# PEEC Development Road Map 2007

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***Abstract*— A road map for the long term development of the partial element equivalent circuit (PEEC) method is presented. Emerging areas are pointed out together with a solution strategy. Special attention is given to speed up approaches, mesh generation, and time domain stability. The purpose with the road map is to facilitate a unified development of the method into an electromagnetic modeling method suitable for incorporation in integrated analysis tools for engineers for electromagnetic compatibility and electromagnetic interference purpose.**

## I. INTRODUCTION

For a couple of years IBM T. J. Watson Research Center, NY, USA [1], Univ. of L'Aquila, Italy [2], and Luleå Univ. of Technology, Sweden [3] have cooperation concerning electromagnetic (EM) modeling based on the PEEC methodology [4]-[6]. The long term target have been the development of the PEEC method to enable complex EM modeling of modern electronic problems encountered by the industry. The modeling approach is PEEC, one of the most fast growing EM modeling method within the field of electromagnetic compatibility (EMC), electromagnetic interference (EMI), electrical interconnect problem (EIP), and signal integrity (SI).

To encourage research on the PEEC methodology a road map for the future development of PEEC is proposed. The road map intention is to identify emerging areas for future research within PEEC and propose direct solutions or indicate directions that will move PEEC simulations to become a tool that seamlessly integrates with SPICE - like [7] circuit simulators, thus allowing a widespread use within the community of electrical engineers both for EMC and EMI problems as well as for other type of wave based problems.

Today the PEEC method is used both within research and product testing, simulation, and development. The activity at companies are lead by the research and development performed at IBM T. J. Watson Research Center [1] where the method was originally developed. Other companies developing PEEC based electromagnetic modeling tools are:

- Advanced EMC Solutions software. The StatMod program for modeling three-dimensional layout structures of PCB and IC designs; [8],
- Applied Simulation Technology. Program for analysis of PCBs, MCMs, and packages [9];
- SimLab Software GmbH. The software PCBMod used for modeling SI, EMC, and EMI effects for high speed digital, analog / mixed signal, or power supply designs; [10],
- AnSoft Corporation. The program TPA for the analysis of semiconductor packages using multipole-accelerated PEEC and model-reduction for simulations of high-speed traces. [11].

And research performed at universities includes for example:

- Prof. J. Drewniak at University of Missouri-Rolla, MO, USA [12],
- Prof. C. Schuster at Hamburg University of Technology, Germany [13],
- Prof. A. Cangellaris at University of Illinois at Urbana-Champaign [14],
- Prof. G. Wollenberg at Otto-van-Guericke University of Magdeburg Institute for Fundamental Electrical Engineering and Electromagnetic Compatibility [15],
- Prof. C. Paul at Mercer University Department of Electrical and Computer Engineering [16].

## II. CURRENT STATUS OF PEEC MODELING

The PEEC approach has evolved over the years with a focus toward EMI and EIP problems. In the beginning, full wave solutions were not necessary for many aspects of the problems and the quasi-static solutions were used. They are still in use, for capacitance [17] and inductance [18] problems. With the increase in the speed and frequency ranges of the VLSI chips, higher frequency solutions became necessary. This made the use of more consistent models necessary and many variants of PEEC models were devised for applications including:

- dielectric PEEC models [19],
- multi-layer power plane modeling [20],
- analysis of embedded passives such as spiral inductors [21],
- SPICE 3f4-based full-wave modeling [22],
- modeling of multi-chip modules [23],
- power-bus structure modeling including discontinuities [24].

A clear and easy notation has been devised to differentiate between the many different possible PEEC models. As an example, the notation $(L_p, P, R, \tau)$PEEC means that the model includes partial inductance $L_p$, coefficients of potential $P$, resistance $R$, and delays $\tau$. For a specific situation, other combinations of elements may be more suitable. This systematic model complexity reduction is unique for PEEC and offers great flexibility in the model creation process.

One of the major benefits is that the PEEC method can be applied in both the time and the frequency domain very much like a typical SPICE type circuit solver where the option *.ac* leads to a frequency domain analysis while *.tran* corresponds to a time domain analysis. Time domain models are used extensively for modeling VLSI circuits and chips while frequency domain models are used for RF type applications. Further, the time domain solution is more efficient than the frequency counterpart since the time delay sparsify the solution coefficient matrix thus enabling faster solution of the EM problem.

The newly introduced nonorthogonal PEEC formulation [25] improves EM modeling for complex structures by allowing quadrilateral and hexahedral elements in the meshing process. This method extension opens up new application areas including resonant cavity (cylindrical and spherical) and conformal antenna analysis and forms the basis for future research areas and collaborative efforts.

Equivalent circuit based approaches to model sound and thermal propagation have been made. In acoustics we find 1D work on acoustic transducers and wave propagation [26]-[28]. For modeling thermal propagation, standard RC-type circuits have been extensively used. heat problem not very much circuit based work is made so far. The modeling of Joule heating has been discussed [29], [30] and very recent combined with a PEEC solution [31].

