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D. Pommerenke and S. Sakaguchi, "Application of Maxwell Solvers to PD Propagation. I. Concepts and Codes," *IEEE Electrical Insulation Magazine*, Institute of Electrical and Electronics Engineers (IEEE), Oct 2002.
The definitive version is available at https://doi.org/10.1109/MEI.2002.1044317

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Application of Maxwell Solvers to PD Propagation—Part I: Concepts and Codes

Key Words: Partial discharge propagation, electromagnetic field analysis, Maxwell solvers, boundary and area methods, time- and frequency-domain methods

David Pommerenke and Sumiko Sakaguchi

Techniques have been developed for numerical transient electromagnetic field analysis, which can solve electromagnetic propagation problems.

Partial discharge (PD) is well established as a diagnostic for high-voltage apparatus. At its source, a PD pulse often has a sub-ns risetime and pulse width in the ns range, implying a bandwidth of about 1 GHz. In the case of relatively large coaxial transmission lines such as SF_6 insulated transmission line or gas insulated switchgear (GIS), he bandwidth extends into the range that can propagate in higher order modes, i.e., other than TEMoo. This results in complex phenomena at elbows, PD coupling devices, etc., which can only be modeled through the use of software that computes electromagnetic phenomena, often known as Maxwell solvers, as they provide an approximate solution to Maxwell's equations. A similar situation arises in solid dielectric cables in the context of a PD pulse propagating in a concentric neutral cable which, as a result of its incomplete shield, really involves propagation in a complex transmission line consisting of the cable conductor, the concentric neutral wires, and ground. The detection of PD pulses through the use of PD "couplers" in complex devices such as a transmission class solid dielectric cable joints is another context that requires solution of the electromagnetic field.

The characterization of high-frequency surges—as relevant to a wide range of technology, including such fields as electromagnetic compatibility (EMC)—has mainly been performed by measurement. Simulations have often been carried out using circuit theory approximations. However, when the device structure is complex, simulation through circuit theory approximations becomes difficult or impossible.

Recently, techniques have been developed for numerical transient electromagnetic field analysis, which can solve electromagnetic propagation problems. Such computations can be approached in a number of ways in both the frequency and time domains. Therefore, several analyses of PD pulse propagation are introduced in this series of three papers. The present article will review the basic approaches to solving electromagnetic propagation in the context of PD detection—as well as available commercial software—introduce the steps required to obtain trustworthy computational results, and give an example of detailed analysis of PD propagation.

Techniques and Commercial Codes for Electromagnetic Field Analysis

Techniques

Electromagnetic field analysis is based on the solution of Maxwell's equations. Numerical approaches to the solution of Maxwell's equations can be classified in several ways:

DISCRETIZATION OF SPACE

- Boundary approach—Only a boundary is discretized
  - Boundary element method (BEM)
  - Method of moments (MoM)
- Area approach—All areas are discretized
  - Finite element method (FEM)
  - Finite difference time domain method (FDTD)
  - Finite integration technique (FIT)
  - Transmission line matrix method (TLM)
  - Spatial network methodSNM)

EVOLUTION THROUGH TIME (FREQUENCY- AND TIME-DOMAIN TECHNIQUES)

- Time-domain method—Sequential solution through time
  - FDTD, TLM, SNM, FIT, and MoM
  - Frequency-domain method—Solution for each frequency component in a wave

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- BEM, MoM, and FEM

(Note: FEM and MoM can also be used in the time domain, although such an approach is not common.)

Table I summarizes the above classification of electromagnetic field analysis techniques.

The boundary type solution requires solving the integral representation of Maxwell's equations with a discrete boundary. Typical approaches include the BEM and MoM. A boundary type solution solves a three-dimensional problem as a two-dimensional boundary problem, resulting in fewer unknowns and the applicability to open domain problems for which volume-type solutions, such as FEM, are weak. On the other hand, boundary type methods are based on the solution of an asymmetric matrix, which is difficult, and the stability of the solution is not good.

The FDTD, FIT, and TLM approaches, which are typical for a volume-type solution, provide solutions as a function of time by expanding the electromagnetic components of Maxwell's equation in three-dimensional space. In FDTD, each electromagnetic field component of Maxwell's equation is calculated successively on the time axis. The TLM method assembles a lattice of discrete points in space as one-dimensional lines and defines the transmission matrix between lattice points, so that successive calculations can be performed. In the spatial network method, the transmission-line nature of the TLM is extended so that by the correspondence of the electric and magnetic fields to current or voltage, space is represented with a perfect equivalent circuit, including the medium in which the electromagnetic field propagates and boundary conditions. Although the number of unknowns increases in a volume-type solution as all of the space must be discretized, programming is simpler because the calculation is repetitive.

