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ON THE EQUIVALENCE BETWEEN RADIATION AND INJECTION IN BCI TESTING

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Abstract– **Bulk current injection and field coupling are analytically compared in order to ascertain if current injection tests are adequate for susceptibility assessment of electronic equipment. Transmission line theory is adopted for modelling wiring harnesses, and the equivalence is discussed by comparing the effects that the two kind of excitation techniques produce at line ends. General results are obtained, which are not affected by any assumptions on the equipment under test. It is shown that, from the theoretical point of view, injection by means of two current probes allows equivalence with any radiated plane wave excitation. The equivalence is achieved by controlling the clamp voltage in order to match the incident field characteristics.**

I. INTRODUCTION

Bulk Current Injection (BCI) testing procedure is often used for the assessment of susceptibility of electronic systems to external interferences. The favour gained by this technique over the radiated susceptibility tests is due to the higher degree of simplicity and the need for low RF power levels. However, a criticism about this testing procedure is that in many circumstances it results to be not equivalent to radiated excitation tests.

The problem of ascertaining the equivalence between these two techniques has been faced in recent years by many authors. In particular, in [1], transmission line theory has been used for modelling linearly loaded wire bundles, and numerical simulations have been carried out with the aim to compare currents induced on individual wires by injection and radiation. In [2], comparison measurements of current induced by radiation and injection have been presented.

This work is concerned with the theoretical comparison of the two excitation techniques. Transmission line theory is used to discuss the equivalence via analytical considerations, and no assumptions are made about the termination networks. It is demonstrated that radiation and injection produce different current distributions on the wires, and the equivalence is investigated for what concerns the effects produced at the line terminations. It is shown that one injection probe is not sufficient to assure the equivalence in the general case, but it is possible to get this result by employing two injection probes. Equivalence is achieved by controlling the RF power injected at the current probes.

II. CHARACTERIZATION IN TERMS OF OPEN-END VOLTAGES

Fig. 1 shows the block-diagram of an electronic network consisting of an equipment under test (EUT) linked via interconnecting wires with the remaining part of the system. EUT vulnerability to external fields is essentially due to the presence of interconnecting wires, which represent the main path for interference entering the system.

In operating conditions, or in radiated immunity testing, distributed coupling of external fields with the wiring allows interference to reach the input pins of the EUT; in this case the EUT is excited by radiation.

In BCI immunity tests, the presence of an external disturbing field is artificially simulated by

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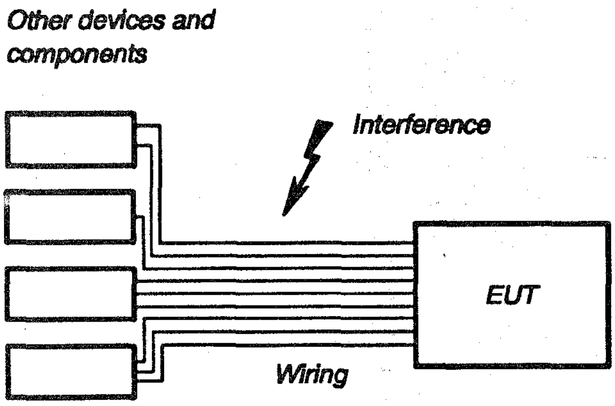

Figure 1: Schematic diagram of an electronic network consisting of an equipment under test (EUT) linked via wiring harnesses with other components.

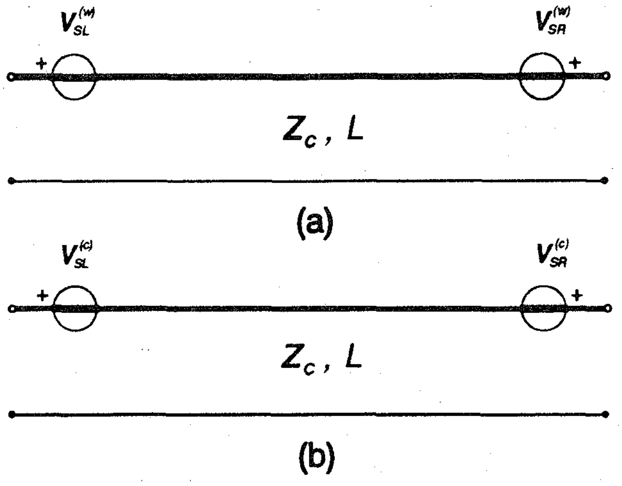

Figure 2: (a) Thevenin equivalent circuit of a MTL excited by an external plane wave. (b) Thevenin equivalent circuit of a MTL excited by a current probe. The thick conductor is an abstract representation of the N separate wires of the MTL; $\boldsymbol{V}_{SL}^{(x)}$, $\boldsymbol{V}_{SR}^{(x)}$, $x = w$, c are vectors of open-end equivalent sources due to the external field and current probe, respectively.

injecting current along the wiring with a toroidal probe; in this case the EUT is excited by injection.

