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Case Study of a Radiated Susceptibility Problem Leading to a TVS Diode Thermal Runaway

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Abstract

During the radiated susceptibility test of an equipment, the thermal runaway of a circuit element (TVS diode) is observed. In this work, the case is systematically investigated to understand how this physical hazard has occurred. By modeling and simulation, the parametric analysis of the induced voltage on the TVS diode has been carried out. Possible solutions are proposed and analyzed. The capacitive filtering solution proves itself both in terms of performance and application easiness point of view.

1 Introduction

During the application of a radiated susceptibility test of an equipment under test (EUT), it was experienced the thermal runaway of a circuit element inside EUT. The circuit element was a transient voltage suppression (TVS) diode which was placed on the power supply lines just after the connector interface. The aim of this work is first to investigate and understand how this physical hazard has occurred and secondly to devise possible solutions to alleviate the problem.

In order for the military equipment to be guaranteed to operate under high-intensity RF fields, the radiated susceptibility tests are applied to the equipment under laboratory conditions. One such test, MIL-STD-461G RS103 requires the application of electromagnetic fields as high as 200 V/m in a very large frequency range (2 MHz – 18 GHz) [1]. These fields are coupled to the equipment under test through its cables and the apertures present on the equipment. The coupling may become maximum at the resonance frequencies of the equipment. Body resonances especially are the critical frequencies at which the energy can be transferred to the structure very efficiently. A spectacular example of such a resonance effect can be found in [2]. In the present case, it is also suspected that the effect is related to the body resonance since the electrical length of the equipment under test nearly equals the half wavelength at the application frequency at which the thermal runaway of the circuit element is experienced.

In order to systematically analyze the problem, the prediction is verified with the simulation of the problem under the same conditions. It is expected that the simulation will show us the strength of the effect on the circuit element and help to understand the events leading to the thermal runaway. Then, the case is simulated for three different geometric configurations of outer cable routing. This stage will allow us to determine the effect of outer cable routing on the coupling results. Finally, two possible solutions are devised to solve the problem; capacitor filtering and ferrite bead filtering. These solutions are investigated and compared.

2 Problem

The EUT is a stand-alone battery-operated military device. It has a simple, all metallic, solid long cylindrical body having a radius of 8 cm and 1.63 m in length. On the EUT body, there is a connector located at approximately 1/3rd length of the body from the forward end. This is the only connection to the outside world through which it is connected to the battery via a 38 cm long cable. The cable is unshielded and consists of two straight wires. EUT is powered by a 28 VDC battery. Apart from this electrical interface, the long cylindrical body of the EUT is mechanically in contact with a plastic housing that supports the battery and the control electronics.

During the radiated susceptibility test, the equipment under test is placed inside a semi-anechoic chamber at a height of 1.65 m from the ground. The long cylindrical body is held in a horizontal position parallel to the ground plane. The equipment under test is illuminated with the test antennas placed 1 meter away as shown in Figure 1.

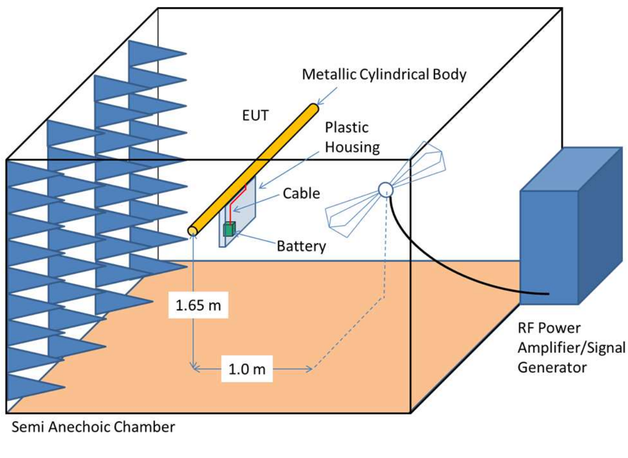

Figure 1. EUT and RS103 Test Setup

The applied field is 200 V/m and it is pulse-modulated at 1 kHz PRF with a 50% duty cycle. The problem occurs at around 90 MHz while applying the electric field in the horizontal polarization, and the EUT shuts down. Since it couldn't be operated again, it undergoes an inspection and it is observed that the transient suppressor TVS diode placed at the input of the power supply is thermally destructed. Other than the TVS failure, the melting of the plastic connector at the battery side is also observed.

