Worst-case model of bonding strap effectiveness for equipment case irradiated by an electromagnetic field

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***Abstract*—The worst-case model to estimate bonding strap effectiveness (the ratio of induced voltage of the interference on equipment case irradiated by an electromagnetic field and grounded with a bonding strap to the voltage of the interference on ungrounded equipment case) is built. The developed computationally efficient model accounts for the resonance in the oscillating circuit formed by bonding strap inductance and the capacity between equipment case and ground plane. The model is designed to analysis of intersystem and intrasystem EMC and makes it possible to estimate increase in voltage on the case for the worst conditions. In addition, a rough worst-case estimate of the absolute value of voltage on equipment case is presented. The model can be used to estimate interferences induced at the shields of cables connected to equipment case. Correctness of the model was proved through validation by the method of moments (the maximum underestimate was 2 dB).**

***Index Terms*—electromagnetic fields, electromagnetic compatibility, bonding, grounding**

I. Introduction

Increase of number and complexity of equipment used in modern big systems (e.g., automobiles) leads to increased complexity of analysis and providing of electromagnetic compatibility and immunity of these systems to external electromagnetic disturbances. Models intended for express analysis of EMC (the main goal of express analysis is to exclude from analysis definitely not dangerous influence paths and spurious couplings) in big systems (e.g., aircraft, ship) [1], [2] and its immunity to electromagnetic disturbances must have high computational efficiency and must guarantee a worst-case estimation in various conditions.

Faulty grounding/bonding of equipment case can make it function as a receiving antenna [3], [4]. If a cable shield grounded at both ends is connected to equipment case (i.e., a closed circuit is formed), the voltage induced at equipment case generates a current in this circuit. The current loop will generate an interference inside the cable through transfer impedance of the cable shield.

If equipment case is not in direct contact with ground plane and, at the same time, a bonding strap is used, then a resonance circuit is formed from sequentially connected capacitance C_C between equipment case and ground plane, inductance L_S of the bonding strap, active resistances R_S (of bonding strap) and $R_{S\,junction}$ (resistance of the contact of the strap with equipment case and ground plane) [5]. At resonance frequencies irradiation of equipment case may result in exceedance of voltage as compared to the voltage on ungrounded equipment case [4].

Resonance frequency of the circuit depends on the capacitance between equipment case and ground plane. The capacitance may change depending on whether the equipment case is painted, rusty, has rubber gaskets and vibrations or exposed to other random factors.

Similar to [4], let us define the efficiency of bonding strap as the ratio of voltage U_{case} on equipment case being irradiated by an electromagnetic wave with using a bonding strap to voltage U on equipment case being irradiated by an electromagnetic wave without using a bonding strap.

The objective of this paper is the development of a worst-case model to estimate decrease in voltage on equipment case being irradiated by an electromagnetic field with the use of a bonding strap in comparison with ungrounded equipment case.

Section II describes physical model of the problem. Section III demonstrates the equivalent circuit. Theoretical model of bonding strap efficiency is described in Section IV; description and validation of the worst-case model is presented in Sections V and VI, respectively.

II. Physical model

Physical model of the problem is shown in Fig. 1. The case is considered as a parallelepiped. One of the sides of parallelepiped is parallel to ground plane. The following notations are in use: E is the projection of electric field strength which is perpendicular to ground plane; h is the height of equipment case above ground plane; H is the height of equipment case; a_x is the length of equipment case side parallel to axis x; a_y is the length of equipment case side parallel to axis y; $S = a_x a_y$ is the area of equipment case side being the closest one to ground plane; l is the length of bonding strap; r is the radius of bonding strap.

Length l of bonding strap is assumed to remain constant when changing the height of case h (i.e., equipment case

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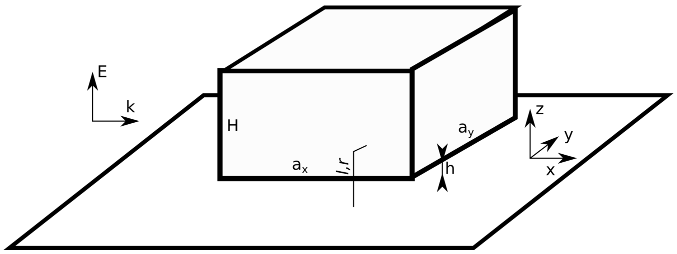

Figure 1. Physical model of the problem

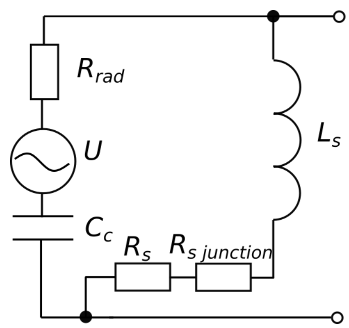

Figure 2. Equivalent circuit

change its position, for example, when operating due to vibration and being grounded with a bonding strap as, for example, LRU).

