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Thermal-electromagnetic susceptibility behaviors of PWM patterns used in control electronic circuit

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***Abstract*—With constraints for high-level integration of electronics, new EMC behaviors have to be considered to prevent real electromagnetic compliance. Especially, in embedded and on-board device's context, environmental temperature has an influence on the circuit behavior and EMC figures. This paper deals with susceptibility studies combined with temperature effects on electronic devices used to control power and transmissions. Specific dual thermal-electromagnetic test set-up developed for this are presented. Main results of an experimental campaign on digital PCB dedicated for generation of Pulse Width Modulation (PWM) patterns are presented. Temperature dependant susceptibility and sensitivity of the PWM parameters are compared and analyzed.**

Keywords—susceptibility; electromagnetic couplings; PCB; Immunity defaults; thermal impacts; PWM; near-field; aggression; TEM;

I. INTRODUCTION

The impacts of real physical environment, as temperature, humidity or reliability for conventional Electromagnetic Compatibility (EMC) behavior of hybrid electronic modules are non negligible. Based on both experimental and simulation works, we try to estimate the realistic impact of external temperature on emissions and susceptibility cases of electronic devices[1][2][3]. An aggressive, external, quasi-static temperature, with high values as 150°-200°C, can be inherently generated inside and around an electronic device, either by motion thermal systems, or by high-power chip's consumption and radiators associated. We actually investigate these effects mainly for one of the most thermal sensitive chips used in power electronic modules, including driver technology [4][5]. Actual state-of-the art of radiated EMC characterizations, both emission and immunity, can be performed over Printed Circuit Board(PCB) and Integrated Circuits(IC) with Near-Field probe's sets guided by a motorized scan table and/or Transverse Electro-Magnetic(TEM) cells[6][7][8]. In these two cases, often dedicated PCB's are especially designed, inherently for TEM cell, to comply with Standardized Cell Aperture (10cm*10cm), and also to separate inside/outer electromagnetic sources and victims [9]. To accede to parametric thermal characterization, we propose modifications of these radiated test set-ups, with a combination of warming plate solution, up to 250°C, inserted in the Near-Field or TEM solutions, and spatial on-board temperature measurements. Localized near-fields and TEM mode aggression cases are described, and specific test PCBs, including the devices and both electromagnetic and temperature sensors, are carefully designed for this. To perform the dual thermal-immunity test, we start on reference immunity behavior of gate devices and integrated circuits, with failure's criteria's that are representative of the component functionality. Pulse Width Modulation (PWM) pattern characteristics in both time-domain and frequency domain are representative of these immunity compliance cases, with potential effects on motion control. As PWM is used to drive and control DC and AC currents in converters, transformers and motors, a slight shift in nominal duty cycle rate (α) for example, less than 1%, can induce a severe fail in the command tasks and current injection. In this work, we present susceptibility responses of PWM circuits to both harmonic and temperature aggressions, and try to identify the impacts on main characteristics and parameters of the PWM signal.

With this first experimental approach, impacts of temperature on the coupling's mechanisms over the PCB's wires and inside the devices can be identified and analyzed to improve immunity solutions.

II. DUAL THERMAL-IMMUNITY EXPERIMENTAL METHOD

A. Near-Field aggression test bench

Separate E-Field and H-field measurements or injection, considered as a near-field approach, can be realized over different areas of the PCB with dedicated probe's set like H-spires and E-dipoles associated to a motorized table system. Electromagnetic probes have been fabricated with high-frequency semi-rigid coaxial cable that can inject RF power from MHz until 3GHz. Characterization resolutions are driven by a 0.3mm diameter for H-spire, 1cm length for E-probe. A warming plate, using inductive heating, can generate temperature until 300-350°C over a fixed glass area. It is placed just under the PCB, with a specific conductive test support. For dealing with both thermal measurements, we use a thermal contact probe, with a touch end of 0.1mm diameter, and a thin body support of 8cm long. It has been coupled on the same scan table moving fixture, with a slightly different Z-axis reference. When moving and positioning the measurement point, thermal probe stays in with the body of the electric element, as near-field probes are just over, as visible in Fig. 1.

