Z0_2 \quad (2)$$

$Z0_1$ and $Z0_2$ are input impedances of channels 1 and 2, respectively. They are extracted from the reflection coefficient measurement of the scope’s channels.

Once amplifiers Z parameters are known, voltages V_1 and V_2 across Z_p are derived as follows:

$$V_1 = I_1 * Z_{11a} + I_{ch1} * Z_{12a} \quad (3)$$

$$V_2 = I_2 * Z_{11b} + I_{ch2} * Z_{12b} \quad (4)$$

Where:

$$I_1 = (V_{ch1} - Z_{22a} * I_{ch1}) / Z_{21a} \quad (5)$$

$$I_2 = (V_{ch2} - Z_{22b} * I_{ch2}) / Z_{21b} \quad (6)$$

$[Z_a]$ and $[Z_b]$ are Z parameters of amplifiers 1 and 2, respectively. The same principle is then followed to compute V_3 and I_3 at the bias tee output. Finally, V_{DUT} and I_{DUT} values are given by:

$$I_{DUT} = -(V_3 - Z_{22c} * I_3) / Z_{21c} \quad (7)$$

$$V_{DUT} = I_{DUT} * Z_{11c} + I_3 * Z_{12c} \quad (8)$$

$[Z_c]$ are Z parameters of the coaxial cable.

Impedance and power can also be deduced as follows:

$$Z_{DUT} = V_{DUT} / I_{DUT} \quad (9)$$

$$P_{DUT} = \mathrm{Re}\,\{(V_{DUT} \times \mathrm{conj}\,(V_{DUT}))/Z_{DUT}\} \quad (10)$$

III. RFIP PROBE AND MEASUREMENT SET-UP CHARACTERIZATION

Once the RFIP measurement principle and the immunity parameters calculation model presented, this section will be dedicated to the characterization of the probe and the measurement bench. The importance of taking into account each element with the maximum possible accuracy arises from the nature of immunity parameters computation procedure, which requires that each calculation step delivers accurate data to the next one in order to achieve proper parameters estimation at DUT level. “Fig.3” shows a picture of the measurement set-up.

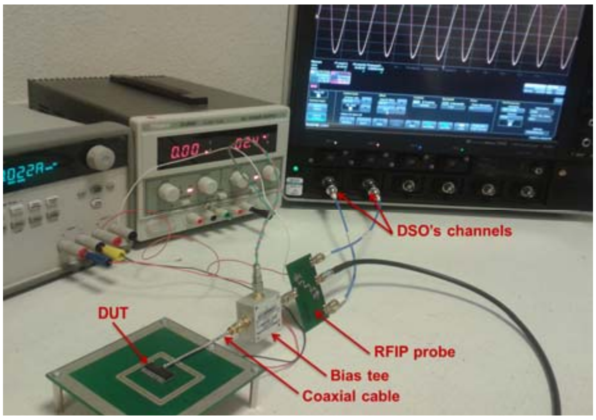

Figure 3. RFIP measurement set-up

A. *RFIP probe characterization*

1) *Amplifiers de-embedding*

The design of the RF amplifier block is structured around a dual-gate MOSFET transistor, which ensures high impedance at the amplifier's input, thus a small amount of current loss for DUT's perturbation. Therefore, the amplifiers act together as a differential RF measurement probe fixed across Z_p impedance.

Both measured signals at the scope (V_{ch1} and V_{ch2}) enable the estimation of voltages across Z_p according to the aforementioned equations. In order to be rigorous, these voltages have to be computed at the immediate vicinity of Z_p (namely V_1 on "Fig.4") Since amplifiers S-parameter measurements are carried out between both input and output SMA connectors (at V_{ch1} and V_1' level), which represent VNA's plane reference, a de-embedding of the connector and the input transmission line has to be fulfilled to obtain V_1 and V_2 for both amplifiers 1 and 2, respectively. A de-embedding kit has been used to get the S parameters of the portion to be removed from the overall S parameters of the amplifiers ("Fig.8"). Agilent's ADS simulation tool allows the application of a static de-embedding approach using predefined models [7].

