LI PE Section

Spellman High Voltage Electronics Corporation

“No man’s design can be better than his understanding of the first principles”

Circuit and Field Simulations in (my, mostly SHV) HVPS Practice

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Contents

- Field or circuit analysis, or both? *The answer is not always obvious*
- General remarks on simulation methodology (more will be interspersed in examples)
- Circuit simulations on PSpice platform–focus on power conversion
  - DC-to-DC converters (open/closed loop)
  - Front end, Miscellaneous
- Field simulations (mostly, on COMSOL platform)
  - Electromagnetic *(AC/DC Module - low frequency)*
    - Electrostatics (ES), Electric currents
    - (Electro)Magnetic fields (including eddy currents)
    - Coupling to external electrical circuit
    - Particle tracing for calculation of BD voltages in gas insulation (module not purchased)
  - Thermal and CFD (Heat Transfer Module)
    - Heat transfer (HT) in solids
    - Heat transfer in fluids
    - Conjugate heat transfer
  - Coupled physics (e.g., EM and HT, ES and fluid dynamics and HT, etc.)

General remarks (mostly, about FEA)

- Ideally, before starting:
  - Understand underlying physics well; make analytical estimates if feasible
  - Will circuit analysis be adequate, or field formulation(s) need to be invoked?
  - For circuit analysis, is lumped parameters approximation good enough?
  - Would an experiment be an easier way? How simulation will be validated?
  - Understand how the results would look like (e.g., in electrostatics, ability sketching equipotential lines)
  - Quantify/justify simplifications/assumptions – garbage in, garbage out!
  - Solve simple cases (e.g., subcircuits, 2D) before transiting to full-blown models
- Initial model build
  - Use linear materials/components before specifying nonlinear properties
  - Build mesh to address physics (e.g., in eddy current problems, choose size matching skin depth, both in frequency and transient domains)
  - Exploit software model-minimizing capabilities (symmetry, periodicity, thin layers, etc.)
- Only in rare cases intuition misleads. Then simulations become really thought-provoking – *you are on to something!*

Equivalent circuits (EqC) of complex circuits and "large" HV objects

- EqC necessary to a) simplify real circuits; and/or b) model EM fields avoiding field simulations; yet keeping sufficient transparency and clarity
- Correct modeling of parasitics is key to meaningful modeling of HV converters
- HV cables can be modeled as capacitors (except on short transients)
- EqC are especially useful for "large" HV structures; analytical solutions are available for many cases (see textbooks on HV engineering or [1] and its references)

[1] Pokryvailo, A., ""Large" HV Structures: Transient Analysis of Voltage Distribution from First Principles", *Proc. 2018 IEEE Power Modulator and High Voltage Conference,* 2018.

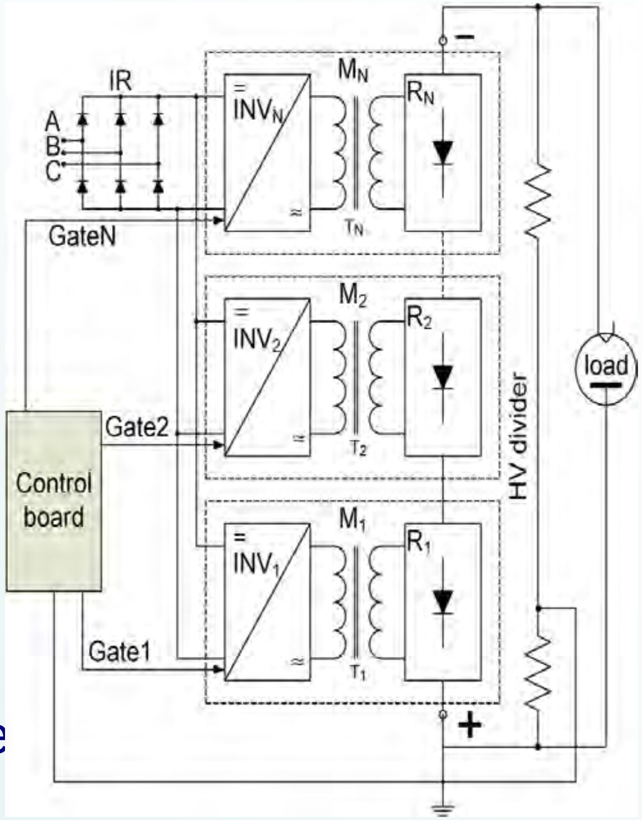
Specific info sought in converter (circuit) simulations

- Desirable/optimal leakage inductance Ls (feasibility to achieve optimal value to be verified in field simulations/physical model)
- Transformers cores flux density (saturation, losses estimate)
- “Real” semiconductor devices losses
- Ripple (especially for multi-phase systems)
- Compression (between multiplier stages)
- Peak and rms currents
- Impact of multiplier parasitic capacitances on rms currents and compression, mostly, in HV/low power designs
- Quantifying dynamic characteristics (e.g., determining risetime)

Modeling HV converters:

Trade-offs to speed simulations *and things to watch*

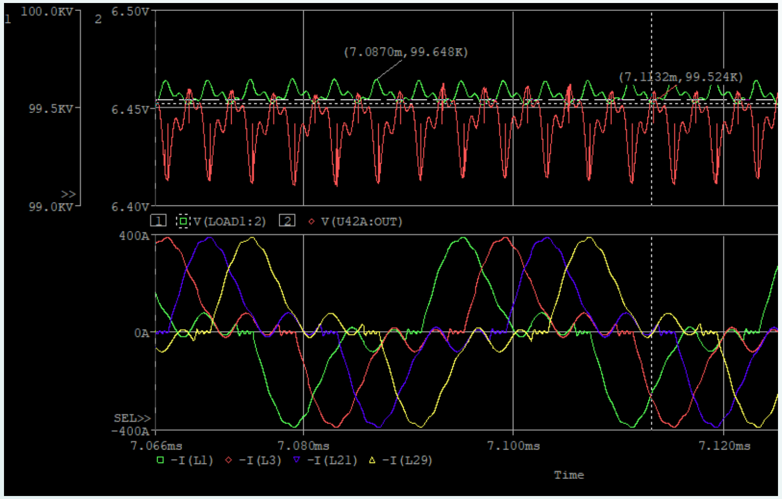
- Correct modeling of parasitics is key to meaningful modeling of HV converters, however, do not overdo!
- Multicell systems can be reduced to a single cell (module); full system can be modeled later (same in physical modeling), e.g., to quantify interleaving
- HV cables can be lumped into caps (except on short transients, e.g., load sparking [1, 2])
- Voltage Multiplier (VM) components, as a starting point, can be modeled as ideal Spice parts

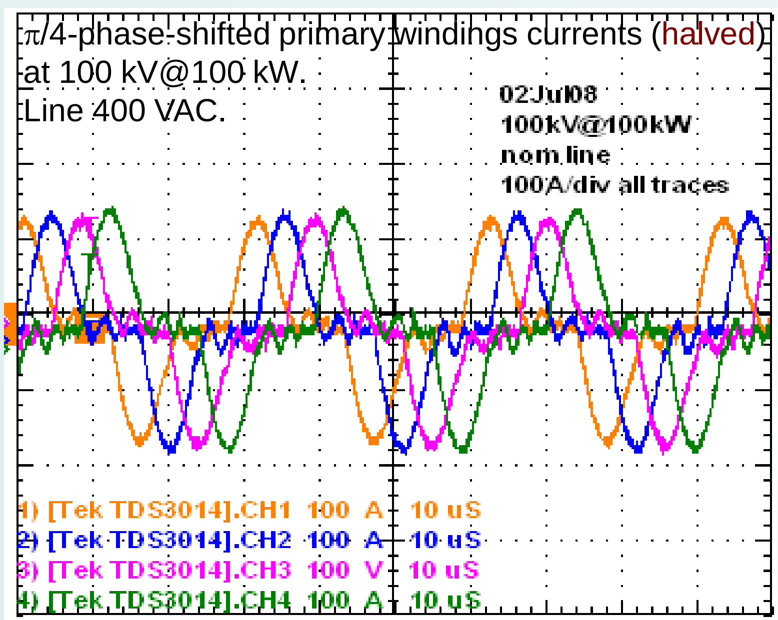


[1] Pokryvailo, A., and Scapellati, C., "Behavior of HV Cable of Power Supply at Short Circuit and Related Phenomena", IEEE TDEI, Vol. 20, No. 1, February 2013, pp. 28-33.
[2] Pokryvailo, A., "Behavior of HV Cable at Short Circuit", IEEE TDEI, Vol. 22, No. 4, August 2015, pp. 1763-1768.

Modeling HV converters

an example [1]: 100kV@100kW PS





A criterion of "good" modeling is fair match of experimental and theoretical waveforms; usually, this is the case if the transformer parameters and other parasitics are modeled correctly

[1] A. Pokryvailo et al., "A High-Power High Voltage Power Supply for Long-Pulse Applications", IEEE TPS, Vol. 38, No. 10, 2010 (available at SHV site)

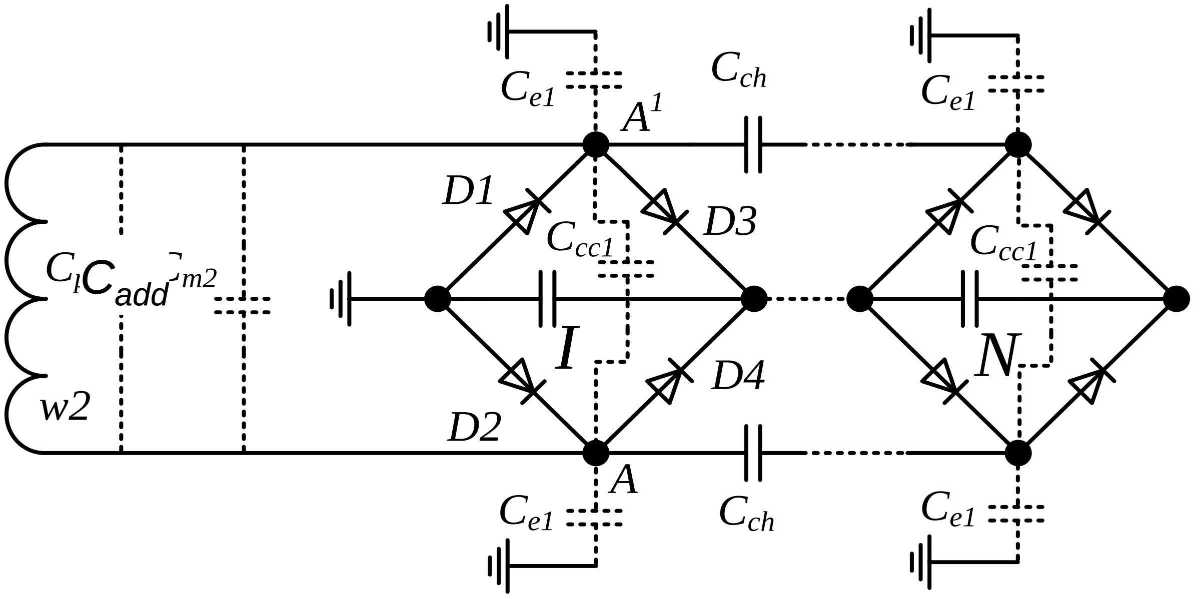
See more examples in:

[2] A. Pokryvailo et al., "High Power, High Performance, Low Cost Capacitor Charger Concept and Implementation", IEEE TPS, Vol. 38, No. 10, 2010

[3] A. Pokryvailo *et al*., "A 100 kW High Voltage Power Supply for Dual Energy Computer Tomography Applications", IEEE TDEI, Vol. 22, No. 4, 2015

[4] A. Pokryvailo, "A High-Power 200 kV Power Supply for Capacitor Charging Applications", IEEE TDEI, Vol. 24, No. 4, 2017

VM Parasitic Capacitance



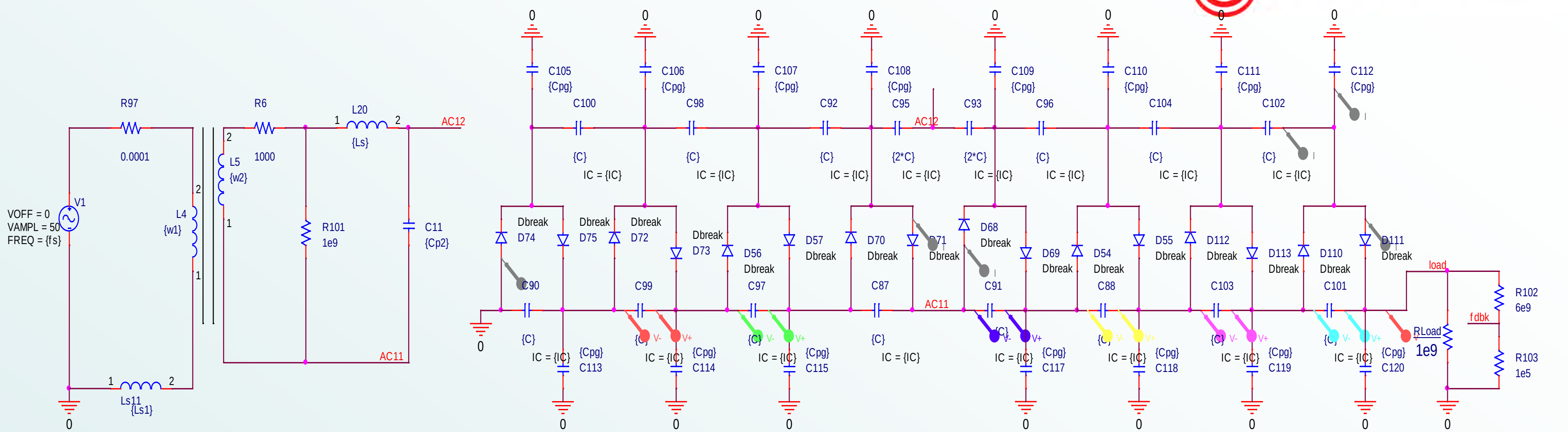
N-stage bridge VM with its parasitic capacitances; C_{p2} is parasitic capacitance of transformer

$C_{add} = C_{cc} + C_e/2$

- In simulations, C_{e1}, C_{cc1} *usually* can be replaced by $C_{m2} \equiv C_{add}$
- In first approximation, C_{m2} is proportional to the number of stages and remains invariant

See a seminal paper by E. Everhart and P. Lorrain, “The Cockcroft-Walton Voltage Multiplying Circuit”, Review of Scientific Instruments 24, 221 (1953).