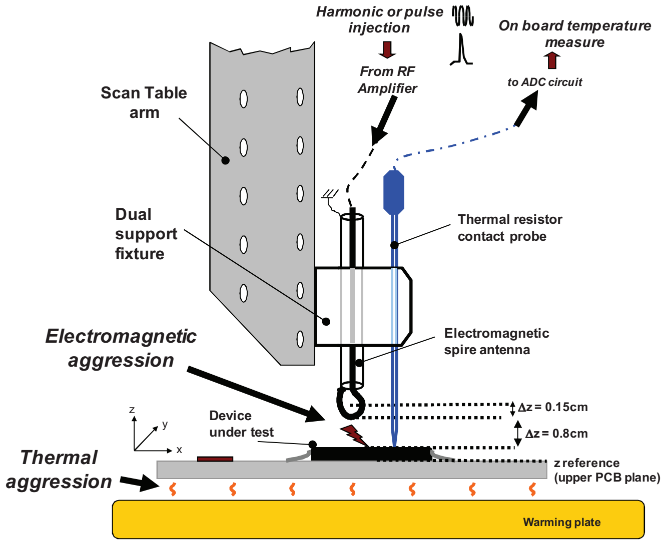

Fig. 1. 2D view of the experimental dual thermal-near field set-up configuration for immunity testing on conventional PCB.

With this configuration, we can inject localized RF waveforms at specific or sensitive area and wires of a PCB test, and rely it with the local real temperature of the injection zone. Some rigorous calibrations procedures have to be completed before, because of the mutual influence of the EM probe and Thermal Probe. The warming plate can also modify the real level of injection of the probe. During the development of this set-up, we use a Microstrip receptor as a reference calibration. We observe that the shift in RF level injected can be about a maximum of 1.2 to 1.5 dB at high temperature. These discrepancies, between level injected from the generator and the victim, is used as a correction factor for a good validity of the experiment. But actual works are concerned and still in progress on this set-up to refine the precision and the reproducibility of the dual EM-Thermal probe characterization.

B. TEM Cell aggression test bench

A complementary immunity experiment is performed with Transverse Electrical-Magnetic mode cell (Crawford TEM cell) configurations, including the thermal experiment solutions. TEM cell is commonly used for EMC characterization, from 1MHz up to 3GHz, at PCB and Integrated Circuits levels[8][9]. As a well-suited alternative to large size experimental equipment for conventional radiated far field characterization, it allows very pertinent solutions for selective electromagnetic characterization of single electronic devices enclosed in the shielded cell environment. For this, specific Printed Circuit Boards have to be designed for TEM cell solution, with the dimension of the aperture cell, the completion of shielding quality of the system with a one-face metallic plane, and the choice of inside components to be coupled with TEM Cell Septum in TEM modes. Starting from this configuration, the PCB test fixed with the TEM cell fixture is placed over the heat zones of the warming plate. Electromagnetic waves are injected on one port of the cell with a RF generator, the other port is loaded by a 50 Ohms HF impedance by the way of RF Powermeter that measure the level of injected Power. The wideband generator is associated with 40 dB gain amplifier system to drive aggression both in frequency and amplitudes levels for device immunity characterization. To complete this configuration, the TEM cell with its test PCB has to be maintained over a maximum of 4cm of the warming plate, so to keep efficient heating action. It's realized by a special fixture arm, the constraint is to report electrical and thermal connections very close to the PCB, and to go at the control-measurement system with a 90° angle so as to not touch the hot warming plate (Fig. 2).