Commercial EM Codes

A multitude of commercial EM codes have become available. Check http://emlib.jpl.nasa.gov/EMLIB/files.html for a very good listing of free and commercial codes.

Codes that discretize volume (e.g., FDTD, TLM, FIT) are well suited for problems that contain many different, lossy dielectric materials. Codes that discretize only the boundaries (MoM, BEM) are well suited for problems that contain only metal and air. But each vendor tries to expand the range of applications of its code. A large set of problems can be solved on a single personal computer (PC), but many codes are suitable for clusters of PCs or UNIX workstations. A great deal of research is devoted to hybrid methods that combine the advantages of, for example, FEM and FDTD or FEM and BEM.

Many vendors allow inclusion of lumped elements and SPICE models into the electromagnetic simulation. For simulations that discretize volume, the maximum possible ratio between the smallest to the largest cell is relevant. In this respect, FEM shows its strength, FIT and TLM are in the middle, and most FDTD implementations are more restricted. On the other hand, FDTD takes the least amount of time to compute one time step.

For FDTD, the simulation time is proportional to the number of cells. As a rough guideline, about 1 s per time step is required for 5 million elements in FDTD on a 2 GHz PC. FIT and TLM take longer per time step, but often need fewer cells to simulate a problem. No exact comparison is possible, as the result depends too much on the problem, the intended accuracy, special features provided by the vendor such as the ability to approximate the effect of structures smaller than the smallest cell, and the implementation of the numerical method.

In Table II, we analyze the problem based on a list of questions and then to contact vendors.

As an example, the propagation of pulses through GIS is conveniently handled by the MoM, while the propagation of PD through a high-voltage cable joint should be computed using FDTD, TLM, or FIT as the cable joint consists of many lossy dielectrics.

The price range of commercial codes is usually $10,000 to 50,000 USD. Someone entering the field of such computations will require at least a few months before the first real problem has been solved and the trustworthiness of the result has been established.

Obtaining Accurate Results in Computational Electromagnetics

The Main Causes of a Calculation Error

In every measurement, the data characterize the physical process that we are interested in, overlaid with measurement errors (e.g., effect of probing, effect of quantization, instrumentation accuracy, etc.). Without knowing the ratio between the intended signal and the measurement errors, the data are quite useless.

The same is true for simulations, and at least the same amount of care must be taken. A multitude of errors and assumptions result in uncertainties in the computed data. Examples include:

- **Volume discretizing (gridding).** The volume throughout a system is discretized into small rectangular blocks. The number of cells, their size, and their orientation with respect to the structural elements will affect the computed data.
- **Dielectric parameters.** The materials within a system may be described as homogeneous, linear dielectrics having a given permittivity. While the assumption of linearity is

Table I. The Classification of Electromagnetic Field Analysis Techniques

Classification by Discretization		Classification by Time Evolution	
Boundary Solution	Volume Discretization	Mainly Time-Domain	Mainly Frequency-Domain
BEM, MoM, mainly	FEM, FDTD, TLM (SNM), FIT, mainly	FDTD, TLM (SNM), FIT and MoM, mainly	BEM, MoM, and FEM, mainly

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Table II. Questions to Aid Decision on Type of Code	
Question	**"Yes" Favors the Following Techniques**
Does the geometry contain lossy dielectrics or many nonlossy dielectrics that need to be modeled?	FDTD, FIT or TLM
Is frequency dependence of material parameters important?	Frequency domain methods, some time domain methods can handle dispersion
Are very fine and very large structures important?	FEM has the best adaptive gridding ability
Do thin, lossy layers dominate the system response?	Some codes offer special solutions for this case
Does skin affect need to be modeled?	Skin effect is often approximated by impedance boundary conditions. Frequency domain methods may be more suitable.
Does nonlinearity of any material need to be modeled?	Time domain methods are preferable
Are the materials anisotropic?	FDTD, FIT and TLM
Do lumped elements or SPICE sub-circuits need to be included?	Depends on the specifics of the code
Does the computation extend over a multidecade frequency range?	Time domain methods: FDTD, FIT and TLM
Are there any high-Q resonances to be expected?	Frequency domain methods

likely to be accurate, greater uncertainties attend permittivity values and their isotropy (e.g., conductivity of the semicon in plane and across the plane).