VM fed by a sine wave source via a transformer



VM fed via transformer: C=0.14nF C_{pg}=3.25pF C_{p2}=12pF R_{load}=100MΩ				
Stage	V_{stage}, kV	K	top, kV	bottom, kV
bot1	9.24	1.68	33.1	28.8
bot2	7.66			
bot3	6.42			
bot4	5.50			
top1	9.50	1.29		
top2	8.44			
top3	7.74			
top4	7.38			

Compression between stages, *K*, asymmetrical for bottom and top halves. C=0.14nF

Pokryvailo, A., “Analysis of Resonant Behavior of Voltage Multiplier”, Presented at 2022 IEEE Power Modulator and High Voltage Conference, Knoxville TN, June 2022

VM fed by a sine wave source via a transformer - resonances

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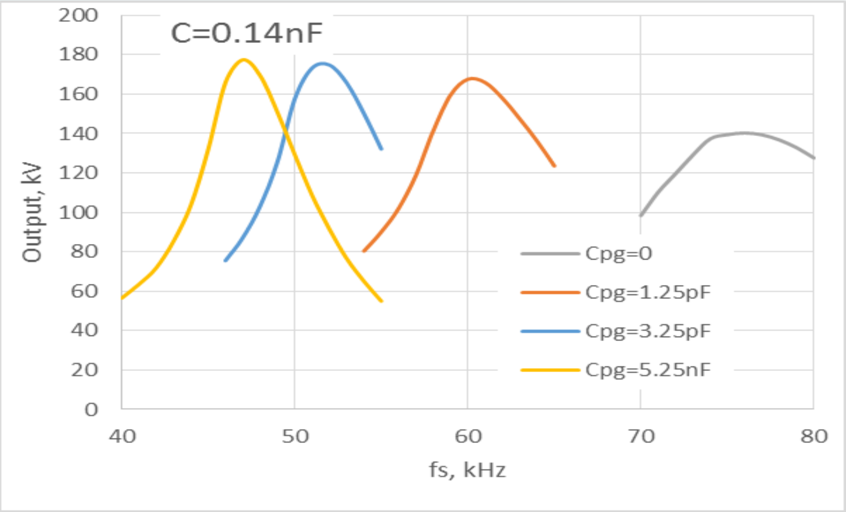
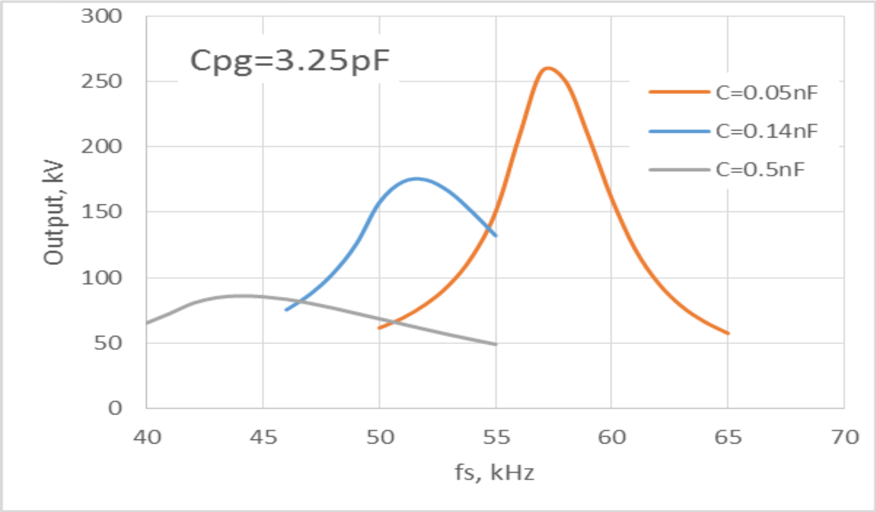
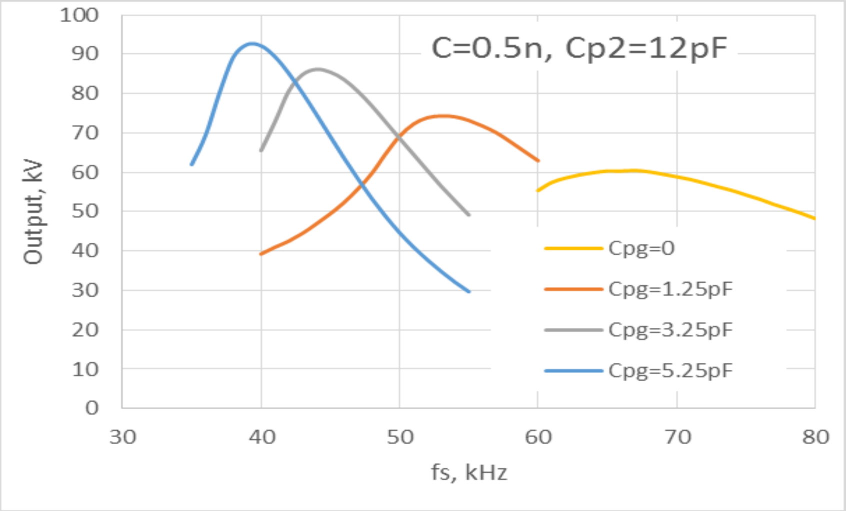
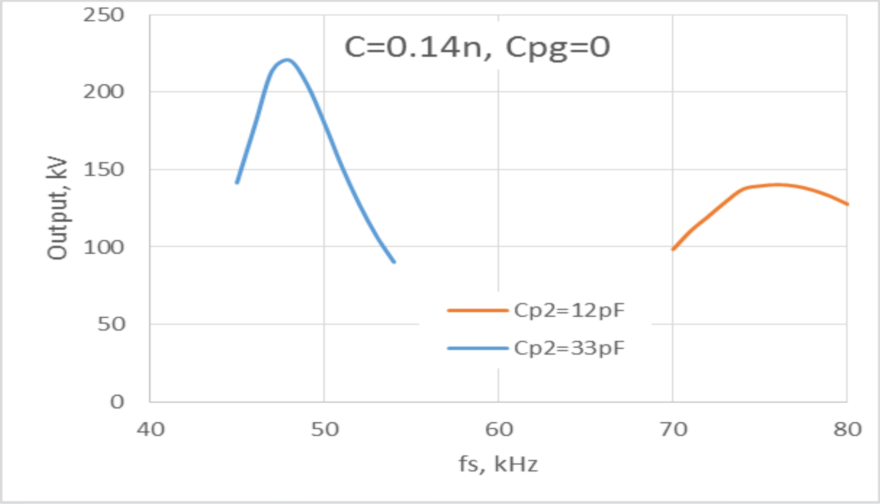








Multiple resonances seen with square waveforms

Circuit simulation

Field simulations examples

understanding underlying physics is key to success

- Electromagnetic (low frequency)
  - Electrostatics (ES)
  - Electric currents (EC)
  - Magnetic fields (including eddy currents) MF
  - *Coupling to external electrical circuit*
  - Particle tracing for calculation of BD voltages in gas insulation
- Thermal and CFD
  - Heat transfer (HT) in solids
  - Heat transfer in fluids
  - Conjugate heat transfer
- Coupled physics (e.g., EM and HT, ES and fluid dynamics and HT, and more)

Electrostatics (ES/EC): scope and applicability

- There are three scenarios with two extreme cases [1]
  - AC/transient (field distribution is governed by permittivities); 99.9% applicable at line frequency
  - DC (field distribution is governed by conductivities)
  - Low frequency/slow transients – both permittivities and conductivities matter
- Space charge is difficult to account for (especially, in liquid/solid dielectrics)
- Conductivity dependence on field and temperature is usually unknown, which renders DC analysis (EC) *quantitatively* useless

$$\nabla \cdot \mathbf{D} = \rho_v$$
$$\mathbf{E} = -\nabla V$$

$$\nabla \cdot \mathbf{J} = Q_{j,v}$$
$$\mathbf{J} = \sigma \mathbf{E} + \mathbf{J}_e$$
$$\mathbf{E} = -\nabla V$$

$$\nabla \cdot \mathbf{J} = Q_{j,v}$$
$$\mathbf{J} = \sigma \mathbf{E} + \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}_e$$
$$\mathbf{E} = -\nabla V$$

[1] Pokryvailo, A., "Analyzing Electric Field Distribution in Non-Ideal Insulation at Direct Current", *Proc. Electrimacs*, Quebec, 2008. *A tutorial paper, available at SHV site*

Case study--flat capacitor with layered insulation

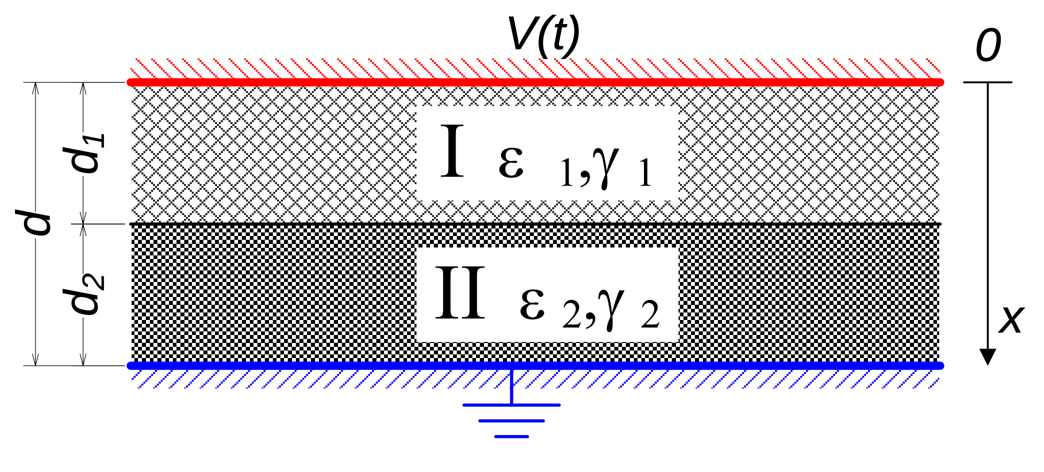


Fig. 1. Flat capacitor with two layers of non-ideal isotropic insulation.

Given:

V_m=1V

$d_1=d_2$=1cm;

ε_1=2.3; ε_2=5;

$\rho_1=1/\gamma_1=10^{13}$ Ω·m;

$\rho_2=1/\gamma_2=10^{11}$ Ω·m;

1st case: DC voltage

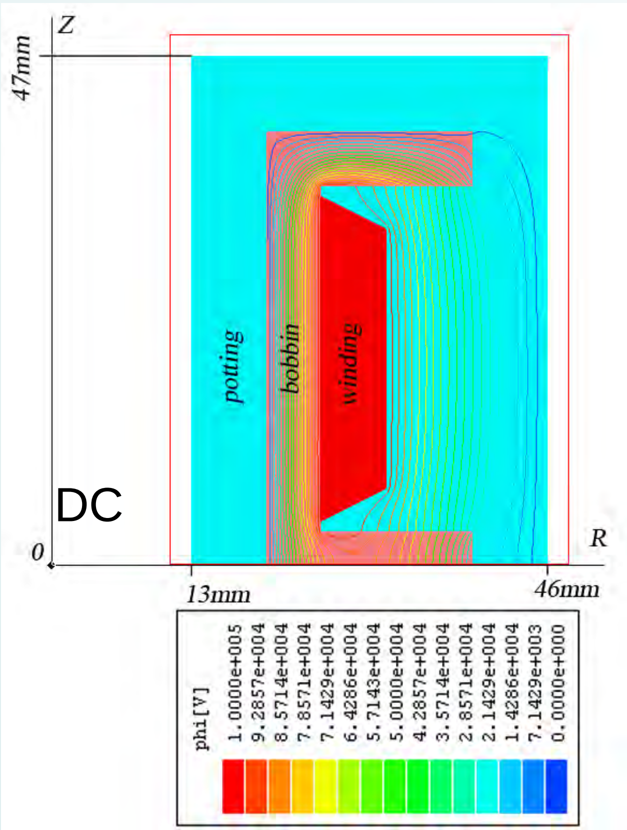
2nd case: AC (f=50Hz)

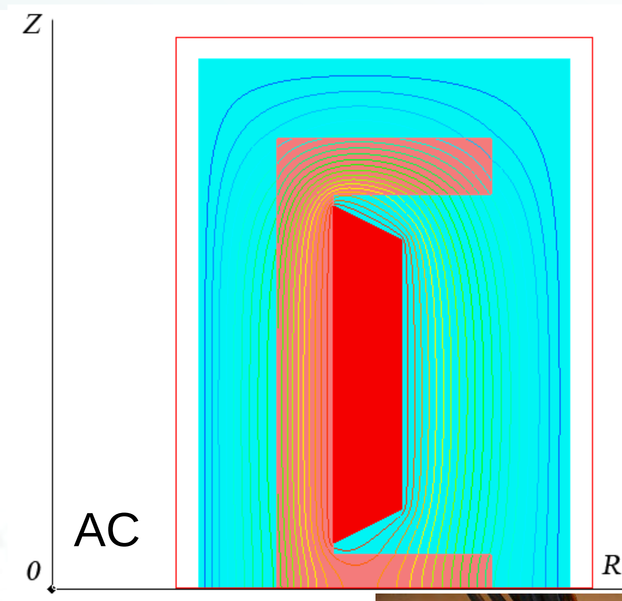
E_1=? E_2=?

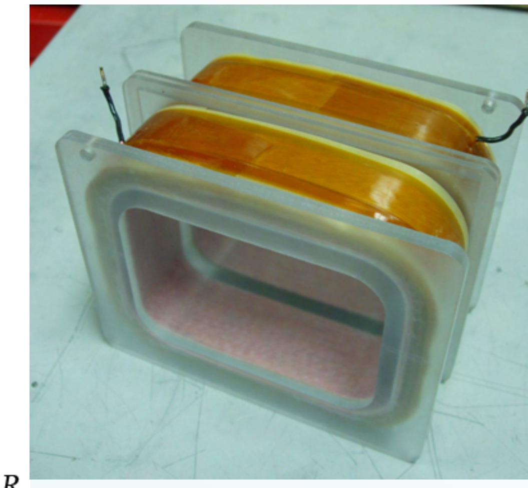
Acceptable accuracy of solution is 1%

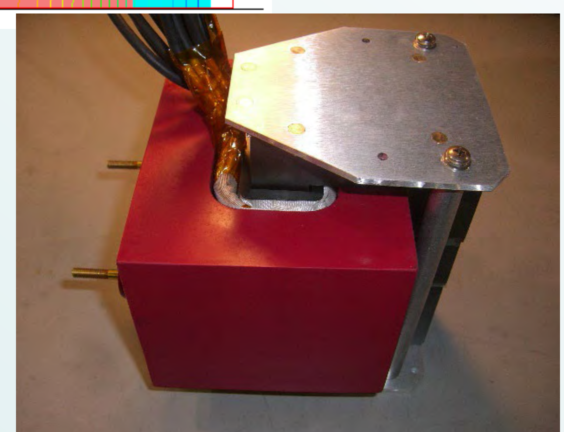
[1] Pokryvailo, A., "Analyzing Electric Field Distribution in Non-Ideal Insulation at Direct Current", *Proc. Electrimacs*, Quebec, 2008. *A tutorial paper, available at SHV site*

Numerical examples (Maxwell 2D Student version)





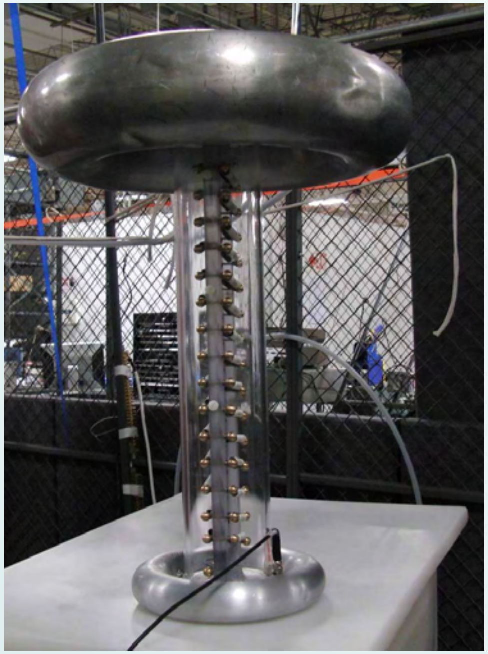


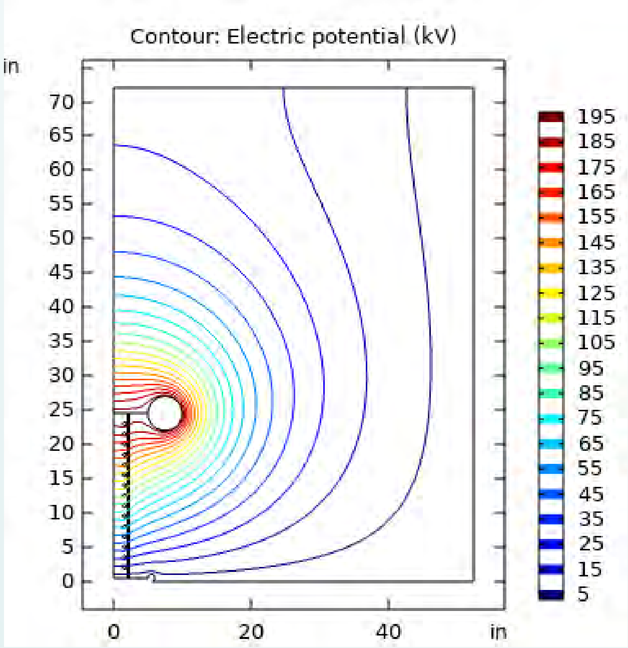


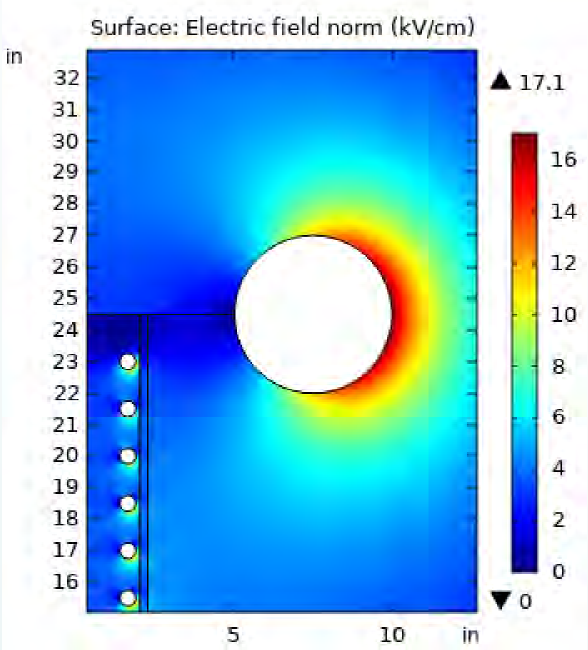
coil wound on plastic bobbin (ε_1=2.3ε_0), further potted in epoxy (ε_1=5ε_0). Their conductivities are related as 1:100. a – DC field (conduction problem); b – AC (electrostatic problem).

