Simulation-Based Design in Electrical Engineering

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Simulation-Based Design in Electrical Engineering

- Introduction
- Dielectric Design of HV Products
- Magnetics in Engineering Design
- Coupled Problem
- Optimization 1
- Optimization 2

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Simulation-Based Design

- Dielectric Design -> Electro-Static
- Temperature hot spots -> Electro-Thermal
- Short-circuit Forces -> Electro-Mechanics
- Shock-structure -> Mechanics
- Acoustics

• Prototype design
• Product design
• Design upgrade

- Dielectric Design -> Electro-Static
- EM / SM Design -> Coupled Analysis
- Cooling of switchgear -> Electro-Thermal
- Explosion-proofing -> Shock-Structure

Prediction of paint application
ElectroDyn.-CFD

MEMS Designing
Coupled EM / Fluidic/
Molecular Dynamics /
Mechanic Simulation

O₂ molecules
SBD: What are the key **business drivers** in the engineering design?

1. Achieve **top device performance** with **minimal development costs**, 
2. Minimize **Time2Market**, i.e. maximal reduction of the product development time.

These two requirements can be mostly fulfilled by replacing the traditional **Experimentally-Based Design (EBD)** with the advanced **Simulation-Based Design (SBD)** through:

1. Accelerating the design process for xxx% - **avoiding prototypes**
2. Better design through **better understanding** of the physical phenomena
3. Recognizing and eliminate the product’s weak points already at the design stage

To stay at the competitive edge, the SBD has to be equipped with the accurate, robust and fast numerical technologies suited for:

1. Analysis of the **real-world 3D problems**, preserving the necessary structural and physical complexity
2. ... but, using such numerical technologies that are enough **user-friendly** to be accepted by the designers
3. ... and, using the numerical technologies suitable for the **daily** design process
Simulation-Based Design

SBD Roadmap

Geometry Design
Mesh Generation
Analysis
Criteria Evaluation
Optimization

CAD
- PTC (Pro/E)
- Catia
- SolidWork
- SolidEdge

• CADfix
• ProE
• Patran
• ...

FEM
- ANSYS
- Infolytica
- Vector Fields
• ...
- BEM
- Polopt (PT)

PT
- FLC
- CVC
- CPC

• FFO
• Parametric Opt.
• FFO & ParOPT

Experimentally-based prototyping

Digital “prototype”
Simulation-Based Design

The physics behind ...

Electro-Magnetismus
(Maxwell Equations)

High frequency
Low frequency
Steady-State
Static / Quasi-Static

Avoid **breakdown appearance** in all operational conditions

Dielectric Design

• Antennas radiation
• Wave-guides
• Scattering problems
• EMC
• …

• Eddy-Current problems
• Electro-Static problems
• Magneto-Static problems

Transformers, Switchgears, Sensors, …
Simulation-Based Design

The physics behind ...

- Elasto-Dynamics
- Fluid-Dynamics
- Heat Transfer

Electro-Magnetismus
(Maxwell Equations)

Electro-Magnetismus
High frequency
- Antennas radiation
- Wave-guides
- Scattering problems
- EMC
- ...

Electro-Magnetismus
Low frequency
- Eddy-Current problems
- Electro-Static problems
- Magneto-Static problems

Avoid mechanical deformations caused by the short-circuit appearance

Steady-State Static / Quasi-Static

El-Mech. Design

Dielectric Design

Avoid mechanical deformations caused by the short-circuit appearance

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Simulation-Based Design
The physics behind ...

Avoid material degradation caused by the thermal overheating

Elasto-Dynamics
Heat Transfer

Electro-Magnetismus
(Maxwell Equations)

Electro-Magnetismus
High frequency

Electro-Magnetismus
Low frequency

Steady-State Static / Quasi-Static

- Antennas radiation
- Wave-guides
- Scattering problems
- EMC
- …

- Eddy-Current problems
- Electro-Static problems
- Magneto-Static problems

Thermal Design
El-Mech. Design
Dielectric Design
Simulation-Based Design in Electrical Engineering

- Simulation-Based Design in Engineering Praxis
- **Dielectric Design of HV Products**
- Magnetic Design in EE
- Coupled Problem
- Optimization 1
- Optimization 2
Main technical challenges

• When designing the HV apparatus (like switchgear, transformers), it is important to properly design the dielectric insulation with respect to possible overvoltages.