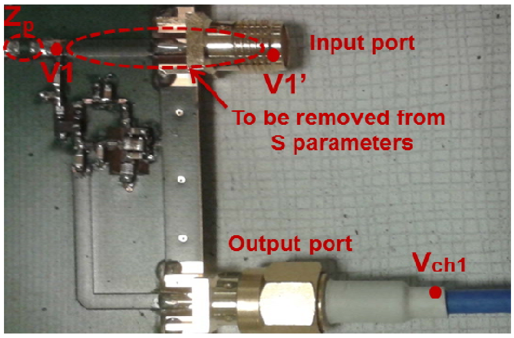

Figure 4. Amplifier block de-embedding

"Fig.5" shows a comparison between reflection and transmission coefficients before and after de-embedding. It can be noticed that the reflection quality of the amplifier has been improved, which corresponds to a measurement near the amplifier's high impedance MOSFET.

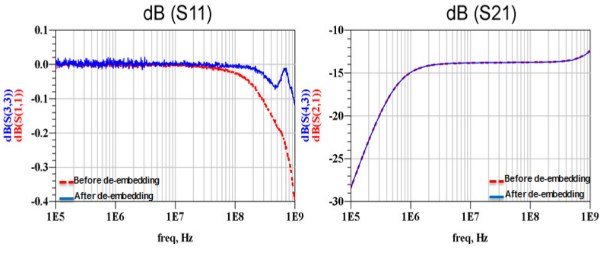

Figure 5. S parameters of the amplifier before and after de-embedding

The main advantage of amplifiers de-embedding is enhancing the accuracy of S-parameter coefficients' phase. This can be observed in "Fig.6". For instance, reflection coefficient's phase has been compensated especially for frequencies above 100 MHz, a frequency beyond which parameters uncertainties considerably influence measurement results.

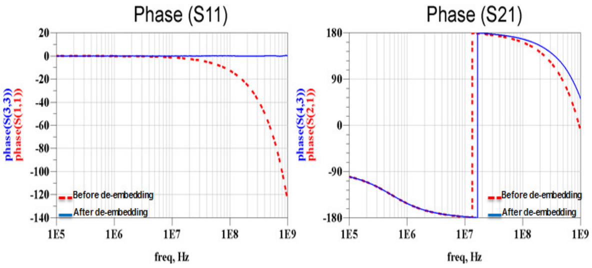

Figure 6. S parameters phase correction

2) *Z_p de-embedding*

A commercial 10 Ω resistor is used in the RFIP probe as the known Z_p impedance across which differential measurement is carried out. It is obvious that the resistor's value is not kept constant over frequency as passive lumped components have often parasitic elements that appear with the frequency rise. That's why an accurate characterization of Z_p impedance variation with frequency is a key factor for obtaining precise measurement results. Hence, an S-parameter measurement of Z_p has been performed. However, measured S parameters include, similarly to amplifiers, SMA connectors and transmission lines contributions whose effect need to be removed. The de-embedding kit is again employed to make three different measurements:

- A load measurement to get entire S parameters.
- An open measurement, which allows negating the effect of parallel parasitic elements.
- A thru measurement, to eliminate series parasitic impedances.

Following an open-thru de-embedding technique, de-embedded Z_p S parameters can be obtained. As the impedance is directly given by the B parameter of an ABCD-matrix in the case of a series impedance measurement [8], de-embedded S-parameter matrix is converted to an ABCD one. From "Fig.7", we can notice the importance of de-embedding especially for frequencies higher than 100 MHz where parasitic elements effect is significant. It is also obvious that A, D and C parameters are closer to theoretical values (respectively 1, 1 and 0) after de-embedding which proves that the extracted impedance value is reliable and accurate.

