Electromagnetic Modeling Using Equivalent Circuits

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Faculty seminar

1. EMC Lab

Ask question during the talk!

The EMC Lab at EISLAB has two main purposes: to serve as a research and teaching facility and as a resource for the electronic industry in the region.

Research is performed on electromagnetic simulations using the PEEC (Partial Element Equivalent Circuit).

The EMC lab has a large, fully attenuated, electromagnetically shielded chamber. The chamber is equipped with antennas, transmission and receiving equipment covering the frequency range 30 MHz - 6 (best case) GHz. Examples of tests performed at the EMC Lab:

- Emission and immunity testing, both conducted and radiated.
- Transient testing (ESD, EFT, surge, burst).
- Network analyzers, digital oscillocopes etc.

EMC Lab, cont.

We used to offer to following courses to undergraduate students:

- High frequency electronic systems.
- EMC Technology.
- Antennas

Driving licence course

We have a basic (mandatory) EMC course for companies who wish to use our lab for (pre-compliance) testing.

2. EMC Research

- Electric equivalent circuit-based electromagnetic modeling:
  - high performance/parallel computing,
  - hybrid methods, and
  - for power electronic systems,

- Train-related research:
  - bearing currents and [1]
  - grounding problems.

[1] Ekman and Wisten, 'Experimental investigation of the current distribution in the couplings of moving trains", IEEE Transactions on Power Delivery, 2009.

Faculty

- Jonas Ekman
- Jerker Delsing
- Åke Wisten
- Andreas Nilsson

PhD Students

- Danesh Daroui
- Sohrab Safavi

3. Introduction to EM modeling & PEEC

- We are talking about electromagnetic (EM) modeling or computational electromagnetics (CEM).
- CEM is used to:
  - predict high frequency behavior,
  - ensure functionality,
  - understand the performance or bottlenecks of electrical interconnects and packaging,
  - calculate EM fields,
  - develop design guidelines,
- Several different methods: FDTD, FEM, MTL, TLM, MoM, FIT, PEEC.
- Due to mathematical differences, different methods are suitable for specific types of problems ⇒ Use the right method for the right problem.
- EISLAB is developing PEEC since it is an electric equivalent circuit approach and we can integrate that with other SPICE-type of work that is going on within the division.

3.1. The Partial Element Equivalent Circuit Method

3.1.1. Basic theory

The theoretical derivation starts from the expression of the total electric field in free space as

$$\vec{E}^T(\vec{r},t) = \vec{E}^i(\vec{r},t) - \frac{\partial \vec{A}(\vec{r},t)}{\partial t} - \nabla\phi(\vec{r},t). \tag{1}$$

If the observation point, $\vec{r}$, is on the surface of a conductor, the total electric field can be written as $\vec{E}^T = \frac{\vec{J}(\vec{r},t)}{\sigma}$, in which $\vec{J}(\vec{r},t)$ is the current density on a conductor. To transform into the electric field integral equation (EFIE), the definitions of the electromagnetic potentials, $\vec{A}$ and ϕ are used.

$$\vec{A}(\vec{r},t) = \sum_{k=1}^{K} \mu \int_{v_k} G(\vec{r},\vec{r}\prime)\vec{J}(\vec{r}\prime,t_d)dv_k \tag{2}$$

$$\phi(\vec{r},t) = \sum_{k=1}^{K} \frac{1}{\epsilon_0} \int_{v_k} G(\vec{r},\vec{r}\prime)q(\vec{r}\prime,t_d)dv_k \tag{3}$$

Combining results in the well known electric field integral equation.