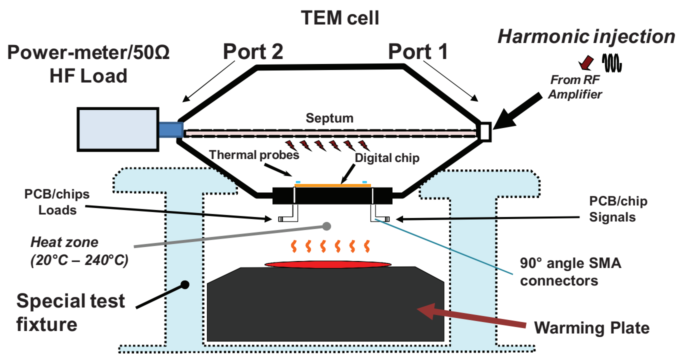

Fig. 2. 2D schematic of Heated TEM-Cell configuration for immunity testing on 10cmx10cm PCB.

The second important development is the acquisition of real external temperature value, close on board and chips. The TEM cell configuration doesn't agree with an external contact thermal probe solution, as used for the surface near-field configuration described previously. To overtaking this, we develop PCB prototypes with the integration of thin thermal probes using thermal resistor principles, as Resistor Thermometric Device (RTD), and realized in Surface Mounted Device (SMD) technology, or Thin Film technology. The choice of RTD material was oriented to Platinum resistor, for good compromises with physical and electrical performances for our applications. Another critical technical constraint is to place SMD thermal resistors either on conductive or dielectric parts on PCB. Dielectric zones are typically the Plastic package of integrated circuit, or Epoxy material of PCB. Conductive parts are typically copper tracks and planes, or circuit package pins. A use of thermal management adhesive is necessary to both set the thermal SMD device and to ensure a maximum heat transfer, but a specific routing, so to connect electrically the probes to its Kelvin–wires, has to be designed.

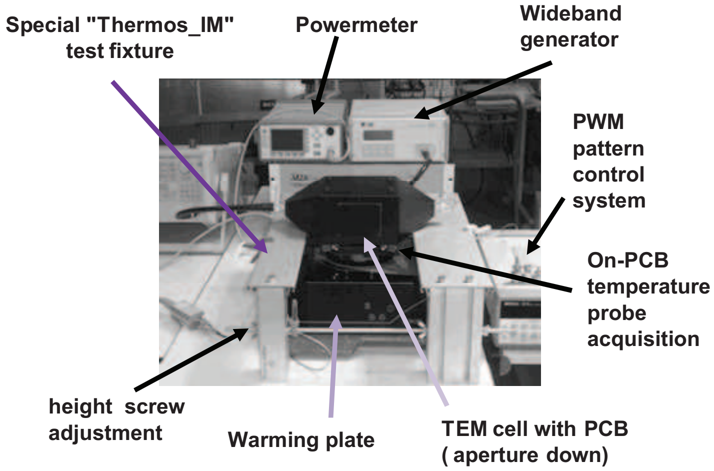

Fig. 3. Global view of the heated TEM-Cell configuration for immunity testing.

A special attention has been made, for pertinent immunity measurements, with the thermal routing network. The four wires connection for each SMD probe must be electrically length optimized to avoid more unwanted radiated noise or parasitic couplings, even if the measure of thermal signal is DC excited, and even if resistance variation have a very low time constant response compared to electromagnetic signal. For TEM Cell configuration, inside-cell probes are connected on the outer with through via-hole techniques, as the others necessary connections ensuring the device functional operation [10], as visible in Fig. 4. With some finite number of temperature points dependant of the study zone considered, and on the different layers, up and down, of the test PCB, we can link and rely it to electromagnetic procedures characterization, and especially for immunity behavior as the topic of this paper.

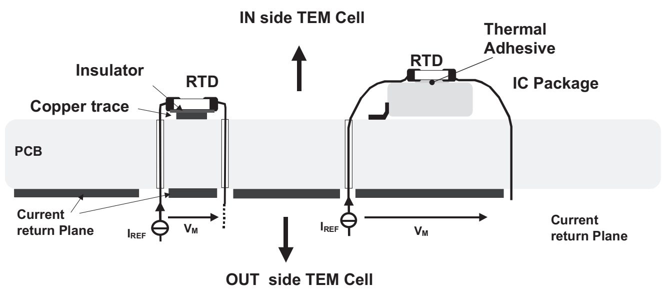

Fig. 4. Transverse view of dedicated PCB specifications with on-board thermal probes.