The thermal runaway of a TVS diode shows that the current passing through the diode exceeds a limiting value which is a parameter of the diode power handling capability. A typical TVS diode (a bidirectional one) has I/V characteristics like the one shown in Figure 2. Once its terminal exceeds the breakdown voltage, the diode begins to conduct. When the voltage on the diode reaches the maximum clamping voltage $V_{CL,max}$, the diode current reaches $I_{pp,max}$. The product of these two parameters gives the power handling capability of the TVS diode. Since the TVS diode is essentially used to suppress the transients, the manufacturers usually specify these parameters under a specific transient effect pulse type. In our case, the clamping voltage and the peak current of the TVS diode under 10/1000 us transient pulse are given as 53.3 V and 7.5 A which results in a power handling capability of 400 W.

In our case, the applied field is of continuous nature so any terminal voltage exceeding 53 V also is expected to exceed the power handling capability of the diode. The test result implies that the terminal voltage on the TVS diode should be larger than 53 V.

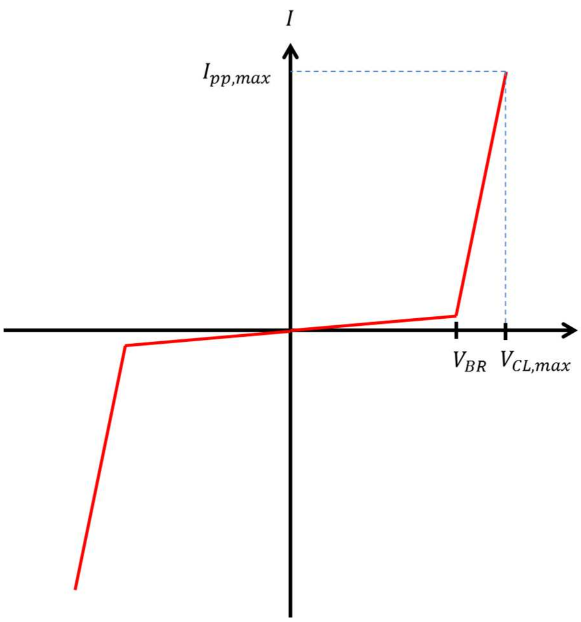

Figure 2. Typical I/V Characteristics of a TVS Diode

3 Modelling and Simulation

To simulate the problem and to find the terminal voltage on the TVS diode, the problem is modelled using a computational electromagnetic tool (FEKO). The EUT is modeled as a metallic cylindrical body. On the cylindrical body, the connector input is modeled as a circular aperture with a diameter of 10 mm at 1.03 m from the rear end. Since there are compartments inside the real EUT, it is decided to simulate the major division between the rear and the forward sections and therefore, a metallic wall is placed behind the connector input at 1.02 m from the rear end. The battery is modeled as a small metallic rectangular box. The cable is modeled as two parallel wires with a 5 mm spacing between them. The routing of the cable is made in accordance with the test setup. The cable first protrudes from the cylindrical body by 0.5 cm at 1.03 m from the rear end and then makes a 90-degree turn and routes along the cylindrical body towards the forward end by 20 cm, then again makes a 90-degree turn towards the bottom and goes 17.5 cm until it reaches the battery. The wires simulating the cable are terminated with common mode and differential mode impedances at the battery end. At the EUT end, one wire is directly connected to the cylindrical body representing 28 VDC return side, and the other wire representing the 28 VDC positive side is terminated with an impedance whose initial value is chosen as 10 kohm. It is difficult to estimate the load impedance behavior in a wide frequency band due to the complexity of the input circuitry about which we have no information. The common-mode terminal impedances at the battery side are chosen as 1 Mohm while the battery side differential mode impedance is chosen as 0.1 ohm. The resulting simulation model is shown in Figure 3.

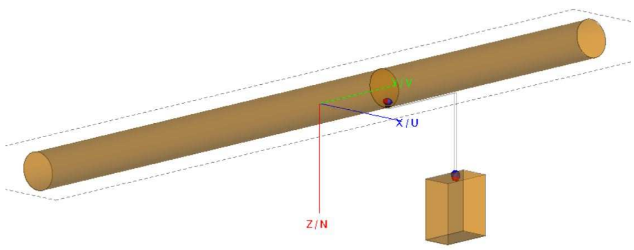

Figure 3. The Simulation Model.

The simulation is carried out between 10 MHz and 1 GHz. The excitation is chosen as a horizontal plane wave with a strength of 200 V/m. Since the TVS diode is placed at the input side of the EUT, the terminal voltage on the load impedance at the EUT side is sought as the result of the simulation. The result of the simulation is given in Figure 4. The load side induced voltage has a peak value of 405 V at 120 MHz. There is also a secondary peak around 300 MHz with a voltage level of 100 V. Clearly, these levels are enough to lead a TVS diode to work outside its power handling limits.