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The EFIE to be solved

$$\vec{E}^i(\vec{r},t) = \frac{\vec{J}(\vec{r},t)}{\sigma} + \mu \int_{v\prime} G(\vec{r},\vec{r}\prime)\frac{\partial \vec{J}(\vec{r}\prime,t_d)}{\partial t} dv\prime + \frac{\nabla}{\epsilon_0}\int_{v\prime} G(\vec{r},\vec{r}\prime) q(\vec{r}\prime,t_d) dv\prime \quad (4)$$

Interpreting the EFIE as KVL

It is possible to interpret each term in the above equation as KVL since

$$V = RI + sLpI + Q/C \quad (5)$$

This results in interpreting:

- The first RHS term as Resistance,
- The second RHS term as Partial inductance
- The third RHS term as Coefficient of potential

The resulting equivalent circuit for a thin wire

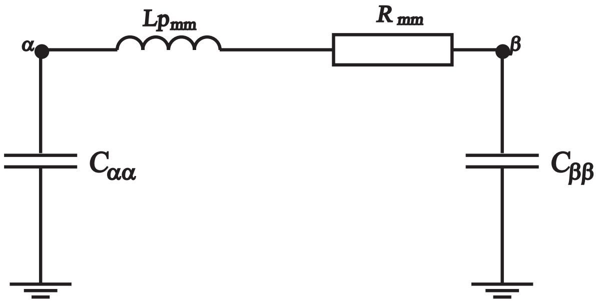


Figure 1: One way of visualizing the interpretation of the EFIE as a partial element equivalent circuit (quasi-static approximation).

The resulting equivalent circuit for a thin wire (FW)

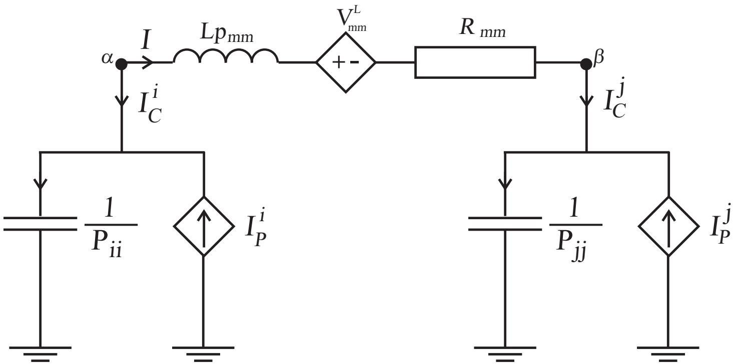


Figure 2: One way of visualizing the interpretation of the EFIE as a partial element equivalent circuit (full-wave = taking care of delays).

3.2. Simple PEEC model for two wires in free space

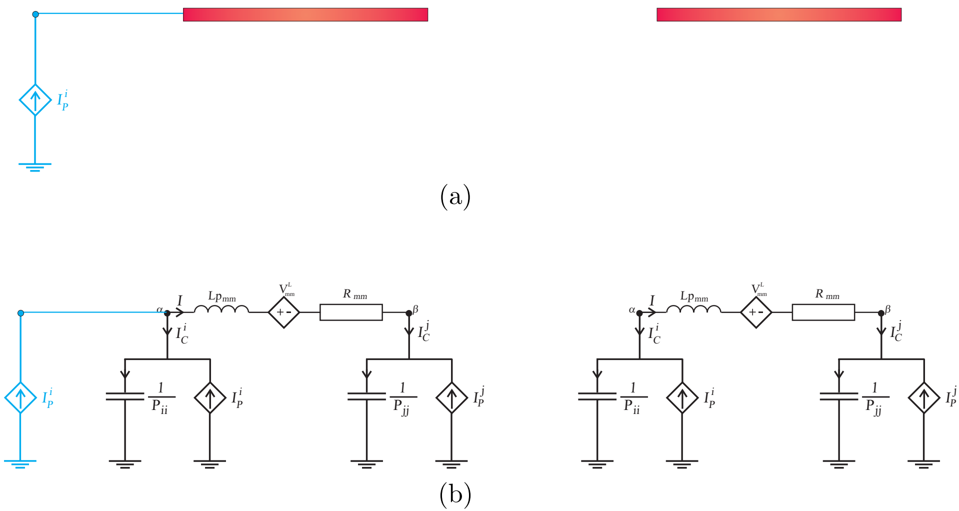


Figure 3: PEEC model for two conducting wires (a) using controlled voltage- and current- sources to account for the electromagnetic couplings (b).