HVD200C (ES)

Goal: reducing E-field below ~24kV/cm to prevent ionization in air at STP







2D axisymmetric model. Field at 200kV. E_{max}=17kV/cm (21kV/cm at 250kV).

Pokryvailo, A., “Fast Measurements with Modified HVD Series of High Voltage Dividers”, *Presented at 2022 IEEE Power Modulator and High Voltage Conference,* Knoxville TN, June 2022

Tapering winding to reduce field

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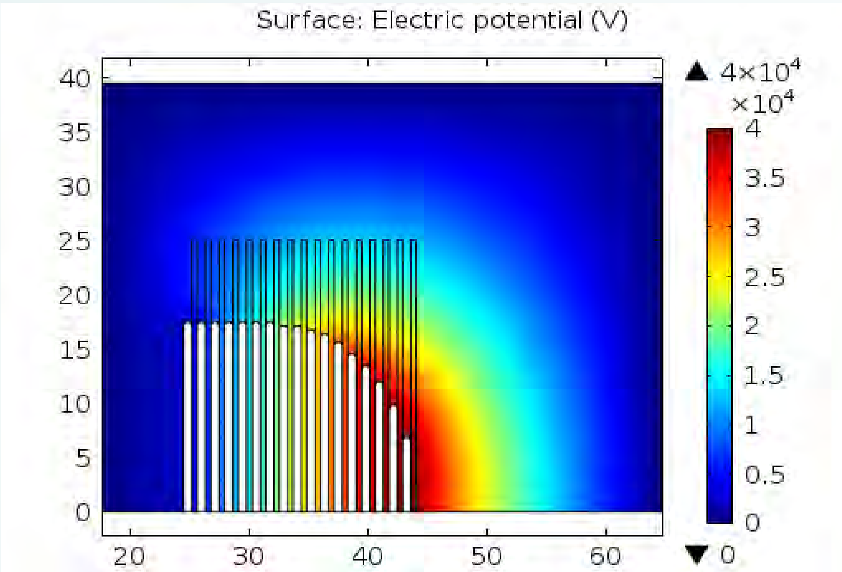
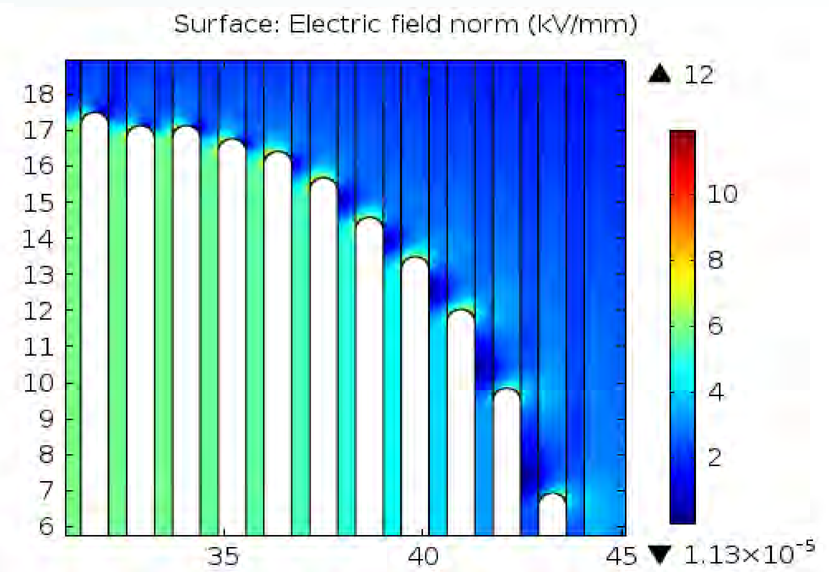
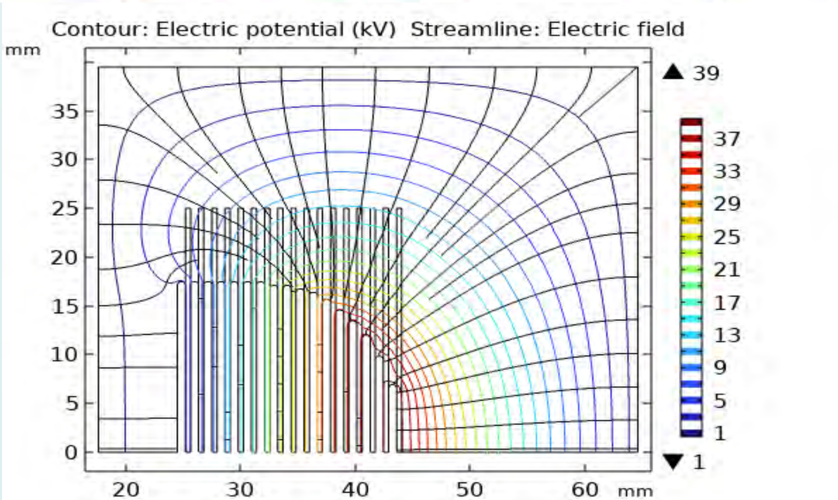
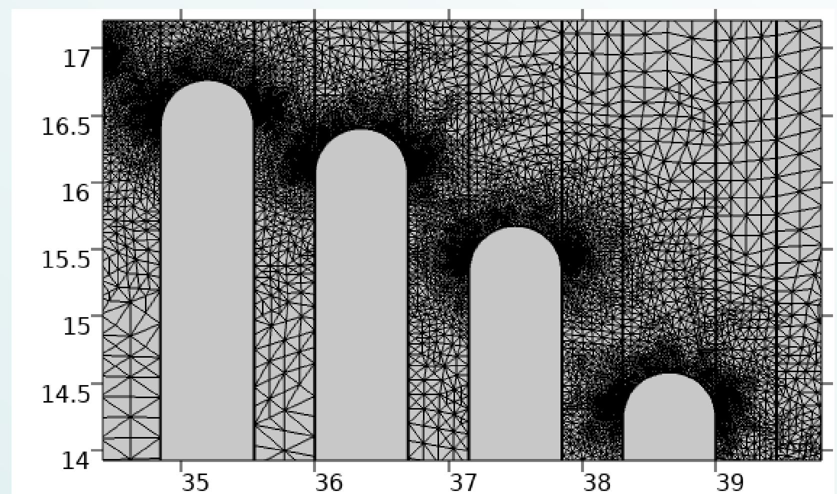
Modeling is in 2D axisymmetric approximation, r-axis being in the plane of symmetry.









“Large” HV structures in HVPS

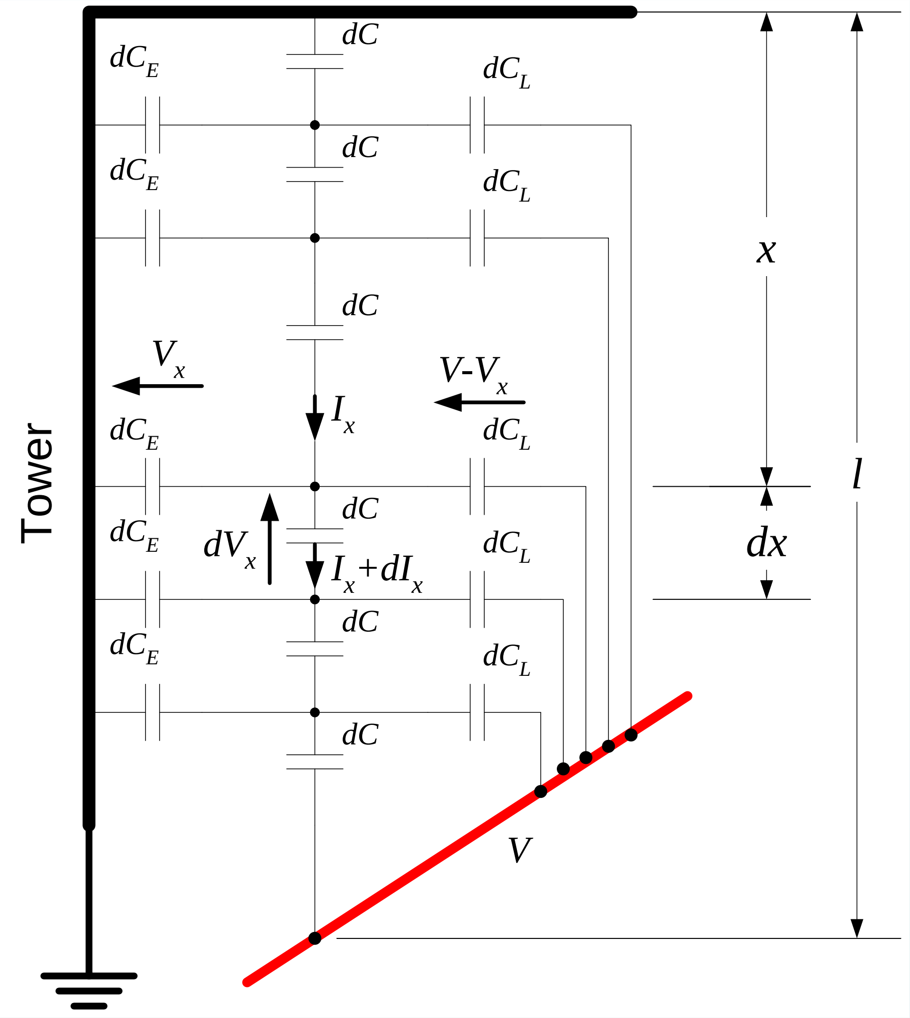
- Strings of HV diodes
- HV dividers (and their components)
- HV windings
- Short circuit current (Arc) Limiters (AL)

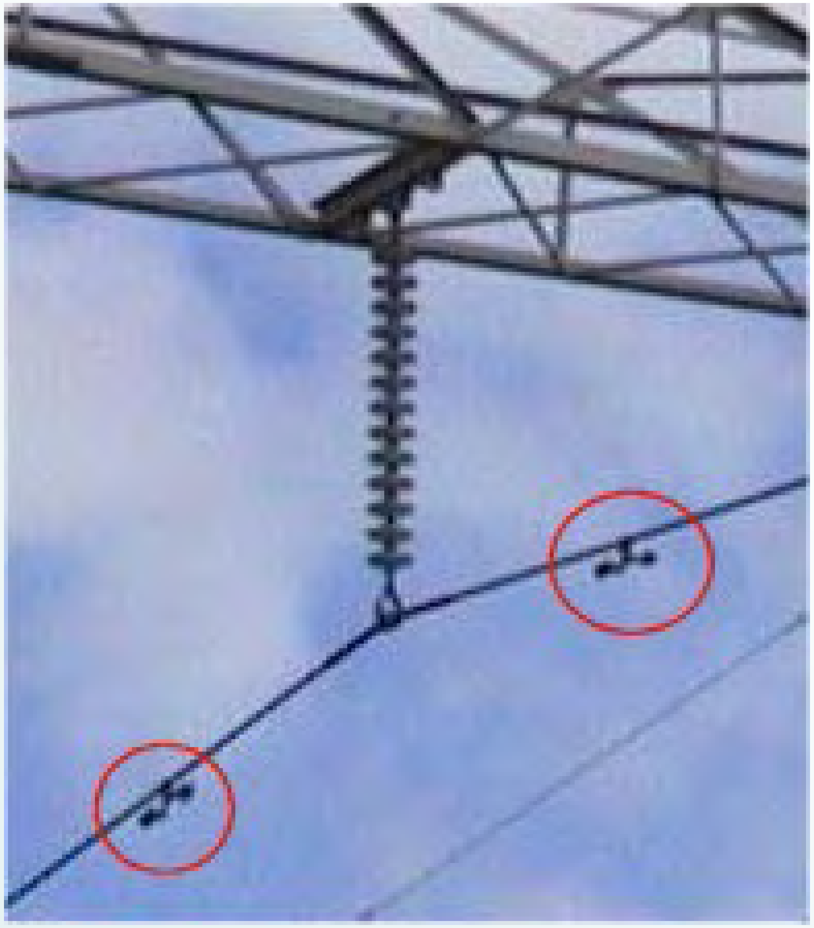
One of the intrinsic properties of HV devices is that the voltage distribution along their structures at transients is largely governed by parasitics. This results in nonuniform stresses on insulation. We will call such systems ***LARGE***.

Analyses of such structures can be made with EqC. Typically, EqCs are homogeneous ladder circuits; analytical solutions are possible. Main problem is derivation of circuit parameters. ***This calls for field simulations*** (most can be done with commercial software)! Thus, stresses on components and insulation can be determined from first principles.

One of the seminal papers: L. F. Blume and A. Boyajian, “Abnormal Voltages within Transformers”, 7th Midwinter Convention of the American Institute of Electrical Engineers, NY, 1919.

Ladder circuits





"Large" HV structures

Voltage distribution in garland (diode string, winding, etc.)