III. Equivalent circuit of connection of equipment case to ground plane

The basis for equivalent circuit to compute impedance of connection of equipment case to ground plane is taken from [3]. This circuit applies the following notations: C_C is the capacitance of equipment case relative to ground plane; L_S is the inductance of bonding strap; R_S is the resistance of the bonding strap itself; $R_{S\,junction}$ is the resistance of the contacts between bonding strap, ground plane and equipment case. In order to account for a plane wave incident on equipment case, one has to add the voltage source U to this equivalent circuit in series with capacitance C_C, as shown in Fig. 2. In the same manner, the resistance of radiation R_{rad} of antenna in the form of equipment case is added to the equivalent circuit in series with the voltage source U.

Resonance frequency f_{res} of the circuit illustrated in Fig. 2:

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{L_s C_c} - \left(\frac{R_s + R_{s\,jinction} + R_{rad}}{L_s}\right)^2} \tag{1}$$

Due to low ohmic resistance:

$$f_{res} \approx \frac{1}{2\pi\sqrt{L_s C_c}} \tag{2}$$

Capacitance C_C is computed by the following expression:

$$C_C = \frac{\varepsilon\varepsilon_0 S}{h} \tag{3}$$

where ε is the dielectric permittivity of the material between equipment case and metallic surface (further assumed to be 0); ε_0 is the electric constant.

As far as a circular cable is concerned, its inductance is computed by the following formula [3, p. 13]:

$$L_S = 0.2\cdot 10^{-6} l\left(\ln(\frac{2l}{r}) - 1 + \mu_r\kappa\right) \tag{4}$$

where κ is skin effect correction factor.

According to [6, p. 316], let's assume κ to be equal to 0.25.

Bonding strap resistance R_S is computed as follows:

$$\begin{aligned}&\delta = 503.3\sqrt{\rho/(\mu_r f)};\\ &R_s(f) = \rho l \max\left(1/(\pi r^2), \tfrac{1}{2\pi r\delta}\right)\end{aligned} \tag{5}$$

where δ is skin depth in meters; f is frequency in Hz; ρ is resistivity of the bonding strap material in ohm-meters; μ_r is relative magnetic permeability of bonding strap material.

The maximum value of $R_{S\,junction}$ is restricted in [7, p.26] to 15 mOhm.

Herein, for the values of bonding strap length and distance between equipment case and ground plane, the wavelength corresponding to resonance frequency f_{res} (2) is much higher than the height of equipment case. Therefore, the value of R_{rad} was estimated as the resistance of electric monopole at low-frequency approximation [8]:

$$R_{rad} \approx 10\pi^2\left(\frac{l}{\lambda}\right)^2, \quad \text{(Ohm)} \tag{6}$$

As for considered values of parameters, it is much less than the active resistance of bonding strap R_S (5) and is further assumed to be zero.

The equipment case is frequently painted [9, p. 136], the only way to establish electrical connection with the ground plane is by the use of a bonding strap, so, the capacitance between the bonded equipment and the ground plane C_C can be of high values [3]. The formed oscillating circuit can have low resonant frequency (from one to tens MHz) [9, p. 138], [6, p. 315] and can result in the leap of the impedance of connection of the equipment case with the ground plane. Due to the resonance, a bonding strap can even increase the level of induced interferences at the equipment case [4, p. 32].

When irradiating equipment case with an electromagnetic field, the worst case will be radiation with a plane electromagnetic wave in which the electric field vector $\overrightarrow{E}$ is directed perpendicular to ground plane. Equipment case can be considered as a monopole having an arm of length H.

