Quasi-static analysis of susceptibility of the spacecraft power bus bar to the effects of electrostatic discharge

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Abstract. We performed a quasi-static analysis of susceptibility of the spacecraft power bus bar to the effects of electrostatic discharge (ESD). For the analysis, we used a schematic diagram of a power bus bar model with branch conductors. The schematic diagram consists of series-connected transmission lines, which represent the cross-sections of each power bus bar element. An ESD pulse with a current shape of fourth severity level was accepted as an excitation. The work shows the voltage waveforms at the beginning and end of the power bus bar when ESD impacts the branch conductors. We localized the maximum amplitude of the voltage in the bus section under ESD exposure. It revealed that when ESD affects the shielding tape covering the negative branch, there is a maximum attenuation (13.5 times) at the positive branch and a minimum attenuation (1.6 times) at the negative branch.

1. Introduction

Currently, space exploration is rapidly developing, which toughens the existing requirements and imposes the new ones to a modern spacecraft. The increase of the interference immunity and reliability of the spacecraft being built will increase their active life. When ensuring the noise immunity and reliability of radio-electronic devices that are part of the spacecraft, it is necessary to take into account all possible signals and influences that arise during operation. Statistics show that the most common cause of spacecraft failures is electrostatic discharge (ESD) [1]. ESD is the most dangerous and destructive type of electromagnetic impact that can damage the radio-electronic equipment of a spacecraft. ESD also affects the performance of various radio-electronic facilities, including the ground-based. For example, the analysis of ESD impact on a personal computer has been performed using simulation. The results of the analysis showed that the most dangerous place of ESD exposure on the PC is the ventilation holes, the impact on which leads to an increase in the electric field strength inside the case to 11 V/m. Moreover, if the integrity of the case is violated, the electric field strength reaches 70 V/m. In [2] the authors have compared the results of simulation with experimental data, which are related to the influence of ESD on the metal cover of the radio-electronic device. The results showed that constructive protection methods are extremely important. It is necessary to strive for the continuity of electromagnetic shielding in the case of electrical circuits, and the ventilation openings should be covered with a metal mesh with small holes, up to 1 mm in diameter. In [3], the temporal characteristics of the interruption of the clock signal of a Pierce crystal oscillator are investigated when it is exposed to ESD. The first experiments in mathematical modeling of the ESD effect on the spacecraft power supply circuits (solar battery, onboard cable network, energy-converting component) have shown unexpected results [4]. On the one hand, real samples demonstrated in-flight operation
without failures and degradation. On the other hand, the simulation revealed the current and voltage amplitudes across the elements in the power circuits significantly exceeding the permissible limits that ensure their normal operation. The power bus bar is one of the important components of the onboard cable network, on which the existence of the spacecraft depends since the power bus bar is not backed up but electrically connects the vital power supply systems of the spacecraft. Thus, ESD susceptibility testing is an important requirement when testing a power bus.

The purpose of the work is to simulate the susceptibility of the model of the power bus bar to ESD impact.

2. Power bus bar design

We designed and built a power bus bar with an interference protection filter (Figure 1). It consists of base 1, branch conductors 2, at the end of which there are connectors 3, and an interference protection filter 4, to which branch conductors 5 come from the base of the power bus bar. The interference protection filter has its branch conductors 6, at the ends of which there are connectors 7 used for connecting the power bus bar to the spacecraft load. The base 1 and branch conductors 2 have a cross-sectional area of each pole of 50 mm² assuming a maximum current of 200 A.

3. Power bus bar model

We created geometric models of cross-sections for the base (Figure 2a, 2b) and branch conductors (Figure 2, d–f) of the elements and the device of the power bus bar. The geometric models contain conductors for forward 1 and return 2 currents, which are made in the form of metal plates and insulators: EP-730 varnish (\(\varepsilon_r=4\)) 3; polyamide film with a one-sided sticky layer (\(\varepsilon_r=2.3\)) 4 and fiber-glass plastic (\(\varepsilon_r=4.3\)) 5. There is a sealant 7 at the junction of the power bus bar with branch conductors (Figure 2b). The outside of the power bus bar is covered with a tape which consists of aramid filaments wrapped in a silver-plated copper wire to protect it from ESD 6. Each branch conductor is made of 10 BS 35-1298 wires (5 for forward and 5 for return currents) (Figure 2c). Near the power bus bar, the cross-section is a set of BS 35-1298 wires located one above the other (Figure 2c, 2d) at a distance between centers of \(w_2=k_1=4\) mm. A branch conductor (Figure 2d) is required to connect the power bus bar to the interference protection filter. All wires are covered with a shielding tape. To reduce the inductance \(L\) and increase the capacitance \(C\), wires of different polarity