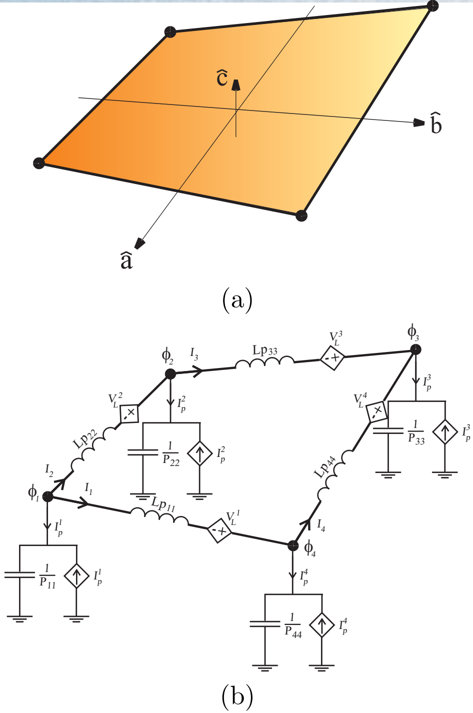
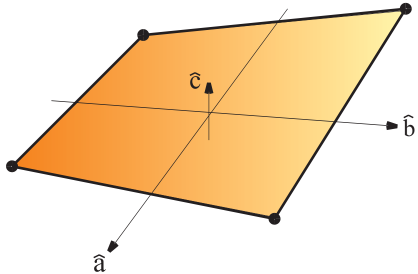
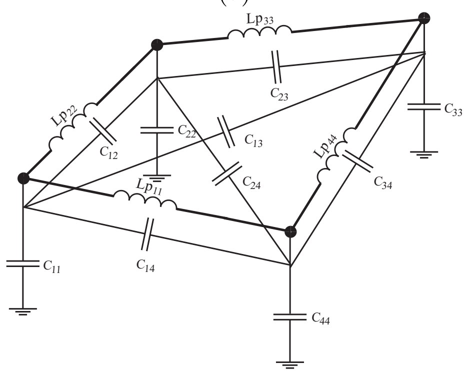


Figure 4: Nonorthogonal metal patch (a) and PEEC model (b).

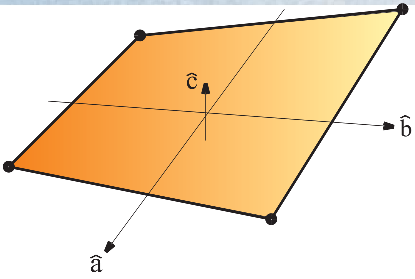


(a)



(b)

Figure 5: Nonorthogonal metal patch (a) and QS-PEEC model (b).



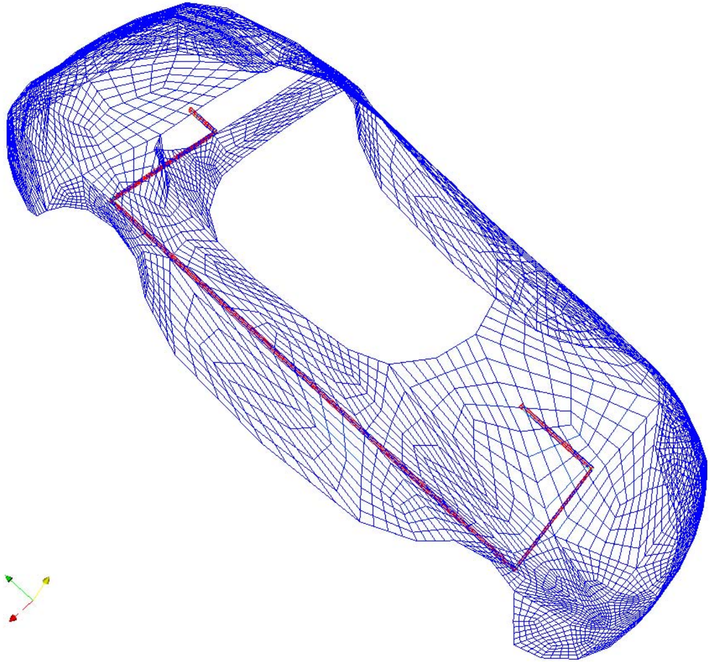
(a)

