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An Electromagnetic Circuit Simulator For Power Electronics

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Abstract — A method for solving the full equations of Maxwell for circuits with discrete non-linear components will be presented. To this end the method of moments is used in combination with a classical circuit simulator. Both work in the frequency domain. A few methods to greatly accelerate the calculations are also presented. The methods are then implemented and tested in Matlab®.

I. INTRODUCTION

The structure of the method for solving the full equations of Maxwell for a circuit is shown in figure 1. A buck convertor is shown as an example. The conductors of the circuit are modeled in 3D and are connected with discrete circuit elements. The points to which the elements connect will be called nodes. At the start of the calculations the program discretizes the conductors. Afterwards the method of moments (MoM) is applied to find an equivalent, frequency dependent, admittance of the conductors. When this admittance is connected with the discrete circuit elements, the resulting equivalent circuit can be solved with a classical circuit solver. The final results are the voltages at the nodes.

Nowadays commercial software exists that can solve the full equations of Maxwell for power electronics. They mostly use the partial element equivalent circuit method (PEEC) [1]. Examples are CST PCB Studio and Cedrat's InCa3D. Often times the PEEC method is used in combination with a classical circuit simulator in the time domain like SPICE. This is good for transient solutions but for electromagnetic interference (EMI) problems a steady-state solutions of the system is desired. This requires simulation of multiple periods in the time domain. A classical circuit simulator in the frequency domain will immediately return the steady-state solution. It's also very easy to incorporate the frequency-dependent equivalent admittance. That is why in this paper the frequency domain circuit simulator is preferred.

II. METHOD OF MOMENTS

A. Full impedance matrix

The MoM is widely studied [2][3] and only the result shall be given here. After discretizing the model into current and charge elements, applying the MoM will result in the full impedance matrix Z:

$$[V_{ext}]_{N_{cu}x1} = [Z]_{N_{cu}xN_{cu}} [I]_{N_{cu}x1} \quad . \tag{1}$$

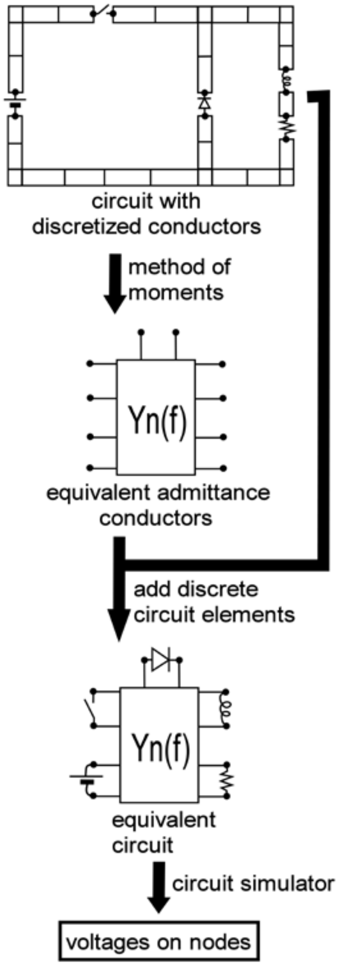

Fig. 1. Structure of the presented method

In equation (1) N_{cu} is the number of current elements, V_{ext} is a vector with the voltages applied across every current element and I is the current through every current element. The full impedance matrix Z is frequency-dependent and involves calculating the following Green functions N_{cu}^2 times:

$$G(\vec{p},V) = \frac{1}{4\pi V}\int_V \frac{e^{-jkr}}{r} dV \quad . \tag{2}$$

In equation (2) k is the wavenumber, r is the distance from the given point p to the integration point inside the volume V. This integration is done numerically and thus consumes a lot of time. As the integrand is a function of frequency the Green functions must be recalculated for every other frequency. But if the dimensions of the current and charge elements are much smaller then the smallest

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wavelength in the system equation (2) can be approximated as:

$$G(\vec{p},V)=\frac{e^{-jkr_m}}{4\pi}\left[\frac{1+jkr_m}{V}\int_V\frac{1}{r}dV-jk\right] \quad . \qquad (3)$$

In equation (3) r_m is the distance from point p to the middle of volume V. Now the integrand of the remaining integral in equation (3) is not a function of frequency anymore. That means the integrals must be evaluated only once and can then be reused for calculating the full impedance matrix at every frequency.

