SPICE Modeling of BCI Probes Accounting for the Frequency-Dependent Behavior of the Ferrite Core

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Abstract

In this paper, SPICE behavioral modeling of injection probes for bulk current injection (BCI) is addressed. The implementation procedure is based on preliminary experimental characterization of the frequency response of the probe core via measurement of the probe input impedance. Two alternative solutions are proposed for the inclusion of frequency-dependent core-related effects. The first solution directly embeds measurement data of the effective permeability spectra of the ferrite core in a SPICE behavioral module; an alternative solution employs a Lorentzian model. Models accuracy and effectiveness are assessed by comparing SPICE predictions of a simplified BCI setup with experimental measurements.

1. Introduction

Over the past twenty-year period, the bulk current injection (BCI) technique has gained great attention due to its simplicity and cost-effectiveness, especially in the industry sectors involving EMC testing of large and complex systems (e.g., the automotive and the aerospace sector). In particular, in recent years the research activity on BCI has concentrated on the following twofold challenge: a) improvement of BCI test reliability by unambiguous correlation of the radio frequency (RF) signal levels used to feed the injection device with the actual noise currents injected into the terminal networks of the wiring harness under the injection probe [i.e., the equipment under test (EUT)], b) investigation of the possibility to design novel test procedures, based on BCI, able to reproduce in the EUT the same (or similar) interference levels induced by radiated susceptibility test procedures. In this context, and in line with the above-mentioned objectives, characterization of the injection phenomenon via accurate modeling of the injection devices is a basic prerequisite. To this end, a lumped-parameter circuit model for injection probes for BCI was recently developed and successfully assessed [1]. The model, based on a preliminary experimental characterization of the probe, has the advantage of accounting for all the relevant phenomena involved in the injection of RF onto a wiring harness. In particular, the frequency-dependent effects due to losses and dispersive phenomena occurring within the ferrite core (which play a role of paramount importance in the probe behavior) are embedded in the model via complex frequency-dependent coupled inductances.

In order to achieve effective circuit simulation of entire and complex BCI setups, this paper explores the possibility of probe model implementation in the SPICE environment [2]. In particular, it is shown that direct implementation in SPICE of the lumped-parameter probe circuit model developed in [1] is straightforward by resorting to suitable behavioral modules available in the SPICE environment. Two possible implementation procedures are presented. One procedure directly embeds measurement data of the effective permeability spectra of the ferrite core (preliminary obtained via measurement of the probe input impedance), and resorts to the **`GFREQ`** module of SPICE. The other employs a Lorentzian model for approximate reconstruction of the permeability spectra, and exploits the **`GLAPLACE`** module of SPICE. The SPICE models are validated by comparing predictions with experimental data (scattering parameters) measured at the output ports of an idealized injection setup. Both the implementation procedures prove to be simple, accurate and effective in predicting the injected RF currents/voltages, in the frequency band of interest for BCI. The SPICE modeling procedures proposed in this paper are physically sound, make the identification of model parameters easier, and improve the accuracy of predictions with respect to a previous SPICE model [3], involving manually adjusted frequency-dependent resistors.

2. Probe Model Description

This section details the derivation of a probe circuit model which allows for implementation in the SPICE environment. The starting point is the lumped-Pi network developed in [1] (see Fig. 11), in which: a) the parameters L_N, C_N are associated with the probe input connector, b) the parameters L_{W1}, C_{W1} account for propagation effects along the inner winding, and c) the coupled inductances $\hat{L}_1(\omega)$, $\hat{L}_2(\omega)$ represent inductive coupling between the conductor wound around the probe core and the clamped wire. Such inductances take complex and frequency-dependent values, due to dispersion and losses in the ferrite core. Estimation of $\hat{L}_1(\omega)$, $\hat{L}_2(\omega)$ can be done experimentally by resorting to probe input impedance measurement (in the absence of the clamped circuitry). In the probe model, magnetic coupling is described by the two-port network in Fig. 1(a), whose port constraints are [1]:

$$\begin{cases} V_1 = j\omega\hat{L}_1(\omega)\cdot I_1 + j\omega\hat{M}(\omega)\cdot I_2 \\ V_2 = j\omega\hat{M}(\omega)\cdot I_1 + j\omega\hat{L}_2(\omega)\cdot I_2 \end{cases}, \tag{1}$$

where

$$\hat{L}_1(\omega) = N_1^2 / \hat{\Re}(\omega), \quad \hat{M}(\omega) = N_1 N_2 / \hat{\Re}(\omega), \quad \hat{L}_2(\omega) = N_2^2 / \hat{\Re}(\omega) + L_{2d}, \tag{2}$$

and N_1 denotes the number of turns of the primary winding of the probe, whereas the secondary winding (i.e., the clamped wiring) is characterized by a number of turns N_2 = 1. In (2), L_{2d} represents the leakage inductance associated with the secondary winding, and $\hat{\Re}(\omega)$ is the complex reluctance of the ferrite core. Such a quantity depends on the geometrical and physical characteristics of the probe core, and takes the expression: $\hat{\Re}(\omega) = \Re_0 / \hat{\mu}_r(\omega)$, where $\Re_0$ is the reluctance that would be measured if the ferrite core had unity permeability, under the condition that flux distribution remains unaltered, and $\hat{\mu}_r(\omega) = \mu_r'(\omega) - j\mu_r''(\omega)$ denotes the complex relative permeability of the core.

For model implementation in SPICE, the alternative two-port representation in Fig. 1(b) is preferable, for reasons that will be made clear in the following. Port constraints associated with such a structure are derived by direct substitution of (2) into (1) and can be cast in the form

$$\begin{cases} I_1 = -j[\omega\hat{L}_1(\omega)]^{-1}\cdot V_1 - 1/N_1\cdot I_2 = I_1' + I_1'' \\ V_2 = 1/N_1\cdot V_1 + j\omega L_{2d}\cdot I_2 = V_2' + V_2'' \end{cases}. \tag{3}$$

Reasons that make port constraints in (3) preferable to those in (1) are twofold. First, in (3) the frequency-dependent phenomena due to the core are described by only one parameter [i.e., the self-inductance $\hat{L}_1(\omega)$]. Second, this formulation fits the characteristics of specific behavioral models available in SPICE, which allow for the representation of frequency-dependent transfer functions by resorting to voltage-controlled voltage sources (VCVS) or voltage-controlled current sources (VCCS), [2, Ch. 6]. Accordingly, the frequency-behavior of the inductance $\hat{L}_1(\omega)$ is preliminary obtained from measurement data, and subsequently included into the SPICE model of the probe by means of a VCCS with transfer function $I_1'/V_1 = -j/[\omega\hat{L}_1(\omega)]$.

3. Model Implementation in SPICE

In this section, model implementation in SPICE is described. As a practical test case for model validation, one of the *ad hoc* fixtures developed in [1] was used. The fixture is composed of a wire parallel to ground with end-points welded to SMA connectors fastened to bulkhead adapters, mounted on rectangular-shape vertical metallic strips. The SPICE schematic modeling the injection probe mounted in the validation fixture (Fig. 3) is reported in Fig. 4. Central blocks (from top to bottom) are used to model: a) the RF generator feeding the probe, b) the BCI probe (the label "inductive coupling" is used to denote the two-port network responsible for frequency-dependent inductive coupling), and c) the portion of clamped conductor under the probe. Lateral blocks are associated with the effects due to: a) the portions of clamped wire by the sides of the probe (modeled as transmission line sections), b) the connectors and the vertical strips at the fixture ends, and c) the terminal loads.

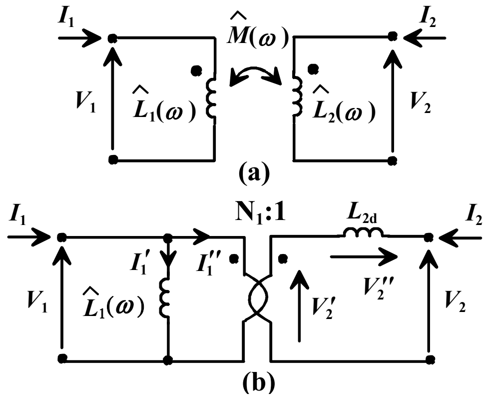

Fig. 1. Alternative two-port network representations used to model inductive coupling: (a) model adopted in [1], (b) equivalent representation used for SPICE implementation.