Lp11 1 4 $\{Lp11_{value}\}$	C11 1 0 $\{C11_{value}\}$
Lp22 1 2 $\{Lp22_{value}\}$	C22 2 0 $\{C22_{value}\}$
Lp33 2 3 $\{Lp33_{value}\}$	C33 3 0 $\{C33_{value}\}$
Lp44 4 3 $\{Lp44_{value}\}$	C44 4 0 $\{C44_{value}\}$
K13 Lp11 Lp33 $\sqrt{\frac{\{Lp13_{value}\}^2}{\{Lp11_{value}\}\{Lp33_{value}\}}}$	C12 1 2 $\{C12_{value}\}$
K24 Lp22 Lp44 $\sqrt{\frac{\{Lp24_{value}\}^2}{\{Lp22_{value}\}\{Lp44_{value}\}}}$	C13 1 3 $\{C13_{value}\}$
	C14 1 4 $\{C14_{value}\}$
	C23 2 3 $\{C23_{value}\}$
	C24 2 4 $\{C24_{value}\}$
	C34 3 4 $\{C34_{value}\}$

(b)

Figure 6: Nonorthogonal metal patch (a) and SPICE .cir-file in (b).

3.3. Example of structure possible to study with the PEEC formulation - in SPICE!



3.4. Summary of approach

- Pros:
  - + Same time- and frequency- domain model.
  - + Direct inclusion of other SPICE circuit elements.
  - + Solvable with SPICE-like solvers.
  - + Engineering-type of approach.
- Cons:
  - - Large number of partial elements (speed-up, approximations).
- Current academic cooperation within CEM:
  2. Giulio Antonini, University of L'Aquila.
  3. Göran Engdahl, KTH.
- Industry (current and past) cooperations with: ABB, Volvo, BMW, Bosch,..

4. PEEC at LTU

4.1. History

1999-2001

Hand calculations + PSpice ⇒ Matlab/Java-routines + PSpice.

> **Lesson learned**
>
> If you feel that you are stuck, stuck, stuck......get help or get out!

2001-2004

Cooperation with UAq. Start with C++ solver with Lp and P calculations from IBM. All-in-one (solve circuit equations=no PSpice).

2004-2007

New solver (PETSc). All-in-one (solve circuit equations=no PSpice). New solver (GMM++) + parallel-PEEC. All-in-one (solve circuit equations=no PSpice). Post-processing in Matlab. Pre-processing in various CAD-formats (Gerber).

2008-

GMM++ going to Intel MKL going to PARDISO and MUMPS and then...

2010-

ABB developing an internal graphical user interface to our solver (now called MultiPEEC). Internal efforts on interfacing OrCAD.

2012-

Working on project funding!

4.2. Pushing and pitching for this work - response to funding application 2003

Hej Jonas.
Tack för svaret. Jag har funderat litet till och känner mig klar. Min bedömning är att metoden inte kan ge ett positivt bidrag till den industriella utvecklingen inom kraftsystem. Det finns andra mer tillförlitliga och hanterbara verktyg utvecklade. Motiv:

- Figur 2 i din ansökan är en mycket enkel krets, som alla kretsberäkningsprogram klarar. Det går även enkelt att räkna för hand.....
- ..

Du hänvisar till att jag skall kontakta Georgios Demetriades för att få veta ABBs intresse för PEEC. Det är närmast en parodi,för Georgios håller just nu på med ett modelleringsarbete för ett HVDC-system. När det gäller modellering har han specialistkunskap, och det arbetet går bra. Men det är vi som i slutändan avgör vilka verktyg vi kan hantera och lita på. Vad jag vet är det inte såmånga andra inom ABB som räknar på sådana här problem där f ältteori och kretsberäkning måste kombineras. Sorry, för det här nedslående beskedet, men jag tror att Du i längden är mest betjänt av ett ärligt svar så Du kan ägna Dina krafter åt något som har större potential att lyckas.

Vänliga hälsningar, Lars-Erik Juhlin, Senior specialist HVDC system design

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Lesson learned

Do not listen to anyone, especially not a specialist, if you know that you are right!

5. PEEC Modeling Examples

5.1. Inductance calculations

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1 × 1 m sq. free-space rectangular loop made of thin wire.