Computational experiments have established that, during irradiation of equipment case with an electromagnetic wave, increase in area S of ungrounded equipment case (while preserving its length) causes significant decrease in voltage on the case. Thus, for equipment case of 0.01 m^2 in area and at a frequency of 10 MHz for $h = 0.5\,\text{mm}$, H=4 cm, the ratio of effective height of ungrounded case to its physical height H was 0.036 instead of 0.5 (theoretical value for a small monopole compared to wavelength). Thus, if additional

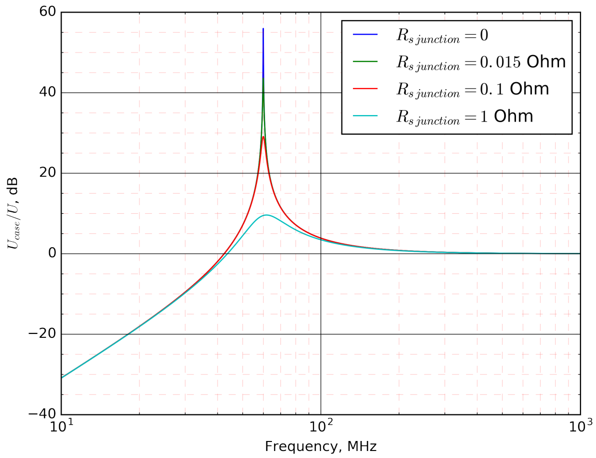

Figure 3. Efficiency of bonding strap by (10) (the ratio of voltage on grounded equipment case to that on the ungrounded one when irradiating with a plane electromagnetic wave)

information is unavailable, a rough worst-case estimate of voltage U on ungrounded equipment case can be obtained as follows:

$$U_{worstCase} \approx 0.5EH \tag{7}$$

Note also that approximation $R_{rad} = 0$ is a worst case (using a monopole with the heitht of an arm equal to the height of case will give overvalued R_{rad}, which will lead to decrease in Q-factor of the oscillating circuit formed by C_C and L_S).

IV. Decrease in voltage on equipment case irradiated with an electromagnetic wave when using a bonding strap

Let us find the voltage on equipment case (see Fig. 2):

$$Z_{total} = \frac{1}{j\omega C_C} + j\omega L_S + R_{rad} + R_S + R_{S\,junction} \tag{8}$$

$$U_{case} = \frac{U}{Z_{total}}(j\omega L_S + R_S + R_{S\,junction}) \tag{9}$$

$$\frac{U_{case}}{U} = \frac{j\omega L_S + R_S + R_{S\,junction}}{\frac{1}{j\omega C_C} + j\omega L_S + R_{rad} + R_S + R_{S\,junction}} \tag{10}$$

Fig. 3 shows frequency dependence (10) for the following parameters: h=0.1 mm; l=0.015 m; r=1 mm; a_x = a_y=0.1 m; strap material is copper; R_S was computed by (5), $R_{S\,junction}$ =[0; 0.015 Ohm; 0.1 Ohm; 1 Ohm]. The shape of obtained result corresponds to the measurements carried out in [4, p. 32].

V. Worst-case model

The worst-case model is based on consideration of the case where C_C, being the quantity most prone to random changes, takes the value that ensures resonance at the frequency of calculation.

Maximum ratio of voltage U_{case} on equipment case grounded by a bonding strap (see (10)) to voltage U on equipment case without a bonding strap and cable braid connected thereto is reached at resonance. Assuming that (see (2))

$$C_C = 1/(\omega^2 L_s) \tag{11}$$

we obtain:

$$\left(\left|\frac{U_{case}}{U}\right|\right)_{max\,res} = \left|\frac{j\omega L_S + R_S + R_{S\,junction}}{R_{rad} + R_S + R_{S\,junction}}\right| \tag{12}$$

If limitations $[h_{min}, h_{max}]$ to height h of the case above the ground plane are known, then one can estimate range of possible resonance frequencies:

$$[\omega_{res\,min}; \omega_{res\,max}] = \left[\sqrt{\frac{h_{min}}{L_S\varepsilon\varepsilon_0 S}}, \sqrt{\frac{h_{max}}{L_S\varepsilon\varepsilon_0 S}}\right] \tag{13}$$

