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Time-Frequency Modelling of Near-Zone EM Coupling with Planar Circuit with NF/NF Transform

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Abstract—This paper is devoted on time-frequency EM coupling modelling between planar microwave device and grounded wire. The computational model is based on the time-frequency method with the combination BLT equation, near-field/near-field (NF/NF) transform and FFT/IFFT operation on EM NF radiation with electrical fast transient excitation. The method was used for investigating coupling between 3cm length metallic wire placed at some mm of microstrip Wilkinson power divider. From the scanned measured EM NF radiated at 3mm above the power divider from 0.7GHz to 1.3GHz, the voltage transfer coupling and the transient coupled voltages across the extremities of the victim wire were determined. The developed method is beneficial compared to 3D EM solver with its computation speed and flexibility to consider complex circuits under burst transient perturbations. The method can be potentially exploited for RF/microwave EMC engineering.

Keywords—BLT equation, near-field (NF) coupling, EMC analysis, transmission line theory, plane wave spectrum theory.

I. INTRODUCTION

The trends on multifunction integration in confined RF/microwave boards can be constrained by radiating near-field (NF) EMC emission [1-2]. Facing to typically burst transient perturbations [3], various standards as IEC 61000-4-4 [4] and EN-55022 [5] were established notably owing to radio disturbances. Due to EM NF illuminations, different modelling methods [6-12] were proposed, for example, to assess the coupled voltages induced across transmission lines (TLs). The EM coupling onto TL was, at the beginning, calculated based on the consideration of both electrical (E) and magnetic (H) illuminating fields [7]. It was reduced to consideration of only E- [8][10] or H- [9] fields by calculating the induced voltage or current, respectively, along the victim line.

More recently, more generalized models were forwarded by considering a hybrid method [11] of aggression EM NF evaluation and the coupled voltage calculation and also the integration of plane wave spectrum (PWS) NF/NF transform [12]. But till now, those models are focused on frequency domain analysis. For this reason, an extension of this model by considering fast transient disturbances as IEEE C62.41:1991 and IEC 897:2004 ESD phenomena. For the better understanding, this paper is organized as follows. Section II is the methodological investigation. Section III describes application results. Section IV draws the conclusion.

II. DESCRIPTION OF THE TIME-FREQUENCY NF COUPLING METHODOLOGY

Fig. 1 presents the configuration of the $L_x \times L_y$ size radiating planar circuit placed at distance z_1 under the victim grounded wire. One supposes that the wire is with length d and fixed at height $(z_2 - z_1)$ on metallic ground (GND) plane. To determine the coupling voltages across the wire extremities $u(y=0)$ and $u(y=d)$, we use the NF/NF transform as introduced in [13].

Fig. 1. Radiating circuit and the victim grounded wire system under study.

A. NF/NF Transform

This NF/NF transform is based on the PWS theory applied to NF scanning [14-15]. For any EM waves generalized as $\vec{X}(x, y, z, t)$ in the $(Oxyz)$ system associated with wave vector $\vec{k}(f) = k_x(f)\vec{u}_x + k_y(f)\vec{u}_y + k_z(f)\vec{u}_z$, one recalls that the PWS operation is mathematically expressed as:

$$\vec{P}_X(f) = \frac{1}{2\pi} \iint_{-\infty}^{\infty} \vec{X} e^{j(k_x(f)x + k_y(f)y)} dx dy, \quad (1)$$

and the associated inverse PWS (IPWS) is written as:

$$\vec{X}(f) = \frac{1}{2\pi} \iint_{-\infty}^{\infty} \vec{P}_X e^{-j(k_x(f)x + k_y(f)y)} dk_x dk_y. \quad (2)$$

The PWS operation enables to transpose the plane wave basic properties as translation ($\vec{X}(z) = f(\vec{X}(z_0))$) [13] and orthogonality ($X_z = f(X_x, X_y)$) [16] both in frequency- and time-domain to non-uniform NF scanned data by taking into account the evanescent waves. This mathematical operation will be handled for extracting E-field components necessary for the application of the Agrawal model [8] in order to

compute $u(y=0)$ and $u(y=d)$. We intentionally choose this model herein due to its simplicity to extract the voltage from only the E-NF.