1. Analytical approach: The inductance is given by

$$L_{analytic} = 0.4((a+b)\ln(\frac{4ab}{d}) - a\ln(a+g) - b\ln(b+g)) + 0.4(2g+d-2(a+b)), \quad (6)$$

where a and b are the length and the width of the loop, d is the wire diameter, and g is the rectangle loop diagonal. With the following data: $a = b = 1$, $d = 0.005$, and $g = \sqrt{2}$ the loop inductance is $\mathrm{L}_{analytic} = 4.17\ \mu\mathrm{H}$.

PEEC approach.

2. You model the 1×1 m sq. free-space rectangular loop made of thin wire.

You get the partial inductance matrix,

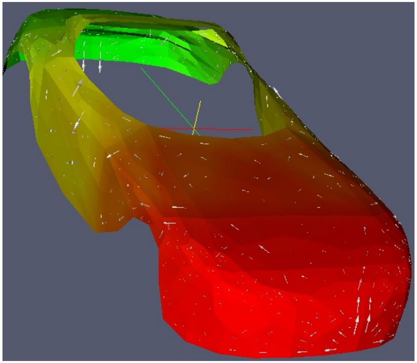
$$L_p = \begin{bmatrix} 1.14 & 0 & 0.11 & 0 \\ 0 & 1.14 & 0 & 0.11 \\ 0.11 & 0 & 1.14 & 0 \\ 0 & 0.11 & 0 & 1.14 \end{bmatrix} \mu H. \quad (7)$$

And then calculate the loop inductance.

3. Or, you run your PEEC model with only partial inductances and resistance and extract the inductance.

But, really! Inductance calculations?! Is that so important?

5.2. Automotive chassis



- Nonorthogonal PEEC
- 2 862 surfaces and 3 816 volumes

- Front bumper is excited using a 1 V, Gaussian pulse with 'rise time' 50 ns.
- The front bumper grounded by a 100 Ω resistor. Back bumper grounded by a 50 Ω resistor.

- FW, TD analysis, 200 points: 4 h, 10 m.
- FW, FD analysis: 50 freqs.: 5 h.
- Regular Linux server with 4 Gb Ram
- Code by LTU, UAq, and IBM.

Animations from transient analysis

Current distribution shown with arrows.

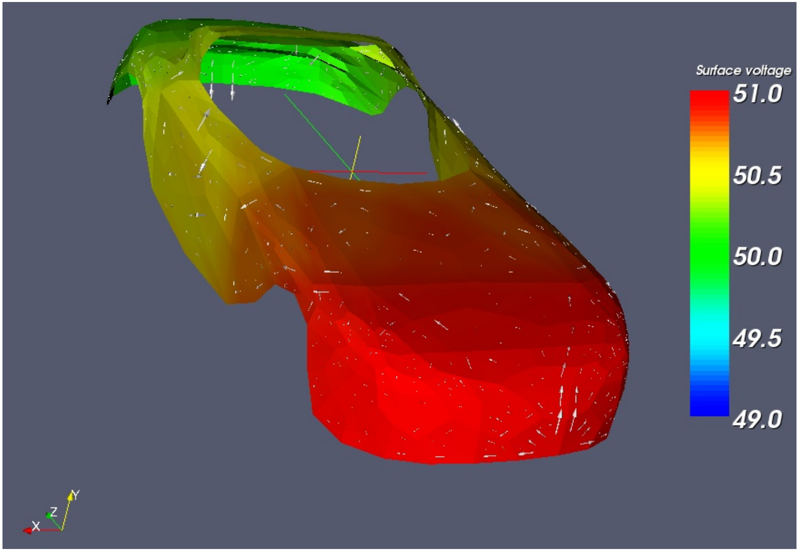
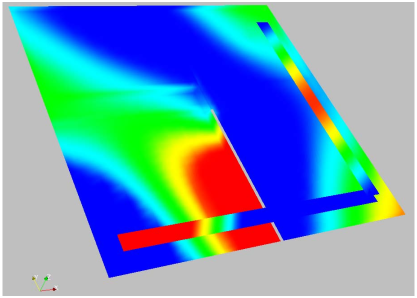


Figure 7: Screenshot from 50 ns for current source excitation at the front

5.3. Aperture in groundplane

A bent conductor over a groundplane with an aperture.