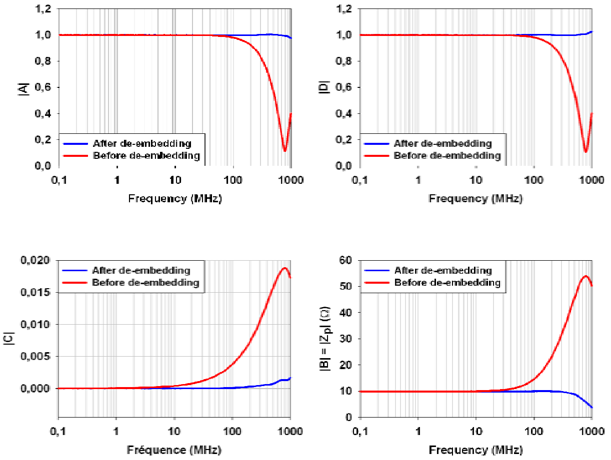

Figure 7. ABCD parameters of Z_p with and without de-embedding

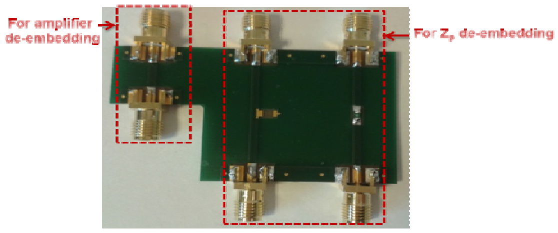

Figure 8. De-embedding kit

B. *Measurement set-up characterization*

1) *DSO's channels input impedances:*

The output signals of the RF amplifiers are driven to the scope's 50-ohm coupled channels in order to measure V_{ch1} and V_{ch2}, which represent the data-points of the immunity parameters computation model. As channels input impedance change with the frequency, it is important to take the impedance value drift with the frequency into account. "Fig.9" depicts the input impedances of both measurement channels.

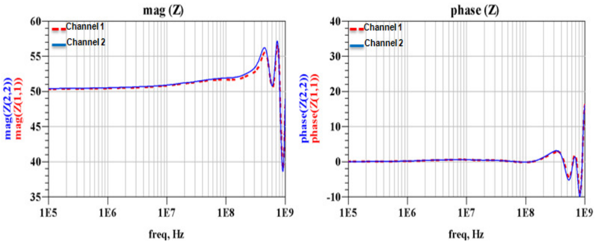

Figure 9. Magnitude and phase of the scope's input impedance

2) *Bias tee and coaxial cable characterization:*

The bias tee and the coaxial cable are the last elements of the measurement set-up before the DUT. Both have been characterized using measured S parameters. "Fig.10" illustrates both reflection and transmission coefficients of the bias tee. We can note that the transmission is quite stable over the measurement frequency band with only 0.4 dB maximum loss of disturbance power.

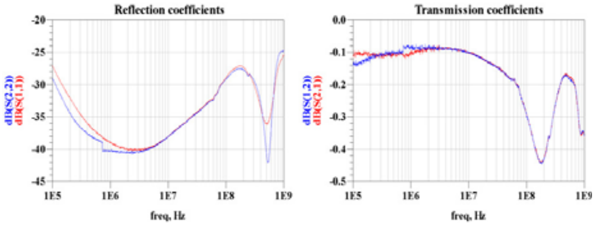

Figure 10. S parameters of the bias tee

As for the coaxial cable, only one-port measurement can be performed. Two-port S parameters have been deduced by simulation after having fitted one-port measurement results with a well-configured coaxial cable ADS model. Reflection and transmission coefficients of the coaxial cable are shown in "Fig.11".

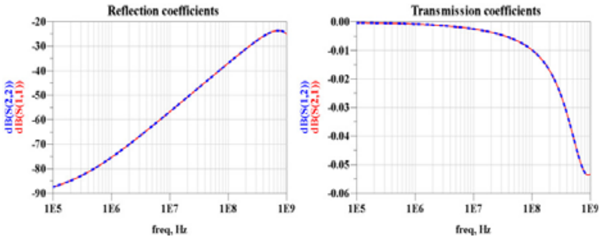

Figure 11. S parameters of the coaxial cable

IV. VALIDATION OF THE METHOD USING SIMULATION

A virtual measurement set-up has been reproduced in simulation using several measured S-parameter files of the characterized elements ("Fig.12"). The aim is to validate the immunity parameters computation model described in section "II.B" by comparing ADS simulation results with those of a Matlab script.

