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SPICE-compatible nonlinear macromodels for fast Power Integrity verification

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***Abstract*—We present a SPICE-compatible frequency-domain macromodeling method that extends the well-known Vector Fitting algorithm to systems that exhibit weakly nonlinear behavior. The models are specifically developed to speed up the transient simulations required for Power Integrity verification of electronic systems equipped with voltage regulators.**

I. Introduction

Transient simulation is crucial for performance verification in Signal and Power Integrity (SI/PI) analyses. The high complexity of systems in the heterogeneous integration era implies an ever-increasing computational cost, especially for PI analyses. This motivation led to the widespread adoption of compact macromodels in commercial tools. Macromodels are typically applied to represent parasitics and resonances of signal and power interconnects, with a very common flow based on the application of the Vector Fitting (VF) [1] algorithm to sampled frequency responses from field solvers.

This work presents an extension of VF to a particular class of nonlinear systems which includes several components and subsystems typically found in voltage-regulated Power Distribution Networks (PDN). Following [2], we show that nonlinear macromodels can be easily extracted and synthesized as SPICE equivalents for fast PI verification, with a significant speedup in runtime.

II. Methodology

The proposed approach is based on fitting the responses of a given component under steady-state periodic conditions. This data can be computed using Harmonic Balance (HB) analysis in commercial solvers. The input-output system behavior is represented through low-order Volterra kernels [3], which are approximated in the frequency domain by multivariate rational functions [2]. A recursive multivariate VF extension computes poles and residues, and a nonlinear state-space system in form

$$\dot{\boldsymbol{x}}(t) = \mathbf{A}\boldsymbol{x}(t) + \mathbf{N}\boldsymbol{x}(t)u(t) + \mathbf{B}u(t), \quad y(t) = \mathbf{C}\boldsymbol{x}(t) \quad (1)$$

is constructed as in [2] and synthesized as a SPICE equivalent via an extension of the techniques presented in [4]. In (1), the input and output signals are u and y, while $\boldsymbol{x}$ are the macromodel states; nonlinearity is encoded by the matrix $\mathbf{N}$.

III. Numerical results and conclusions

The proposed method is illustrated on a PDN whose voltage is stabilized by a Low DropOut (LDO) regulator (Fig. 1). A nonlinear macromodel of the relation between the load current $i_L(t)$ excitation and the load voltage $v_L(t)$ response

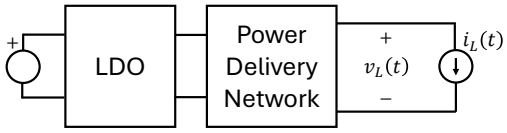

Fig. 1. Block diagram of the test device: an LDO loaded with a PDN.

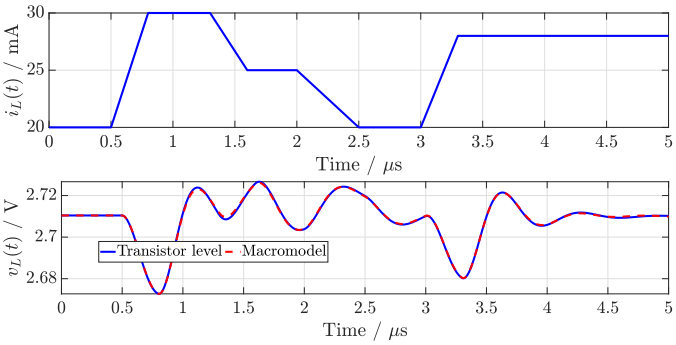

Fig. 2. Time-domain simulation of the nonlinear device in Fig.1. Top: load current signal (input). Bottom: Load voltage responses computed by HSPICE.

was constructed by first computing via HB the periodic responses excited by up to three tones on input, and then applying the proposed multivariate VF extension and nonlinear synthesis. Fig. 2 shows that, for a given load current signal (top), the macromodel response closely matches the transistor-level reference (max error: 1.2 mV). The HSPICE runtime is reduced from 26.1 s to 2.1 s, with a speedup larger than 12×. Due to its generality and rigorous mathematical formulation, we believe that this approach has a large potential to become a standard tool in several numerical verification flows for SI/PI.

Take-home messages

- Extension of Vector Fitting to nonlinear circuits and systems.
- Automated macromodel extraction from frequency data.
- SPICE-ready for fast transient Power Integrity analyses.

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