![Figure 1. Power bus bar prototype.](image-url)
are placed close to each other. In this case, the positive and negative terminals are located in the vertical plane (positive from above) (Figure 2c, 2d).

The above mentioned cross-sections (Figure 2) were used to develop the schematic diagram of a power bus bar (Figure 3). The branched sections (Trl13 and Trl17) have a length $l=30$ mm with a cross-section from Figure 2(c), and the sections (Trl14 and Trl16) have a length $l=215$ mm (Figure 2a). The section between the power bus bar and the interference protection filter (Trl15) has a length $l=10$ mm (Figure 2b). The branch conductors (Trl18 and Trl19) have a length $l=80$ mm (Figure 2d), and at the junction with the interference protection filter (Trl20 and Trl21) it is $l=20$ mm. At the beginning and the end of the central conductor, there are taps which connect the power bus bar to the devices that are part of the spacecraft. In this case, the cross-section $«+/-»$ of the tap contains 10 BS 35-1298 wires (Trl9-Trl12) 350 mm long (Figure 2f). Near the connector, the wires branch out and have a separate cross-section for each pole, 5 wires each (Trl1-Trl6) and 100 mm long (Figure 2e). Cross-sectional changes in the connectors are not taken into account as they have a short length of 25 mm.

![Figure 2. Cross-sections of power bus bar elements.](image)
4. Simulation results

To assess the results of ESD impact on the power bus bar, the signal waveforms were simulated at the near and far ends of the branch conductors. Resistances $R_1$–$R_{16}$=50 Ohm of a standard measuring path were connected to the beginning and end of each conductor. In the simulation, the height of the power bus bar above the infinite ground plane was $h=0.1$ m.

The simulation of ESD impact on the shielding tape was performed for two cases. In the first case, it was made in the place where the positive branch covers the power bus bar. For this, a current generator $I_1$ was connected to the resistance $R_2$, simulating the impact of ESD. In the second case, the impact of ESD on the shielding tape was carried out in the place where the negative branch covers the power bus bar. For this, a current generator $I_2$ was connected to the resistance $R_4$, simulating the impact of ESD. As an excitation we accepted an ESD pulse with a current waveform of the fourth severity level ($\tau_1=1.1$ ns, $\tau_2=2$ ns, $\tau_3=12$ ns, $\tau_4=37$ ns, $I_1=30$ A, $I_2=16$ A, $n=1.8$) according to IEC 61000-4-2 [5].

For the first case, the voltage waveforms at the beginning ($V_1$) and end ($V_5$) of the conductor imitating the shielding tape are presented in Figure 4a. Figures 4b and 4c show the voltage waveforms at the beginning ($V_3$, $V_4$) and the end ($V_7$, $V_8$) of passive conductors, respectively. For the second case, the voltage waveforms at the beginning ($V_2$) and the end ($V_6$) of the shielding tape are presented in Figure 4d. Figures 4e, 4f present the voltage waveforms at the beginning ($V_3$, $V_4$) and the end ($V_7$, $V_8$) of passive conductors.

![Figure 3. Schematic diagram of a power bus bar with branch conductors.](image)
Figure 4. Voltage waveforms at the beginning and end of the shielding tape (a), "+" (b) and "-" (c) branches when ESD impacts the shielding tape that covers the positive branch. Voltage waveforms at the beginning and end of the shielding tape (d), "+" (e) and "-" (f) branches when ESD impacts the shielding tape that covers the negative branch.