• Typically, two class of problems relate to the dielectric design:
  1. Determination of the voltage stress which the insulation must withstand
  2. Determination of the response of the insulation, when subjected to these voltages stresses

The balance between the electrical stress on the insulation and the dielectric strength of the insulation is a key task of the insulation coordination within dielectric design!
Within DD of HV products, each HV devices’ series has to be tested against:

- **Power frequency voltage** (1min. test under 50Hz (60Hz))
- **Switching impulse** – recommended for the equipment under the voltages above 300kV
- **Lightning impulse voltage**

*Form of the lightning impulse voltage. Peak is reached within 1.2μs*
Those kinds of tests are usually carried out in the specialized HV lab. One of the very well know is **KEMA** in Holland / USA.

An equivalent laboratory in Italy is **CESI**.

*HV testing laboratory KEMA, Holland*
How the design process of one the HV products looks like?
HECS-PS: new product in ABB GCB environment!

HECS-PS road map

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160 kA
3 sec

7 months!
SBD in ED: Dielectric Design of HV Products

SBD Roadmap

Geometry Design
Mesh Generation
Analysis
Criteria Evaluation
Optimization
**SBD in ED: Dielectric Design of HV Products**

- Mathematical model
- Numerical representation
- Some examples
Maxwell Equations

Gauss' law for electricity: \( \nabla \cdot D = \rho_e \)
- General case: \( D = \varepsilon_0 E + P \)
- Free space: \( D = \varepsilon_0 E \)
- Isotropic linear dielectric: \( D = \varepsilon E \)

Gauss' law for magnetism: \( \nabla \cdot B = 0 \) (no magnetic monopoles!)

Faraday's law of induction: \( \nabla \times E = -\frac{\partial B}{\partial t} \)

Amper's law: \( \nabla \times H = J + \frac{\partial D}{\partial t} \)
- General case: \( B = \mu_0 (H + M) \)
- Free space: \( B = \mu_0 H \)
- Isotropic linear magnetic media: \( B = \mu H \)

The electric flux leaving a volume is proportional to the charge inside.

The total magnetic flux through a closed surface is zero.

The voltage induced in a closed loop is proportional to the rate of change of the magnetic flux that the loop encloses.

The magnetic field integrated around a closed loop is proportional to the electric current plus displacement current.
Electrostatics

Assuming that there is no magnetic field, (B=0)

*Gauss' law for electricity:* \( \nabla \cdot D = \rho \)

*Faraday's law of induction:* \( \nabla \times E = 0 \)

\[ \begin{align*}
\text{Gauss' law for electricity} & : \quad \nabla \cdot D = \rho \\
\text{Faraday's law of induction} & : \quad \nabla \times E = 0
\end{align*} \]

Different Notation:

\[ \begin{bmatrix}
\text{div} D = \rho \\
\text{curl} E = 0
\end{bmatrix} \]

Boundary conditions

\[ \begin{align*}
\varphi_1 &= \varphi_2 \\
\varepsilon_1 \frac{\partial \varphi_1}{\partial n} - \varepsilon_2 \frac{\partial \varphi_2}{\partial n} &= \sigma
\end{align*} \]

For homogeneous media, where the space charge \( \rho = 0 \)

\[ \nabla^2 \varphi = 0 \quad \text{Laplace's equation} \]
Electrostatics

Numerical methods

- FDM
- FEM
- BEM

Basic idea: simulation of real charges/currents on electrodes and dielectrics by the equivalent sources of single or double layer

Original Problem

Equivalent Problems

Single Layer Charge (Current)

Double Layer Charge (Current)

Direct

Indirect

Double Layer

Single Layer

Collocation

Galerkin
BEM for Dielectric Problems

**Formulation: Single-Layer Ansatz**

\[
\Delta \varphi = 0 \quad & \quad \phi_1 = \phi_2 \quad & \quad \varepsilon_1 \frac{\partial \phi_1}{\partial n} - \varepsilon_2 \frac{\partial \phi_2}{\partial n} = \sigma
\]

\[
\varphi(I) = \frac{1}{4\pi \varepsilon_0} \int_S \sigma(J) \frac{1}{r_{IJ}} dS_J
\]

**Implementation:**

- **Method:** Collocation / Galerkin
- **Ansatz:** Direct / Indirect
- **Approximations:**
  - geometry-quadratic
  - sources - linear

\[
\sigma(I) = \frac{\lambda}{2\pi} \int_S \sigma(J) \cdot \frac{r}{u} \cdot \hat{n}^0 \cdot \hat{n} \cdot \frac{r}{u} \cdot \frac{3}{u} dS_J
\]