B. Integration of Agrawal Model

As illustrated by the equivalent circuit sketched in Fig. 2, we need only E_x and E_z located in the hatched surface area delimited by the wire and the ground plane for extracting the voltages across the TL loads $Z_L(0)$ and $Z_L(d)$. Those voltages can be determined by integration of elementary voltages $u_0(y)$ onto the elementary cells $L_u C_u$ (by assuming TL as lossless).

Fig. 2. Circuit configuration of the victim line illuminated by essential components of aggression EM field.

The distributed coupling current and voltage along the transmission line can be extracted via [8]:

$$\begin{cases} \frac{du_0(y)}{dy} + j\omega L_u i(y) = -E_z(y, z=z_1) \\ \frac{di(y)}{dy} + j\omega C_u u_0(y) = 0 \end{cases}, \quad (3)$$

with ω is the radian frequency. By denoting $\rho(y)_{y=0,d} = (Z(y) - Z_c)/(Z(y) + Z_c)$ the reflection coefficients at the extremities of the wire, the coupling voltages are generated from BLT equation [10]:

$$\begin{bmatrix} u(y=0) \\ u(y=d) \end{bmatrix} = \begin{bmatrix} 1+\rho_1 & 0 \\ 0 & 1+\rho_2 \end{bmatrix} \begin{bmatrix} -\rho_1 & e^{\gamma \cdot d} \\ e^{\gamma \cdot d} & -\rho_2 \end{bmatrix}^{-1} \begin{bmatrix} u_1/2 \\ u_2/2 \end{bmatrix}, \quad (4)$$

where γ is the TL propagation constant and:

$$\begin{cases} u_1 = \int_0^d e^{\gamma \cdot y} E_y(y, z_1) dy + \int_{z_2}^{z_1} (E_z(0, z) - e^{\gamma \cdot d} E_z(d, z)) dz \\ u_2 = -\int_0^d e^{\gamma \cdot (d-y)} E_y(y, z_1) dy + \int_{z_2}^{z_1} (E_z(d, z) - e^{\gamma \cdot d} E_z(0, z)) dz \end{cases}. \quad (5)$$

C. Extraction of Time-Frequency Coupling Voltages

The methodology combining the routine algorithm including the NF/NF transform, BLT equation and FFT/IFFT is summarized in Fig. 3. We determine first the coupling voltage transfer function $T_v(j\omega)$. Then, for any excitation signal $u_e(t)$, the coupling voltage $u(t, y = \{0, d\})$ are calculated with IFFT of $T_v(j\omega) \cdot \text{fft}(u_e(t))$. Of course the time and frequency parameters should be adequately synchronized to achieve successful convolution results. After implementation of Matlab routine algorithm traducing this work flow, one gets the application discussed in the following section.

Fig. 3. Work flow illustrating the time-frequency modelling methodology.

III. COMPUTATION ANALYSIS RESULTS

Fig. 4 monitors the photograph of the 8cm×10cm size Wilkinson power divider (in left), IRSEEM NF scanner considered during the test and the victim grounded wire (in right). The metallic wire loaded by $Z_L(0)=Z_L(d=3\text{cm})=50\Omega$ is a cylindrical in copper with $d=3\text{cm}$ length and 1mm diameter placed at 0.7mm above the GND plane.

Fig. 4. Photograph the power divider implemented in microstrip technology (in left), IRSEEM NF scanner (in medium) and victim wire (in right).