This section is devoted to derive circuit models for the structure of Fig. 1 in the two specific cases of radiation and injection. Throughout the analysis, the multiconductor transmission line (MTL) model is adopted for the system wiring.

In the case of radiation, external interference is modelled as a plane wave, and leads to distributed voltage sources placed along the wiring harnesses. In the case of injection, the circuit model adopted for the disturbance consists of lumped voltage generators located along the line conductors at the same position of the probe [1].

Since the selection of a specific excitation technique (radiation or injection) affects only the source terms placed along the wires, we consider the system wiring detached from EUT and other devices or components, connected at the line ends. We model the wiring harnesses as an excited MTL, for which we derive the Thevenin equivalent circuit. Such circuit is composed by the original MTL used in the system characterization, and by open-end voltage sources.

This approach allows us to get general results, which do not require any assumptions on the EUT. Furthermore, this method allows to compare the effect of radiation and injection only at the line ends, i.e. at the input ports of the EUT. This is not a limitation, since the final goal of BCI testing is reproducing the same current levels determined by radiation at the input pins of the EUT, rather than generating the same current profiles along the wiring.

Figs. 2(a) and 2(b) show the Thevenin equivalent circuits for radiation and injection, respectively.

In Fig. 2(a) symbols $\boldsymbol{V}_{SL}^{(w)}$, $\boldsymbol{V}_{SR}^{(w)}$ represent vectors of the open-end equivalent voltage sources located at left and at right end, respectively; superscript (w) denotes the wave effect. Analytical expressions for such quantities are obtained from the solution of the field-to-wire coupling problem [3]:

$$\begin{aligned}\boldsymbol{V}_{SL}^{(w)} \;\simeq\;& 2E_0(s)h\,\{-G(\theta,\eta)+F(\theta,\psi,\eta)\\ &\cdot\frac{\gamma_0 e^{-\hat{\gamma}_0\mathcal{L}}-\gamma_0\cosh(\gamma_0\mathcal{L})+\hat{\gamma}_0\sinh(\gamma_0\mathcal{L})}{\gamma_0\sinh(\gamma_0\mathcal{L})}\Big\}\,\mathbf{1} \qquad (1)\end{aligned}$$

$$\mathbf{V}_{SR}^{(w)} \simeq e^{-\hat{\gamma}_0 \mathcal{L}} \, \mathbf{V}_{SL}^{(w)\,*} \tag{2}$$

where $\mathcal{L}$ is the line length, $\gamma_0 = jk_0 = j\omega\sqrt{\varepsilon_0\mu_0}$ is the line propagation constant, and $\mathbf{1}$ is an N-dimensional column vector of 1's. In (1) and (2) symbol $*$ denotes complex conjugation, and the following auxiliary quantities have been used:

$$F(\theta,\psi,\eta) = \frac{\cos\theta(\cos\theta\cos\psi\cos\eta + \sin\psi\sin\eta)}{1-\sin^2\theta\cos^2\psi}$$

$$G(\theta,\eta) = \sin\theta\cos\eta$$

In similar fashion, in the Thevenin equivalent circuit of Fig. 2(b) the effect of the current probe is represented by the open-end voltage generators $\mathbf{V}_{SL}^{(c)}$, $\mathbf{V}_{SR}^{(c)}$; superscript (c) stands for clamp. Explicit expressions of such sources are deduced from the solution of the above-described model [3]:

$$\mathbf{V}_{SL}^{(c)} = \frac{\sinh(\gamma_0\mathcal{L}_R)}{\sinh(\gamma_0\mathcal{L})} V_c \, \mathbf{1} \tag{3}$$

$$\mathbf{V}_{SR}^{(c)} = -\frac{\sinh(\gamma_0\mathcal{L}_L)}{\sinh(\gamma_0\mathcal{L})} V_c \, \mathbf{1}, \tag{4}$$

where V_c is the clamp voltage.

III. EQUIVALENCE OF THE TWO EXCITATION TECHNIQUES

Direct comparison of equations (1), (2) with equations (3), (4) proves that, in general, radiation and injection produce different current distributions. However, it has to be noted that, if the final goal is electromagnetic immunity testing of an equipment connected at one end of the line, equivalence of induced current distributions is unimportant. The equivalence of the two excitation techniques has to be ascertained with reference to currents induced at the line terminations, i.e. at the input pins of the EUT.

From a circuit standpoint, this entails that the circuits sketched in Fig. 2(a) and Fig. 2(b) have to be compared, and their equivalence must be stated at the terminal ports. Therefore, the required conditions are

$$\begin{cases} \mathbf{V}_{SL}^{(c)} - \mathbf{V}_{SL}^{(w)} = \mathbf{0} \\ \mathbf{V}_{SR}^{(c)} - \mathbf{V}_{SR}^{(w)} = \mathbf{0} \end{cases} \tag{5}$$

where $\mathbf{0}$ is the null column vector with dimension N.

Imposing equivalence between injection and radiation requires to satisfy two independent conditions, in order to find the clamp voltage V_c which simulates the effect of the external wave. However, solution of equations (5) would produce two different expressions for the clamp voltage. Hence, (5) cannot be satisfied, at least in the general case.