A second advantage of the formulation in equation (3) is that calculating the remaining integral has already been studied and optimized in quasi-static programs like FastCap and FastHenry.

B. *Node admittance matrix*

Equation (1) gives the relation between the voltages applied over every current element and the current through every current element. But the discrete elements are only adjacent to N of those current elements, N being the number of nodes. That means only the relation between voltage and current of those current elements are required. That relationship is given by the node admittance matrix Y_n:

$$[I_s]_{Nx1}=[Y_n]_{NxN}[V_s]_{Nx1} \quad . \qquad (4)$$

I_s are the currents through the nodes and V_s are the voltages at the nodes. The matrix Y_n can be found by solving equation (1) for the current vector N-1 times. This consumes time but it greatly accelerates the calculations in the classical circuit simulator as the dimensions of Y_n are many times smaller than Z.

III. CIRCUIT SIMULATOR

The circuit simulator in the frequency domain will solve the following non-linear matrix equation[4] iteratively:

$$[Y]_{NHxNH}[V]_{NHx1}+[I_s]_{NHx1}+[I_{nl}(V)]_{NHx1}=0 \quad . \qquad (5)$$

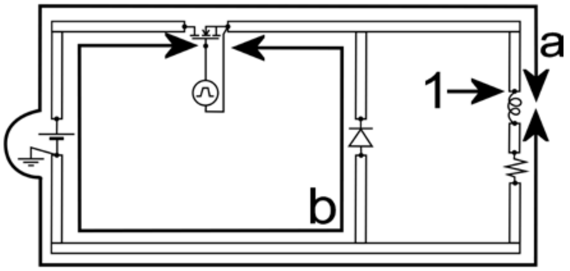

Fig. 2. Buckconvertor with visualized standing waves

The equations (5) state that the sum of the currents leaving a node must be zero. This must be true for all H frequencies. To solve matrix equation (5), the non-linear term will be linearly be approximated at every iteration k:

$$[I_{nl}(V)]\approx[I_{nl}(V^k)]+[J_{nl}(V^k)]([V]-[V^k]) \quad . \qquad (6)$$

Evaluating the Jacobian J_{nl} numerically is very time consuming. The calculation can be accelerated greatly by using the fact that the unknowns are quantities in the frequency domain that represent a time domain signal. Derivation of this method is given in [4].

IV. RESULTS

The two big parts of the program were tested separately. The implementation of the method of moments is tested by comparing the output of the program with analytical solutions and with the output of PCB-MoM [5] for different circuits. The circuit simulator is tested by comparing the output with PSpice. All the results matched very well.

The whole program is then applied to a buckconvertor with a switching frequency of 6MHz. The convertor is shown in figure 2. The simulation was run with 120 harmonics. The resulting voltage in the time domain at node 1 is shown in figure 3. Clear resonance is seen at the frequencies of 350 MHz and 430 MHz. These come from two standing waves: one when the switch is open (arrow b in figure 2) and a second one when the switch is closed (arrow a in figure 2).

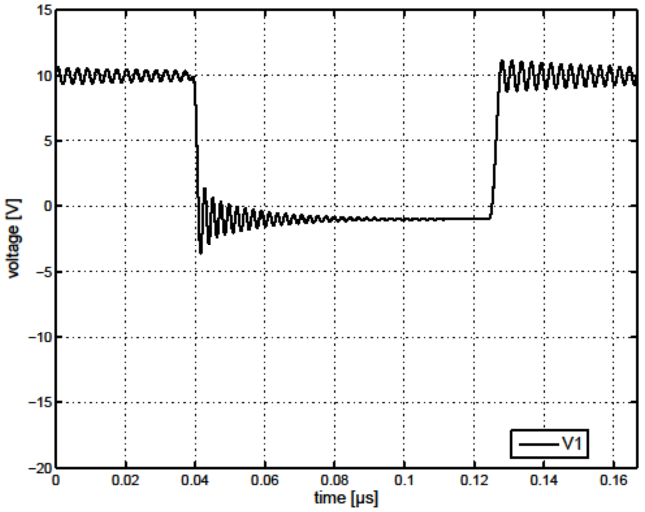

Fig. 3. Voltage on node 1 from figure 2 switching at 6 MHz

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