The global electrical conditions of the circuits tested are for operating in the 0-5V range for V_{DD}, 1kHz-5MZ clock for the frequency range. Electromagnetic disturbances issued from these boards are observed or attended in the range of 1MHz-1GHz for frequency spectrum repartition. Immunity cases can occur with a minus of 10dBm of aggression levels (harmonic case, low-voltage circuits). A specific roadmap procedure has been established, for sweeping all complex cases during the characterization. A computational algorithm, for driving, storage and post-processing characterization data has been realized with Computer Aided Tools for these objectives, and complete all the technical characterization set-up's developed.

III. Application on PWM circuit boards

As control circuit boards are used to drive power converter designed for well-suited motion or energy supply function [4], we want mainly to focus on their real EMC behavior with non-ambient temperature environment. PCB prototypes have been designed for these studies, using either SMD chips reported on PCB, either programmable integrated circuits type with Pulse Width Modulation program inside. Both of these two PWM generators are controlled by cyclic rate input command.

A. First demonstrator: Integrated PWM Circuit

The first study concerns a PCB with a PWM integrated circuit and electrical network up on one layer, which has been placed on dual thermal–EM near-field bench. A schematic view of this configuration is represented in figure 5. The general level of supply is V_{DD}=5V, provided by a high-speed current switching voltage source, in respect with internal IC consumption time rate. Programmable circuit operates in synchronous mode, with a clock reference of 5MHz. Two inputs are used to modulate the output square signal, with an absolute cyclic rate from 5% to 46% (Input 2) and inversion mode (Input 3). Signal output is delivered on internal capacitance load (500fF) in parallel to external capacitance load(1pf).

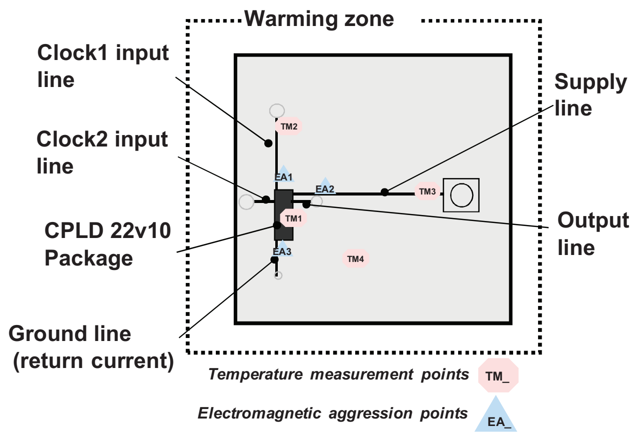

Fig. 5. Upper view of the layer of the first PCB configuration

Main phenomena observed for susceptibility aspects are generally, for digital mode device, the modifications of thresholds levels and switching times. This is due to the couplings of external parasitic signals on supply and I/O ports. The main significant effect is related to the potential shift of average signal during a PWM sequence, normally designed by the cyclic rate, so to drive current injection in power switches. So, for our main immunity criteria, we choose to observe discrepancies, in the frequency domain, of spectrum waveform of the output switching current for example. The results presented in figure 6 have been realized in harmonic mode, using an Amplifier-RF source system. Power injection is realized from 1MHz to 1GHZ, with a maximum level of 40dBm. Immunity control of the device can be determined by the two variations of the output signal: cyclic rate characteristics (time-domain, digital oscilloscope) and switching current frequency characteristics (frequency domain, spectrum analyzer). For our study, coupling the wave aggression impact with temperature, we look especially on the shift in frequency and amplitude of main peak of the current consumption spectrum.