- **Source model.** Electromagnetic codes allow many different source types. Not every source has a physical equivalent.
- **Numerical error.** The numerical error can be significant in the solution of matrices. This is mainly relevant for frequency domain methods. In time stepping methods the numerical error is often relevant if the difference of two large values is taken. This may happen in the solution of shielding problems. It is also often relevant if the two spectral densities are compared.
- **Boundary error.** Every structure is embedded into its surrounding. If this is open space, most methods provide either an exact equivalent to open space (e.g., MoM) or they provide an approximation of the open space (e.g., FDTD). If an approximation is used, some reflection will remain at the boundary and/or the boundary may not fulfill electro- or magnetostatic field continuation, leading to errors in capacitance and inductance values.
- **Time – Frequency transformation errors.** If a calculation is carried out in the time domain and the results are transformed into the frequency domain, the effects of truncation, sampling, maximal possible dynamic range, etc. need to be considered. Otherwise, incorrect results will be produced. If a result is obtained in the frequency domain, and transformed into the time domain, care must be taken to analyze the effect of errors at each frequency on the time domain result. A time domain signal obtained from the frequency domain should not have any significant imaginary part and should not have any signal before time = 0. A large imaginary part or signals before $t = 0$ indicate errors and should never be ignored.
- **Dynamic range of the amplitude.** This is mainly important if the difference of large values is taken or if the spectral content of the excitation is low in some range.
- **Other Issues: Dispersion Error, Modeling of Skin Effect, Thin Layers, Anisotropy.** Listing all the simplifications made and estimating their effect on the simulation is good practice, prior to starting the computation.

Testing Against Simplified Analytical Models

The simulation results need to be checked against analytical estimates. This often requires strong simplifications and only allows testing certain aspects of the computational results. For example:

- Is there a quasi-static solution (i.e., low-frequency solution) to which the system should converge?
- Can the conservation of charge or energy be used to check the results?
- Can propagation delays be calculated by hand and used to check the simulation results?
- Can field strengths be approximated by Ampere's law or by voltage/distance? If so, the simulation results should be tested against such approximations.
- Is there a simplified structure (e.g., made from transmission lines, L, R, C) that describes the expected behavior of the

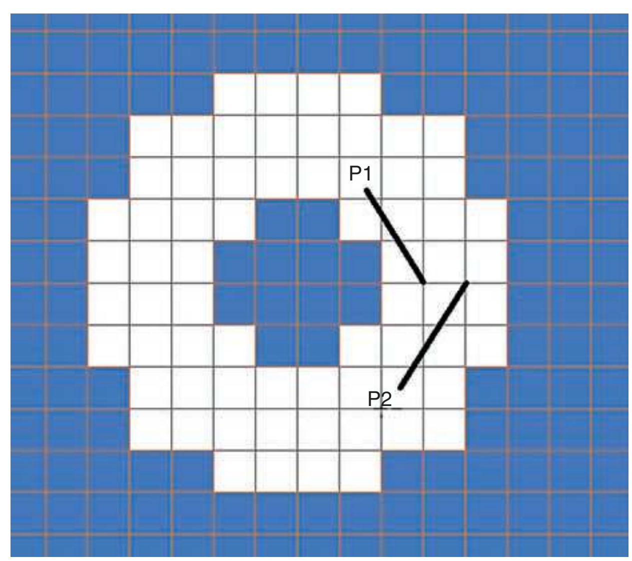

Figure 1. Two different locations for calculating the current from the magnetic field.

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structure in simplified terms? If so, one should also simulate the results for such a structure (for example, using SPICE) to aid the physical interpretation of the EM-simulation results.

An example is shown in Fig. 1. The example is somewhat artificial but illustrates the principle. A coaxial cable is modeled using very few elements. The magnetic field can be measured at a given distance from the conductor and Ampere's law can be used to obtain the current. If this is done for P1 or for P2, the same current should be predicted. In reality, there will be differences and such differences provide a basis for estimating the accuracy of the computation. Knowing the differences allows estimating one's ability to obtain the current from the simulation.