## III. Vision

We propose a vision for the long term research and development of the PEEC method into a complete modeling methodology for wave based phenomenon. Thus PEEC will be capable of full wave solution for wave based problems in electromagnetics, acoustics, and heat. The result will form a PEEC based simulation technology feasible for industrial applications. It is projected that this will fully integrate into a SPICE-like environment. A suite of tools will emerge that make integration between a physical world modeling and electronics modeling feasible. Thus problems ranging from basic EMC, EIP, SI at circuit level to physically large electronic structures like general power distribution systems will be addressable. Further combined wave problems where optics, acoustics, and heat problems are integrated with electronics will be possible to handle.

## IV. Basic PEEC method development

PEEC is still in an early development phase compared to many other EM simulation methodologies. To enable usage for different applications more development is needed. Further additions of other field parameters like acoustics, optics and heat will introduce new possibilities. In all these cases a number of basic problem areas related to the PEEC methodology can be identified. We will here identify such areas and discuss possible approaches for their solution.

### *A. Emerging areas*

To reach the stated vision, a number of developments are needed. We here list a number of basic challenging areas for the PEEC methodology. These are identified as important for PEEC to become a robust and easy applicable tool for different applications. The identified areas are:

1) speed up of PEEC based EM modeling thus enabling analysis of electrically large problems;
2) development of mesh generators and strategies taking to account PEEC specific behavior enabling increased accuracy and speed,
3) development of PEEC based hybrid methods;
4) techniques to improve stability and accuracy;
5) development of a suite of PEEC based tools seamlessly integrate into a SPICE-like environment.

Each of these areas where more development is needed will be detailed below. For each of the identified areas a number of attractive solution routes have been identified. These are:

*1) Speed up of PEEC based solvers:* The computational complexity of PEEC based solvers makes problems larger than 10 000 nodes to be impractical even on larger workstation with computing times of hours per timestep/frequency and more. To enable simulation of real world problems clear improvements on simulation speed is needed. We foresee improved PEEC simulations speed using the following major approaches.

*a) Grid computing for PEEC.:* In recent work, an existing full-wave, frequency domain, nonorthogonal PEEC-based EM modeling code was modified to enable grid computing on a heterogeneous grid using Alchemi [36]. The technology with heterogeneous grid computing was shown to be very young and extensive work, including the construction of a linear algebra library suitable for heterogeneous computing, was required to enable satisfactory results.

*b) PEEC for high performance computing.:* It is clear that to enable the modeling of electrically large problems, parallel-PEEC-based EM-solvers have to been developed and test. The strategies for parallelizing PEEC solvers are many and two approaches are presented in [32], [33]. To further refine and/or combined the presented approaches would extend to modeling capabilities to, for example, automotive applications as for the recent presented parallel implementation of the Method of Moments based program NEC [34].

*c) Mathematical techniques for improving partial element calculations.:* The basis for all PEEC solvers are the calculation of the partial elements (partial inductances and coefficients of potential). Continuous work on speed up is essentially for helping the speed up for the complete PEEC solver.

Further interesting areas are (1) pre-corrected FFT methods for iterative PEEC solvers, (2) optimization and parallelization of PEEC blocks, (3) model order reduction for full-wave PEEC simulations, and (4) higher order PEEC solvers.

*2) Preprocessing - mesh generation:* The mesh generation have turned out to be a critical process for PEEC solutions to become stable and accurate. Thus development of mesh generators and strategies taking into account PEEC specifics is highly needed. We suggest the following development of specific PEEC meshing generator functionality:

*a) Meshing for stability and accuracy.:* I has been shown that the meshing of the geometrical structure into inductive and capacitive partitions impact a great deal on the (time domain) stability properties for the corresponding PEEC model. In [35] it was shown how quasi-static PEEC models could be unstable if the meshing was performed in a random fashion. To devise a meshing strategy that takes into account the features of the PEEC solution is therefore important to ensure the usability of the full-wave PEEC model as needed for studying upcoming high-speed electronic circuitry.

*b) Guidelines for nonorthogonal meshing strategies:* We foresee the problem with the automatic meshing of electronic designs from CAD and electronic design automation (EDA) tools with the PEEC model since current commercial meshing software does not take into account the specifics of the PEEC method when creating the mesh. This can result in poorly constructed models with possibly time domain stability problems and an excessive number of unknowns. Therefore, mesh guidelines for the PEEC method have to be established to further improve the usage of the method.

*3) Hybrid methods:* To enable solutions for real applications, hybrid techniques will be a possibility to obtain the computational speed needed. The following development of PEEC based hybrid methods for improved performance is suggested.

*a) PEEC and cable models:* For the purpose of speeding up computation of realistic electrical interconnect structures, hybrid EM modeling using the PEEC and simplified cable models, like multi-conductor transmission line theory, is of great interest. The equivalent circuit formulation used in the PEEC method is valuable, and sections fulfilling the conditions of, for examples, transmission lines can be modeled using transmission line theory.

