Hybrid modelling of near-field coupling onto grounded wire under ultra-short duration perturbation

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Abstract. A time-frequency (TF) hybrid model (HM) for investigating the interaction between EM near-field (NF) aggression and grounded wire is addressed. The HM is based on the combination of techniques for extracting the EM NF radiated by electronic structures and the calculation of electrical disturbances across the wire due to EM coupling. The computation method is fundamentally inspired from transmission line (TL) theory under EM illumination. The methodology including flow chart interpreting the routine algorithm based on the combination of frequency and time domain approaches is featured. An experimental result showing the EM coupling between patch antenna-wire from 1.5-3.5GHz reveals the efficiency of the HM in frequency domain. The relevance of this HM was illustrated with a structure comprised of 20cm aggressor and 5cm victim I-shaped wires placed above a planar ground plane. The aggressor was excited with 40ns duration perturbation signal. After Matlab implementation of the HM, the disturbance voltages across the extremity of the victim wire were extracted. This simple and fast HM is useful for the EMC engineering during the design and fabrication phases of electrical and electronic systems.

1. Introduction
The modern electronic systems integration density and complexity are unintentionally threatened by electromagnetic compatibility (EMC) problems. The electrical wires interconnecting the electronic systems are usually involved. All level of electronic engineering as automotive and aeronautic and so forth is concerned by the occurrence of harmful EM coupling between nearby electronic component radiation causing embarrassing malfunctioning [1-3]. As the EMC analysis of these structures is challenging, methods enabling to predict disturbance voltages and currents, for example, across the victim transmission line (TL) under EM illumination were introduced [4-7]. At the beginning, the both E- and H-fields effects on the TL were proposed in [4], then it was adapted to only E- [5] and H- [6] fields. Those methods were limited to the TL interacting with planar and uniform EM far-fields [4-6]. More recently, the computational method was extended to cases of more complex systems composed of radiating circuits but operating only in a very limited band frequency [7]. It means that a more efficient approach is needed to extend this method for the case of radiations in wide frequency range as the case of surge currents, burst, lightning and also standard transient signals as identified in IEC/EN 61000-4-2. The aim of this paper is to propose a simple and fast time-frequency (TF) model of the EM near-field (NF) coupling onto grounded wires by taking into account ultra-short duration perturbations as electric static discharge (ESD) and electrical overstress phenomena.

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2. Methodology of the time-frequency (TF) hybrid method (HM) for extracting the disturbance from EM NF coupling

A radiating electronic device placed in proximity of planar grounded wire constitutes the structure under study [7]. The proposed TF HM consists in characterizing the transient EM radiation and the disturbance across the wire by coupling voltages. These couplings are generated in function of the perturbation signals on the aggressor circuit convoluted with coupling transfer function.

Fig. 1 explains the functioning principle and indicates the five main steps of the proposed model. i) Step 1 is aimed to the determination of EM data radiated by the aggressor. This can be obtained with different ways, from measurements [1] or simulations with the 3D EM tools or models [2-3] or both combined [7]. The NF data provided is generally expressed in the frequency domain (FD) as the case of standard IEC61967. ii) Step 2 is the analytical modelling of the victim under the EM aggression according to TL equations. iii) Step 3 is the extraction of the HM transfer function,

\[ T_x(j\omega) = \frac{U_x(j\omega)}{U(j\omega)} \]  

(j\omega is the radian frequency variable) between the excitation signal \( U(j\omega) \) and the disturbance \( U_x(j\omega) \) induced at the extremity of the victim line. iv) Step 4 is the spectral analysis of the perturbation signal exciting the aggressor. Then, v) Step 5 is the convolution between the perturbation signal and the HM transfer function to determine the disturbance in the time-domain (TD) via IFFT.

For the theoretic illustration, the victim wire loaded by \( Z(x=0) \) and \( Z(x=d) \) is with length \( d \), placed at the height \( z_0 \) above the ground plane in \((Oxyz)\) Cartesian system and oriented along x-axis as in [5-7]. The circuit model of this wire is formed by LC-network characterized by per-unit length inductance \( L_u \) and capacitance \( C_u \). With this circuit model, we use the Agrawal model [5] to determine the disturbance or coupling voltages \( U(x=0) \) and \( U(x=d) \) thanks to its simplicity. In this case, the coupling equations require only \( E_z \) component as EM input data. More concretely, by denoting \( \omega \) the radian frequency, the differential system generating the wire disturbance can be materialized by:

\[ \frac{\partial U(x)}{\partial x} + j\omega \cdot L_u \cdot I(x) = E_z(x, z = z_0), \frac{\partial I(x)}{\partial x} + j\omega \cdot C_u \cdot U(x) = 0, \]  

with the boundary conditions: \( U(x=0)=Z(x=0)I(x=0) \) and \( U(x=d)=Z(x=d)I(x=d) \).