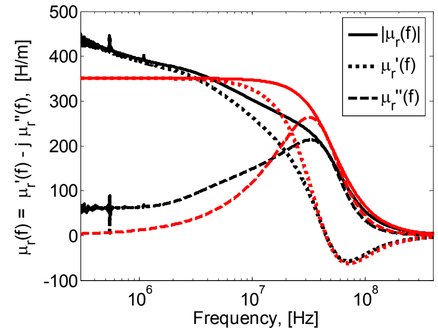

Fig. 2. Complex permeability spectra of the ferrite core.

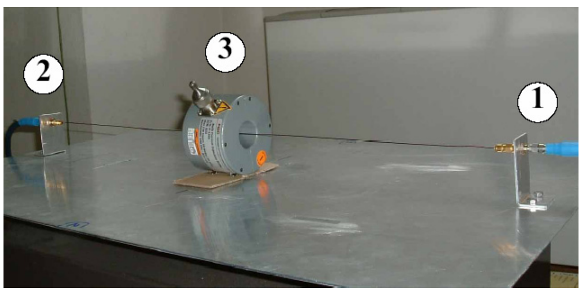

Fig. 3. Experimental setup used for validation purposes.

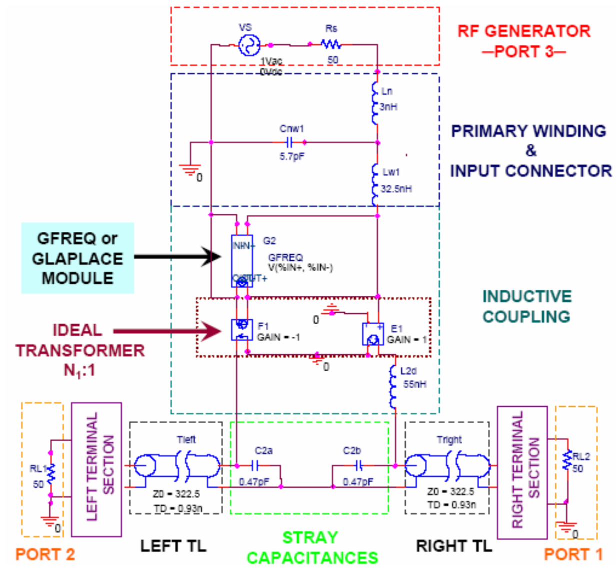

Fig. 4. SPICE schematic of the BCI setup in Fig. 3.

As regards the block which describes the inductive coupling, the following comments are worth of note. A VCVS (**E1**) with gain $1/N_1$ and a current-controlled current source (**F1**) with gain $-N_1$ were used for modeling the ideal transformer in Fig. 1(b). Two different solutions are proposed for inclusion in the SPICE model of the frequency-dependent effects due to the ferrite core. The first solution is based on the use of **GFREQ** module, [2, Ch. 6]. This is a VCCS used to reproduce the transfer function $I_1'/V_1 = -j/[\omega\hat{L}_1(\omega)]$ by means of a look-up table, reporting the amplitude and phase of the ratio I_1'/V_1 frequency by frequency. To this end, the complex inductance $\hat{L}_1(\omega)$ is preliminary obtained by substituting in (2) the effective permeability spectra extracted from measurement data (via the de-embedding procedure in [1]). The second solution makes use of the **GLAPLACE** module, and requires an analytical expression for the description of the frequency behavior of the probe core. To this end, a Lorentzian model is adopted in order to provide an approximate representation of the spectra of the effective permeability. Accordingly, $\hat{\mu}_r(\omega)$ is approximated by $\hat{\mu}_r(\omega) \cong \hat{\mu}_{Lorentz}(\omega) = 1 + A\omega_0^2/(s^2 + s\Delta\omega + \omega_0^2)$. For the case at hand (probe FCC F-130A), suitable values of parameters A, ω_0, and $\Delta\omega$ result to be: $A = 350$, $\omega_0 = 280$ Mrad/s and $\Delta\omega = 440$ Mrad/s. In Fig. 2, the complex permeability spectra evaluated via the Lorentzian model (red curves) are compared with the spectra obtained from measurement data (black curves). According to the theory, the Lorentzian model proves to be effective at high frequencies, where a dimensional resonance occurs, and poor at low frequencies, where dispersive phenomena are dominant and the use of a Debye model would be preferable.