*4) Stability:* The potential instability of the discretized electric field integral equation (EFIE) in the time domain is well known, e.g. [37]. Several reasons to instabilities have been identified and solution strategies proposed [38]-[40]. We thus foresee research for improved stability along the following lines.

*a) Accurate inclusion of damping:* With increasing frequencies and model complexity, the need to accurately model the damping in electromagnetic couplings have been illustrated in recent publications [41] - [43]. It has been shown that several strategies can be used to accurately model the damping above the maximum frequency range of the PEEC model to improve stability. Further research is however needed in order to refine one of the techniques to stabilize the general PEEC model.

*b) Advanced meshing strategies:* See Section IV-A.2.

*5) Accuracy:* The simulation accuracy is dependent on a variety of factors as meshing and partial element accuracy [40], and time- and frequency- domain solution strategy. We thus expect improvement along the following lines of research:

*a) Improved meshing strategies.:* See Section IV-A.2.

*b) Nonorthogonal formulation:* Development of high accuracy partial element calculation routines for use with the newly presented nonorthogonal PEEC formulation [25].

*6) Tool suite:* To make PEEC a practical tool for engineers it has to be easily accessible. Since PEEC emerges from a circuit based paradigm where SPICE is the dominant tool we propose that PEEC should be a seamless extension of SPICE. Thus we foresee the development of a suite of PEEC based tools seamlessly integrate into a SPICE-like environment using.

*a) Command language as an extension to SPICE.:* Modified nodal analysis (MNA) [44] based solvers for the use of widespread developed MNA stamps,

The above given emerging areas are related to general problems for circuit based solvers which originate from the work on electromagnetic wave propagation. When we start to handle other type of wave problems like optics and acoustics we expect new emerging areas to arise. When we further start work on combined problems with for example electromagnetics and heat diffusion another dimension of problems will occur. Examples are:

- different wave propagation speeds, i.e. heat diffusion versus electromagnetic wave propagation;
- feedback between at least two wave phenomena i.e. heat waves generated by current pulses causing changes in transistor parameters implicating changes in transistor operation;
- handling of material characteristics altering wave propagation;
- ..

To further enable the connection between electronics and other type of wave problems we need for example capabilities to handle transducers for acoustics and optics. Specifically work is needed on 2D and 3D transducers.

To organize and develop a lasting research strategy a work matrix is presented, Table I. These development will in the future enable PEEC to become a versatile tool for both single and combined wave problem simulation and analysis.

## V. PEEC APPLICATIONS DEVELOPMENT

Due to the basic mathematical formulation, PEEC is fundamentally more suited to classes of problems identified as dense and electrically large. Example of problems where PEEC methodology today is applied are:

- high speed electronic chip design;
- three dimensional inductance and capacitance extraction;
- high speed electronic interconnect and packaging analysis;
- EMC problems;
- electronics on-chip and off-chip SI problems;

TABLE I

WORK MATRIX

| Important areas | Subject | Approach | Result |
|---|---|---|---|
| Stability improvements | Late time instabilities<br>Broadband PEEC models | MNA system sub-matrix analysis<br>Meshing strategies | Stable PEEC formulation<br>Model improved stability |
| Fast PEEC based EM solver | Long simulation times | Parallelization<br>Hybrid methods, PEEC and MTL | Simulation of real electronic problems<br>Simulation of real electronic problems |
| Electrothermal PEEC based simulations enabling thermal feedback into component models | Increasing power radiation in electronic designs that influence on component behavior | Direct (ohm) heating calculations<br>Coupled EM and thermal simulations, hybrid method, PEEC and FD | Use in high current applications<br>Use in general applications |
| Material handling | Large problem sizes due to discretization of materials | Green's function approaches | Improved modeling capabilities |
| Innovative materials modeling | Dispersive dielectrics, bi-anisotropic and metamaterial PEEC models | Broadband models | New applications in the field of antennas and microwave components |
| 3D Nonorthogonal formulation | Accuracy and speed in partial element calculations | Mathematical | Combined classic and nonorthogonal formulation. New application areas |
| Meshing strategies | Accuracy and stability of PEEC models | MoM 'research', practical observations, modeling experience | Improved stability and accuracy |
| SPICE components in PEEC environment | | MNA PEEC based solver | Industry interest |

- large system analysis as general power distribution- networks;
- power electronic systems;
- ...

For the future applications with combined wave problems will be of very high interest. Such problems are for example optic and acoustic sensing and their combination with the necessary electronics. Other areas are where heat and system heat generation will introduce feedback into an electronics, optics or acoustics design.

We here propose that the successful simulation of these problem areas using PEEC will be much improved in the future based on this road map.

## VI. CONCLUSIONS

The continuous research concerning the PEEC method would result in a method fully capable of handling many of the complicated problems faced by the industry today. The suite of tools that could be based on the PEEC method would improve modeling of a large variety of wave based problems both single and combined wave type problems.

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