A Higher Order Convergent (in Time) Self-Consistent Electromagnetic-Circuit Coupled Solver

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Numerical simulation of electromagnetic systems is a staple of the modern engineering design process. Electromagnetic coupling into circuit systems is an important problem in electromagnetic compatibility analysis, signal integrity, and antenna design. A common approach to solving these problems is coupling a circuit-level modified nodal admittance (MNA) system with either a finite element (FE) or an integral equation (IE) formulation of the electromagnetic problem. Much work has been done on coupling MNA systems with both time-domain integral equations (TDIE) and frequency-domain integral equations (FDIE) and solving the coupled EM and circuit systems self-consistently (Aygun, K, *A Fast Hybrid Field-Circuit Simulator for Transient Analysis of Microwave Circuits*, IEEE Trans. on Microwave Theory and Techniques Vol. 42, No. 2, 2004). The frequency domain methods have also seen extraction of equivalent circuit parameters. A principal advantage of TDIE based solvers is the possibility of including non-linear elements in the simulation.

However, one of the bottlenecks that has hampered the viability of TDIE based solvers is late time stability. Stability is an especially important factor in nonlinear coupled systems due to higher order harmonics that can be be generated. While methods have been proposed to ameliorate the effects by choosing higher order polynomial basis functions, bandlimited basis functions, low pass filters, etc., these methods essentially delayed the onset of instability but did not cure it. The cause of instability is well understood, and a method to overcome this is to use exact evaluation of integrals (B. Shanker, *Time Domain Integral Equation Analysis of Scattering from Composite Bodies via Exact Evaluation of Radiation Fields*, IEEE Trans. on Antennas and Prop., Vol. 57, No. 5, May 2009). This approach is computationally challenging and not viable. An alternate approach was presented in (Pray, *A Higher Order Space-Time Galerkin Scheme for Time Domain Integral Equations*, IEEE Trans. on Antennas and Prop., Vol. 62, No. 12, 2014). This method was shown to be stable for a range of challenging and complex targets (e.g., analysis of scattering from a VFY218 using the electric field integral equation) as well as higher order convergent.

In this paper, we propose to develop a self-consistent coupled electromagnetic-circuit solver that leverages our TDIE stabilization procedure. Our goal is to test the method for a variety of nonlinear elements to determine robustness and stability of the resulting algorithm.