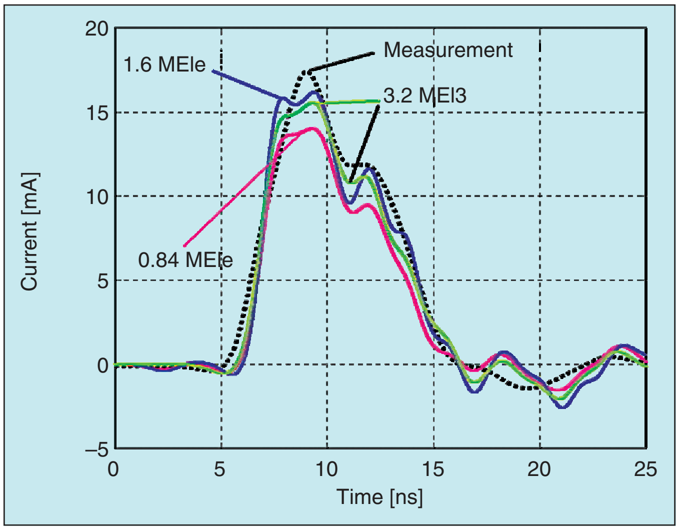

Figure 2. Effect of different cell size for the computation of a pulse traveling through a slip-on cable joint relative to the measurement. Number of cells: 0.84, 1.6, 3.2 million.

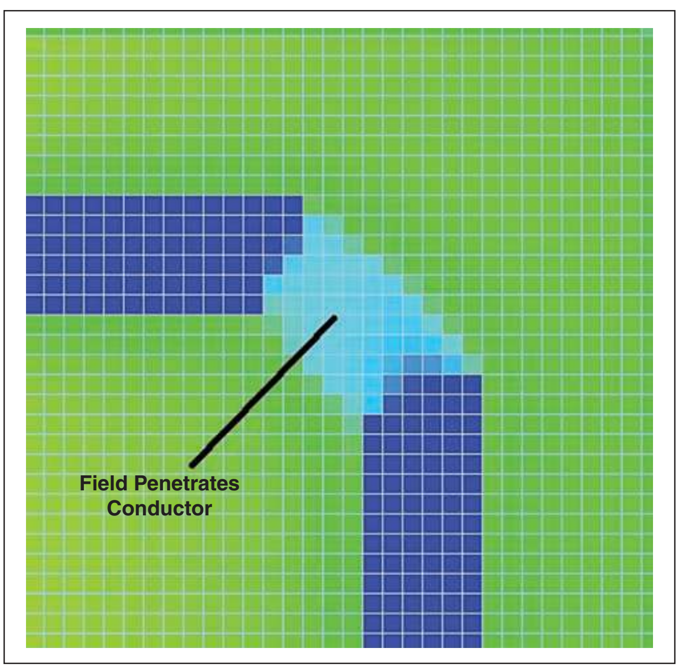

Figure 3. Field strength map.

Listing all of the possible tests and the expected results prior to starting a numerical simulation is a good practice.

Convergence Study Before Publishing Results

In the case of FDTD, the following should to be carried out before any simulation result is published:

- Vary the grid-cell size; pay special attention to thin layers.
- In open problems: Vary the calculation domain size.
- In open problems: Vary the boundary conditions.
- Test for the effect of calculating more or less time steps.

The steps outlined above can be adapted to other methods, e.g., MoM. An example of the effect of the cell size on the output signal is shown in Fig. 2, which shows a pulse that travels through a cable joint for different numbers of cells, along with the measured value. The uncertainty in the amplitude is about +/- 10%, which is not un-typical for FDTD, TLM and FIT.

Most EM software can display the electric and magnetic fields, as well as the energy-flow in the near field, which make impressive pictures. In most cases, showing near field data in presentations is poor practice, as the audience cannot understand them within the available time. But the near field data are very useful to check the simulation. For example, if two pieces of metal have not been connected because of an input error, the near field will show that RF passes through them. To check the model, the near field data should be inspected very carefully! Figure 3 shows example of field strength map: dark blue indicates no field. The field penetrates the connection, which is made of conductor, between two conductors, as an incorrect material property was assigned. The conductivity of the connection was accidentally set to 1 instead of 108 S/m.

Let us assume that a simulation takes 48 hours, which sounds acceptable. The real difficulty with such a long simulation time shows up when one wants to establish trust in the simulation. For example, increasing the number of grid cells may lead to week-long calculation times. The calculation time in FDTD is proportional to the number of grid cells, but if the grid cells are smaller the time step will be reduced (i.e., more time steps are required).