M. Beyer, W. Boeck, K. Möller, and W. Zaengl, *Hochspannungstechnik*, Springer-Verlag, 1986, 1992. Translation to Russian 1989 (Moscow, Energoatomizdat).
p. 48; a=x/l; v_a*:*V_x*/V*

$C := 1$ $\quad C_E := 0.1$ $\quad C_L := 0.5$

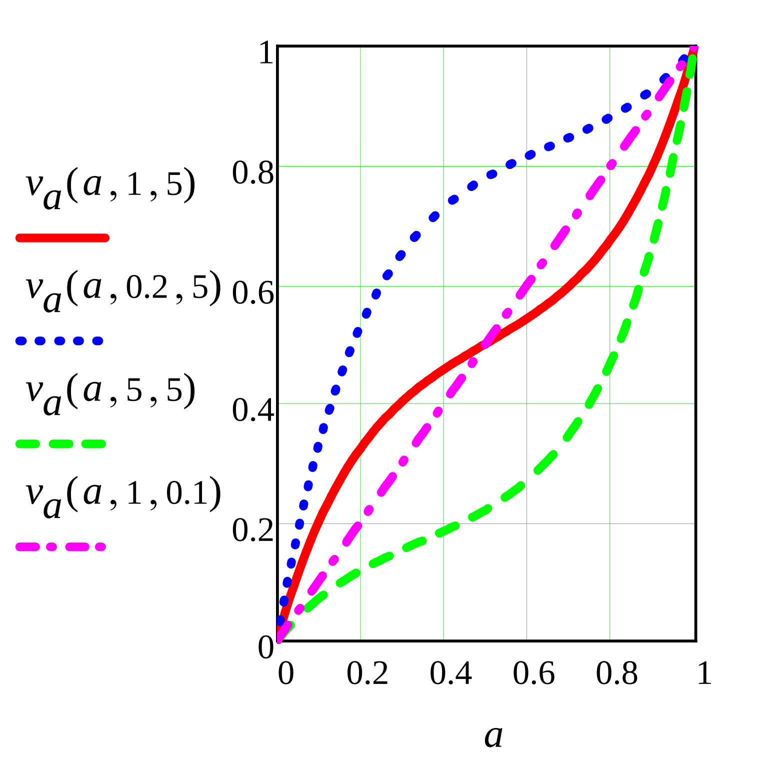
$$\lambda := \sqrt{\frac{C_E + C_L}{C}} \qquad D := \frac{1}{\frac{C_E}{C_L} + 1}$$

$$\theta := \frac{C_E}{C_L} \qquad a := 0, 0.01 .. 1$$

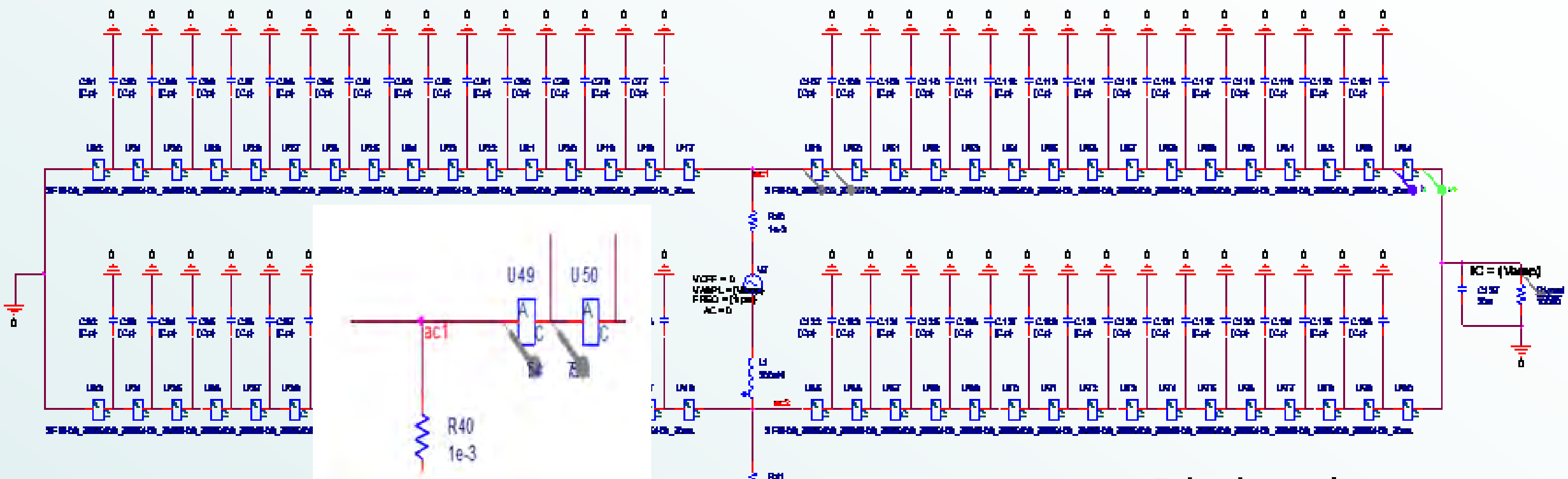
$$v_a(a,\theta,\lambda) := \frac{1}{1+\frac{1}{\theta}} \cdot \frac{\sinh(\lambda \cdot a)}{\sinh(\lambda)} + \frac{1}{1+\theta} \cdot \left[1 - \frac{\sinh[\lambda \cdot (1-a)]}{\sinh(\lambda)}\right]$$

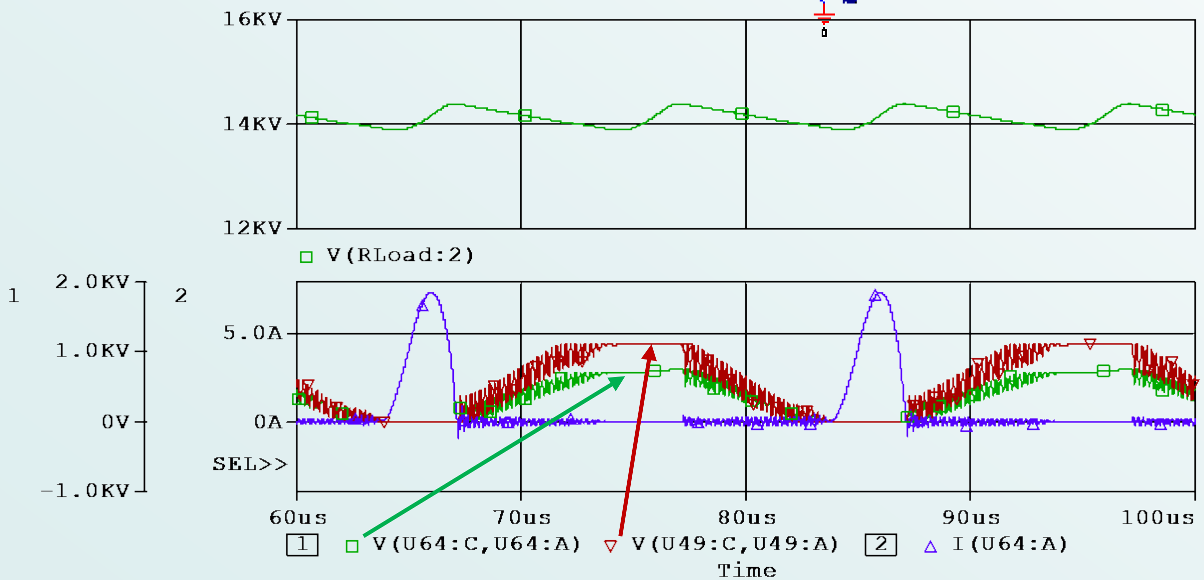
$$E_a(a,\theta,\lambda) := \frac{1}{\left(1+\frac{1}{\theta}\right)} \cdot \cosh(\lambda \cdot a) \cdot \frac{\lambda}{\sinh(\lambda)} + \frac{1}{(1+\theta)} \cdot \cosh[\lambda \cdot (1-a)] \cdot \frac{\lambda}{\sinh(\lambda)}$$

$$v_b(a, C_E, C_L) := \frac{1}{C_E + C_L} \cdot \left[C_E \cdot \frac{\sinh(\lambda \cdot a)}{\sinh(\lambda)} + C_L \cdot \left[1 - \frac{\sinh[\lambda \cdot (1-a)]}{\sinh(\lambda)}\right]\right]$$



Diode string



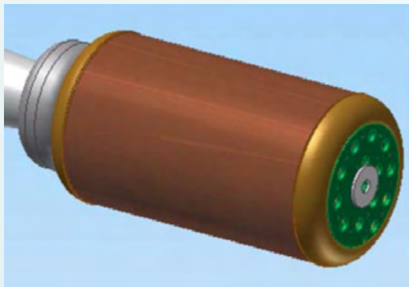


Diodes close to ac connection avalanche

Y. He and D. J. Perreault, “Diode Evaluation and Series Diode Balancing for High-Voltage High-Frequency Power Converters”, TPEL VOL. 35, NO. 6, June 2020, pp. 6301-6314

Frequency response of a solenoid

Can it isolate oscillations of fractions of MHz to several MHz at peak voltage of ~350kV? (NO!! Maybe, if capable withstanding large gradients.)



Number of turns: 700
Diameter: 125mm
Height: 200mm
Wire: AWG#32

1. L. F. Blume and A. Boyajian, “Abnormal Voltages within Transformers”, Presented at the 7th Midwinter Convention of the American Institute of Electrical Engineers, NY, 1919.
2. B. Heller and A. Veverka, Stosserscheinunungen in Elektrischen Maschinen (Wave processes in Electrical Machines), Veb Verlag Technik, Berlin 1957. Russian translation 1960, 632pp.
3. L.I. Sirotinski, High Voltage Engineering, Part III, GEI, Moscow, 1959, 368pp, in Russian.
4. Charles Q. Su, Electromagnetic Transients in Transformer and Rotating Machine Windings, Information Science Reference, Hershey PA, 2013, 473pp.

A. Pokryvailo, "An LCR Network for Current Limiting at Hundreds of kV and Tens of MHz," *2021 IEEE Pulsed Power Conference (PPC),* 2021

Analysis can be made on the base of EqC (see cited literature)

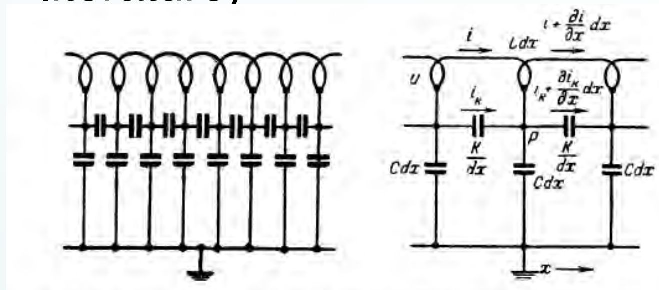
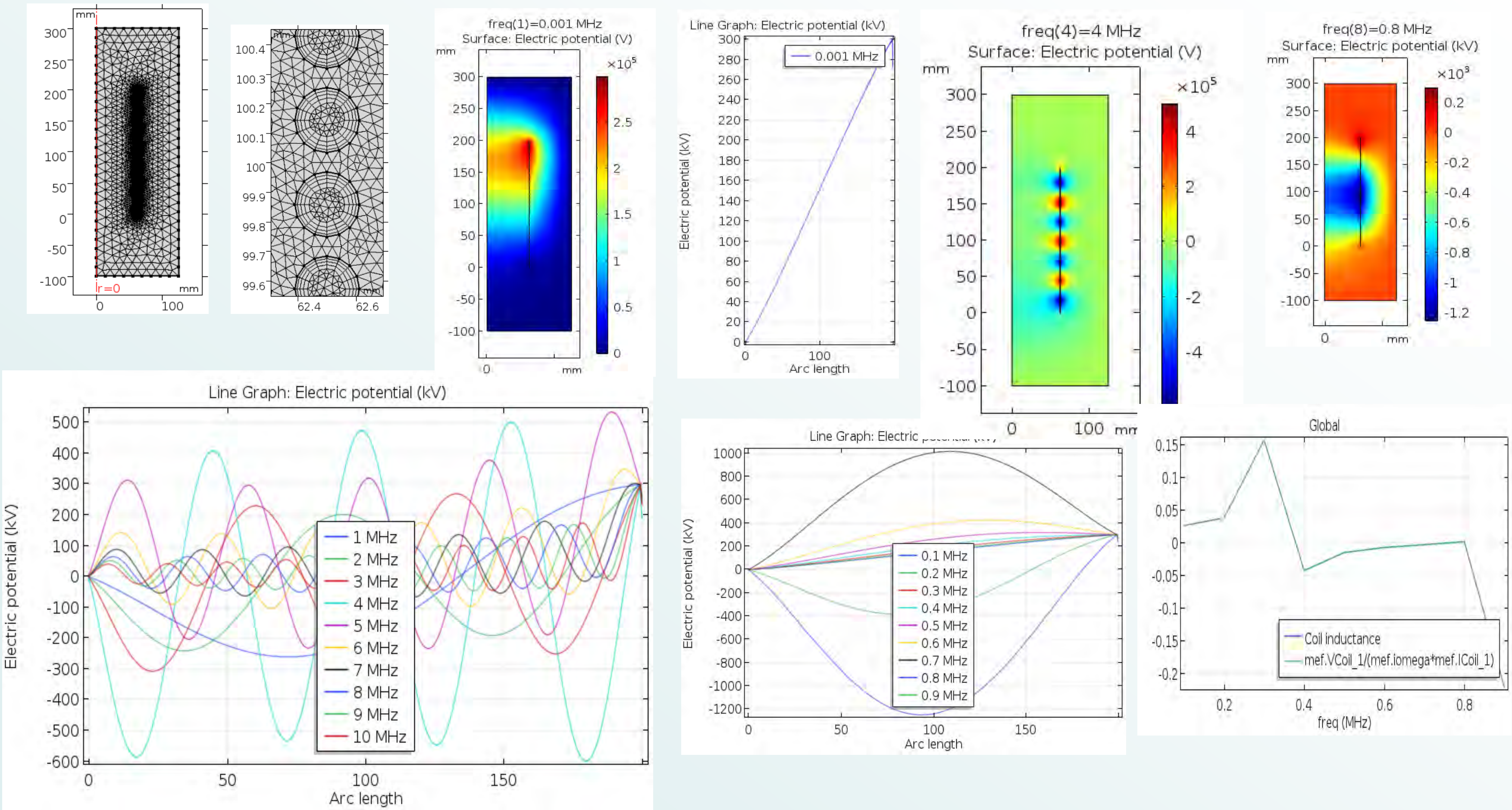


Figure 11. Equivalent circuit of a solenoid without magnetic coupling of individual turns.

Field analysis in *non-radiative* approximation: a cost-efficient alternative

$$\nabla \cdot \mathbf{J} = 0$$
$$\nabla \times \mathbf{H} = \mathbf{J}$$
$$\mathbf{B} = \nabla \times \mathbf{A}$$
$$\mathbf{E} = -\nabla V - j\omega \mathbf{A}$$
$$\mathbf{J} = \sigma \mathbf{E} + j\omega \mathbf{D} + \sigma \mathbf{v} \times \mathbf{B} + \mathbf{J}_e$$

Frequency response of a solenoid (cont.)



Axisymmetric model; solved in *Magnetic and Electric Fields* Interface (COMSOL)

Arc limiter (outside PS)

- Necessary to protect charger [1, 2] from load voltage reflections (up to 370kV peak, several MHz)
- Behaves as a transmission line at fast transients
- Design based on circuit and field simulations, to ensure a) low insulation stress at charge state, b) at discharge, voltage sharing between the stages/components (similar to stress in power transformer windings; *measurements are difficult if not impossible*)

1. A. Pokryvailo, “A High-Power 200 kV Power Supply for Capacitor Charging Applications”, *IEEE Trans. on Diel. and Electr. Ins.,* Vol. 24, No. 4, 2017

2. A. Pokryvailo, "An LCR Network for Current Limiting at Hundreds of kV and Tens of MHz," *2021 IEEE Pulsed Power Conference (PPC),* 2021

See also Pokryvailo, A., ““Large” HV Structures: Transient Analysis of Voltage Distribution from First Principles”, Proc. 2018 IEEE Power Modulator and High Voltage Conference, Jackson Lake Lodge WY, 2018, pp 306-311.

Calculating BDV in *gaseous* insulation using streamer criterion of BD

We calculate integrals (along field lines) that are *ln(N)* of the number of electrons *N* in avalanche:

(1) $\int_0^S \alpha_{eff}(E)dz = K$, integration across the whole gap,

(2) $\int_0^{z_{cr\_hv}} \alpha_{eff}(E)dz = K_{hv}$, $z_{cr\_hv} < S$, (anode-directed),

(3) $\int_0^{z_{cr\_gnd}} \alpha_{eff}(E)dz = K_{gnd}$, $z_{cr\_gnd} < S$, (cathode directed).

In all cases, integration is limited by condition $\frac{E}{p} \geq E_{pcr}$

A. Pokryvailo, “Calculation of Breakdown Voltage of Gas Gaps with Weakly Nonuniform Field: Sphere and Donut Gaps”, *IEEE Trans. on Plasma Science*, vol. 48, no. 10, pp. 3358-3366, Oct. 2020.