- Orthogonal PEEC
- 724 surfaces and 1 244 volumes

- Near-end differentially excited with 1 A, Gaussian pulse with 'rise time' 1 ns.
- Far-end grounded by 50 Ω resistor.

- FW, TD analysis, 200 points: 4 h, 10 m.
- FW, FD analysis: 250 freqs.: 5 h.
- Regular Linux server with 4 Gb Ram
- Code by LTU, UAq, and IBM.

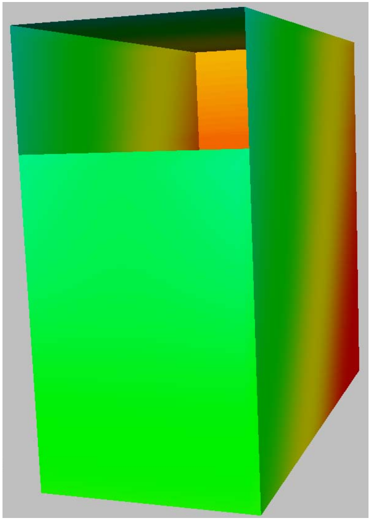
Animations from frequency domain analysis

250 frequency steps from 10 Hz to 2 GHz. Voltage distribution shown with colors and current distribution show with arrows.

(Click! Top view)

5.4. Metallic case

A 19x43x38 cm (LxWxT) case with one opening (19x10) in the front is modeled in the time- and frequency domain.

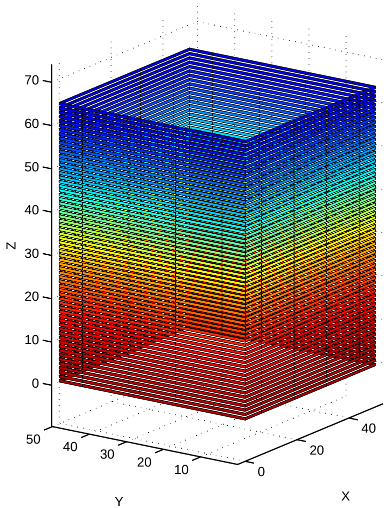


- Orthogonal PEEC
- 1 470 surfaces and 2 703 volumes

- Front excited with 1 A, pulse with rise time 1 ns.
- Case grounded at 2 locations.

- FW, TD analysis, 250 points: $\sim$ 1 m
- FW, FD analysis: 200 freqs.: 30 mins.
- Regular Linux server with 4 Gb Ram
- Code by LTU, UAq, and IBM.

5.5. Reactor



- 1.8 m high free-space reactor, 1 m sides
- Orthogonal PEEC
- 1 200 surfaces and 800 volumes

- Near-ends excited with 1 A, 'Gaussian' pulse with different rise times.
- Near and far-ends grounded.

- QS, TD analysis, 300 points: $\sim$ 50 s.
- Regular Linux server with 4 Gb Ram
- Code by LTU, UAq, and IBM.

Animations for reactor

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(Click to view)

Figure 8: Animation for winding voltages from 0 to 2.5 μs.

6. PEEC Research Project

6.1. Reactor PEEC Modeling

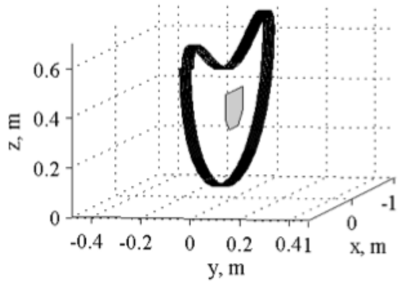
Project goals are to (1) use PEEC to construct high frequency (up to 10 MHz) models for reactors, (2) synthesize into (reduced) equivalent circuits, and (3) exported to SPICE-like solvers for use in system studies[2]

Funded by: Elforsk/ELEKTRA
Industry partners: ABB, Banverket, STRI
Period: May 2005 to Dec. 2007
Contact: Dr. Jonas Ekman
PhD Student: Mathias Enohnyaket

[2]Enohnyaket & Ekman, ‘Analysis of air-core reactors from DC to very high frequencies using PEEC modelss”, IEEE Transactions on Power Deliveryy, 2009

6.2. PEEC-modeling of RFID system with moving transponders

Show a simulation environment which enables description of a complete RFID system including moving and rotating transponders as well as a complex, industrial environment[3].