If the dielectric parameters are also varied along with some details in the meshing, the overall time needed to achieve a *trustworthy result* will certainly take many weeks of intensive computational work. For any new problem, 90% of all calculation time is used to test parts of the large model (e.g., the excitation) and to establish the trustworthiness of the result.

Example of More Detailed Analysis of Pulse Propagation

Distinguishing Between Acceptable Modeling Errors and Missing Important Physical Processes Using FDTD

Differences between measured data and computational results are normal. The user must ask, "Is this a severe difference requiring further investigation?" That decision is not easy and often will be revised. In a simulation of the pulse

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propagation through a 110 kV slip-on cable joint, the frequency-dependent insertion loss was used to verify the numerical model of the cable joint. This property was selected as it could be measured quite easily.

The model of the slip-on joint was developed from mechanical drawings. Dielectric parameters were taken from manufacturers' data, scientific literature, and measurements and, for the stress cone material, by optimizing the match between the simulation and the measurement. In these optimizations, the dielectric parameter of the stress-cone material was varied within a range bounded by measured data of different stress cone and semicon materials. In spite of these efforts, no better match than that shown in Fig. 4 could be achieved.

The inability to simulate the resonance at around 150 MHz was of concern. This led to the conclusion that some important physical process was not modeled correctly or that the measurement was incorrect. The measurement setup is quite simple and the measurement had been carried out by an expert. The time and frequency domain measurements matched quite well. This diminished the possibility of a measurement error. On the other hand, the model had been created from mechanical drawings from which the joint had been built. It turned out that the mechanical drawings had been missing an important detail that was only shown in a subdrawing.

While the drawings showed the inner conductor connection to be a solid metallic part, the construction was different. After welding the inner conductor, a metallic shell, constructed from two semi-shells, is installed around to obtain the same diameter as the XLPE insulation. These semi-shells are connected to the inner conductor via two copper strips. The inner volume between the conductor and shells is filled with epoxy for thermal and mechanical reasons.

The shells form a resonant circuit. The shell against the inner conductor constitutes a capacitor, the copper band, an inductor (Fig. 5).

After including these important details in the simulation, a much better match was achieved.

Detailed Analysis of PD propagation Using Method of Moments (MoM)

Although FTDT has been the subject of many papers and books, MoM has been discussed much less in the literature. Below, we also describe the general concepts of MoM.

General Concepts of MoM

MoM is the method commonly used in antenna analysis. In antenna analysis, the current that flows on the surface of a conductor is calculated, and the electromagnetic field is calculated from the current. Here, we describe how to calculate the current.

The continuous current that flows on the surface of a conductor, as shown in Fig. 7(a), is expressed as the sum of currents in a segment, shown in Fig. 7(b). Here, we consider the case that current flowing on the conductor is a sine wave as

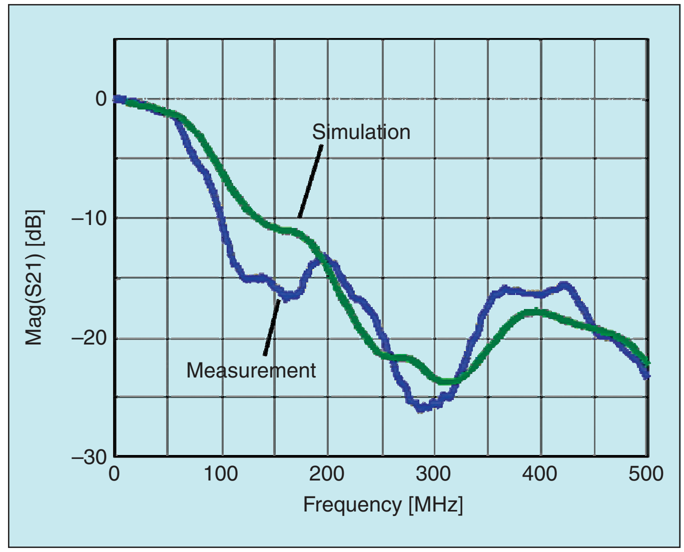

Figure 4. Simulated and measured insertion loss of a 110 kV cable slip-on joint.