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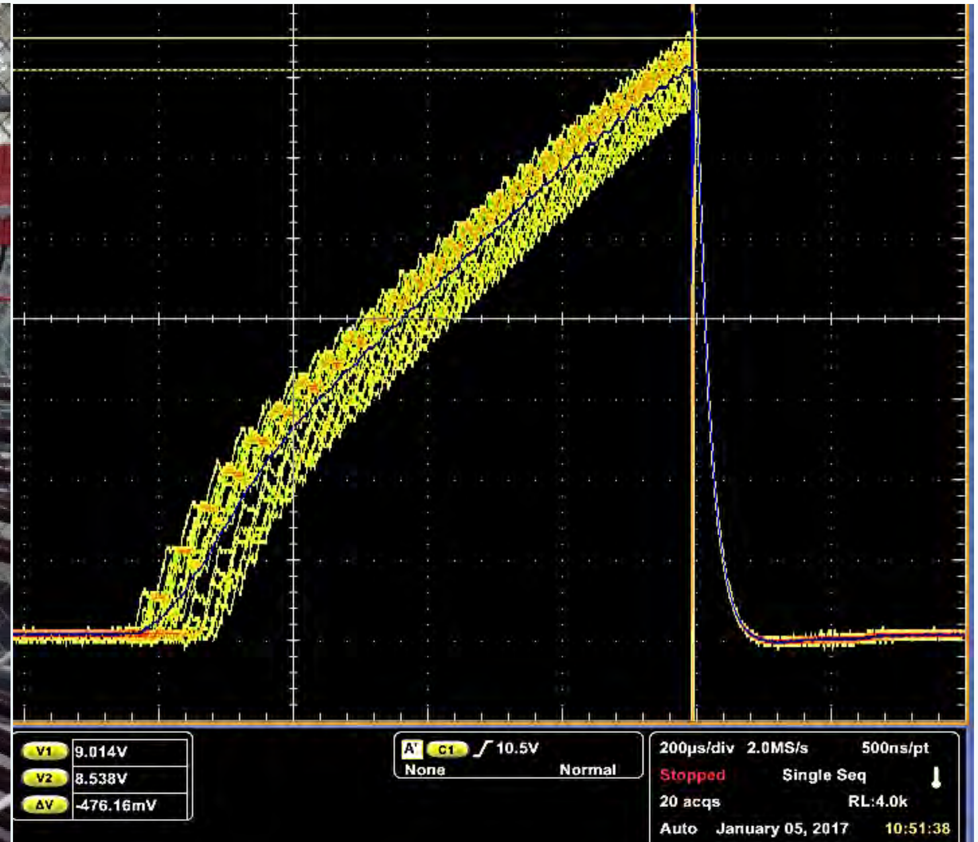
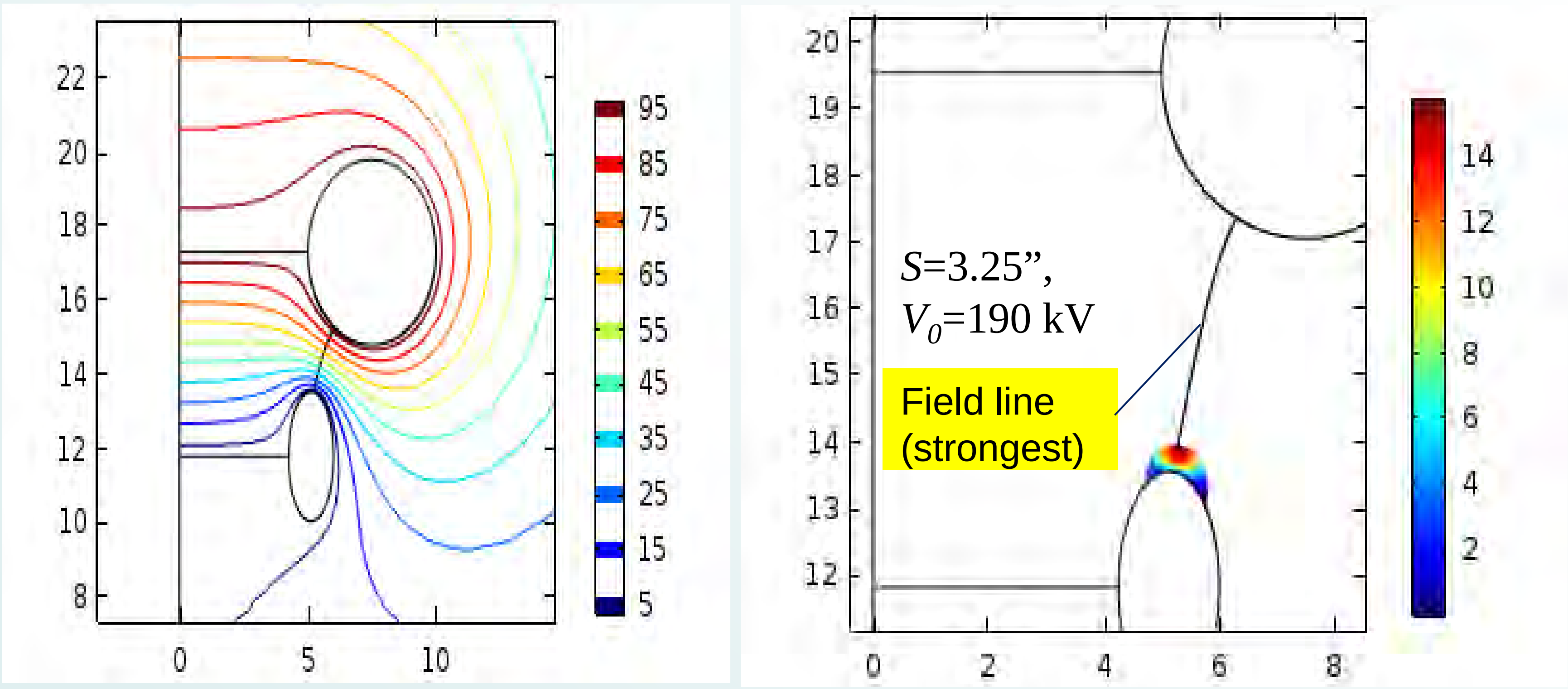
Donut electrodes

A compact, adjustable spark gap



Vertical 1V=22 kV, horizontal 200 µs/div. PRR=5 Hz. Gap 8.9 cm. Blue is avg of 20 shots.

Critical avalanches:
calculating integrals along field lines



Donut SG. Critical cathode-directed avalanches (integrals) shown by color legend. Dimensions are in inches.

ElectroMagnetic fields

transformers, inductors, special cases

$$\nabla \times \mathbf{H} = \mathbf{J}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\mathbf{J} = \sigma \mathbf{E} + \sigma \mathbf{v} \times \mathbf{B} + \mathbf{J}_e$$

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t}$$

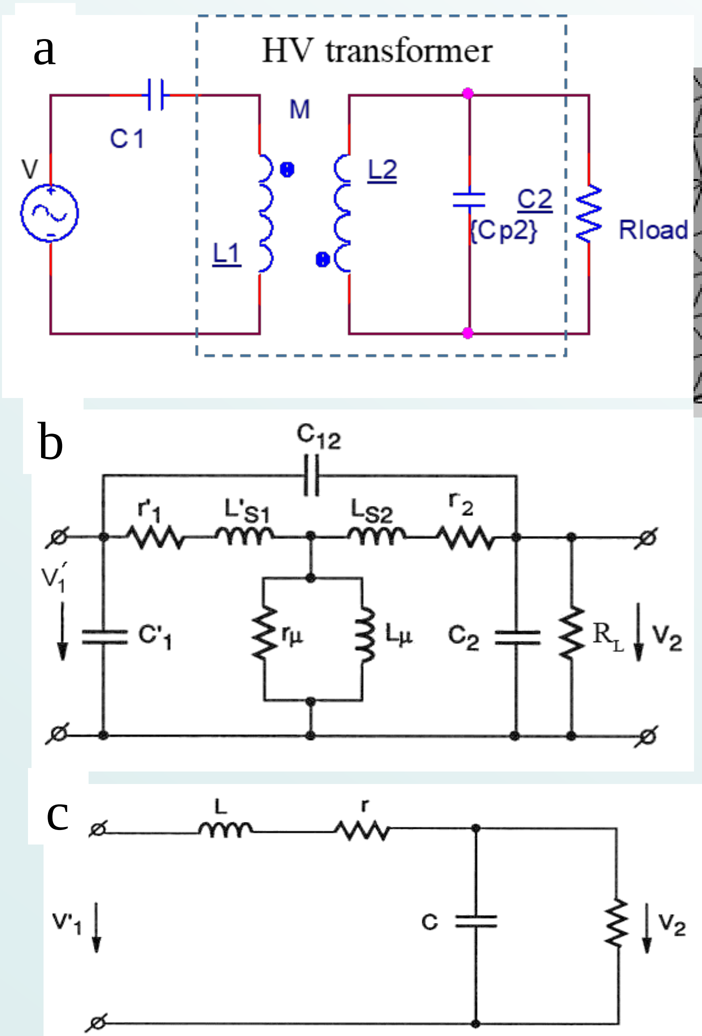
- ***Leakage inductance***
- Self, mutual inductances
- Core behavior
- Eddy current losses (and their influence on inductances), fringe fields
  - Nearby components, especially ferromagnetic
  - Increase of windings’ resistance
- “Wireless” power transfer
- *Coupling to electric circuit – a powerful feature for system analysis*

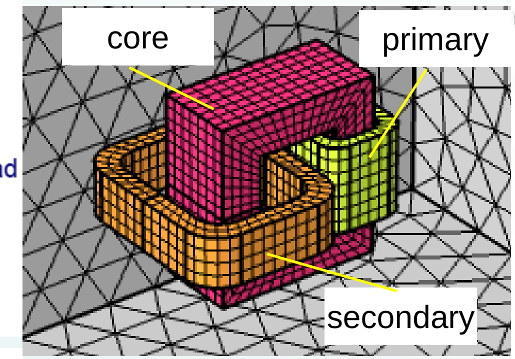
Magnetic fields - *TRANSFORMERS*

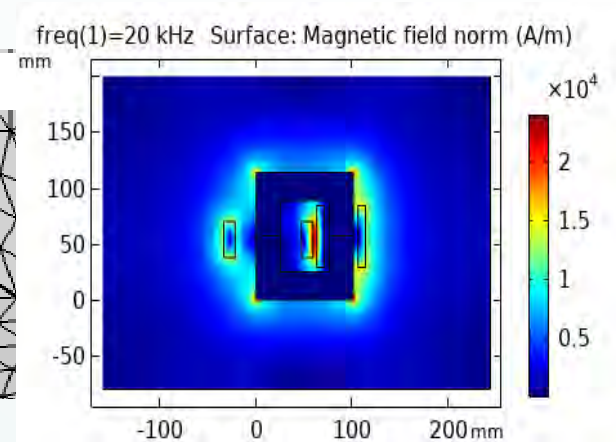
A. Pokryvailo, "Use of COMSOL Multiphysics in High Voltage Electronic Transformers Design", *Proc. COMSOL Conference,* Boston MA, 2019, 7pp.

A tutorial paper, Available at COMSOL site. *See its references.*

Lumped parameters for equivalent circuit/s *are derived from EM field*







$$L_s = \frac{2E_m}{I^2}, (1) \qquad C_p = \frac{2E_{es}}{V^2}, (2)$$

- Eq. (1) prescribes using equivalent circuit c because the windings' currents are assumed equal (when reflected to the same winding).
- Another implication of (1) is that ***only one Ls value is assigned to a transformer***, lumping together Ls1 and Ls2.
- Makes sense for transformers with good coupling. Using the term "leakage" inductance for loosely coupled coils (e.g., Tesla transformer), may be counterproductive.

Calculating leakage inductance with FEA – *higher accuracy than analytical methods*

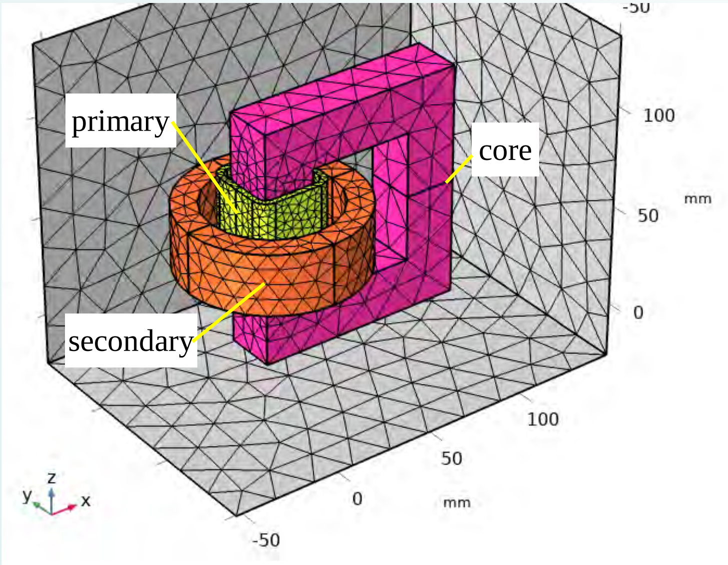
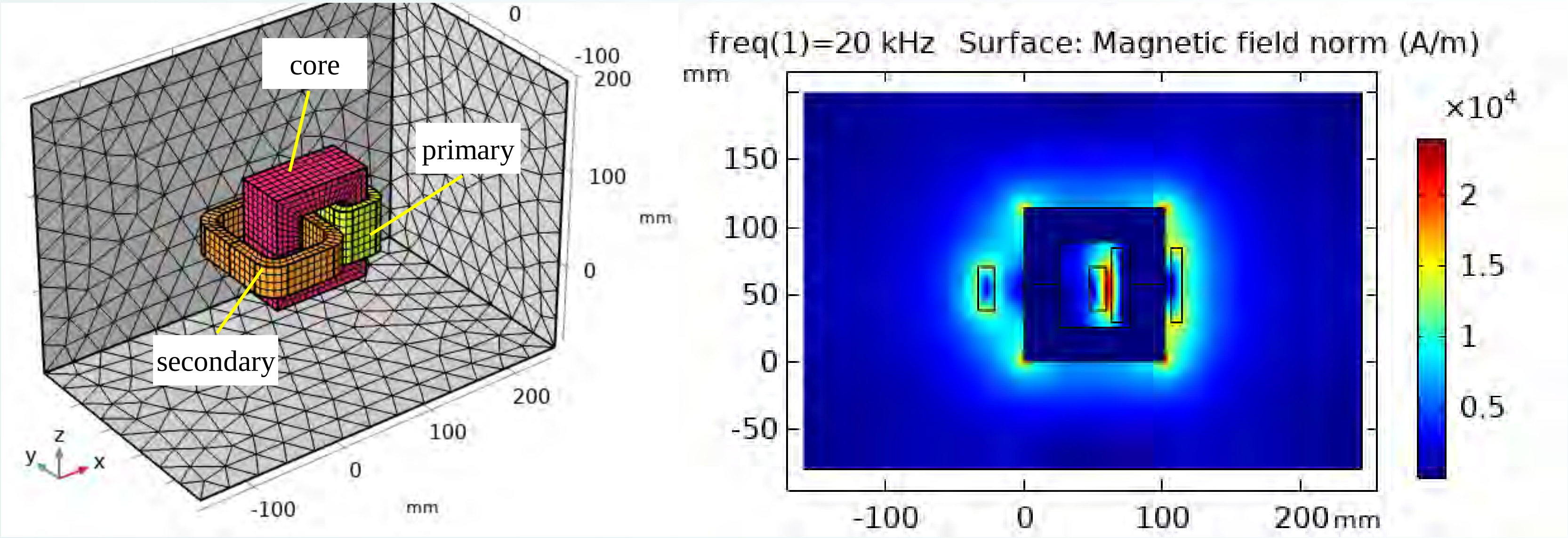


Figure 2. Core U100/57/25. w1=18, w2=270. From stationary MF analysis, L_{s2}=4.71mH. AC analysis at a number of frequencies, up to 50kHz, yields the same value. Experimental L_{s2}=5.3mH with long primary leads.

$L_s = \frac{2E_m}{I^2}$, E_m found by volume integration *everywhere outside the core*

1. Following classic methods of calculating Ls, one can find L_s from stationary or frequency-domain analysis driving the windings by equal, opposing currents. Results are close to those of 2*.
2. Mimicking the experimental method of measuring L_s, the primary can be driven by current, secondary shorted (or the opposite; Magnetic Field – MF- coupled with Electric Circuit – EC- interfaces).
3. Since stationary analysis is fastest of all, usually there is no justification for a more complex MF-EC analysis for finding L_s of *closed-core** transformers.
4. It is possible to associate leakage with different windings or even their parts.

