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Complex Analysis of IEMI in Grounding Circuits of Critical Equipment: Preliminary Results

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Abstract— **The paper discusses the problem of intentional electromagnetic interference (IEMI) in grounding circuits of critical equipment. Here, we present the preliminary results of a big research that includes theoretical and practical studies. The research relies on three main types of analysis: circuit-based, quasi-static, and electrodynamic ones, as well as their possible hybrids. The following excitations are considered: a harmonic one in the frequency domain, a trapezoidal ultra-short pulse, signals of real generators, a dumped sinusoid, and an electrostatic discharge. The research focuses on a wide range of ground types and grounding schemes, including new structures with modal reservation. The scientific novelty of this research consists, predominantly, in the comprehensiveness of the problem, as well as in its multiple individual variations. Within the theoretical study, mathematical models must be created that allow developing algorithms and computer programs to perform simulations over a range of parameters to analyze a variety of IEMI in different grounding circuits. Within the practical study, available devices and new created prototypes must help to experimentally validate simulation results. In this paper, we give some details of general approaches to perform theoretical analysis, emphasizing on the structures to be considered (EMI filter, autonomous navigation system, and structures with modal filtration), the features of their simulation, and some important conclusions. Although these are preliminary results of the complex analysis, they are crucial for the following research.**

Keywords—grounding, electromagnetic compatibility, intentional electromagnetic interference, IEMI, modal reservation

I. INTRODUCTION

The relevance of solving the electromagnetic compatibility (EMC) problem is caused by several factors [1]. On the one hand, the complexity and package density of radioelectronic equipment, component placement, and circuit tracing are rising continuously. On the other hand, the upper frequency of useful signals and interfering disturbances spectra are rising together with decreasing the levels of useful signals and increasing the levels of interfering disturbances. Meanwhile, radioelectronics is increasingly penetrating into all spheres of human activity. Thus, EMC assurance becomes vital and very relevant.

However, it is particularly critical to solve the EMC problem in the case of intentional electromagnetic interference (IEMI) because of its high power [2]. IEMI can penetrate into various systems in very different ways; each of them must be carefully considered to timely reveal the vulnerability and implement an adequate technique to protect critical systems. The easiest way to do this is to first simulate the problems.

Meanwhile, to successfully implement the whole research, it is useful to regularly reflect on conceive recently obtained results. If the research concerns a direction being new for researchers, then it is especially useful to begin to summarize preliminary results as early as possible. Preliminary results can be based on the consideration of general approaches to solving the problem, as well as on details and first implementations of the approaches.

The aim of this paper is to present the preliminary, but important for the following studies, results of complex analysis of IEMI in grounding circuits of critical equipment. (Unfortunately, very well-known general [1] and special [3] books left this issue without consideration.) To achieve this aim, we consider some details of general approaches for the research under consideration.

II. GENERAL APPROACHES

The whole research is aimed at ensuring EMC, in particular, at solving the task of complex analysis of IEMI in grounding circuits of critical equipment. Recent military activities demonstrated the relevance of solving this problem. However, it is not simple.

To properly and effectively solve this problem, we used all three main types of analysis: circuit analysis (lumped circuits, Kirchhoff lows), quasi-static analysis (multiconductor transmission lines theory), electrodynamic analysis (Maxwell equations), and their possible hybrids (to accelerate solutions). As for possible threats, we considered a number of impacts: a harmonic excitation in the frequency domain, a trapezoidal ultra-short pulse, a standardized dumped sinusoid, an electrostatic discharge, and signals of real generators designed to create conducted IEMI. Finally, we analyzed a wide range of ground types (case, power, and circuit, including analog and digital) and grounding schemes (single point, multi-point, and daisy chain), including new structures with modal filtering (modal reservation of different multiplicity and cable structures with additional extended conductors grounded at their ends).

The scientific novelty of the research consists, first of all, in the comprehensiveness of the problem defined above, as well as in a wide range of its individual options. Through this study,

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mathematical models must be created to analyze a variety of IEMI in various grounding circuits. Based on these models, developed algorithms and computer programs must perform simulations over a range of parameters. The available devices and new created prototypes must help to experimentally validate simulation results. The obtained models, algorithms and programs will allow for the first time to simulate complex processes of IEMI propagation along typical and new grounding circuits. This will ultimately allow the vulnerabilities in critical equipment to be identified without additional costs of expensive or even unfeasible tests.