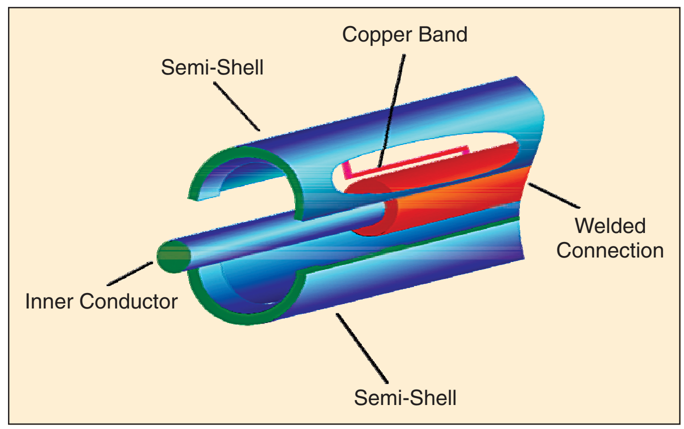

Figure 5. Detail of the connection of the inner conductor.

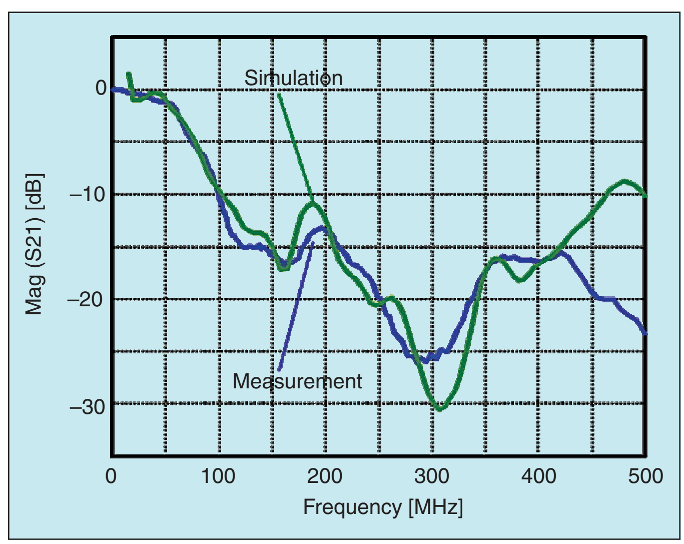

Figure 6. Comparison of the simulated and measured results after including details of the conductor connection.

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in Fig. 7(c). Figure 7(d) shows the discretization of the current shown in Fig. 7(c), and the current of each segment can be expressed by the known basis function I' shown in Fig. 7(e) and the coefficient α. In this case, the basis function shown in Fig. 7(e) is a pulse. More generally, continuous current is expressed by the basis function and coefficients α as

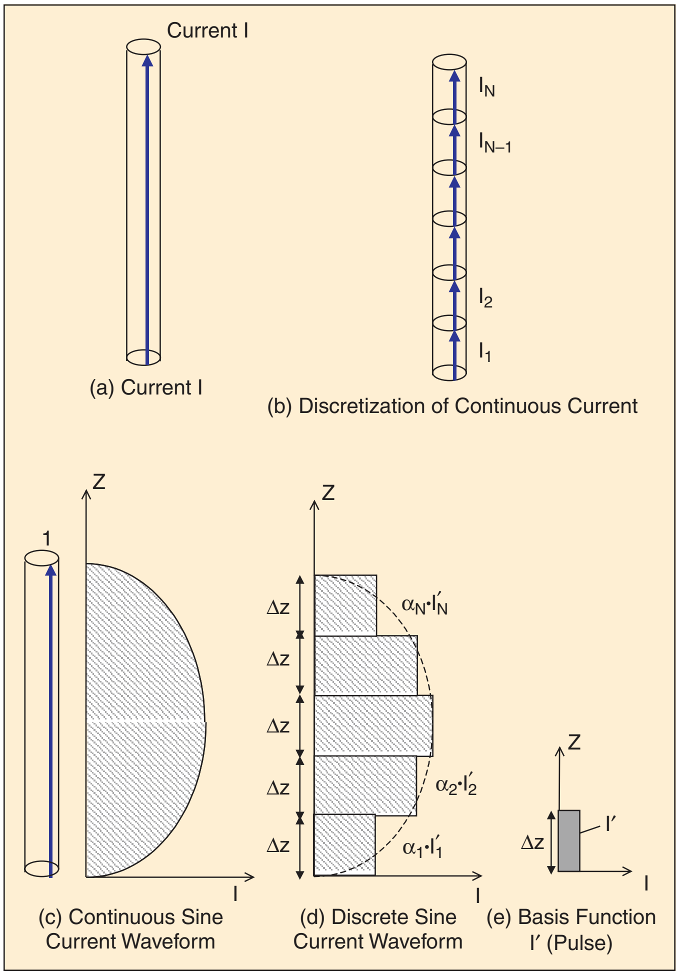

Figure 7. Discretization and description using basis function of continuous current, I.