Calculating leakage inductance in COMSOL (cont.)



Windings on separate legs. Core 2xU100/57/25. w1=10, w2=320. Ls2=33mH. Primary driven by current, secondary shorted (MF-EC interfaces used).

- Analytical estimates are difficult for the case of *not overlapping* windings. Leakage field is truly 3D, and simulations become especially useful.
- ***To allow field to "leak", bounding box must be "large". Its size has major impact on results.***

Coupled field and circuit simulation

Inductive power transfer

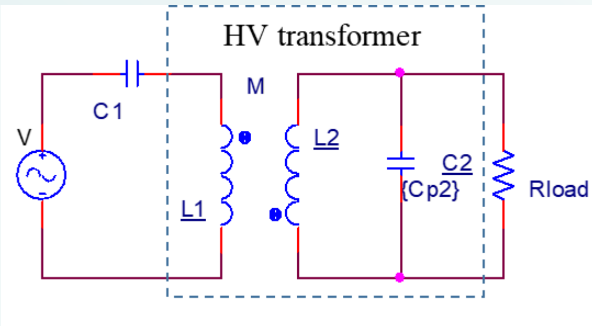
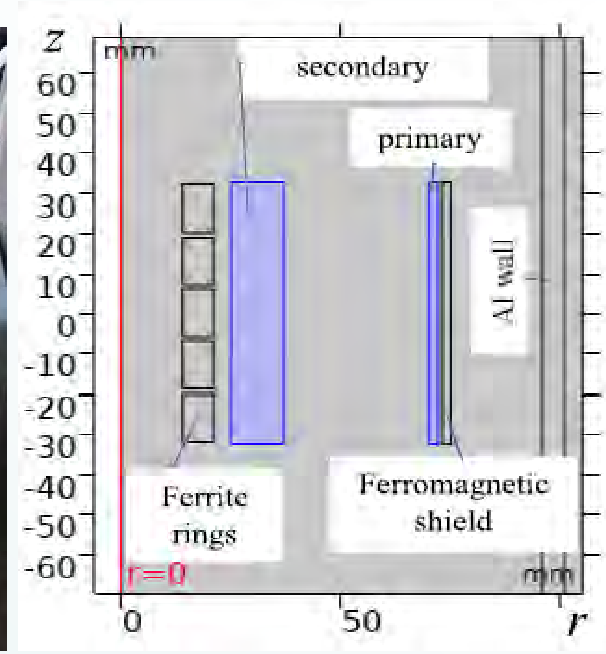


Fig. 2. Two inductively-coupled loops. C2 is parasitic capacitance of transformer/load.



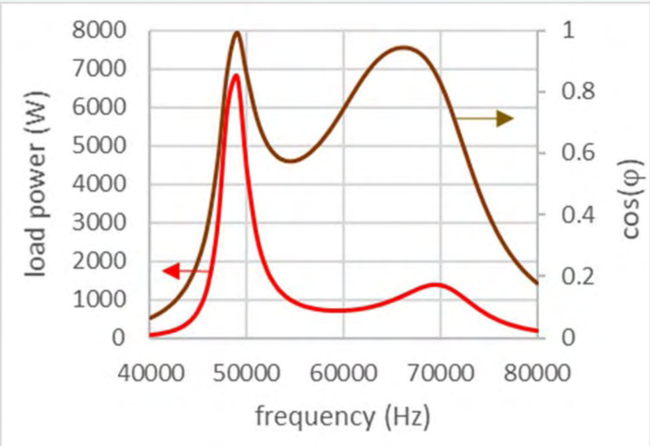
1-kW, 20-kV transformer prototype. Outer cylinder carries primary with *w*1 = 50 turns, Litz 420/38. It is covered by a ferromagnetic shield (amorphous metal tape). Inside cylinder (secondary bobbin) carries secondary (12 sections, number of turns varied from 2000 to 3500). Secondary can be lined with ferrite toroids (optional, accommodated inside secondary bobbin). Cross section shows homogenized secondary (COMSOL axisymmetric model).

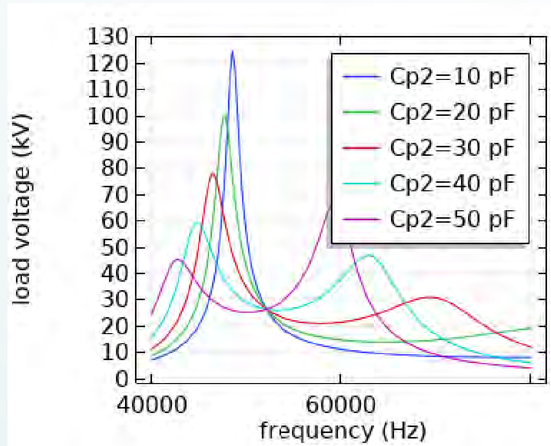
Coupled MF-circuit simulation synergistically analyses both the geometry and the coils' interaction with external circuitry

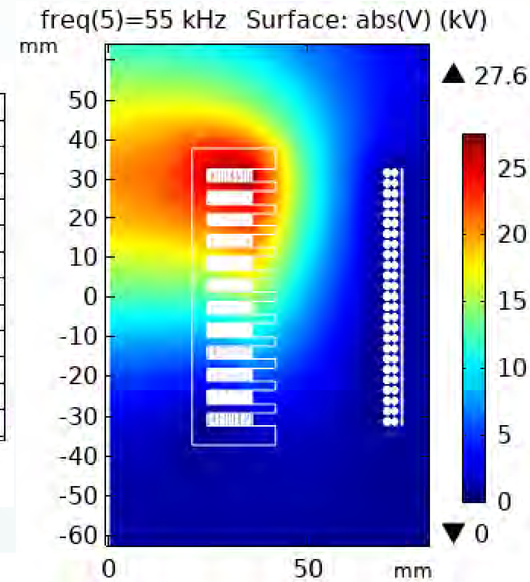
A. Pokryvailo and H. Dave, "Coupled Magnetic Field-Circuit Analysis of Inductive Power Transfer in High-Potential Transformers", IEEE Transactions on Plasma Science, vol. 48, no. 10, pp. 3279-3288, Oct. 2020.

Coupled field and circuit simulation

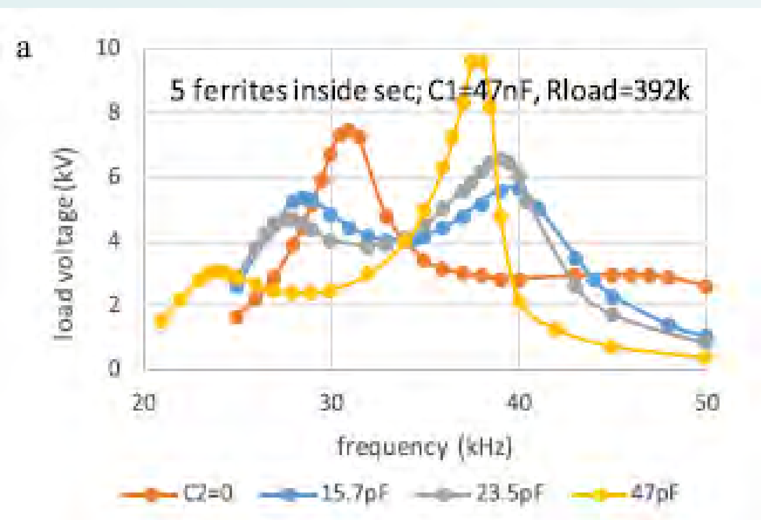
Inductive power transfer

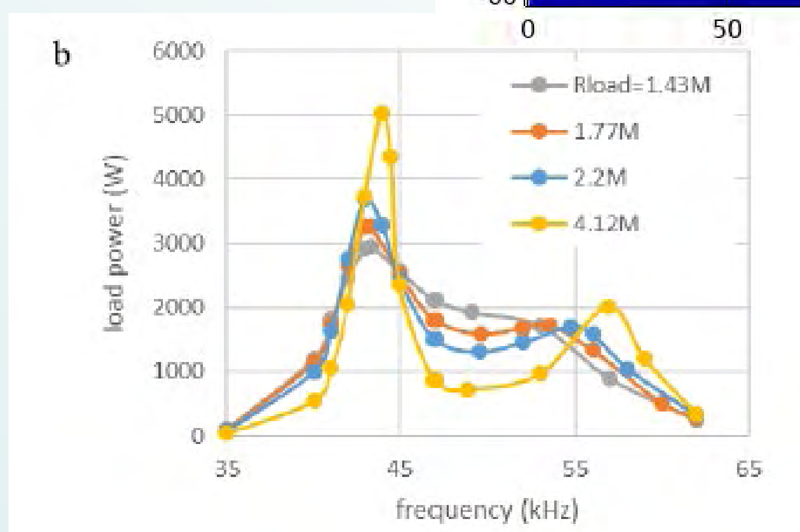






Simulated

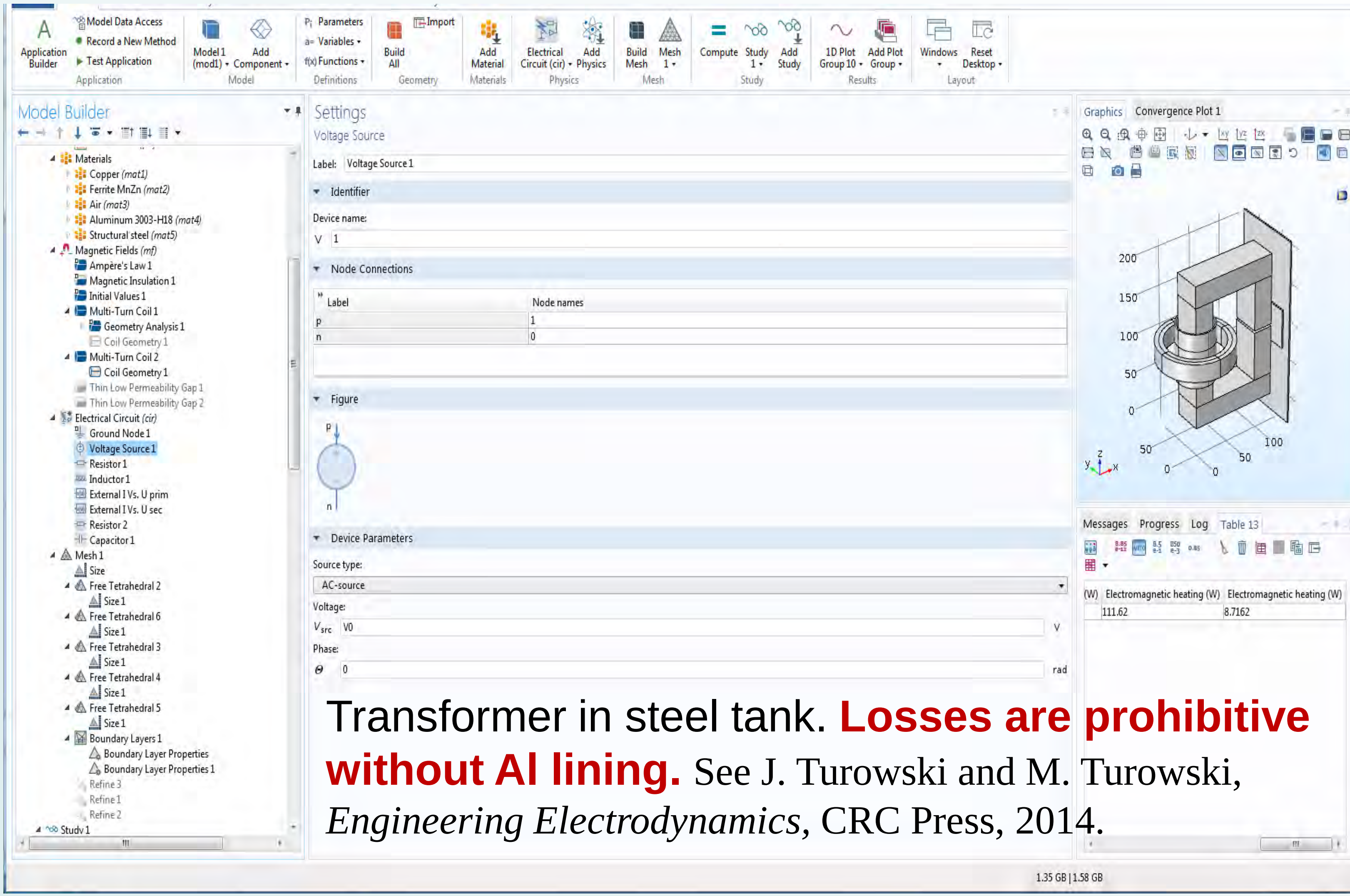




Experimental

A. Pokryvailo and H. Dave, "Coupled Magnetic Field-Circuit Analysis of Inductive Power Transfer in High-Potential Transformers", IEEE Transactions on Plasma Science, vol. 48, no. 10, pp. 3279-3288, Oct. 2020.

Eddy currents



Transformer in steel tank. **Losses are prohibitive without Al lining.** See J. Turowski and M. Turowski, *Engineering Electrodynamics*, CRC Press, 2014.