4. Validation of the SPICE Models

In order to validate the proposed SPICE models, the injection probe FCC F-130A was mounted in the validation fixture in Fig. 3 (fixture length is $\mathscr{L}$= 62 cm). The overall structure was characterized experimentally at

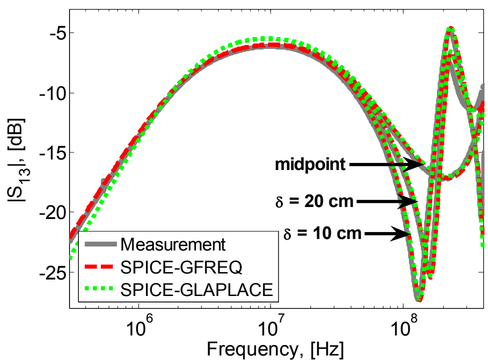

Fig. 5. Magnitude of S_{13} for different positions of the probe.

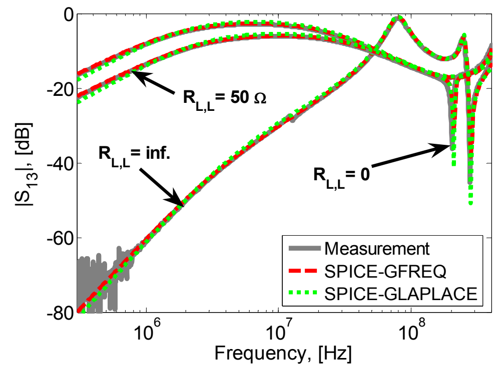

Fig. 6. Magnitude of S_{13} for different loading conditions.

the ports in terms of scattering parameters. A selection of plots comparing measurement data and predicted values is reported in Fig. 5 and Fig. 6. These curves represent the transmission coefficient between port 3 and port 1 (S_{13}) in Fig. 4 in the case of: a) different positions of the probe along the clamped wire (Fig. 5, where δ denotes the distance of the probe from port 1), and b) different values of the terminal load attached to port 2 (Fig. 6). The gray curves represent measurement data, the red curves are SPICE predictions obtained following the first modeling approach (**GFREQ** module), whereas the green curves are obtained by resorting to the second approach (**GLAPLACE** module). Both the SPICE models provide accurate predictions of the scattering parameters measured at the setup ports. In particular, it is worth noticing that also the use of **GLAPLACE** module (green curves) leads to fairly precise predictions, even though the Lorentzian model provides only an approximate representation of the permeability spectra extracted from measurement data (see Fig. 2).

5. Conclusion

In this paper, we have investigated possible solutions for the development of SPICE models for injection probes for BCI. In particular, two alternatives have been identified, that differ for the way in which the frequency response associated with the ferrite core of the probe (preliminary characterized via measurements [1]) is embedded in the SPICE model. The first approach makes direct use of measurement data of the effective permeability spectra, and exploits the **GFREQ** module for SPICE implementation. The second approach employs a Lorentzian model for approximate reconstruction of the permeability spectra, and exploits the **GLAPLACE** module. SPICE predictions were compared with experimental data (scattering parameters) measured at the output ports of an idealized injection setup. Both the SPICE implementations prove to be accurate and effective in the prediction of the injection phenomenon. The modeling procedure proposed in this paper overcomes limitations of previous SPICE models of injection probes, and is suited for model extension to the practically relevant case of injection devices clamped onto multi-wire bundles. The basis for such an extension is the replacement of the inductive two-port element in Fig. 1(b) with an inductive multi-port network, likewise in [4].

6. Acknowledgments

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7. References

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