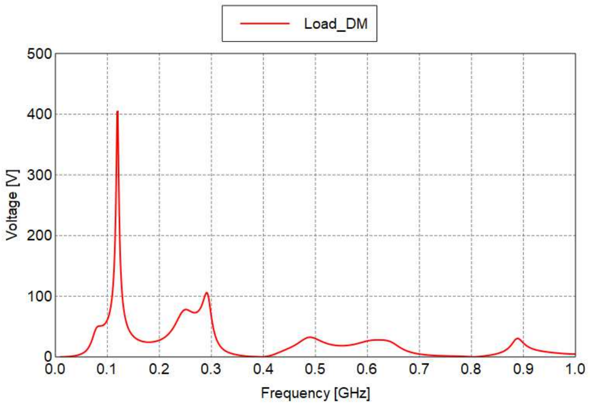

Figure 4. Terminal Voltage on Load Impedance at EUT Side

Since melting is experienced at the terminals of the battery, it may be interesting to look at the current passing through the battery terminals. The current through the battery differential mode impedance is given in Figure 5. As seen at 120 MHz, 1.06 A RF current is passing through the battery terminals. This result explains the melting phenomena.

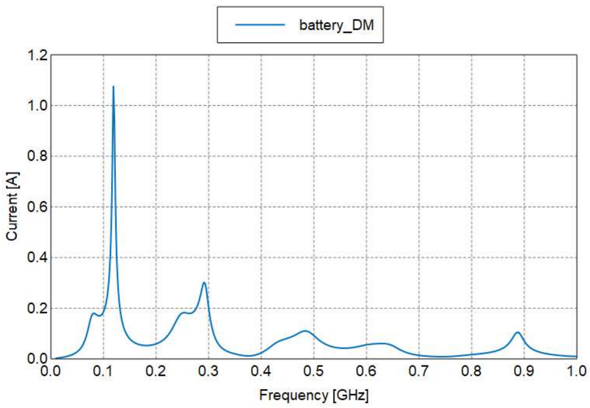

Figure 5. Current Through the Battery Differential Mode Impedance

The current distribution on the EUT and its associated cables and battery is given in Figure 6. Currents exceeding 1 A level are present on the wires between EUT and its battery at 120 MHz.

The simulation results clearly show us that the thermal runaway of the TVS diode is a consequence of a resonance condition. However, there is a discrepancy between the resonance frequency obtained in the simulation (120 MHz) and the one obtained in the test (around 90 MHz). This may largely be due to the wire routing and the wire length. The other unknown parameter is the load impedance value. To see its effect on the induced levels, a parametric study has been carried out. For different load impedance cases, the simulation is repeated.

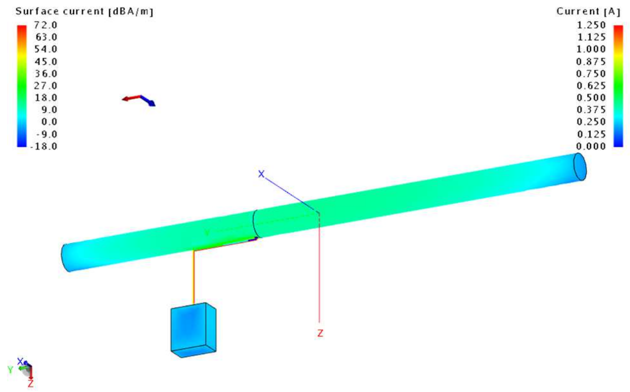

Figure 6. Current Distribution on the EUT and its Cables and Battery

The simulation results for the parametric study are given in Figure 7. The changing trend can be seen as the load impedance varies from 100 kohm to 100 ohm. The upper curves show the induced voltage levels and the lower curves show the induced current levels. As can be noted, the resonance frequencies do not change, but the efficiency of the resonances differs. As the impedance goes higher the induced voltage at the resonance frequencies goes larger whereas as the load impedance gets smaller, the induced voltages decrease. The reverse relationship is valid for terminal current levels. The interpretation of these results requires further study including complex loads. On the other hand, whatever the load impedance is, there are large currents on the wires and high voltages at the terminals. The melting of the battery terminals shows this clearly. At this point, it is time to focus on the remedy of the problem.