Lining steel with Al to reduce losses

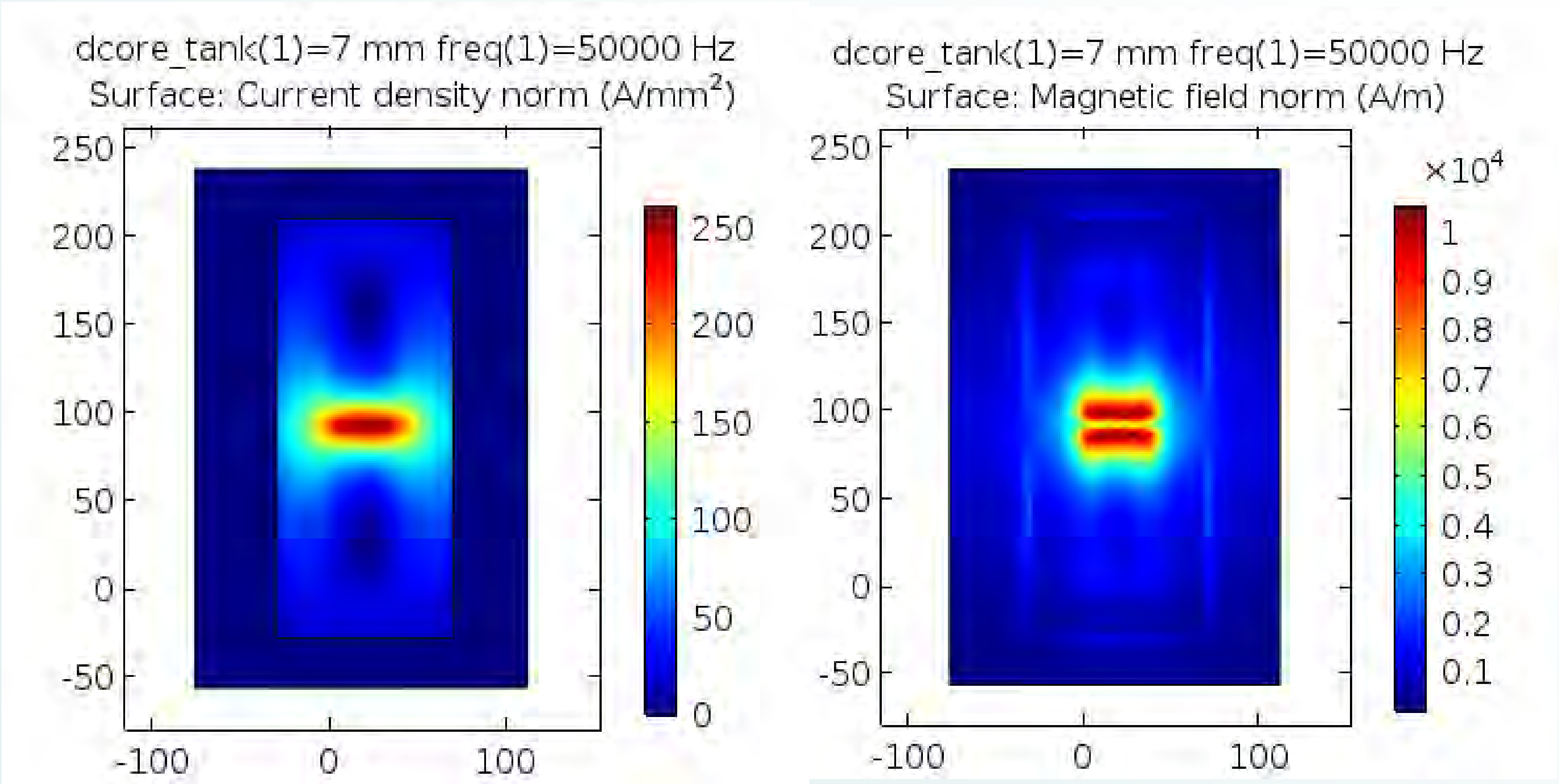
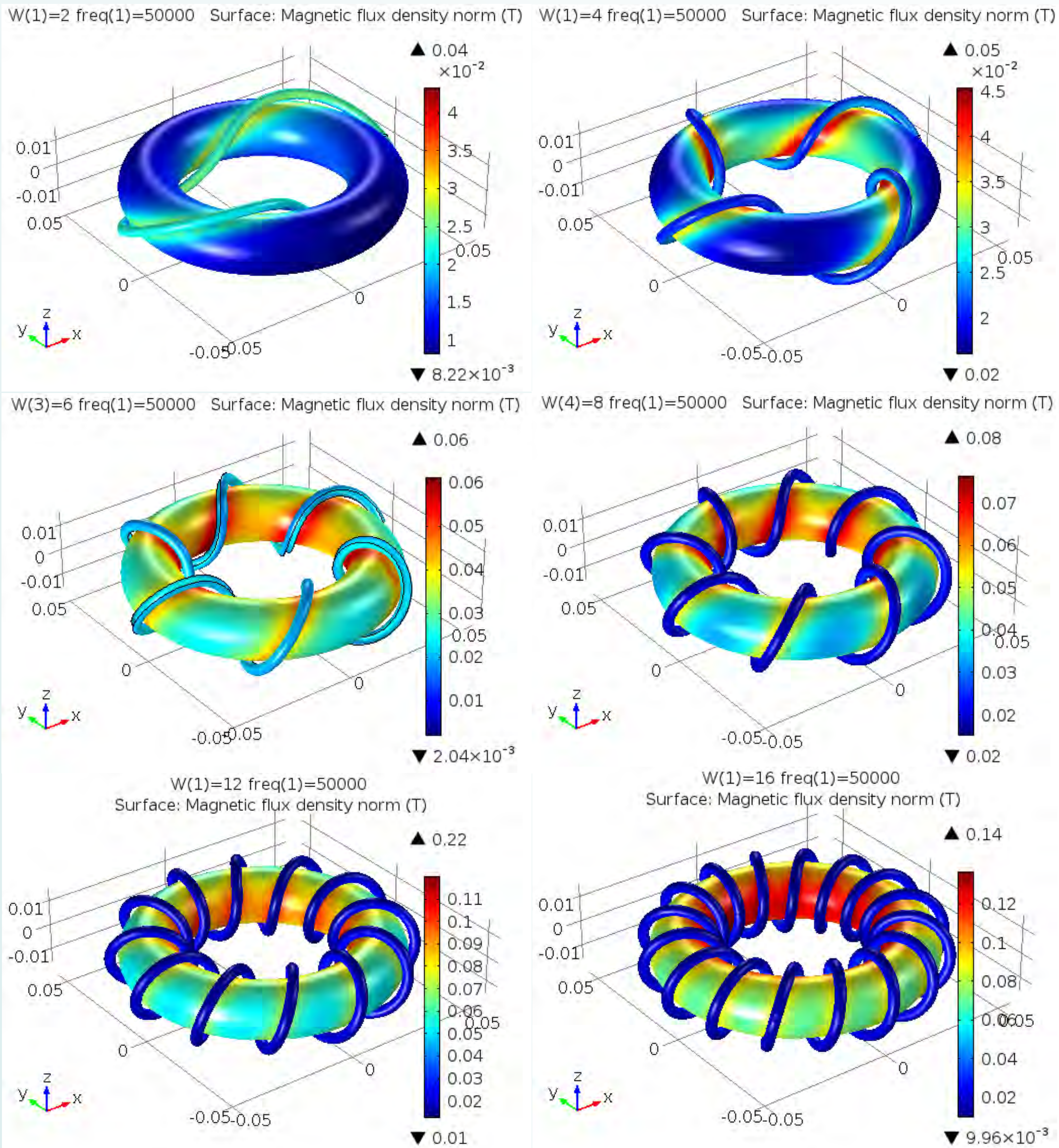


Figure 42. Steel plate lined by same size Al plate 2-mm-thick. Core gap 1/8". Loss 8.5W in steel, 13W in Al. a – j in Al close to surface proximal to core; b – j in steel. Loss 282W in steel w/o lining.

Inductors – dc chokes, ac chokes, etc.

- **Inductance and its dependence on current (core saturation)**
- **Losses – frequency dependence, especially, at pulsed currents; impact of core presence**
- **Fringe fields**

Sparsely Wound Toroidal Coils



Flux density for w=2, 4, 6, 8, 12, 16. Winding current is 150Arms for all cases. μ_r=10, rwire=2mm.

Use of periodicity is possible.

Inductance of sparsely wound coils deviates from datasheet:

1. Dependence of the inductance on number of turns is far from being quadratic;
2. For low-permeability cores, wire inductance is a considerable factor for low number of turns and large-diameter, small cross-section area cores.

Pokryvailo, A., "Calculation of Inductance of Sparsely Wound Toroidal Coils", *Proc. Comsol Conference 2016,* Boston MA, 5-7 October 2016, 7pp. Available at Comsol site.

AC Chokes

- **Inductance and its dependence on current (core saturation)**
- **Losses – frequency dependence, especially, at pulsed currents, core presence**

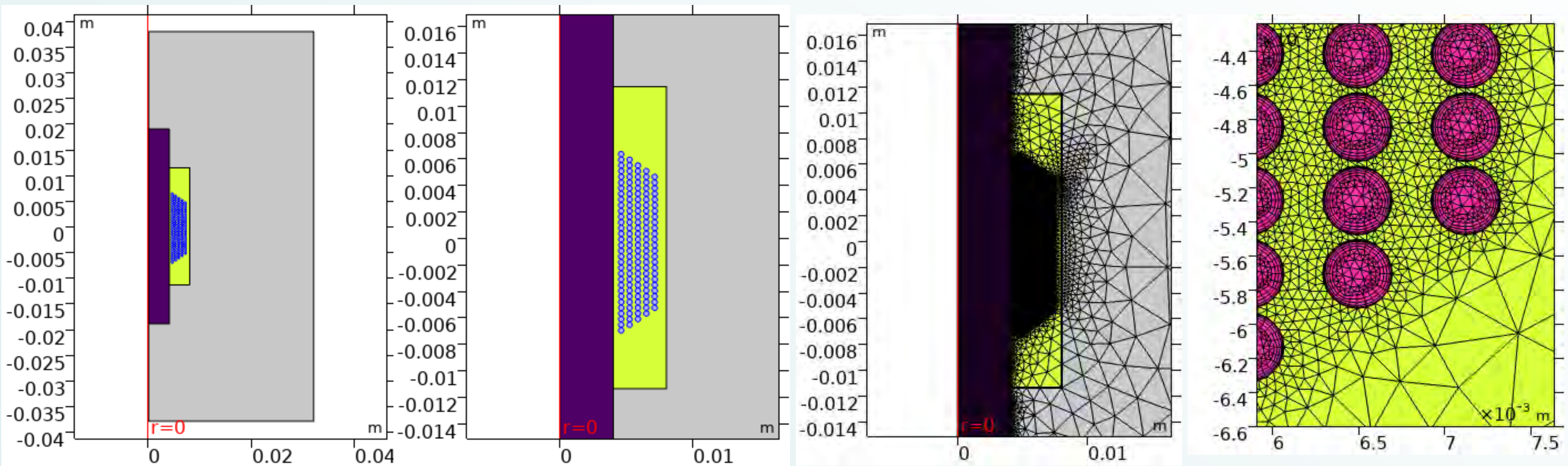
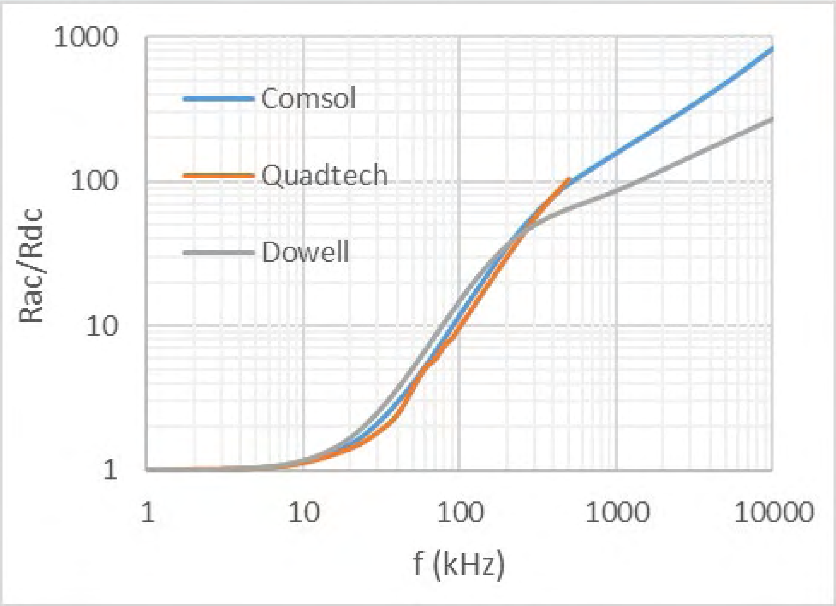


Figure 1. Axisymmetric model of a choke: geometry and mesh adapted to skin depth. Symmetry in midplane is used to reduce model size in some models.

A. Pokryvailo and H. Dave, “Calculation and Measurement of Winding Loss at High-Frequency Pulsed Currents”, *Proc. COMSOL Conference 2020,* Boston MA, 7-8 October 2020, 7pp. Available at Comsol site.

AC chokes



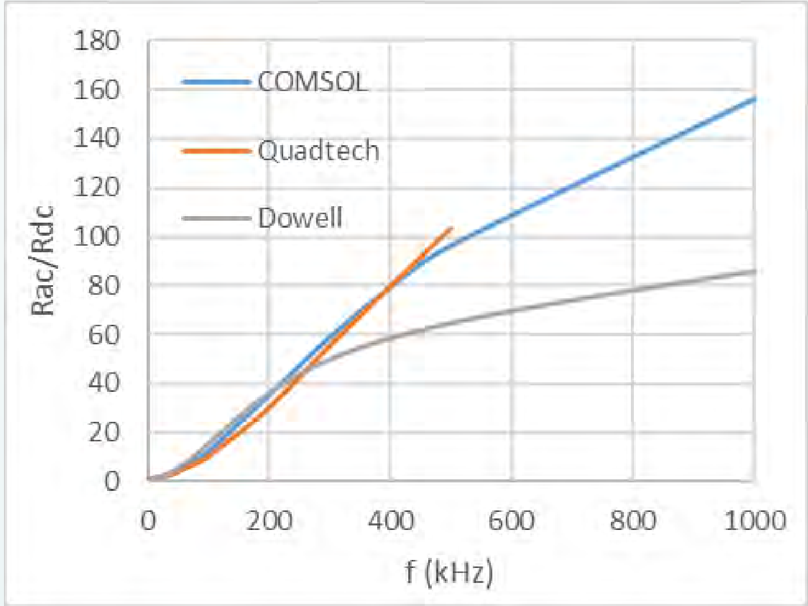


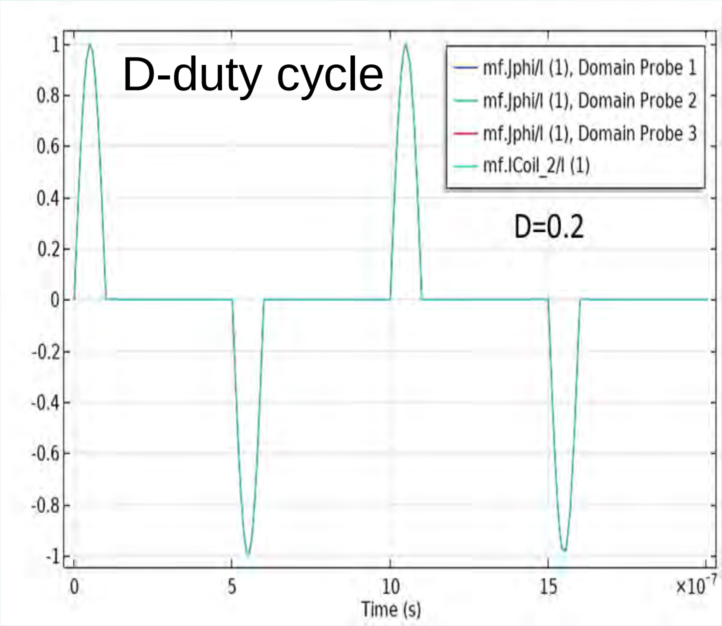
Figure 2. Frequency dependence of Rac/Rdc at sine waves. Stationary nonlinear analysis to calculate L as a function of current

Selected References

[1] G. R. Skutt, T. G. Wilson, A. M. Urling, and Van A. Niemela, “Characterizing high-frequency effects in transformer windings—a guide to several significant articles”, 4th APEC Baltimore MD, 13-17 Mar. 1989, pp. 373-385.
[2] P.L. Dowell, “Effects of eddy currents in transformer windings”, Proceedings of the IEE, vol. 113, no. 8, 1966.
[3] W. G. Hurley, E. Gath, and J. G. Breslin, “Optimizing the ac resistance of multilayer transformer windings with arbitrary current waveforms,” IEEE Trans. PE., vol. 15, Mar. 2000, pp. 369–376.
[4] M. E. Dale and C. R. Sullivan, “Comparison of Single-Layer and Multi-Layer Windings with Physical Constraints or Strong Harmonics”, IEEE Int. Symp. on Industrial Electronics, Montreal, Que., Canada, July 2006, pp. 1467–1473.
[5] R. Severns, “Additional losses in high frequency magnetics due to non ideal field distributions”, APEC 1992.