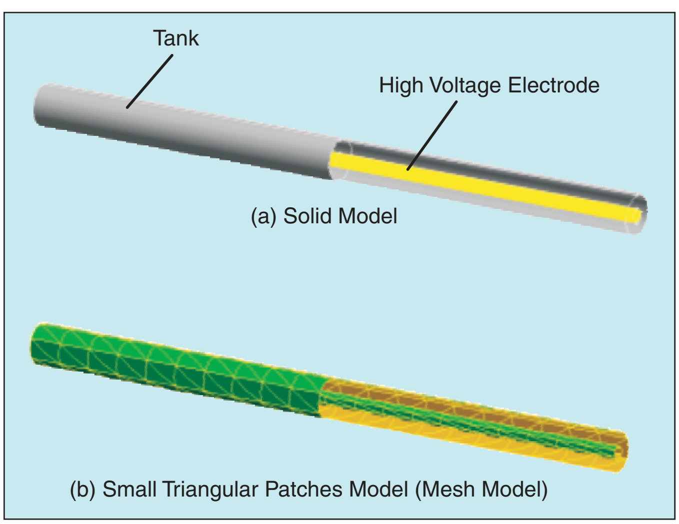

Figure 8. Example of calculation model.

$$I = \sum_{n=1}^{N} \alpha_n I'_n \tag{1}$$

Even if the current I is unknown, the current can be approximated in the form of (1). In this case, the coefficient α in each segment becomes an unknown. In MoM, we use this discrete current formulation.

Next, the electric field of all space is calculated by integration of the current as shown in (2):

$$E = F(I) = \sum_{n=1}^{N} \alpha_n \{F(I'_n)\} \tag{2}$$

In antenna analysis, the electric field, E, may be known although the currents that flow on the antenna surface are not known. In such a case, if the current on the antenna surface is discretized in N pieces about the known E, N simultaneous equations are obtained from (2), which can be solved for the N unknown coefficients α from which the unknown current I can be calculated. Using I, we can obtain the electromagnetic field.

In addition to the above, in MoM, after multiplying the both sides of the (2) by a weighting function w and integrating the equations as shown in Eq. (3), we obtain the unknown coefficients α.

$$\int_{l_1}^{l_2} E\, w_m\, dl = \sum_{n=1}^{N} \alpha_n \int_{l_1}^{l_2} \{F(I'_n)\}\, w_m\, dl \tag{3}$$

$$m = 1, 2, 3, \ldots, N$$

where l is the current path. Through the use of the weighting function and integral, the unknown function, which can include rapid changes, is obtained after being transformed to a smooth function. The method resembles determining the electromagnetic field after obtaining the potential distribution, which is the integration of the electromagnetic field. Thus, a more exact solution is obtained through integrating. This is called "method of moments," because the integration resembles the moment of dynamics.

Application to Power Devices

Since the MoM is a boundary element method, only the boundaries (the electrode surfaces and boundary between dielectrics) enter the computation. Therefore, it is very effective for modeling complex configurations such as connectors, discontinuous parts, etc., which are difficult to approximate in a circuit theory analysis.

The boundary of the model is divided into small triangular patches shown in Fig. 8, and the current density J in each triangle element is used as an unknown function, as already mentioned. The current, I, flowing vertically across the edge shared by two small triangle patches of boundary shown in Fig. 9 is defined as an unknown coefficient. In this analysis, we use two kinds of basis function—the triangle element

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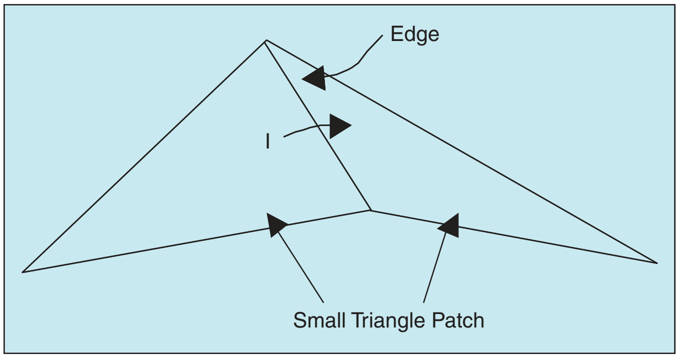

Figure 9. The edge shared by two triangle patches and current I flowing vertically across the edge.