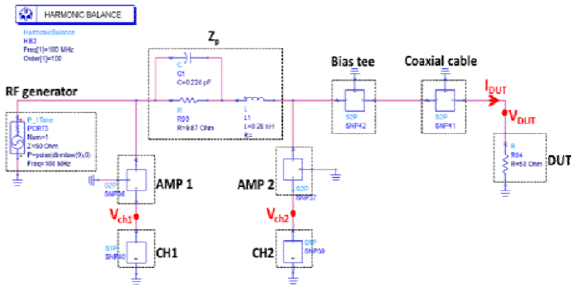

Figure 12. Virtual measurement test-bench in simulation

Simulation results show that all the immunity parameters have been correctly estimated for a 50-ohm load case. Results are depicted in "Fig.13". The method is then used for immunity parameters determination in real cases.

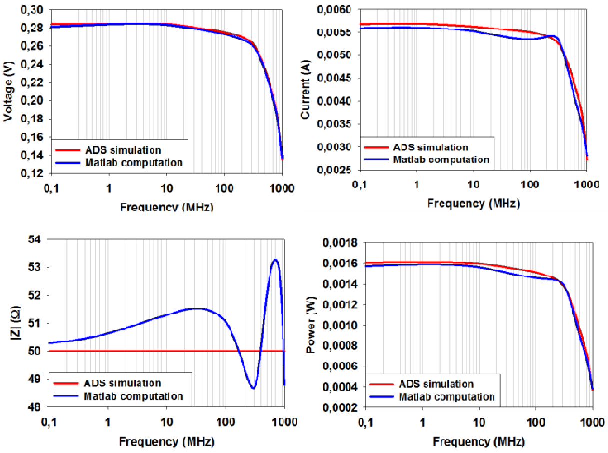

Figure 13. Immunity parameters estimation

V. RESULTS AND DISCUSSION

A. DUT presentation

An RFIP immunity measurement test was conducted on a microcontroller's 10-bit analog-to-digital converter. The disturbance gets through the component by the A_{REF} pin which represents the DC voltage reference for the converter. A thorough study of the disturbance coupling paths inside the ADC shows the possible followed tracks [9]. "Fig.14" illustrates the ADC's block diagram as well as the coupling paths.

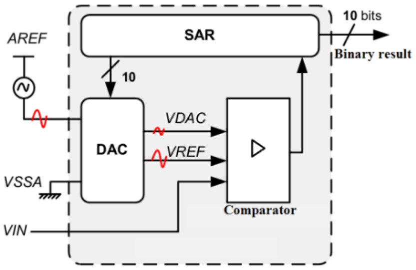

Figure 14. Block diagram of the ADC

Since the ADC's output is a binary result, it would be suitable to choose the number of lost LSBs (*Least Significant Bits*) as the immunity criterion for the measurements. An LSB corresponds to the smallest variation in voltage that results in a change in the decimal conversion result.

B. Measurement results

ADC's immunity curves for different parameters have been extracted for both 16 and 32 LSBs criteria between 1 MHz and 900 MHz. These criteria are chosen because they correspond to specific steps of the 10-bit conversion result [9]. As the RFIP method is proclaimed to complement DPI, a comparison between both methods estimated disturbance power for 16 LSBs criterion is shown in "Fig.15".

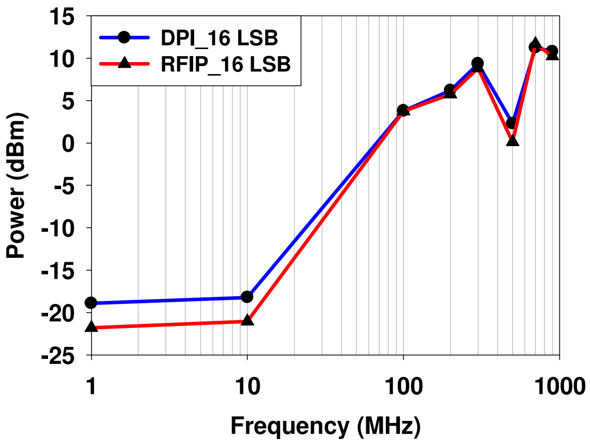

Figure 15. Comparison between RFIP and DPI power

It is obvious that both curves fit satisfactorily for frequencies above 30 MHz which shows that the RFIP method is able to describe similar immunity behaviour as the DPI. Nevertheless, the correlation between power immunity curves is not very good for lower frequencies. In fact, this behavior is totally independent from the frequency; it depends on the nature of the measured impedance. More precisely, the ADC's input impedance is quite high in this frequency band. High impedance DUTs represent a certain difficulty for the RFIP method. Actually, whenever the DUT's impedance is high, V_1 and V_2 voltages become sensitively close to each other so that V_p tends to zero which makes it difficult to be determined. The first reason is purely experimental. The measured V_{ch1} and V_{ch2} voltages are nearly equal and the scope's precision can influence the quality of the overall measurement results.

