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Electromagnetic field vulnerability of complex systems – an application of EM topology

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Abstract. In complex systems like ships or airplanes many tasks vital to the function of the system are executed by electronic equipment. Earlier research Camp (2004)–Nitsch (2005) has shown that there are frequency ranges in many of these systems, in which disturbances in the system will be observed if an external electromagnetic field exceeds a certain amplitude limit. On the basis of a simplified model in which the dominating coupling mechanisms in complex systems are shown, we will present a method which allows to analyze the vulnerability to electromagnetic fields. The method is based on the segmentation of the initial problem into subproblems with respect to the coupling mechanisms. Under the assumption that the obtained classes can be handled separately, the subproblems are solved and superposed to the overall solution. The Electromagnetic Topology Baum (1982)–Lee (1982) is used to solve the subproblems. This leads to a hybrid method combining different solution approaches. The subproblems are decomposed into smaller subproblems with respect to the shielding levels. This procedure allows us to determine the coupled disturbances into the system. Finally the solution is verified with respect to prescripted limits.

1 Introduction

Complex systems comprise a considerable amount of electric and electronic devices, which contain COTS (commercial-of-the-shelf)-components. In many of these systems frequency ranges exist in which disturbances in the system can be observed starting from a particular magnitude Camp (2004)–Nitsch (2005). In the case that the spectra of electromagnetic fields (EM-fields) produced by impulse generators are within those frequency ranges, the vulnerability of such systems to EM-fields must be evaluated. A methodology will be applied which allows us to identify the critical coupling paths of a system during an electromagnetic attack.

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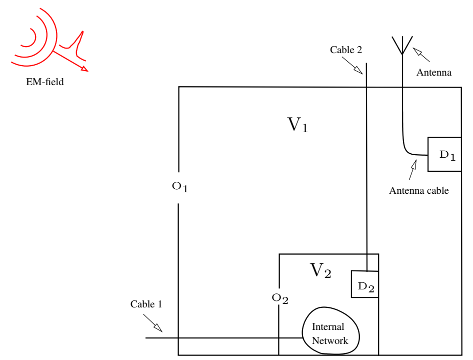

Fig. 1. Geometry of the system illuminated by an EM-field.

2 Analysis of the problem

The model of the considered system is shown in Fig. 1. The system consists of two volumes V_1 and V_2 with the corresponding apertures O_1 and O_2. Within the volume V_1, the volume V_2 and the device D_1 are located. D_1 is connected to an external antenna via an antenna cable. The volume V_2 contains the internal network to be analysed, as well as the device D_2. Both of them are connected to the outside world via separate cables. The entire system is illuminated by an EM-Field. In order to clarify the dominating interaction mechanisms in complex systems, i.e. aperture coupling, conductive coupling, radiation of cables, the following assumptions are made:

– the antenna cable radiates (bad shielding, low symmetry of the antenna or insufficient balun at the antenna),

– cable 2 radiates only within the volume 2 (no shielding),

– cable 1 does not radiate (ideal shielding of the cable 1 in both volumes 1 and 2).

Figure 2 shows the coupling model corresponding to Fig. 1, which is used for evaluation of the internal network in volume 2, taking into account all intermediate results.

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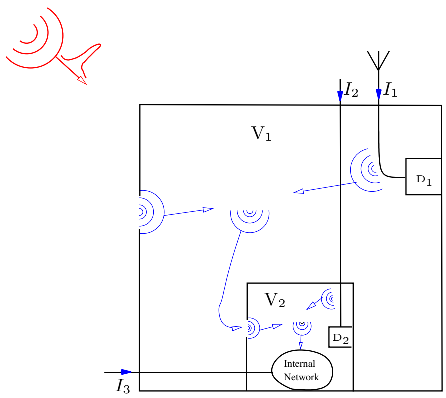

Fig. 2. Coupling paths in the subvolumes.