Results are reported in figure 6: relative amplitude of waveform of current switching device, I_{VDD}, is reported with significant harmonic frequency impact couplings, at ambient temperature, in the 100 MHz-800MHz zone. This variation is enforced when increasing, step by step, the external temperature and so the device package measured temperature. This indicates and confirms the modifications of switching current performances, and more significantly, a non negligible impact of high external temperature on electrical behavior of the programmable chip under electromagnetic pressure.

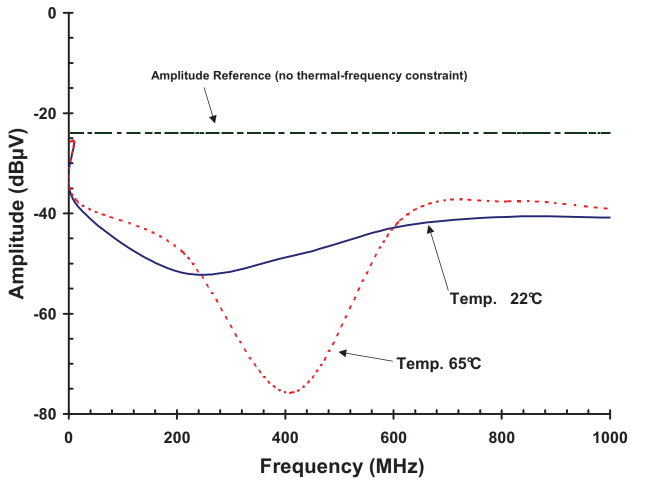

Fig. 6. Relative variation of switching current amplitude of Integrated PWM circuit with dual thermal-harmonic wave aggressions

B. Second demonstrator: Two Discrete PWM circuits

The second study concerns a dual PWM generator, dedicated for driving independently two DC brushless motors. The two signals are realized with discrete SMD digital devices. The PCB is compliant with TEM Cell aperture (10cm*10cm) but the area of the overall circuit is about 3cm*3cm. The level of supply is V_{DD}=5V. The nominal frequency of the two PWM is f_0=10kHz. Four main default criteria's are defined for these test: the shift on duty cycle rate α, on frequency f_0, on switching margins VDD-GND, and on the mean value VMEAN. This board has been tested with the TEM cell/thermal configuration (Fig.2). The two output signals, PWM00 and PWM01, have nominal characteristics at 20°: f_0=10kHz, Vpp= 5V, α1= 70%, α2= 30% . A digital wide-band/high sampling rate oscilloscope realizes the acquisition and the control of these parameters. Each default criteria is tested independently, each à 1% of its nominal value. Examples of EM couplings and effects on these characteristics of the PWM waveforms in time domain are shown in Fig. 7. Then, EM aggression is realized, by sweeping the frequency between 1MHz and 1GHz, and the levels of RF power from -40dBm to 40dBm. The fig. 8 shows the results of susceptibility responses for the four criterias at ambiant temperature. A main common sensitive zone is depicted in the rage of 300MHz-500MHz. This first test,realized at ambiant temperature(20-22°C), is the reference susceptibility test. Then, tests are repeated with steps of temperature of 20°. At About 90°, the shifts of PWM characteristics over 1% are continuously due to this temperature, because of the high impact of temperature on semi-conductor on the board. Among a wide number of parametric results, depending both of frequency, injection levels, temperature steps, and the kind of defaults, we present synthetisis of the main pertinent results in fig. 9 and fig. 10. As the apparition of a default on the duty cycle with a maximum shift of 1% is critical for our applications, the figure 9 is dedicated to this parameter. Compared to the reference measure at 20°C, it's significant that the levels of EM agression for the “cyclic rate criteria” are lower of about 10 to 20 dB, in some narrow range of frequency, as 200 MHz, 700 MHz, and a minimum for all the temperature at 900MHz (GSM Band!)