Special cases exist in which, due to specific choices of the external wave parameters and clamp position, equations (5) merge into a single condition and lead to a unique solution [3].

In order to address the general case, the restriction of employing only one current probe has to be released. In particular, it is possible to show that if two injection probes are used, equations (5) accept general solution.

If probes are placed at distances $\mathcal{L}'_L$ and $\mathcal{L}''_L$ from the left end of the line, and if probe voltage sources are denoted by V'_c and V''_c, from (5) we get

$$\begin{pmatrix} V'_c \\ V''_c \end{pmatrix} = D(\gamma_0)$$

$$\cdot \begin{bmatrix} -\sinh(\gamma_0\mathcal{L}''_L) & -\sinh(\gamma_0\mathcal{L}''_R) \\ \sinh(\gamma_0\mathcal{L}'_L) & \sinh(\gamma_0\mathcal{L}'_R) \end{bmatrix} \cdot \begin{pmatrix} V_{SL}^{(w)} \\ V_{SR}^{(w)} \end{pmatrix} \tag{6}$$

where

$$D(\gamma_0) =$$

$$\frac{\sinh(\gamma_0\mathcal{L})}{\sinh(\gamma_0\mathcal{L}''_R)\sinh(\gamma_0\mathcal{L}'_L) - \sinh(\gamma_0\mathcal{L}'_R)\sinh(\gamma_0\mathcal{L}''_L)}$$

and symbols $V_{SL}^{(w)}, V_{SR}^{(w)}$ denote the entries of the vectors of the open-end voltages given in (1) and (2), respectively.

This is a general result which states the equivalence between radiation by an arbitrary impinging plane wave and injection by two current probes placed along the line. Notice that equation (6) states the equivalence of the two excitation techniques, independently of the termination networks which are connected at the line ends.

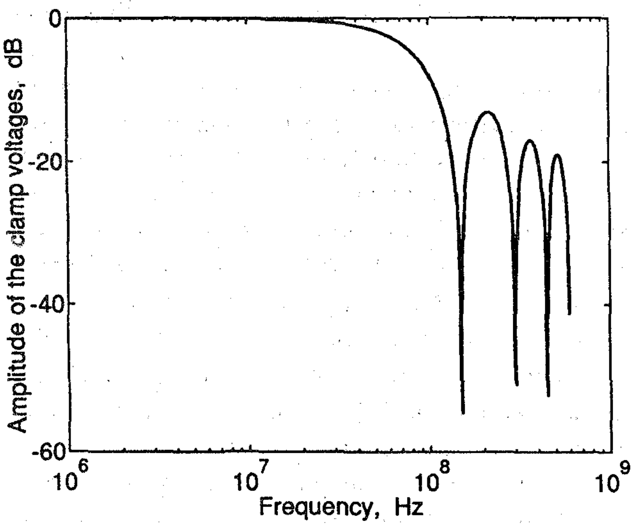

Figure 3: Frequency plot of the magnitude of the clamp voltages needed to simulate the effect of a wave characterized by $E_0 = 1$ V/(m×Hz), $\theta = 90°, \psi = 90°, \eta = 0°$ The voltage curves are coincident due to the symmetrical location of the clamps.

As an example, in Fig. 3 the magnitude of the clamp voltages needed to reproduce the effect of a specific wave are plotted. The simulated wave is characterized by $E_0 = 1$ V/(m×Hz), $\theta = 90°, \psi = 90°, \eta = 0°$. The length of the wire bundle is $\mathcal{L} = 2$ m, its height above ground is $h = 5$ cm. The two clamps are supposed to be placed at $\mathcal{L}'_L = 0.9$ m and $\mathcal{L}''_L = 1.1$ m from the left end, respectively. The choice of symmetrical clamp positions allows equal magnitudes for the clamp voltages, and phases differing by 180°.

In this specific case, the frequency behavior of the injection probe voltages is rather regular, and it seems to be possible to implement. However, extensive simulations of different interfering waves show that there are cases in which the equivalence implies to control the injection clamps with complicated frequency-dependent voltages. Hence, although from the theoretical point of view injection by means of two current probes allows equivalence with any radiated plane wave excitations, in practice difficulties still remain in controlling the probe voltages in order to match the incident field characteristics [4].

V. CONCLUDING REMARKS

In this work, radiation and injection on a wire bundle have been analytically compared. We have found that stating the analytical equivalence implies controlling the injection probe with a voltage depending on several parameters. Moreover, we have shown that one injection probe is not sufficient to assure the equivalence in the general case, but it is possible to achieve this result by employing two injection probes.

Unfortunately, due to the complexity of the frequency-dependent weighting functions needed to modulate the injected power, realization of a BCI measurement that satisfies the equivalence conditions derived in this paper is difficult. The use of computer-driven power generators feeding the probes can make the measurement possible at least in some cases [4], however in practice difficulties are to be expected.

The results obtained are relevant to ascertain if BCI test procedures are adequate for the susceptibility assessment of electronic equipment.

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