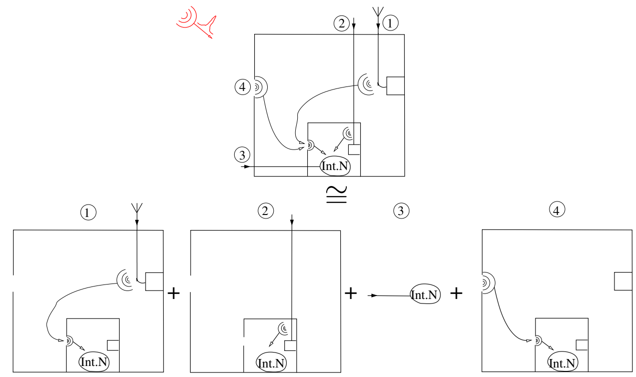

Fig. 3. Decomposition of the initial problem into subproblems.

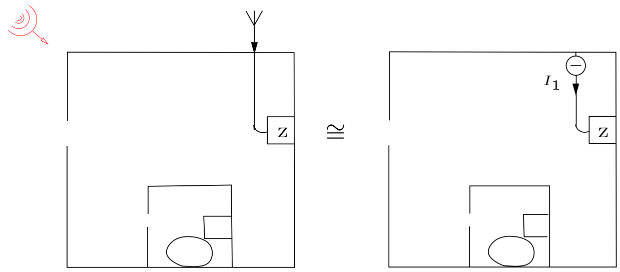

Fig. 4. Replacement of the antenna current with one equivalent current source.

Consequently the coupling paths in the subvolumes can be described:

- the internal field in the volume 1 is caused by the presence of the aperture 1 and the radiating antenna cable,
- the internal field in the volume 2 is generated by the radiation of the aperture 2 and the radiating part of cable 2 in volume 2.

If the EM-fields of the complete system were calculated using a numerical solver, it could be observed that the solution depends on several coupling mechanisms. But the influence of a single mechanism can't be investigated separately in this way. In addition, this solution method requires a completely new calculation of the problem for any change in the system. In order to eliminate these disadvantages we propose the following modifications of the solution method: The initial problem will be solved based on the solutions of the subproblems. Therefore the subproblems must be classified (see Fig. 3). If the initial problem

1. can be reduced to these subproblems,
2. these subproblems can be solved, and
3. all solutions can be combined at the component-level,

then the vulnerability analysis of the internal network under an external electromagnetic attack is possible.

3 Methodology for the vulnerability analysis

The methodology explained in this chapter, in order to assess the vulnerability of a system to electromagnetic attacks, is primarily based on the decomposition of the whole problem into subproblems (classes) with respect to the coupling mechanism. For this segmentation a detailed knowledge of the system is required. This, for example, can be acquired by geometrical analysis or by precise measurement of the transfer functions of the system. The main objective of this decomposition is to allow a separate solution of the resulting subproblems. As a consequence, a change in the structure of the system (e.g. addition of new coupling paths or removal of nonrelevant coupling paths) does not necessarily require a change of the whole solution approach. Therefore it is possible to reuse the old results in further computations. Figure 3 illustrates the segmentation of the original problem into subproblems with reference to the first shielding level.
The classification of the subproblems is as follows:

1. radiation of a cable into a subvolume,
2. direct radiation of a cable into the internal network,
3. direct coupling to the internal network through a connected wire,
4. coupling through apertures.

The solution of the generated classes allows an identification of the significant and nonrelevant coupling paths. Thus, it is possible to simplify the simulation of the complete system by omitting the nonrelevant coupling mechanisms. After the segmentation of the problem, the subproblems will be solved separately or treated in subgroups with the help of the Electromagnetic Topology (EMT). The significant results of these intermediate steps are the internal EM-fields

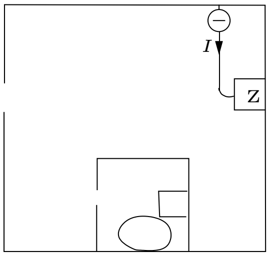

Fig. 5. Placement of one fictitious current source in order to compute the impedance at the low end of the antenna.