Let's find which one of limiting values $[h_{min}, h_{max}]$ must be used in computations at frequencies out of range $\frac{1}{2\pi}[\omega_{res\,min}; \omega_{res\,max}]$. According to (10), if $\omega < \omega_{res\,min}$, then $|U_{case}/U|$ has maximum level at $h = h_{min}$. Similarly, if ω¿$\omega_{res\,min}$, then $h = h_{max}$ must be used as a worst case. Then:

$$\left(\left|\frac{U_{case}}{U}\right|\right)_{max} = \begin{cases} \frac{U_{case}}{U}\Big|_{h=h_{min}}, \\ \quad \text{if } \omega < \omega_{res\,min}; \\ \left(\left|\frac{U_{case}}{U}\right|\right)_{max\,res}, \\ \quad \text{if } \omega \in [\omega_{res\,min}; \omega_{res\,max}]; \\ \frac{U_{case}}{U}\Big|_{h=h_{max}}, \\ \quad \text{if } \omega > \omega_{res\,max}. \end{cases} \tag{14}$$

where $\frac{U_{case}}{U}$ is computed according to (10), $\left(\left|\frac{U_{case}}{U}\right|\right)_{max\,res}$ is computed according to (12), and $[\omega_{res\,min}; \omega_{res\,max}]$ is computed according to (13).

If h_{min}=0 and/or $h_{max} = \infty$ (one or both limitations for the case height above ground plane are not defined), then (14) is still applicable.

Note: when the equipment case is fixed to the ground plane by screws (i.e. $h \approx l$ and both tends to zero), L_s, according to (4), will tend to zero faster than C_C. Correspondingly, f_{res} will tend to infinity; this agrees with practical observations.

Shielded cables with shield grounded at both ends can be connected to the equipment case. As a rule, length of connected cables is much more than length of the bonding strap. Therefore, bonding strap inductance will be much less than inductances of connected cables, and total inductance will be changed insignificantly. So, value of resonant frequency (2)

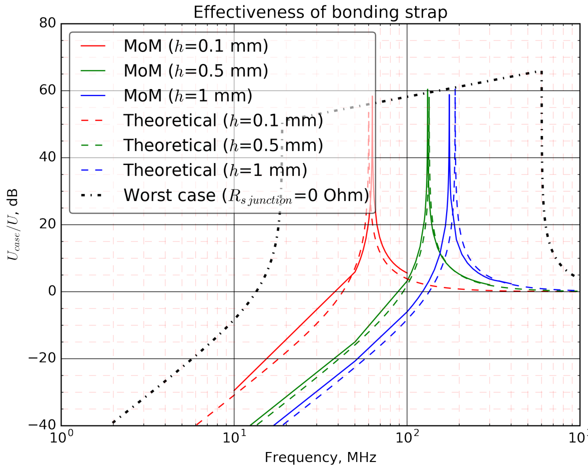

Figure 4. Frequency dependence of the ratio of induced voltage of the interference on equipment case irradiated by an electromagnetic field and grounded with a bonding strap to the voltage of the interference on ungrounded equipment case (calculations by MoM and using the developed model (10), (14)).

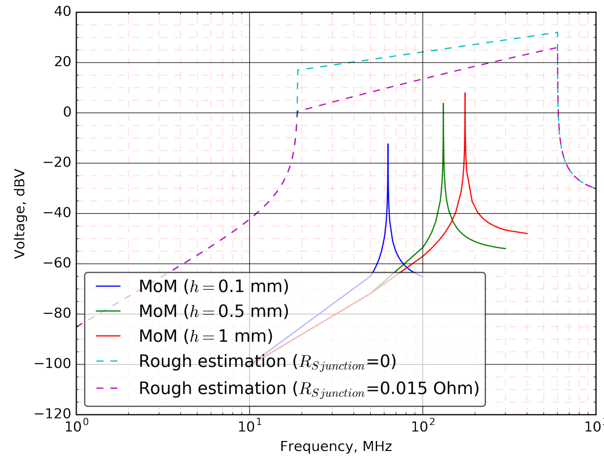

Figure 5. Frequency dependence of induced voltage of the interference on equipment case irradiated with an electromagnetic field and grounded with a bonding strap. Calculations were carried out by MoM. and by developed model (7), (14).

will have only slight change, and the model (14) is applicable when there are several cables connected to the equipment case.

VI. Validation of the Developed Model by Computational Electromagnetics Methods

To validate the model (14), we used MoM (Method of Moments). Excitation with a plane wave propagating towards x was applied (electric field is perpendicular to ground plane). Dimensions of ground plane were chosen 1 m x 1 m .

The length of bonding strap l was chosen fixed and equal to 15 mm; r=1 mm. The chosen material of bonding strap is copper. The height of equipment case h above ground plane was changing from 0.1 mm to 1 mm. Equipment case was a box with dimensions of $a_x = a_y$=0.1 m, H=0.04 m.