A. NF/NF Transformed Results

As aforementioned, E-field scans are necessary for the application of Agrawal model introduced in II.b. So, $E_x(z_0=3\text{mm})$ and $E_y(z_0=3\text{mm})$ NF radiated by the circuit shown in Fig. 4 were scanned by using metallic dipoles as NF probes. The scanning was swept from $f_{min}=0.7\text{GHz}$ to $f_{max}=1.3\text{GHz}$ with $n_f=201$ samples. The surface scans are delimited in $(x_{min}=0, x_{max}=44\text{mm}, n_x=45\text{samples})$ and $(y_{min}=0, y_{max}=62,$

$n_y=42$ samples). Fig. 5 displays the maps of the scanned E_x and E_y magnitudes and phases @ $f=1\text{GHz}$. From this initial scan data, $E_z(z_0=3\text{mm})$ was extracted based on the NF/NF transform whose amplitude and phase are viewed in Fig. 6. Then, via PWS/IPWS translation operations, the essential fields E_y and E_z in the surface area between the metallic wire and GND plane were computed. As illustrative results, the $E_y(z=6\text{mm}, 11\text{mm})$ and $E_z(z=6\text{mm}, 11\text{mm})$ maps were presented in Figs. 7 and 8. As expected, the amplitude of E-fields is inversely proportionnal to the distance between the radiating circuit plane and the victim wire. The E-NF data will be considered for determining the total field including the GND plane reflection via image theory. Then, we apply the routine on BLT equation to determine $|T_v(f)|$ and $\phi(T_v(f))$.

Fig. 5. Maps of scanned $E_{x,y}$ @ $\{f=1\text{GHz}, z_0=3\text{mm}\}$.

Fig. 6. Map of E_z from $E_{x,y}$ @ $\{f=1\text{GHz}, z_0=3\text{mm}\}$.

Fig. 7. Maps of E_y and E_z @ $\{f=1\text{GHz}, z=6\text{mm}\}$ from $E_{x,y}(f=1\text{GHz}, z_0=3\text{mm})$ by NF/NF transform.

Fig. 8. Maps of $E_{y,z}$ @ $\{f=1\text{GHz}, z=11\text{mm}\}$ from $E_{x,y}(f=1\text{GHz}, z_0=3\text{mm})$ by NF/NF transform.

B. Computed Coupling Voltages Across the Victim Wire

Figs. 9 and 10 display the frequency plots of T_v magnitude and phase respectively, obtained by considering the power divider radiation and the grounded wired system.

Fig. 9. Coupling voltage transfer function magnitudes.

Fig. 10. Coupling voltage transfer function phase shifts.

The signal u_e plotted in Fig. 11 was assigned as transient perturbation. Then, it was extracted FFT(u_e) from f_{min} to f_{max} in order to perform convolution with T_v . Then, the calculated coupled voltages corresponding to $z=\{3\text{mm}, 6\text{mm}, 11\text{mm}\}$ are plotted in Fig. 12. As we can see the coupled voltages presented amplitude increased from about 2mV to 25 μ V when the victim wire is placed in this area. One emphasizes that the CPU time of the whole method implemented into Matlab run with PC equipped by windows 7 having Intel® Core™ i5-2467M CPU @1.6GHz 4Go RAM was of about five seconds.

Fig. 11. Time-domain plot (a) and spectrum (b) of the excitation signal.

Fig. 12. Extracted transient coupling voltages.

IV. CONCLUSION

A time-frequency modelling method of near-field coupling between planar circuit and grounded wire is performed. The modelling method is based on the combination of NF/NF transform with PWS theory applied to EM NF radiation, TL coupling BLT equation and FFT/IFFT with an external signal. The routine algorithm was applied to analyse the EM coupling between Wilkinson power divider and metallic wire. Extraction of EM NF in the area of interest from 0.7-to-1.3GHz was realized from the scanned data. Then, the coupling transfer functions were suggested. Via convolution with transient perturbation, time-domain voltage couplings across the victim wire were determined and discussed.

The model investigated is useful for the analysis of complexity electronic equipment in embedded systems especially for automotive and aeronautic applications with RF/microwave PCBs located in confined space. It allows a

preliminary study on RF/electronic modules under EM radiations and to meet the standards as EN 61000-4-3, IEC 61000-4-4 [4] and EN 55022 [5]. Fast and easy quantitative knowledge on the behavior and EM environment effects for the radiating emitting and immunity can be conducted.

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