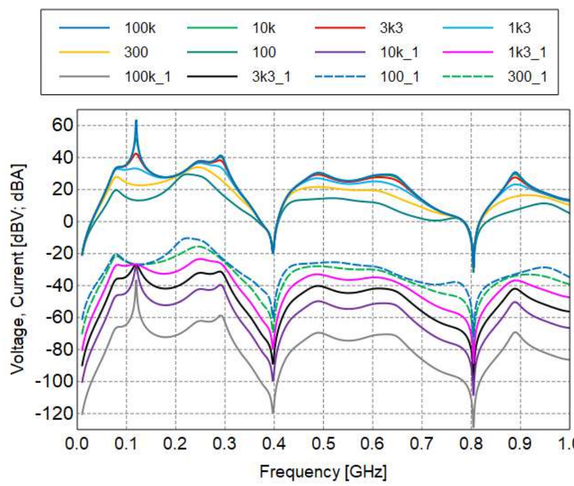

Figure 7. Effect of Load İmpedance on Induced Voltage Levels and Currents

4 Proposed Solutions

To reduce the terminal voltages, filtering is the only way since shielding the cable is not an applicable solution from the application point of view. Two types of filtering can be candidates for the solution. One uses the parallel capacitor as the filtering component while the other uses the series ferrite bead component. A parallel connected 1 nF capacitor is chosen for the capacitive filtering option. For the ferrite bead filtering, the wires are loaded with RLC circuits at the entrance of the EUT. The parameters of the ferrite bead are chosen as R= 120 ohm, L= 600 nH and C= 0.3 pF to represent a practical ferrite bead. Both wires are loaded with individual ferrite beads. The obtained results are compared with 10 kohm load impedance case.

From the results (see Figure 8), the capacitive filtering offers at least 60 dB suppression at the resonance frequency reducing the voltage under 400 mV level. On the other hand, ferrite bead offers no attenuation, and in fact, the same response with the reference case is obtained. It is seen that capacitive filtering is the best solution in terms of both the suppression performance and the easiness of the application (placing an SMD capacitor parallel to the TVS diode on the PCB board). The ferrite bead performance is largely based on the terminal impedance levels and for higher impedances, its performance is drastically reduced.

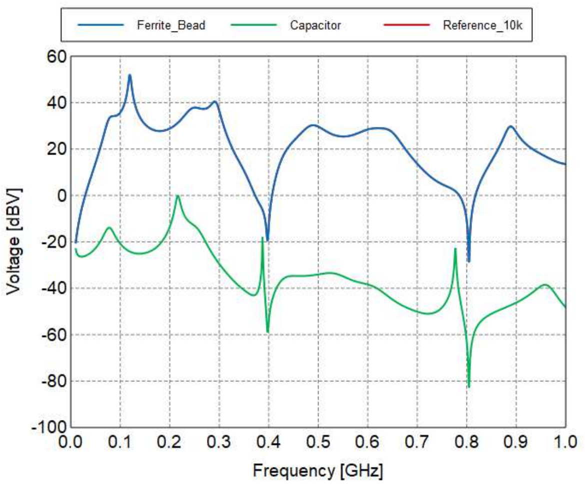

Figure 8. Effect of Capacitive Filtering and Ferrite Bead on Induced Voltage Levels

Although it is found that the capacitive filtering is suitable for the load side, it is imperative to investigate what is going on at the battery side since there are also problems at the battery side such as melting of the plastic connector. When we apply the capacitive filtering at the load side, the battery differential mode induced current also decreases more than 50 dB at the resonance frequency as can be seen from Figure 9. Although there are peaks 388 MHz and 777 MHz, these peaks are at least 10 dB lower than the reference case.

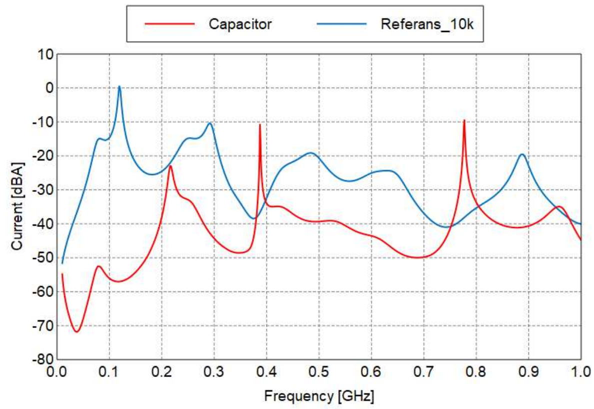

Figure 9. Effect of Capacitive Filtering on Induced Current Levels

5 Conclusion

A practical problem experienced in a real case is investigated. Although first-order engineering solutions are practically useful for solving the problem, in this work it is preferred to examine the case systematically to verify the engineering predictions. It is verified that the predictions are correct. The capacitive filtering solution proves itself by showing a substantial amount of attenuation. However, there are still some intricacies related to terminal impedances. Understanding the high-frequency impedance behavior of various types of active circuits will be beneficial to obtain realistic simulation results.

7 References

1. MIL-STD-461G, “Requirements For The Control Of Electromagnetic Interference Characteristics Of Subsystems And Equipment”, US Dep. of Defense, 2015.

2. F. Üstüner, "Practical papers, articles and application notes: Interaction of an AM broadcast transmitter with a large crane posing health hazards: A real-world event analysis," in IEEE Electromagnetic Compatibility Magazine, vol. 1, no. 2, pp. 41-49, Second Quarter 2012, DOI: 10.1109/MEMC.2012.6244973.