Elektrotechnik

Torben Wendt

Hybrid Simulation of Multiport Structures for Diode Based Shielding Applications

SHAKER
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Summary

This thesis presents computational techniques applicable to the modeling of the interaction between transient electromagnetic fields and nonlinear circuits. Adopting the proposed methods, practical applications of nonlinear field-circuit interaction are studied. The numerical results are compared against commercial grade full wave solvers, yielding excellent agreement and validating the proposed approach. Generally, the herein investigated problems consist of electromagnetically large structures, meaning that wave effects have to be considered in order to obtain accurate models. Connected to the structures are lumped, nonlinear circuit elements, which interact with voltages and currents induced by either external excitations, in the form of plane waves, or internal excitations, in the form of transient voltage sources. The herein adopted modeling approach is of hybrid nature and exploits that the compound system can be decomposed into a linear part, capturing the wave effects, and a nonlinear part, describing the nonlinear properties of the lumped elements. Using an iterative solver based on Waveform Relaxation, the voltages and currents are computed at the interfaces of the subsystems, making use of numerically efficient formulations of both the linear macromodels and the nonlinear circuit elements. The presented method is used to model *i)* perfectly conducting boxes with nonlinear diode shields across apertures under transient illumination, *ii)* signal integrity impairments of transient voltage suppressor diodes on low voltage differential signals and *iii)* electrostatic discharge events in power delivery networks on printed circuit boards. The presented method is validated against commercial full wave solvers as well as state of the art circuit solvers, showing excellent accuracy and a decrease in computational cost for the investigated examples. Using the proposed method, parameter sweeps are performed in order to gain a better understanding of the physics in the novel field of nonlinear shielding. Investigations are carried out for different terminations, excitations and levels of complexity for structures loaded with up to 100 ports.

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Contents

Acronyms

BEM	boundary element method
CEM	computational electromagnetics
DC	direct current
DFG	German Research Foundation
EDA	electronic design automation
EFIE	electric field integral equation
EM	electromagnetic
ESD	electrostatic discharge
FC	flip-chip
FD	frequency domain
FDTD	finite-difference time-domain method
FEM	finite-element method
FFT	fast Fourier transform
FIR	finite impulse response
FIT	finite integration technique
HB	harmonic balance
HIRF	high intensity radiated field
IDD	iteration dependent decoupling
iFFT	inverse fast Fourier transform
IIR	infinite impulse response
LEMP	lightning electromagnetic pulse
LTI	linear time invariant
LVDS	low voltage differential signaling
MoM	method of moments

MOR	model order reduction
MTL	multiconductor transmission line
NEMP	nuclear electromagnetic pulse
NRMSD	normalized root mean square deviation
PAM	pulse-amplitude modulation
PCB	printed circuit board
PDN	power delivery network
PEC	perfectly electrically conducting
PEEC	partial element equivalent circuit
PI	power integrity
PML	perfectly matched layer
PRBS	pseudorandom binary code
PWL	piecewise linear
RMSE	root mean square error
SE	shielding effectiveness
SF	shielding factor
SI	signal integrity
SVD	singular value decomposition
TD	time domain
TDIE	time domain integral equation
TLM	transmission line modelling
TVS	transient voltage suppressor
VF	vector fitting
VLSI	very large scale integration
VNA	vector network analyzer
WR	waveform relaxation

Notation

$\mathrm{X}(s)$	Macromodel in Laplace domain
$\mathcal{X}(j\omega)$	Continuous transfer function
$\breve{\mathrm{X}}(j\omega_n)$	Discrete transfer function
$\breve{\breve{\mathrm{X}}}(j\omega_n)$	Delayed discrete transfer function
$\bar{\mathrm{x}}(j\omega)$	Delayed continuous transfer function
$\mathrm{x}(t)$	Macromodel in time domain
$\overline{x}$	Complex conjugate
$a * b$	Convolution
$a \circledast b$	Recursive convolution
$a \star b$	Discrete convolution
$\mathrm{diag}\{\boldsymbol{X}\}$	Diagonal of matrix
$\mathcal{L}\{\cdot\}$	Laplace transform
$\boldsymbol{X}$	Matrix
$\sigma(\boldsymbol{X})$	Singular values of $\boldsymbol{X}$
x	Scalar
$\boldsymbol{X}^{\mathsf{H}}$	Hermitian matrix
$\boldsymbol{X}^{\mathsf{T}}$	Transpose matrix
$\boldsymbol{x}(t)$	Vector-valued signals or matrix-valued operators in time domain (TD)
$\boldsymbol{X}(s)$	Vector-valued signals or matrix-valued operators in frequency domain (FD)
$\mathcal{O}(\cdot)$	Bachmann–Landau notation or asymptotic notation

List of Symbols

c_0	Speed of light in vacuum
$\mathcal{E}_{\mathrm{inc}}(t)$	Incident electric field waveform
$\vec{\mathcal{E}}_{\mathrm{obs}}(t)$	Observed electric field
$\mathcal{E}^{\mathrm{x}}_{\mathrm{obs}}(t)$	Component of electric field
k	Excitation index
K	Number of excitations
n	Frequency index
N	Number of frequency samples
o	Observer index
O	Number of observers
p	Port index
P	Number of ports
ν	Iteration index
mod	Modulo operator
$\Re(\cdot)$	Real part of complex argument
$\Im(\cdot)$	Imaginary part of complex argument
$\mathbb{R}$	Real numbers
$\mathbb{C}$	Complex numbers
$\mathbb{N}$	Natural numbers
ω	Angular frequency
$\mathbf{S}$	Scattering parameters
$\mathbf{Y}$	Admittance parameters
$\mathbf{Z}$	Impedance parameters
$\mathcal{G}(\cdot)$	Nonlinear scattering wave relationship

$\mathcal{N}(\cdot)$	Nonlinear voltage-current relationship
B	Plane wave to port voltage coupling
C	Port voltage to electric field coupling
D	Plane wave to electric field coupling
$a(t)$	Incident voltage scattering wave
$b(t)$	Reflected voltage scattering wave
$\theta(t)$	Scattering source term
$i_{\mathrm{sc}}(t)$	Short circuit current
$i(t)$	Port current
$v(t)$	Port voltage
$v_{\mathrm{oc}}(t)$	Open circuit voltage
$_{\mu}$	Reference resistance
μ	Reference resistance index
$\boldsymbol{S}_{\mu}$	Scattering parameters referenced to R_{μ}
$\vec{\kappa}$	Propagation direction or normalized wave vector ($\lvert\vec{\kappa}\rvert = 1$)
$\vec{\boldsymbol{r}}_o$	Observer location
r_{ph}	Radius of phase reference sphere
τ	Time delay
δ_t	Time step