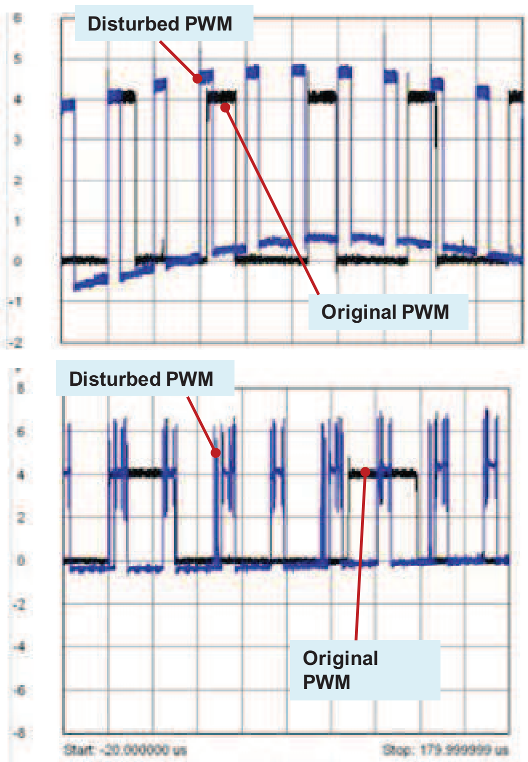

Fig. 7. Two views of signal shifts on nominal PWM waveforms during harmonic aggression.

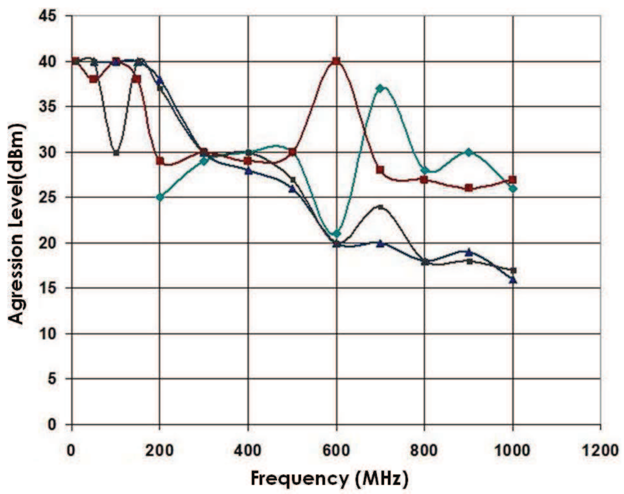

Fig. 8. Immunity table reference(20°C) for the four criterias:
◊ duty cycle α ☐ frequency jitter Δ Switching margins VMEAN

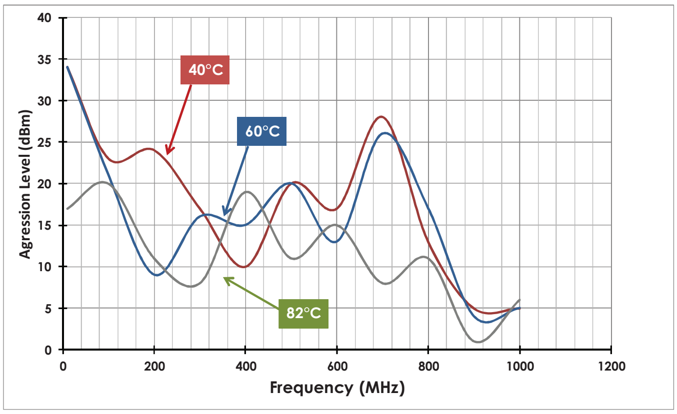

Fig. 9. Immunity table at temperature steps of 20°C for criteria "1%" on duty cycle α

In Fig. 10, the defaults for both five criteria's of PWM susceptibility have been represented, in 3D-view, so to be compared. The table I resumes the criteria's considered and the range of the nominal values controlled during dual electromagnetic-thermal aggressions.

Table 1: PWM criteria's values.