Figure 4 demonstrates bonding strap effectiveness calculated by (10) and that obtained by MoM (EMCoS Studio package [10]), as well as worst-case estimate (14) (with $[h_{min}; h_{max}]$=[$1{\cdot}10^{-5}$ m;$1{\cdot}10^{-2}$ m]). Maximum underestimate of the worst-case model is 2 dB (for h=0.1 mm) and lies within tolerable limits. Mismatch of resonance frequencies is not important as in the operation of equipment the capacitance between equipment case and ground plane C_C will constantly change. Thus, model (10) ensures a good match with the computational experiment and worst-case model (14) may be used for system-level analysis of EMC.

At very high frequencies, when length l of the bonding strap is more than 1/5 of wavelength, arising of other resonance effects is possible [11]. The model (14) does not describe these resonant effects. In case of considered test situation (l=0.015 m), resonant effects not described by (14) can arise at frequencies higher than $c/(5l) = 4$ GHz (c is speed of light).

In addition, Fig 5 illustrates frequency dependence of voltage on equipment case bonded with a strap. The dependence was calculated by MoM (EMCoS Studio package [10]) and by using the developed model (7), (9), (14). Parameters of the problem are the same to those for Figure 4. Figure 5 makes it clear that estimate (7) is very rough and may be used when other estimates of voltage on ungrounded equipment case cannot be obtained.

As an example, Fig. 6 also shows frequency dependence of current in the shield of a cable connected to equipment case for the following parameters: h=[0 mm; 0.1 mm, 1 mm]. The dependence was calculated by MoM. Cable parameters: length l_{cable} =0.1 m; radius r_{cable}=2 mm; h_{cable}=0.02 m. Cable is placed in parallel to the ground plane. Shield end opposite to the end connected to the equipment case is connected to the ground plane by vertical metallic wire. Fig. 6 allows calculation of active resistance $R_{rad}+R_S+R_{S\,junction}$ in the equivalent resonance circuit through Q-factor of the circuit. The width of resonance curve by 0.7 level for h=0.1 mm is Δf=72.26 MHz-72.15 MHz=0.11 MHz. Active resistance of series resonance circuit is $R_{rad} + R_S + R_{S\,junction} = 2\pi\Delta f L_S$.

Then, active resistance estimate is 0.0055 Ohm. The resistance according to (5) is 0.0051 Ohm. The values are close, and this additionally confirms that the radiation resistance R_{rad} is negligibly small for the considered case.

In a number of cases, to decrease the impedance of the connection between the equipment case and the ground plane there's used a number of bonding straps, which are separated from each other for the decrease of mutual inductance between them [6, p. 320]. According to [9, p. 136], it's preferable to have four such straps. For the accurate account, it's possible to consider their parallel connection [6, p. 320], but it is not necessary for the worst-case model.

VII. Conclusion

The model (14) is developed for computation of the worst-case value of bonding strap effectiveness to reduce voltage on

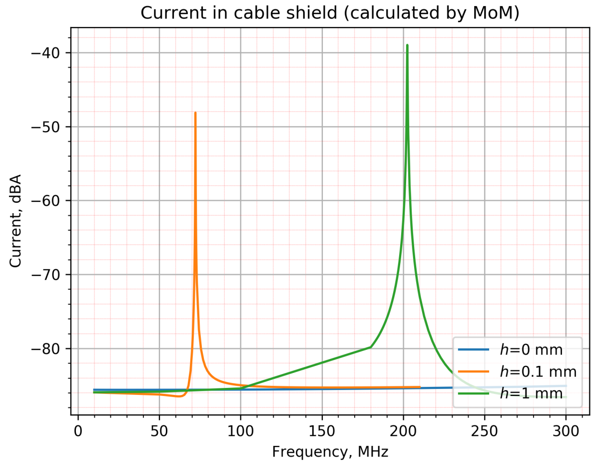

Figure 6. Frequency dependence of current in the braid of a cable connected to equipment case and grounded at both ends.

equipment case being irradiated with an electromagnetic field. The model is characterized by high computational efficiency. Correctness of the model is proved by means of computational experiment using the method of moments.

Expression (7) is given to make a rough estimate of voltage on ungrounded equipment case.

The model may be used in express-analysis of EMC to consider possible impact of resonance effects, caused by using a bonding strap, on the level of voltage on equipment case.

Directions of model refinement: more precise determination of voltage on ungrounded equipment case irradiated with an electromagnetic field (see (7)).

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