III. DEVICES UNDER STUDY

A. *EMI filter*

To properly recognize the essence of a new problem to be solved, it is necessary to consider its possible solution on a commonly used example. As such example, a usual electromagnetic interference (EMI) filter can be considered as, for instance, in [4]. Therefore, for this aim, we used a simple EMI filter from a typical class-room computer table (Fig. 1).

Fig. 1. Original EMI filter.

All real-world devices have certain tolerances in component parameters. These tolerances can give some deviations in important characteristics; therefore, a number of samples must be considered. We took 10 available EMI filters shown without shielding cases in Fig. 2. Visual examination of the internal filter wiring allowed us to draw the following conclusions that should be taken into account to properly consider the common-to-differential mode conversion of IEMI.

1. First of all, the input wiring of protective earth conductors differs considerably in the length and form.

2. As for output sockets, their wiring also differs considerably. The recommended symmetrical tracing of the line and neutral power conductors relative to the protective earth conductor is absent.

3. In addition, the printed circuit board (PCB) of the filter must be carefully considered at the top and bottom sides regarding to the asymmetry (Fig. 3).

4. Finally, the total influence of variations and asymmetry must be obtained to estimate particular final effects of EMI.

Fig. 2. 10 samples of EMI filters without shielding cases.

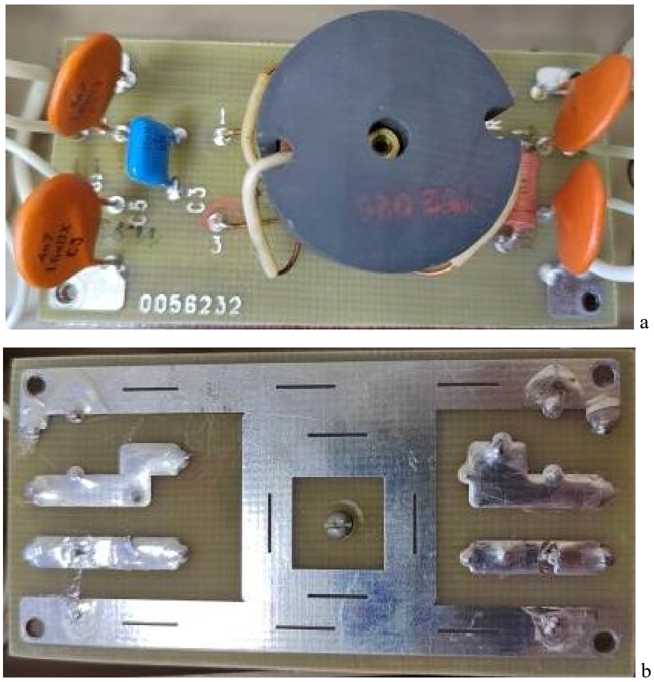

Fig. 3. EMI filter: (a) TOP and (b) BOTTOM views of the PCB.

B. *System of spacecraft autonomous navigation*

The EMI effect on critical systems is especially important [2] and each system of a spacecraft can be a good example. However, there are particularly critical systems, for example, a navigation system. More specifically, a relatively new one is a system of spacecraft autonomous navigation. It allows the orbit of an unmanned spacecraft to be regularly corrected. However, this correction is done not manually by commands from Earth, but automatically by a spacecraft itself thanks to the spacecraft autonomous navigation system. Therefore, its functioning is critical. Some efforts to increase its reliability and EMI immunity by means of modal reservation have been made earlier [5]. However, the protection of the system against IEMI through its grounding system has not been considered. In the meantime, this issue is important with regard to possible electromagnetic weapons and regular electrostatic discharges in space.

For our research, we studied the system of spacecraft autonomous navigation proposed in [5]. The all-body of the system is shown in Fig. 4; it is a case ground and has a relatively complex form. The system includes three PCBs placed at both sides of the all-body: a PCB of a measuring module, a PCB of a receiving module, and a PCB of secondary power sources (Fig. 5). The last PCB (Fig. 6) is the simplest of all PCBs and can be the best one for the first consideration.