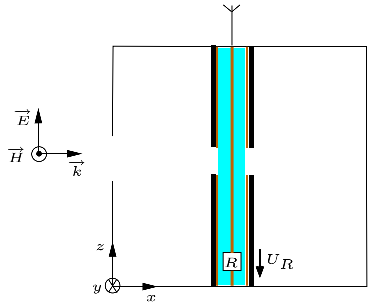

Fig. 7. Laboratory set-up for the validation of the method.

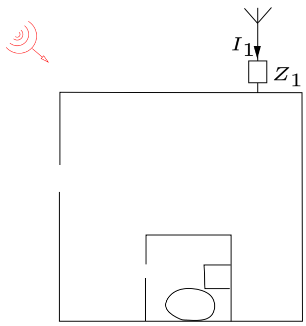

Fig. 6. Replacement of the network (antenna cable + Z) with Z_1 in order to compute the equivalent current source. I_1

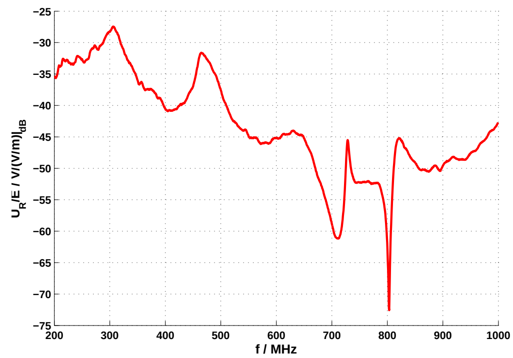

Fig. 8. Measured transfer function U_R/E.

due to the respective mechanisms as well as the external equivalent sources. Both are used for the excitation of the internal network on the basis of equivalent generators along the cables and wires (tubes) or as lumped sources at the gates of the devices or terminals (junctions). With knowledge of the equivalent sources, the propagation behavior of the waves along the *tubes* as well as the scattering behavior of the connected devices is described with the BLT (Baum, Liu, Tesche)-equation Tesche et al. (1996)–Paul (1994). The BLT-equation was firstly implemented by Tesche and Liu in the QV7TA code Tesche and Liu (1978). More recent work resulted in the CRIPTE software package ESI/ONERA (2003)–Parmantier et al. (1993). The main advantage using EMT for the vulnerability analysis of complex systems to EM-Fields is that results of different solution approaches (e.g. measurements and numerical simulations or a combination of different kinds of simulations like FDTD and CRIPTE) can be combined. Thus, for each subproblem the most efficient method can be chosen.

After the solution of the subproblems their results will be superposed to obtain the general solution. In the last step this will allow an assessment of the vulnerability of the system. This general solution will finally be compared to the prescripted limits from the standards Steinmetz (2006). When the obtained general solution for a specific EM-field generator is below the prescripted limits the system will be considered as non vulnerable against electromagnetic fields produced by this field generator. Otherwise, it is considered as vulnerable.

4 Handling of the wire's coupling on one shielding level

In the case of a connection of an external antenna with an internal cable as well as in the case of a cable feedthrough on one shielding level, the delimitation of a volume is not realisable when using the EMT. The use of equivalent current sources is helpful in this situation. For the example of the previously explained first class, Fig. 4 demonstrates the described situation. The device D_1 has been replaced by its input impedance Z. In this approach the antenna is replaced by a current source I_1 which generates the antenna current at its foot point. The current I_1 is determined as follows: The impedance Z_1 of the device D_1 including the cable within V_1 is determined as seen from the antenna foot point. This is done through the definition of a fictitious internal current source I that replaces the excited external antenna (see Fig. 5). Its input impedance represents the impedance Z_1. Now the equivalent current I_1 can be calculated. By doing this, the above-mentioned network (antenna cable + Z) is replaced through the previously determined (input) impedance Z_1 (see Fig. 6).