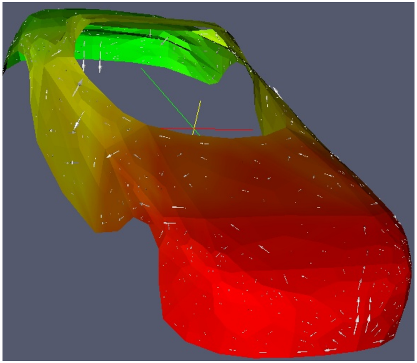
Funded by: ProocessIT Innovations
Period: 2008 to 2009
Industrial partner: Electrotech
PhD student: Tore Lindgren

[3]Lindgren, Kvarnström, & Ekman, "Monte Carlo simulation of an radio frequency identification system with moving transponders using the partial element equivalent circuit method", IET Microwaves Antennas & Propagation, 2010

6.3. EM modeling for automotive applications

Project goals are to develop PEEC for combined analysis of:

- chassis and multi-conductor transmission lines,
- chassis and antennas‘ [4].



Funded by: CASTT
Period: May 2006 to Dec. 2008

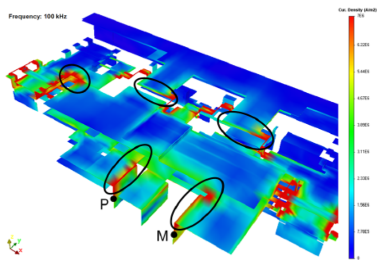
Contact: Dr. Jonas Ekman
Student: Peter Anttu

[4] Antonini, Miscione, & Ekman, "PEEC modeling of automotive electromagnetic problems", Applied Computational Electromagnetics Society Newsletter, 2008.

6.4. PEEC for power electronic systems analysis

Project goals to enable realistic PEEC-modeling of PES[5]. For example:

- inductance calculations, resistance calculations,
- impedance matrix extraction, field calculations, acceleration, robustness

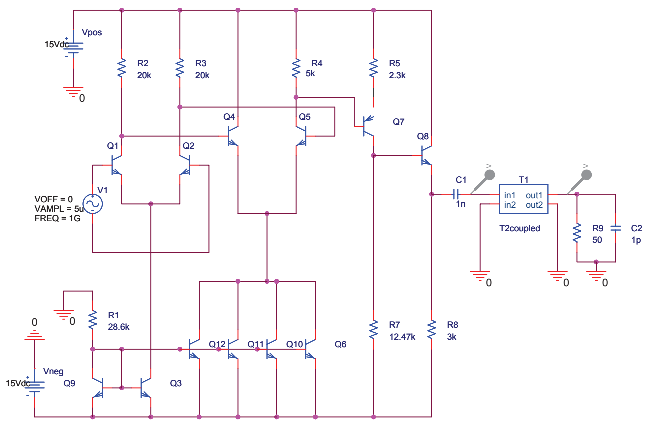


Funded by: ABB/Elforsk
Industry partners: ABB, Switzerland
Period: 2008 to 2013
PhD Student: Danesh Daroui

[5] Daroui & Ekman, "Efficient PEEC-based simulations using reluctance method for power electronic applications", Applied Computational Electromagnetics Society Journal, 2012.

6.5. PEEC and SPICE Solution

Project goals to enable realistic PEEC-modeling and complex additional circuitry analysis - All-in-one!: Full PEEC model and Full SPICE/OrCAD-solver[6].



Funded by: ESIS
Period: 2010 to 2013
PhD Student: Sohrab Safavi

[6] Safavi & Ekman, "Feasibility analysis of specialized PEEC solvers in comparison to SPICE-like solvers", Journal of Computational Electronics, 2012

6.6. Future

PEEC Road map[7]:

- Magnetic material handling.
- Full SPICE/OrCAD-solver.
- Meshing / discretization of complex structures.

[7] Antonini, Delsing, Ekman, Orlandi and Ruehli, "PEEC development road map", working paper. 2009

END

Thank You!