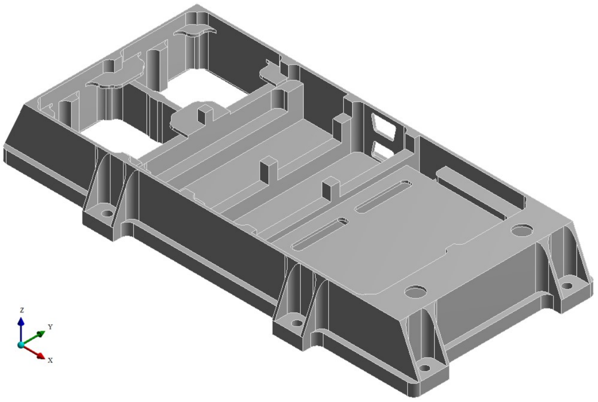

Fig. 4. Geometric model of the autonomous navigation system all-body

A similar visual inspection of the PCB tracing in the secondary power sources motivated the following conclusions that should be taken into account to properly consider common-to-differential mode conversion of IEMI.

1. This PCB is important as an input for IEMI propagation through external grounding and also as a power source for all other PCBs.

2. This PCB is a usual double-sided board and hence has no continuous ground plane for the circuit ground. Instead of the plane, the board features printed conductors (polygons) of various widths as the circuit ground.

3. The placement of this PCB (inside of all-body and over the case ground) considerably defines the symmetry of power and ground conductors relative to the case ground. Unfortunately, the total asymmetry is observed.

Fig. 5. Simplified models for PCBs of (a) a measuring module, (b) a receiving module, and (c) secondary power sources.

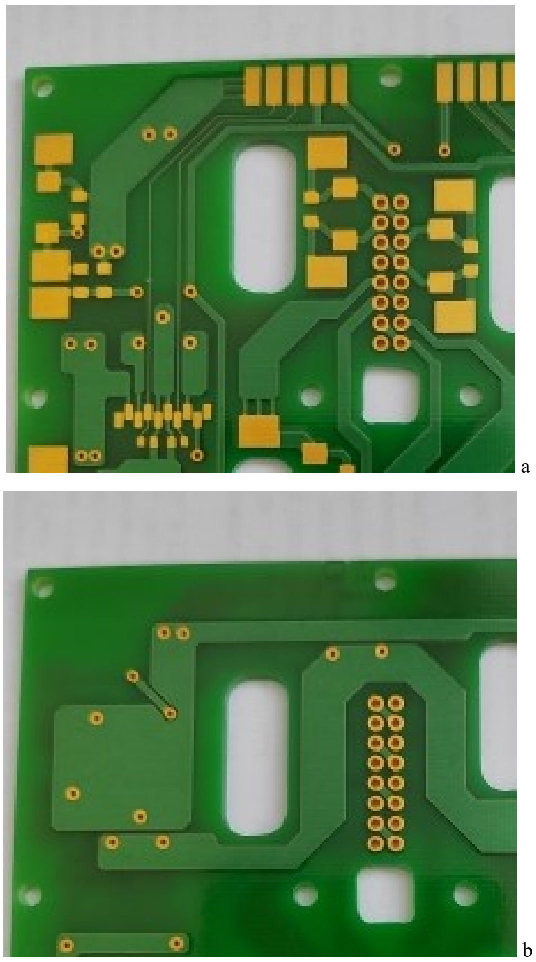

Fig. 6. TOP (a) and BOTTOM (b) views for the PCB of secondary power sources.

C. *Structures with modal filtration*

Structures with modal filtration are investigated intensively to improve protection of electronic equipment against IEMI. These structures can vary; they can be based on strip structures [6], double-sided PCBs [7], meander lines [8], microstrip lines with usual [9] and very wide [10] grounded conductors. A stand-alone direction of using modal filtration is modal reservation [11]. In such structures, grounded conductors are often used, for example, in single [12] or even in double section [13] structures. The cross-section examples of structures for single and triple modal reservation in flat printed cables are shown in Fig. 7, while with very wide grounded conductors – in Fig. 8.