In Figure 4 it can be seen that when ESD impacts the shielding tape which covers the positive branch conductor, the crosstalk amplitude at the beginning of the positive conductor is 418 V, and at the end of the conductor it is 37 V (Figure 4b). In this case, at the beginning of the negative conductor, the amplitude does not exceed 82 V, and at the end it does not exceed 30 V (Figure 4c). When ESD impacts the shielding tape which covers the negative branch conductor, the crosstalk amplitude does not exceed 104 V at the beginning and 65 V at the end of the positive conductor (Figure 4e). In this case, at the beginning of the negative conductor, the amplitude is maximum (430 V), and at the end it does not exceed 32 V (Figure 4f).

In addition, the localization of the voltage amplitude maximum resulted from the impact of ESD was performed to identify hazardous areas along the conductors of the power bus bar elements. When ESD impacts the shielding tape that covers the positive branch conductor, the negative branch conductor exhibits a maximum amplitude (179.5 V) (Figure 5(a)) in the Tr1\textsubscript{4} section at a length of 50 mm from its beginning. Figure 5b shows the voltage waveform across the positive branch conductor when ESD impacts the shielding tape that covers the negative branch conductor. In this
case, the maximum voltage amplitude (141.5 V) is in the same section \((Trl_{14})\), but at a length of 65 mm from its beginning. Consequently, in a given area in a real design, it may be advisable to increase the insulation layer to avoid breakdown.

![Figure 5](image_url)

**Figure 5**. (a) Voltage waveform in the \(Trl_{14}\) section when ESD impact s the shielding tape that covers the "+" branch. (b) Voltage waveform in the \(Trl_{14}\) section when ESD impacts the shielding tape that covers the "-" branch.

Analyzing the results obtained, we can conclude that the maximum amplitude in all cases is observed from the side of the ESD impact on the power bus bar and weakens when it passes further. Also, when ESD impacts the shielding tape, the maximum voltage amplitude at the negative branch conductor appears in the \(Trl_{14}\) section at a length of 50–65 mm.

Table 1 shows the values of the voltage amplitudes at the beginning and at the end of the conductors during the ESD impact on the shielding tape, as well as positive and negative branch conductors.

| Impact                  | Shielding tape "+" branch | Shielding tape "-" branch | "+" branch | "-" branch |
|-------------------------|---------------------------|----------------------------|------------|------------|
| "+" (beginning)         | 417.76                    | 103.92                     | 540.73     | 165.01     |
| "+" (end)               | 36.82                     | 64.48                      | 189.55     | 36.76      |
| "-" (beginning)         | 81.5                      | 429.17                     | 118.08     | 527.31     |
| "-" (end)               | 29.18                     | 31.82                      | 45.86      | 161.06     |
| Shielding tape (beginning) | 502.27                | 518.97                     | 429.6      | 424.37     |
| Shielding tape (end)    | 84.03                     | 98.57                      | 50.41      | 35.03      |

From Table 1 it can be seen that when ESD impacts the shielding tape that covers the positive branch conductor, the voltage amplitude at the end of the line, both on the active and passive conductors, decreased. On the shielding tape, the voltage amplitude decreased by 6 times, and on the positive and negative branch conductors, by 11.3 and 2.3 times, respectively. In the case of impact on the shielding tape which covers the negative branch conductor, the amplitude at the end of the line decreased by 13.5 times on the negative branch conductor, by 5.3 times on the shielding tape, and by 1.6 times on the positive branch conductor.

When ESD impacted the positive branch conductor, the amplitude at the end of the line decreased by 8.5 times on the shielding tape, and by 2.9 and 2.6 times at the positive and negative branch conductors, respectively. When ESD impacted the negative branch conductor, the amplitude at the end
of the line decreased by 12.1 times on the shielding tape, and by 4.5 and 3.3 times at the positive and negative branch conductors, respectively.

Thus, when ESD impacts the shielding tape that covers the negative branch conductor, there is a maximum attenuation (13.5 times) at the positive branch conductor and minimum (1.6 times) on the negative branch conductor. Note that the maximum and minimum attenuations are observed when ESD impacts the shielding tape.

5. Conclusion
The simulation of the ESD impact on the shielding tape of the power bus bar was performed, which showed a decrease in amplitude by 6 to 13.5 times. A section of the power bus bar with the maximum voltage amplitude under the influence of ESD was identified. This area requires maximum attention during testing. The maximum (13.5 times) and minimum (1.6 times) attenuations are observed when ESD impacts the shielding tape covering the positive and negative branch conductors, respectively.

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