3. Applications

3.1. Experimental validation in the FD

Fig. 2(a) represents the experimental setup and layout of the device under test (DUT). It consists of a patch antenna resonating at about 3GHz whose layout displayed in Fig. 2(b) as aggressor circuit. It is placed in proximity of \( d=10cm \) length cylindrical copper wire fixed at the heights \( z_1=1cm \) and \( z_2=3cm \) above the planar ground plane. After measurement scanning of the active electrical field component \( E_z(f) \) from 1.5GHz-3.5GHz in the surface area delimited by the wire and the ground plane, we extracted the coupled voltages \( U(x=0,z)=U(x=d,z) \) (due to the symmetry). In Fig. 2(c), it is displayed the comparison between the computed results from the HM and full wave simulations from HFSS.
commercial tool. We found a correlation between the behaviour of the coupling level which increases with the frequency despite the slight difference around the resonance frequency. The computation run time with PC equipped by operating system windows 7 having Intel® CPU @ 2.3GHz - 2Go RAM was 5 seconds compared to the HFSS simulations which took about 40 minutes.

3.2. Analysis of the TF HM with perpendicular configuration wire placed above ground planes

More general analysis including Matlab numerical applications in both the FD and TD is proposed in this subsection by considering a surge signal with 40ns duration as signal perturbation.

3.2.1. Description of the structure under study. Fig. 3 represents a structure composed of two perpendicular Copper wires (P1P2) and (P3P4). The first one is assigned with 20cm length and diameter Ø=1mm excited by a transient signal at P1 is the aggressor. The second one (P3P4) oriented along x-axis having 5cm length and Ø=1mm and 50Ω loaded at P3 and P4 is set as the victim.

3.2.2. Computed results from the TF HM. First, we computed the TD EM radiation in the surface plane delimited by (P3P4) and the ground plane when the aggressor (P1P2) is excited by the transient signal u(t) with 40ns duration and 5V amplitude double exponential waveform (see Fig. 5(c)). Second, the EM NF emission in TD is extracted with full wave simulations, the active electric field E_x(t) from the aggressor at the arbitrary instant time t_0=9ns is displayed in Fig. 4(a). Then, via FFT, we generated the equivalent data E_x(f) in the FD from DC to about 0.5GHz.

Figure 4. Maps of the E-field active component: (a) TD real component, and FD (b) magnitude and (c) phase in the surface plane delimited by the victim wire and GND plane.
The E-field amplitude and phase maps at the arbitrary frequency $f_0=50$ MHz are shown in Figs. 4(b) and 4(c). To determine the couplings, the equivalent circuit model of the victim line should be drawn. The LC-model of $(P_3P_4)$ presents per unit length parameters $L_u=518 \text{nH/m}$, $C_u=21.5 \text{pF/m}$ and characteristic impedance $Z_c=155 \Omega$. We point out the victim wire conductive loss was neglected. Thanks to the methodology instructed earlier in Fig. 1, we obtain the transfer functions $T_{x=0}(j\omega)$ and $T_{x=d}(j\omega)$ of the structure transfer functions plotted in Figs. 5(a) and 5(b). Then, we extracted the coupling voltages $U_{x=0}(j\omega)$ and $U_{x=d}(j\omega)$ in FD. Finally, via another IFFT, we calculated the time-dependent induced couplings $u_{x=0}(t)$ and $u_{x=d}(t)$, plotted in dashed lines of Fig. 5(c). As expected, we can see that the transient disturbances with mV level were found at the extremities of $(P_3P_4)$.

4. Concluding remarks

A computational HM aimed on the investigation on the coupling between an electronic devices and planar grounded wires applied to the radiated EMC analysis is introduced and experimentally validated. The HM principle is managed by combining the EM data representing the of the aggressor radiation onto the victim wire and the TL theoretical approach for calculating the disturbances in both FD and TD. The effectiveness of the proposed modelling approach was verified in the FD with a structure composed of a patch antenna and grounded metallic wire. The results were validated with HFSS simulations. Then, another application based on the coupling between wires under transient perturbation was analysed. After determination of coupling transfer function, the transient disturbance voltages across the victim line in function of the excitation voltages were generated. Compared to the existing EMC analysis and simulation tools, the TF HM offers benefits with outstanding speed computation time and in term of flexibility to operate in both the FD and TD.

As ongoing research, the extension of this TF HM for more complex systems constituted by series of PCBs placed in harsh environment by taking into account temperature effect is one of the main ultimate targets of this work.

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