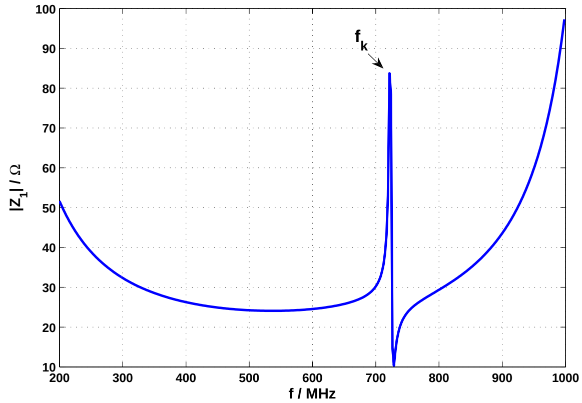

Fig. 9. Simulated input impedance in the closely vicinity of the fictitious current source. I

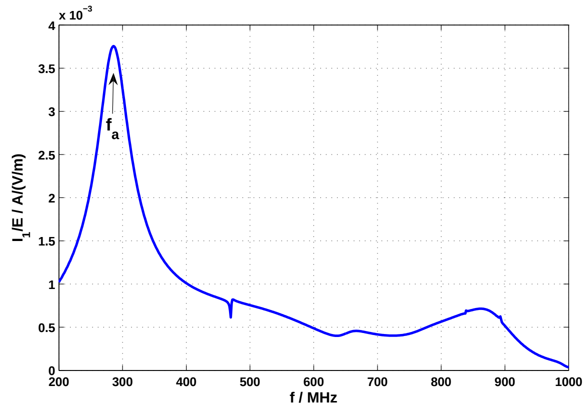

Fig. 10. Simulated current at the low end of the antenna.

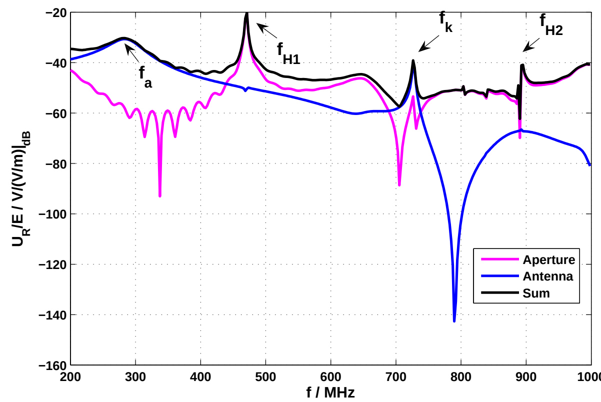

Fig. 11. Simulation results of both subproblems: Aperture und cable coupling.

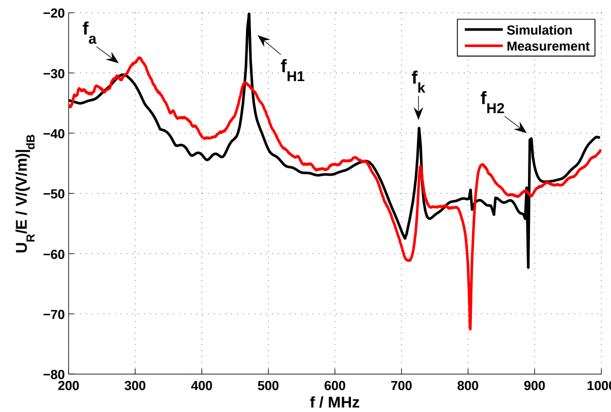

Fig. 12. Identification of the measured resonance frequencies.