- I FIE (potential continuity)
- II FIE (flux continuity)
BEM for Dielectric Problems

**Formulation: Double-Layer Ansatz**

\[
\Delta \phi = 0 \quad \& \quad \phi_1 - \phi_2 = \frac{1}{\varepsilon_0} \tau \quad \& \quad (E_1 - E_2) \cdot n = 0
\]

\[
\varphi(I) = \frac{1}{4\pi \varepsilon_0} \int \sigma(J) \frac{1}{r_{IJ}} dS_j 
\]

\[
\Omega_p \left( \varepsilon_r - 1 \right) + 4\pi \left( \varepsilon_r - 1 \right) \tau_i (P_o) + \int_{S_d} \tau_i \frac{n_i \cdot r_{IJ}}{4\pi r^3} dS = -\varepsilon_0 \phi_{Ex} (P_o)
\]

Flux-density potential:

\[
\varphi_J = \varphi_{cl} + \varphi_{d} = \int_{S_k} \sigma_I \frac{1}{4\pi r_{JI}} dS_I + \int_{S_d} \tau_I \frac{n_I \cdot r_{JI}}{4\pi r^3} dS_I
\]

Flux density:

\[
D_J = -\nabla \varphi_J = \int_{S_k} \sigma_I \frac{r_{JI}}{4\pi r_{JI}^3} dS_I + \sum \tau_I \int_{\Delta d} t_i \times r_{JI} \frac{3}{4\pi r_{JI}^3} dL_i
\]

J. A. Stratton: *Electromagnetic Theory*
McGraw-Hill, Inc. 1941, ISBN 07-062150-0

**Formulation: Double-Layer Ansatz**

\[ \varphi(I) = \frac{1}{4\pi\varepsilon_0} \int_{S} \sigma(J) \frac{1}{r_{ij}} dS_j \]

\[ \Omega_P \left( \varepsilon_r - 1 \right) + \frac{4\pi}{4\pi} \tau_1 \left( P_o \right) + \int_{S_d} \tau_1 \frac{n_i \cdot r}{4\pi r^3} dS = -\varepsilon_0 \phi_{Ex} \left( P_o \right) \]

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Potential distribution of IEC surge-arrester model

a. IEC surge-arrester model with two floating electrodes and grading ring;

b. Potential distribution along the zinc-oxide / HV / LV components

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4/30/2018

www.polopt.com
Indirect Approach: Double-Layer Electrostatic Formulation

\[
\varphi(I) = \frac{1}{4 \pi \varepsilon_0} \int \sigma(J) \frac{1}{r} dS_j
\]

\[
\Omega_r(\varepsilon_r - 1) + \frac{4 \pi}{4 \pi} \sum \tau_i(P_n) + \int \frac{n \cdot r}{4 \pi r} dS = -\varepsilon_0 \varphi_e(P_n)
\]

Sources approximation

\[
\sigma = \sum_{i=1}^{N} \sigma_i \cdot N_i
\]

Geometry approximation

\[
\tau(I) = k_1 \sum_{All\ domains\ GP} \bar{\sigma}(J) \cdot \bar{K}_1 \cdot \Delta S_e
\]

\[
\bar{\varphi}(I) = k_2 \sum_{All\ domains\ GP} \bar{\tau}(J) \cdot \bar{K}_2 \cdot \Delta S_e
\]

\[
\begin{bmatrix}
    a_{1,1} & a_{1,2} & a_{1,3} & \ldots & a_{1,n} \\
    a_{2,1} & a_{2,2} & a_{2,3} & \ldots & a_{2,n} \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    a_{m,1} & a_{m,2} & a_{m,3} & \ldots & a_{m,n} \\
    a_{m+1,1} & a_{m+1,2} & a_{m+1,3} & \ldots & a_{m+1,n} \\
    a_{m+2,1} & a_{m+2,2} & a_{m+2,3} & \ldots & a_{m+2,n} \\
    a_{n,1} & a_{n,2} & a_{n,3} & \ldots & a_{n,n}
\end{bmatrix}
\begin{bmatrix}
    \sigma \\
    \tau
\end{bmatrix}
= 
\begin{bmatrix}
    \phi \\
    0
\end{bmatrix}
\]

\[
[A][x] = [V]
\]
**Static problems**
(dielectric design)