Again, the visual analysis of their cross-sections allowed making the following conclusions that should be taken into account to properly consider IEMI in these structures.

1. All these structures have more than one ground conductor. Therefore, the IEMI current injected in a ground has several ways of flowing (according to the ground conductors).

2. The currents induced in signal conductors due to the IEMI current flowing in the ground conductors can be defined by capacitive and inductive couplings between all conductors.

3. The resulting threat from IEMI can be estimated as a total voltage drop between two important points of the structure.

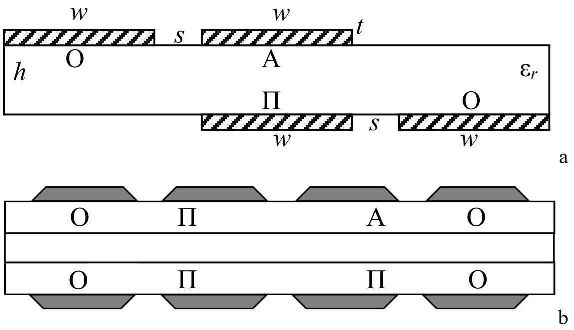

Fig. 7. Cross-sections of structures for single and triple modal reservation in flat printed cables.

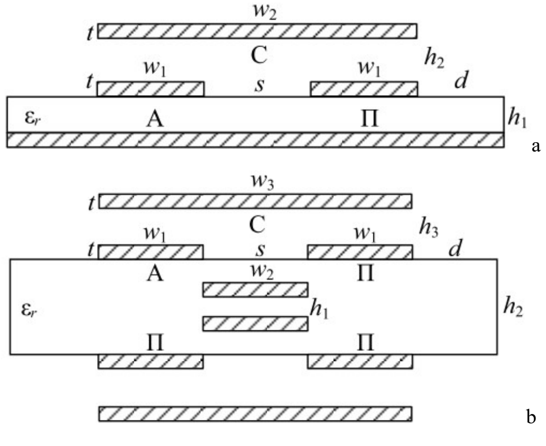

Fig. 8. Cross-sections of structures for single and triple modal reservation with very wide grounded conductors.

IV. SIMULATION APPROACHES

As for simulation approaches that begin from power cable excitation, consider one old simulation example [14]. Two excitations of a power transformer (Fig. 9) revealed very good propagation of 1 us rise time pulse along the power cable to the input outlet (Fig. 10). A surprising result that is important for this study is that the second excitation is as low as 4 times. It proves a possibility of good conditions for common-to-differential mode transformations. However, this excitation is close to direct IEMI injection in the ground conductor.

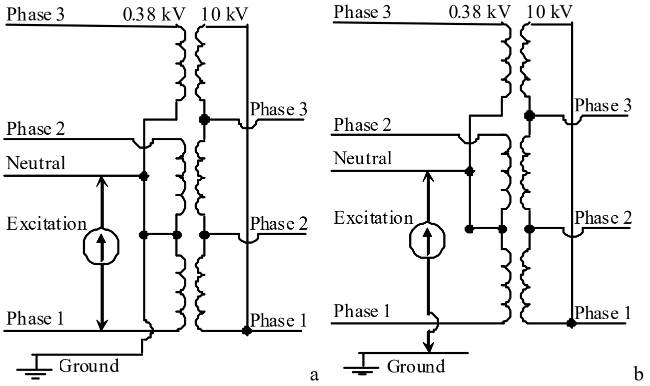

Fig. 9. Excitation on (a) Phase-Neutral and (b) Neutral-Ground circuits [14].

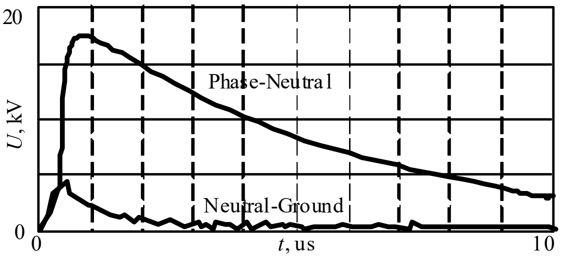

Fig. 10. Overvoltages at the input outlet of a device connected to the power line with Phase-Neutral and Neutral-Ground 20 kV excitations from Fig. 9 [14].

