SPICE-Compatible Stamps for Semi-Discrete Approximations of Maxwell's Equations

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Abstract

In order to provide for concurrent electromagnetic/circuit simulation, most hybrid, time-domain electromagnetic/circuit simulators utilize the discrete electromagnetic model, resulting from the spatial discretization of Maxwell's equations on a finite difference or finite element grid, for the incorporation of lumped circuit element-based models of electronic devices and/or electrically-small passive electrical components. In such a modeling approach, the electromagnetic field solver becomes the underlying simulation framework, with the voltage/current state variables in the non-linear system of time-domain equations governing the behavior of the lumped circuit components being interfaced with the discrete electric and magnetic fields in the grid through appropriately-defined line integrals.

While such an approach is most appropriate for those cases for which the lumped (circuit) components constitute an electrically-small portion of the overall electromagnetic structure of interest, the reverse approach, namely, the incorporation of a semi-discrete electromagnetic model for a portion of the structure under investigation inside a circuit-based model of the structure is also useful, particularly in relation to the modeling of multi-physics phenomena involving multiple spatial scales of large disparity.

To provide for the incorporation of the semi-discrete (state-space) model, resulting from the spatial discretization of Maxwell's equations in general-purpose, non-linear circuit simulators such as SPICE, we have developed a methodology that leads to the representation of the semi-discrete systems in terms of stamps for the differential equations governing the temporal evolution of the discrete electric and magnetic field components. Of particular interest is the case where a uniform, rectangular Yee's lattice is utilized for the discretization of the curl operators in Maxwell's equations. For such a grid, the stamps assume fairly simple forms, and can be expressed in terms of lumped circuit elements, coupled inductors and dependent sources.

The presentation will consist of an explanation of the methodology used for the development of the stamps and the validation of the resulting SPICE-compatible description of the semi-discrete electromagnetic system. In particular, it will be shown that there is a very close relationship between Maxwell's curl equations and the mesh analysis formalism of Kirchhoff's equations which can be readily utilized for identifying the appropriate state variables to be used for the SPICE-compatible description of the semi-discrete (state-space) form of Maxwell's equations.