Fredholm integral equations

1 DOF (real scalars)
Typical problem size: 10.000-20.000 unknowns
Typical matrix size: < 200Mb
Matrix: full populated, diagonal dominant

Typical calc. time: ~1 Hours (serial)
Accuracy: mesh insensitive

**Steady-state problems**
( eddy-currents)

H-φ formulation

Min. 3 DOF (complex vectors)
Typical problem size: 10-20.000 unknowns
Typical matrix size: > 4 Gb
Matrix: full populated, diagonal dominance depends on material parameters

Copper (μ=1)
Steel (μ=200)

Typical calc. time: 1-2 days (serial)
Accuracy: highly mesh dependent
BEM: Integration

Major Problems

Matrix generation:

"Near-field" integration
- singular integration
- nearly-singular integration
- aspect ratio problem

"Far-field" integration

Major Impact:

Accuracy, Robustness

Speed

Matrix solution:

Matrix conditioning

Convergence

Standard BEM

- Main bottlenecks: Full populated matrices
- huge memory size
- long computational time
$$G_{ij} = \int_0^1 \int_0^1 \varphi_i(x) g(x, y) \varphi_j(y) \, dx \, dy$$

**Kernel:** Singular for $x=y$

Smoothly decaying for $|x-y| \to \infty$

**Key idea:** Divide space of interest into near-field and far-field.

Near-field: exact computing of $G_{ij}$

Far-field: only approximations of $G_{ij}$

**Difference between techniques:** Far-Field treatment!

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J. Carrier, L. Greengard, V. Rokhlin: *A Fast Adaptive Multipole Algorithm for Particle Simulations*  

M. Bebendorf, S. Rjasanow: *Adaptive low-rank approximation of collocation matrices*  
Computing, 70 (2003), 1-24
ES: Time for matrix generation

- Clustering
- Full
- Multipol

CPU

ES: Storage

- Clustering
- Full
- Multipol

.. x19

.. x17
BEM for Dielectric Problems

*Formulation: Double-Layer Ansatz*

**Main features**

- Highly accurate treatment of dielectric problems independent of the material features of the dielectric components,
- Robust calculation of the problems exhibiting geometrical singularities (edges and corners),
- Novel singularity-less calculation of the electrical field / flux,
- The calculated charge densities correspond to the real physical quantities (instead of fictitious as in SCM!),
- Thanks to 4, capacitances of the analyzed model are inherent output i.e. direct function of the calculated charges (no need for extra capacitance run!)
- Easy treatment of the floating–potential problems.
SBD in ED: Dielectric Design of HV Products

- Mathematical model
- Numerical representation
- Some examples
Electrostatic Problems Classification

a.) TEC  
TEC - Total Electrode Charge

b.) MIM  
MIM - Mirror-Imaging Method

c.) MIM

d.) Standard BEM?

e.) Standard BEM
Task:
Predict a breakdown voltage (safety margin) for all operating conditions:
- Nominal voltages: 17-30 kV
- Nominal currents: 6-28 kA
- Short-circuit currents: 50-160 kA
Can the simulation at the **component level** give an prediction on the **safety margin** of the entire system?

What is a level of the **model simplifications** that still guarantee the proper solution?
Electrical field distribution in the GCB

Field distribution is just a "primary information", i.e. a necessary but not a sufficient condition!
Field distribution is just a “primary information”, i.e. a necessary but not a sufficient condition!
Field distribution is just a "primary information", i.e. a necessary but not a sufficient condition!

Breakdown criteria evaluation!!!

Electrical field distribution along the field line
Reliable / Robust / Fast tools for the simulation of the entire assembly required!

Electrical field distribution in the GCB
Meshing: 2 min.

- 160,000 second order triangle elements
- 70,000 nodes (DOF)

Analysis: 2.3 h

- 22 node PC cluster (Pentium3)
Dielectric
Design Criteria
Dielectric Design Criteria

SBD Roadmap

Geometry Design
Mesh Generation
Analysis
Criteria Evaluation
Optimization

- Pro/E
- Ideas
- Catia
- SolidWork
- SolidEdge
- ...

- CADfix
- ProE
- Patran
- Ideas
- ...

FEM
- Ansys
- Maxwell
- Vector Fields
- ...

- BEM
- IES
- Polopt

POLOPT/Laplace
- FLC
- CVC
- CPC


A. Blaszczyk: Flashover Workshop 2006, Baden Deattwil

What is a main purpose of the Design Criteria (DC)?