To simulate the EMI filter under consideration, we obtained a circuit diagram for the PCB (Fig. 11) for traditional (lumped circuits, Kirchhoff lows) simulations. In the meantime, additional parasitic parameters of components can considerably change simulation results, especially for ultra-short pulses of high frequencies. Therefore, all parasitic parameters of the EMI filter components must be taken into account properly (for example as in [15] for a common mode choke) in order to extend the original circuit diagram considering only ideal components (Fig. 11) to equivalent circuit diagram with parasitics (Fig. 12).

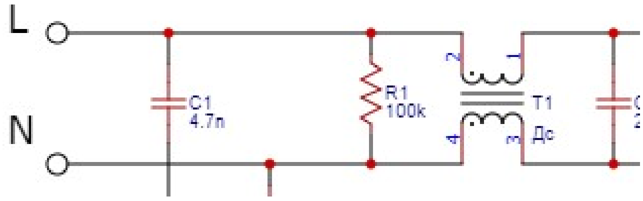

Fig. 11. Circuit diagram for the EMI filter PCB.

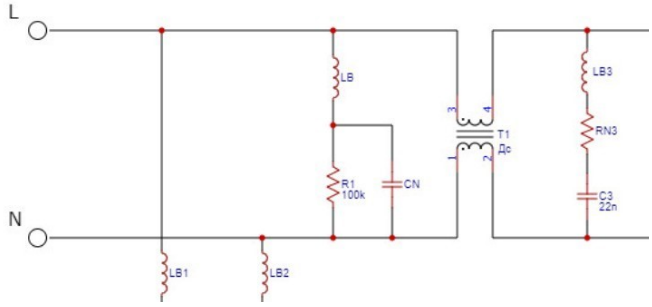

Fig. 12. Equivalent (with parasitics) circuit diagram for the EMI filter PCB.

Moreover, taking into account the existence of metal case of the filter, the whole EMI filter can be simulated more correctly (multiconductor transmission lines theory). In this case, the accurate estimation of its resistance becomes very important. Particularly, we must take into account the resistance of metal case and the resistance of the PCB ground plane additionally to the resistance of each printed trace. Therefore, it is necessary to use the accurate estimation of the per-unit-length frequency dependent resistance matrix **R** to solve telegraph equations. Besides, it becomes especially important to properly understand the role of the current flow in the ground plane. It is similar to the representative influence [3] of the return current in the ground plane from the active signal trace on the neighboring passive signal trace (Fig. 13). One can see that some current flowing in the signal ground under a signal conductor gives a voltage drop on finite (nonzero) impedance of the ground. This voltage drop is applied to a signal circuit as an additional (interference) voltage source.

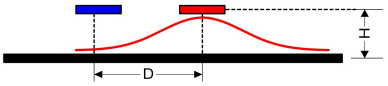

Fig. 13. Influence of the return current in the ground plane from the active signal trace on the neighboring passive signal trace [3].

Finally, the IEMI current injection in the grounding system can also be considered as the excitation of wire or patch antenna gap (Maxwell equations). Indeed, it may be a key issue of this study to recognize and properly represent the grounding system not as a classic way for return currents flowing from signal excitations, but as a subject undergoing the IEMI excitation and maximum currents generating couplings to signal conductors.

In any case, it is helpful to appeal to recommendations for help in the new study. For this aim, for example, Russian [16] and international [17] standards can be used.

V. CONCLUSION

A problem of EMC, particularly IEMI, has been discussed. We highlighted only first preliminary results of the complex analysis but they are important for the following research. Particularly, we presented some details of general approaches to perform this analysis, which are focused on real structures to be considered, features of their simulation, and important preliminary conclusions. The obtained preliminary results allow for the beginning of the systematic implementation of the study described. This work is a beginning; mathematical models are created to obtain first simulation results. However, the whole study must be finished during 2024–2025 years after the experimental confirmation of simulations.

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