5 Validation of the method

5.1 Geometry of the considered system

The following laboratory set-up has been examined for the validation of the method described above. A 50 cm×40 cm×20 cm metallic box with an aperture of 20 cm×8 cm at the front was used. At the cartesian coordinates (25 cm, 2.5 cm, 20 cm) a 25 cm monopole antenna was placed. This antenna was connected to a 50Ω load resistance via a 20 cm coaxial cable. There was a gap in the middle of the cable shield. The system was illuminated by a vertical polarised EM-field. The incident field was monofrequent. In the frequency range of 200 MHz to 1 GHz, we measured the induced voltage U_R at the load resistance R. Figure 8 represents the measurement's results of the transfer function U_R/E.

5.2 Results and analysis

The objective of the simulations was the identification of the resonance frequencies, which were observed by measuring the transfer function U_R/E. E and U_R represent the magnitude of the incident electrical field and the magnitude of the induced voltage at the load resistance R respectively. To accomplish this, we used the numerical code PAM-CEM/CRIPTE. This is a combination of the FDTD based code PAM-CEM and a multiconductor transmission line code named CRIPTE.

5.2.1 Input impedance

The magnitude of the input impedance Z_1 in the close vicinity of the fictitious current source I is illustrated in Fig. 9. It is obvious that the simulated impedance strongly depends on the frequency, although the load resistance R has a constant value. The lowest magnitude of Z_1 occurs at the frequency $f_k \simeq 725$ MHz and is about 10 Ω. For the worst case analysis, this impedance value was used while simulating the equivalent current source (see Fig. 10). The resonance peak f_k corresponds to the resonance frequency of the antenna cable (λ/2-dipole). As a result, if a resonance is observed near this frequency while measuring the transfer function of the system, then this is due to the antenna cable.

5.2.2 Antenna current

The magnitude of the current I_1 at the foot point of the antenna is represented in Fig. 10. At the frequency $f_a \simeq 295$ MHz a significant peak can also be observed. This frequency corresponds to the expected resonance frequency of the used antenna. Due to the fact that the antenna current was used for the excitation of the internal network, a resonance should be expected at this frequency during the computation of the cable coupling subproblem.

5.2.3 Subsolutions and overall solution

The simulation results of both subproblems (aperture and cable coupling) as well as their superposition to the general solution is represented in Fig. 11. The general solution is composed by a simple addition of both magnitude's values (worst case). With the help of the previous analysis (simulation of Z_1, simulation of I_1), it is possible to determine the first as well as the third resonance frequency. The first resonance frequency f_a is caused by the antenna as already mentioned above. The third resonance frequency f_k results from the direct connection of the antenna cable to the antenna (cable coupling) and also from the antenna cable (aperture coupling). The second and the fourth resonance frequencies correspond to the frequencies of the cavity modes, that can be obtained by using the following formula:

$$f_{\mathrm{mnp}} = \frac{c}{2}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{c}\right)^2} .$$

For the used geometry (a=0.5 m, b=0.4 m, c=0.2 m), the frequencies $f_{\mathrm{H}_1} \simeq 480.2$ MHz and $f_{\mathrm{H}_2} \simeq 890.6$ MHz correspond to the frequencies of the (1, 1, 0) and (1, 1, 1) mode respectively.

5.2.4 Simulation vs. measurement

In order to assess the above simulation approach, measurement and simulation results of the general problem are shown in Fig. 12. Both results agree well. Thus, the resonance frequencies can be accurately determined using this method. Hence, critical coupling paths can be easily localised. It can be used to develop specific protection measures for the improvement of the shielding of the system.

6 Conclusions

Resulting from the different type of couplings in complex systems, a simplified model has been presented, which clarifies the dominant interaction mechanisms in a possible electromagnetic attack. From this model, a coupling model for the transition of the original problem into subproblems and a solution method for those subproblems has been presented. The developed method has been verified with the help of a laboratory set-up through simulation and measurement. With the help of this new approach, the identification of critical coupling paths becomes easier.

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