Design Criteria serve to predict weather or not the Breakdown/Flashover can happened!
What is a flashover?

- **Flash-over** – is a discharge in a gas along the surface of a solid dielectric [IEC].
- **Spark-over** – is a discharge across a gap between electrodes in a gas.
- **Withstand voltage** - is the highest voltage applied to an arrangement that, with a low probability (<2%), can lead to a discharge.
- **Breakdown voltage** is a voltage that will lead to a discharge.
Prediction of withstand voltage in a design system

SBD Roadmap

Geometry Design  Mesh Generation  Analysis  Criteria Evaluation  Optimization

• Pro/E  
• Ideas  
• Catia  
• SolidWork  
• SolidEdge  
• ...

• CADfix  
• ProE  
• Patran  
• Ideas  
• ...

• FEM  
• Ansys  
• Maxwell  
• Vector Fields  
• ...

• BEM  
• IES  
• Polopt

Withstand Voltage Prediction

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Dielectric Criteria Roadmap

(1) Evaluate *inception* voltage $U_{di}$ based on *streamer criterion* along field lines $\Rightarrow$ numerical field analysis

(2) Calculate *withstand voltage* as a product of $U_{di}$ and empirical coefficients
Discharge mechanism in gases: **Inception**

- After the initial electron has appeared an avalanche of electrons according to **Townsend mechanism** may develop.

- An avalanche leads to the **exponential growths** of the number of electrons.

- If the number of avalanche electrons exceeds a specific limit a self-propagating **streamer discharge** will occur.
Streamer criterion

Assumption:

(1) The avalanche of electrons will develop along a field line started from the high stress area on an electrode.

(2) The critical number of electrons $N_\sigma$ can be obtained by integrating the effective ionization coefficient along the field line:

$$\int_0^{x_c} \alpha_{eff}[E(x)] \cdot dx > \ln(N_\sigma)$$

Streamers criterion:

- 9.15 for air
- 10.5 for SF6

Based on latest investigation performed by ETH Zurich (in the past, a value of 18.4 = ln(10^8) has been commonly assumed)
Ionization coefficient for air and SF6

\[ \alpha = 0 \text{ for } E < 2.6 \text{ kV/mm at 1bar} \]

\[ \alpha = 0 \text{ for } E < 8.9 \text{ kV/mm at 1bar} \]
Inception versus breakdown

- Inception voltage $U_{di}$ can be accurately calculated for any arbitrary electrode configuration (in 3D)
  - $U_{di}$ determines the partial discharge inception

- Inception can be influenced by the microscopic field enhancement => surface roughness

- Streamer inception not always leads to a breakdown! The following factors can contribute to a breakdown voltage higher than the inception voltage:
  - Field in-homogeneity
  - Short duration of the applied voltage (“time lag”) (this is more important for lightning impulses in SF6)
Withstand voltage for needle-plate arrangement in air
Stream the Criteria

$U_{br}=136.8$ kV,
(137 kV, IEC Pub. 52)

$E_{cr}/p=2.16 \times 10^6$ V/mbar

$E_{min}/p > E_{cr}/p = 2.16 \times 10^6$ V/mbar $\to$ SM I

$U_{br}=246$ kV,
(241 kV, IEC Pub. 52)

$E_{min}/p < E_{cr}/p=2.16 \times 10^6$ V/mbar $\to$ SM II

$E_{cr}/p=2.16 \times 10^6$ V/mbar

$E_{min}/p > E_{cr}/p = 2.16 \times 10^6$ V/mbar $\to$ SM I

$E_{cr}/p=2.16 \times 10^6$ V/mbar

$E_{min}/p < E_{cr}/p=2.16 \times 10^6$ V/mbar $\to$ SM II
Example I: Two spheres (single-load opt.)

- **Field distribution [V/m]** at the starting point of the field line (HV electrode);
- **Breakdown voltages [V]** for each of 21 optimization step

a) Non-optimized spheres

b) Optimized spheres

- **$E_{\text{max}}$: 76%**
- **$U_{\text{br}}$: 90%**
Improving the withstand of the NAL earth switch
Flashovers in a 40 kV cable compartment (R40, CHSEC)
Evaluation of withstand voltage (R40)

This spot is critical -> possible flashovers
Simulation-Based Design in Electrical Engineering

- Simulation-Based Design in Engineering Praxis
- **Dielectric Design of HV Products**
- Magnetic Design in EE
- Coupled Problem
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