PWM parameter	Nominal Value	Range
Duty Cycle α min	27.42 %	24.67 % / 30.16 (10%) 27.14%/27.69%(1%)
Duty Cycle α max	71,3 %	64.17 % / 78.43 (10%) 70.58%/72.01%(1%)
V_{TOP}	4.65 V	4.6V/4.69V
V_{BASE}	0.01 V	-0.05V/+0.05V
V_{MEAN} (α min)	1,265V	1.25V/1.277V
V_{MEAN} (α max)	3.348V	3.31/3.38
Frequency	9.67 kHz	9.57kHz / 9.76kHz

This figure shows a real global shift of the sensitivity of the PCB and the PWM signals, at the maximum allowed temperature of test (85-90°) of the experiment. The previous sensitive zones(fig. 8) are enforced (280 MHz / 500 MHz/ 720 MHz/850Mhz), for all the criteria's. Also the most sensitive signal parameter at this temperature is the Mean Value (Vmean) of the PWM, which is unfortunately the worst case of integrity or robustness of the nominal specification of the PWM pattern for driving.

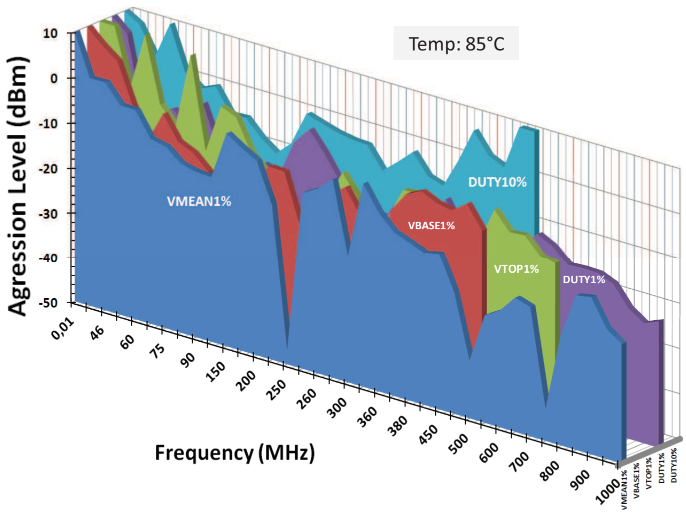

Fig. 10. 3D table representation of worst-case's immunity with PCB temperature of 85°C, for 5 criterias of the PWM: Duty10%, Duty1%, Vtop1%, Vbase1%, Vmean1%

IV. Conclusions

With these works, new modified EMC characterization approach is in progress, for real-case EMC investigations. Specific test benches have been developed based on conventional Near-Field and TEM cell immunity test setups. External aggression of light range of temperature (20°-100°) has been correctly added, so to combine both EM-Thermal effects on susceptibility of electronic chips on PCB. The first test bench (Near-Field) is dedicated to conventional PCB, with the need of localized EM injection and temperature measurements, often on the component face of the PCB. The second one, using a TEM cell, is dedicated for demonstrator PCB, where specific design and routing of chips and thermal sensors must be initially performed for the test. A focus has been made on immunity cases on PWM signals, which need to be well driven for main applications. After a measurement campaign that has produced a wide range of different susceptibility responses of the demonstrators, main significant results are synthesized in this work. These thermal immunity cases results for PCB boards confirm a main influence of temperature on susceptibility levels of programmable or discrete chips: some critical defaults, as the shift of more than 1% of the duty cycle rate or Mean value VMEAN, are very sensitive with a non-ambient temperature, and critical for immunity of these applications.

With this first review of thermal-immunity experimental study on PCB, some refinements and calibration progress of the two set-ups have to be completed: the mutual influence on measurements and aggression of both TEM Cell, Near-Field probes and Thermal probes have to be considered. In parallel, modeling investigations are also actually performed to try to understand and reproduce these effects of external temperature on EMC characteristics (emission, susceptibility) on electronic PCB [3]. With this modeling completion study, a first complete review of new EMC behavior cases dealing with new embedded and hybrid technology constraints will be validated, so to promote the merging of new concerns of EMC approach on electrical transport and embedded applications[11]

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