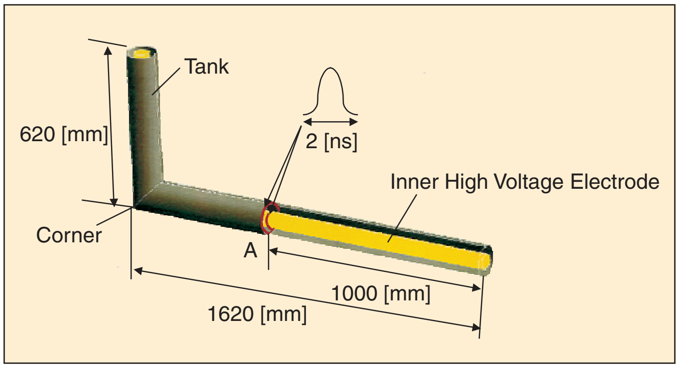

Figure 10. Calculation model (L-shaped GIS).

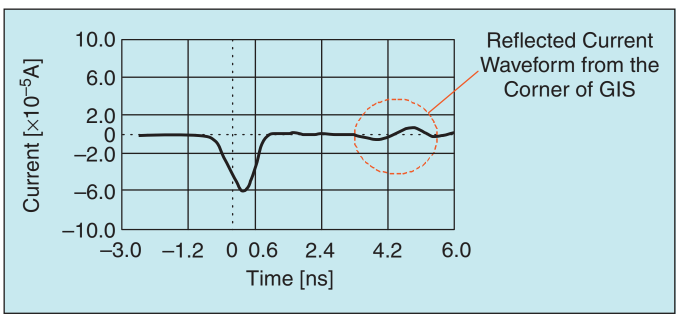

Figure 11. Current waveform near A on the tank.

function and the piecewise triangle function. The triangle element function is used as the basis function of space, and the piecewise triangle function is used as the basis functions of time. By calculating the current I, we obtain the current density J. The vector potential, the scalar potential, and the electric field are obtained from J.

There are two approaches to implementing MoM:

- Frequency-domain method
- Time-domain method

In the frequency-domain method, the above calculation is performed at each frequency in the spatial Fourier decomposition, and after obtaining the frequency characteristics, we obtain the current. However, if the model becomes complicated, the computation must be carried out at a large number of frequencies. Moreover, when the analytical model becomes large, the computation time for one frequency becomes very long. Thus, the overall computation time is very long when large models, such as a power devices, are treated.

In the time-domain method, we calculate the unknown current, I, at every time step. The current I at time step t_i can be obtained from the prior current time step t_{i-1}. Thus except for an initial time step, we do not need to solve simultaneous equations. Since solution by substitution is possible, the unknown current can be calculated rapidly. This is the big advantage of the time-domain method. On the other hand, the solution can become unstable.

Example Calculation

Here, we show simple computational results based on the above time domain method. PD pulse propagation analysis was carried out for an "L"-shaped coaxial conductor as shown in Fig. 10. A 2 ns voltage pulse is applied between the conductor and enclosure at point A as shown in Fig. 10. Figure 11 shows the result of a simulation for the current waveform near A on the enclosure. In Fig. 11, we can see the initial incident pulse and reflected current from the discontinuous bend of L-shaped conductor. It is difficult to obtain such reflected current by usual circuit analysis.

Conclusion

In this paper, we have reviewed techniques and available commercial software for numerical transient electromagnetic field analysis and introduced more detailed and trustworthy computational examples for PD propagation in complex apparatus. As stated above, numerical transient electromagnetic field analysis is a powerful tool for solving such phenomena.

The next two papers in this series will discuss applications to PD propagation in cable joints and high-voltage apparatus.

David Pommerenke received his diploma and Ph.D. from the Technical University Berlin while he was researching and teaching EMC and High Voltage. In 1996, he joined Hewlett Packard in Roseville, CA as EMC engineer. In 2001, he accepted a position as Associate Professor in the EMC group at the University Missouri-Rolla. His areas of interest are EMC, electrostatic discharge, numerical methods, and partial discharge detection. He can be reached at: pommerenke@ece.umr.edu.

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