Another reason is the VNA's accuracy for the measured S parameters used in the immunity parameters computation. Studies show that reflection coefficients accuracy declines with weak and high measured impedances [10]. This is the case for amplifiers reflection coefficients where the input impedance is considerably high. On the other hand, estimated RFIP impedance seems to be invariant for different immunity criteria ("Fig.16").

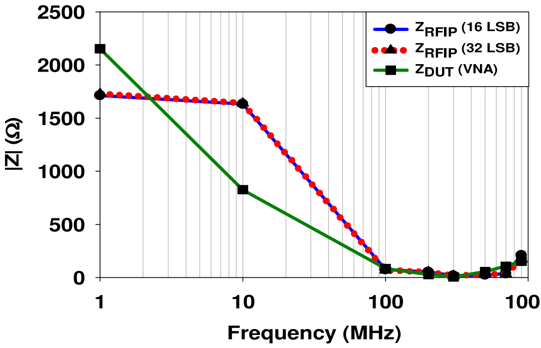

Figure 16. Comparison between RFIP and VNA impedance

We can deduce that the DUT's impedance when the fault occurs is not influenced by the magnitude of the disturbance for these immunity criteria. This means that the coupling paths of the electromagnetic interference are kept the same for the ADC and does not differ according to the disturbance strength, which is in accordance with the realized studies on the coupling paths inside the same ADC [9]. Actually, such a result is important since we can rely on the determination of a unique PDN (*Passive Distribution Network*) for the DUT's immunity modeling, using the ICIM-CI model for instance [11]. Concerning the differences between RFIP and VNA impedances in the low frequency region, the same reasons as for the power case can be evoked to explain the origin of these differences. The VNA accuracy itself can result in several hundred ohms uncertainty when measuring high impedances.

The main advantage of the RFIP method remains the knowledge of the disturbing current and voltage. "Fig.17" represents the immunity curves related to these parameters.

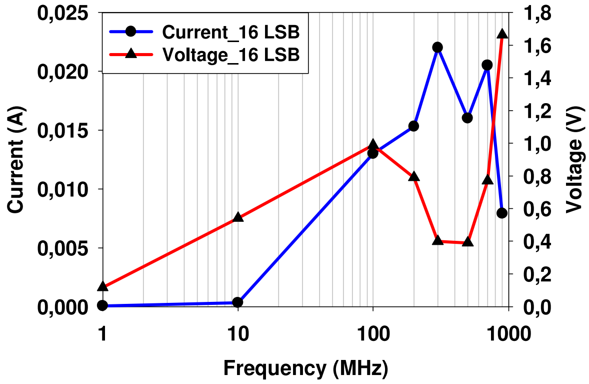

Figure 17. RFIP voltage and current immunity curves

The information given by the current behaviour can be used to determine the nature of the impedance when the fault happens even if it is not separately computed. For instance, we can deduce that the impedance of the DUT is high in the low frequency region since the current level is weak. In addition, beyond 100 MHz, RFIP voltage and current don't follow the same variation but the impedance is approximately constant.

VI. CONCLUSIONS AND PROSPECT

The RFIP measurement method represents an enhancement for a better characterization of integrated circuits immunity. Although a limitation in the characterization of high impedance DUTs, this method can restore different immunity parameters with an acceptable accuracy. With a good knowledge of the chip design, voltage and current immunity curves can give us further information about the parameter which is most responsible for generating the DUT's fault.

This work can be extended to the extraction of integrated circuits immunity models using RFIP advantages. Given the amount of data related to different immunity parameters, the models that would be constructed may become more reliable for an early estimation of IC's immunity during design phase.

ACKNOWLEDGEMENT

This work falls within the SEISME project [5] which is interested, among other, in developing measurement and modeling techniques for emission and immunity characterization at IC level.

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