AC chokes

Frequency dependence of R_{pulsed}/R_{sine} at pulsed *sine waves*



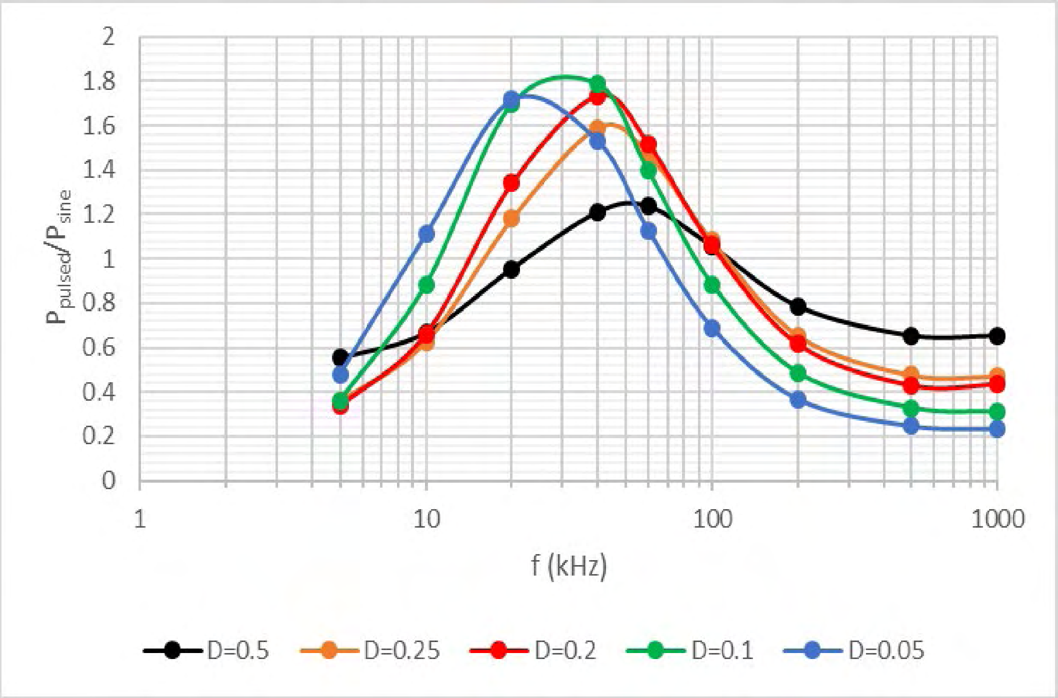


Figure 11. Frequency dependence of the ratio of losses P_{pulsed}/P_{sine} at pulsed excitation by a half-sine wave (D<1) to those at sine wave (D=1). $P_{pulsed} \equiv P_{sine}(D)$.

Time-domain simulations. Too many harmonics needed for f-domain at small D's.

Also calculated for rectangular and triangular waveforms

Losses in thin shields

Losses in shield encircling a wire bundle with zero net current

Wire bundle connecting inverters to transformers overheated. EMC shield blamed – but why?? Worked fine in previous systems…

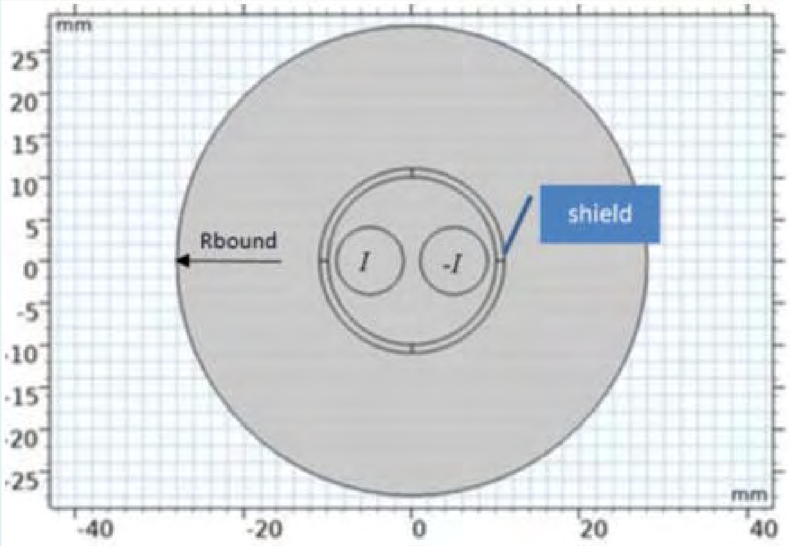
***Abstract*—Losses in very thin metal shells induced by high frequency electromagnetic fields have been analyzed.**

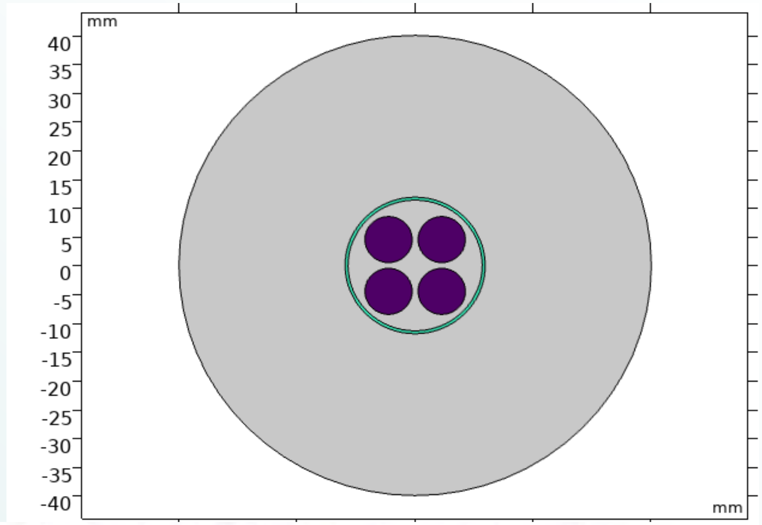
- It has been shown that the loss dependence on the shell thickness has both minima and maxima. The latter are attained at thicknesses ***two orders of magnitude smaller than skin depth,*** or at units of micrometers at several tens of kHz in aluminum and copper.
- In shielding applications, an inopportune choice of the shield may result in very high losses, bringing about shield overheat, melting, and even evaporation within fractions of a second. Both analytical and numerical analyses are presented, supported by an experimental demonstration. It is shown that specific losses maximize with decreasing thickness down to a certain threshold.
- The obtained results are valid within the limitations of the macroscopic Maxwell equations.

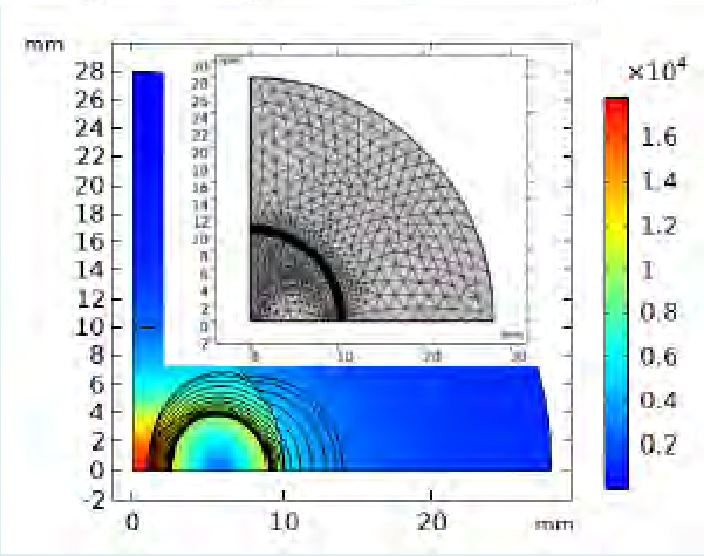
A. Pokryvailo, "Anomalous Losses in Thin Metal Shells Due to High-Frequency Magnetic Fields and Related Phenomena", *IEEE Trans. on Plasma Science*, vol. 49, no. 2, pp. 835-844, Jan. 2021

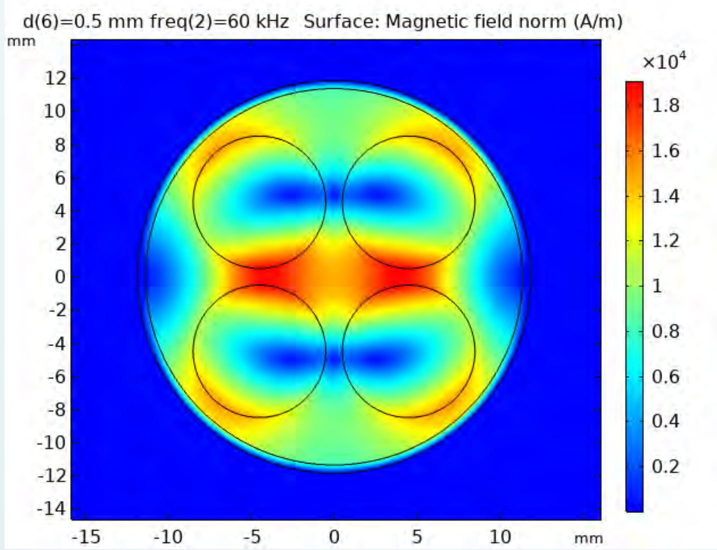
Losses in thin shields

PRACTICAL PROBLEM: WIRE BUNDLE WITH NET ZERO CURRENT INSIDE A SCREEN







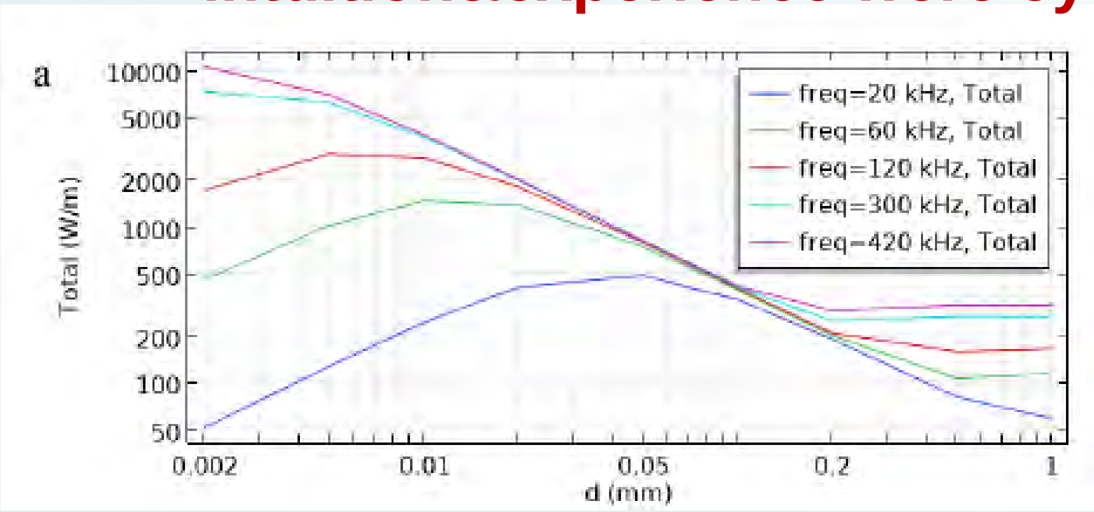


Losses in thin shields

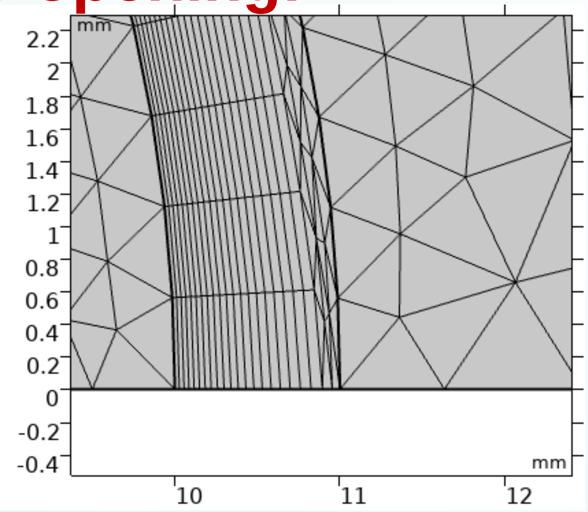
PRACTICAL PROBLEM: WIRE BUNDLE WITH NET ZERO CURRENT INSIDE A SCREEN

- First, solved in 2D by brute force; results were put into doubt. Increasing loss at smaller *d's* considered numerical artefacts
- Some literature data indicated same; experiments with foils provided proof
- Analytical models were solved – found in perfect agreement with numerical

Thus, simulations running counter to intuition&experience were eye-opening!



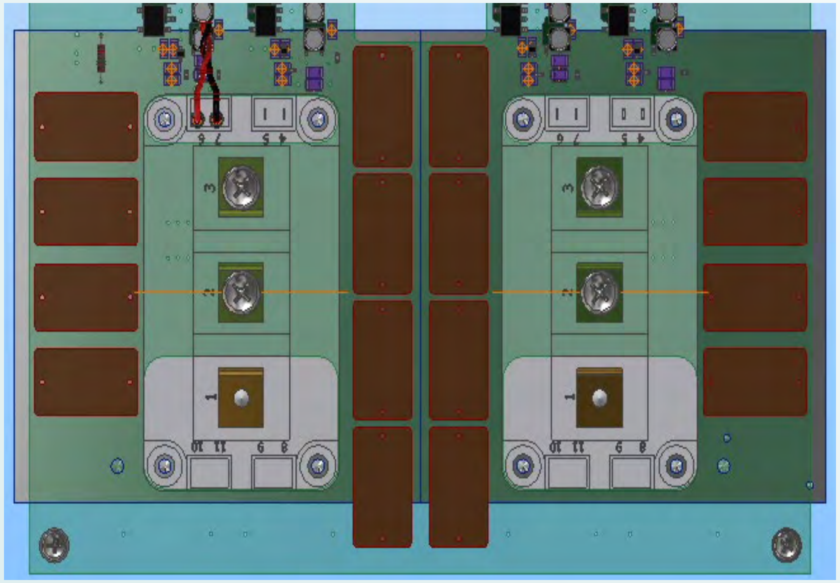
Loss dependence on screen thickness, *d*, for pure Al at several frequencies. I_m=300A

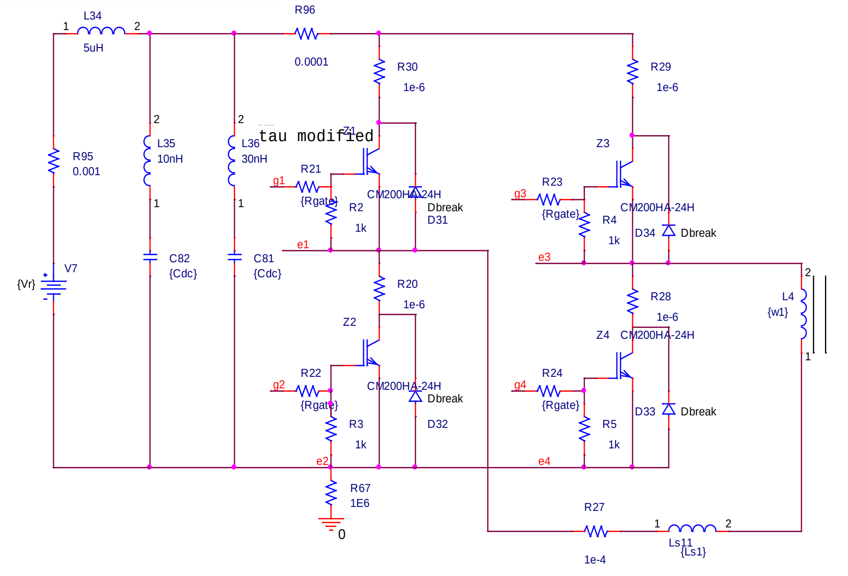


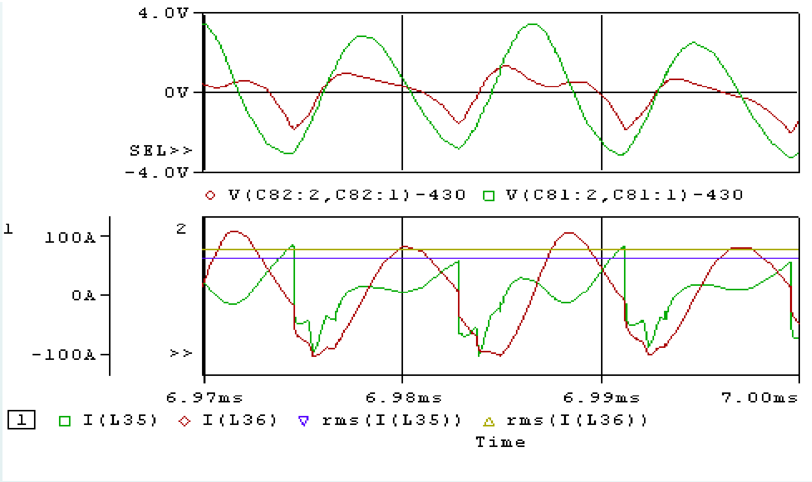
Mesh in screen

Analyzing Electromagnetic Modes of Integrated Busbars Implemented as PCBs

Circuit simulations need to be done first to determine current flow, magnitudes, make simplifications

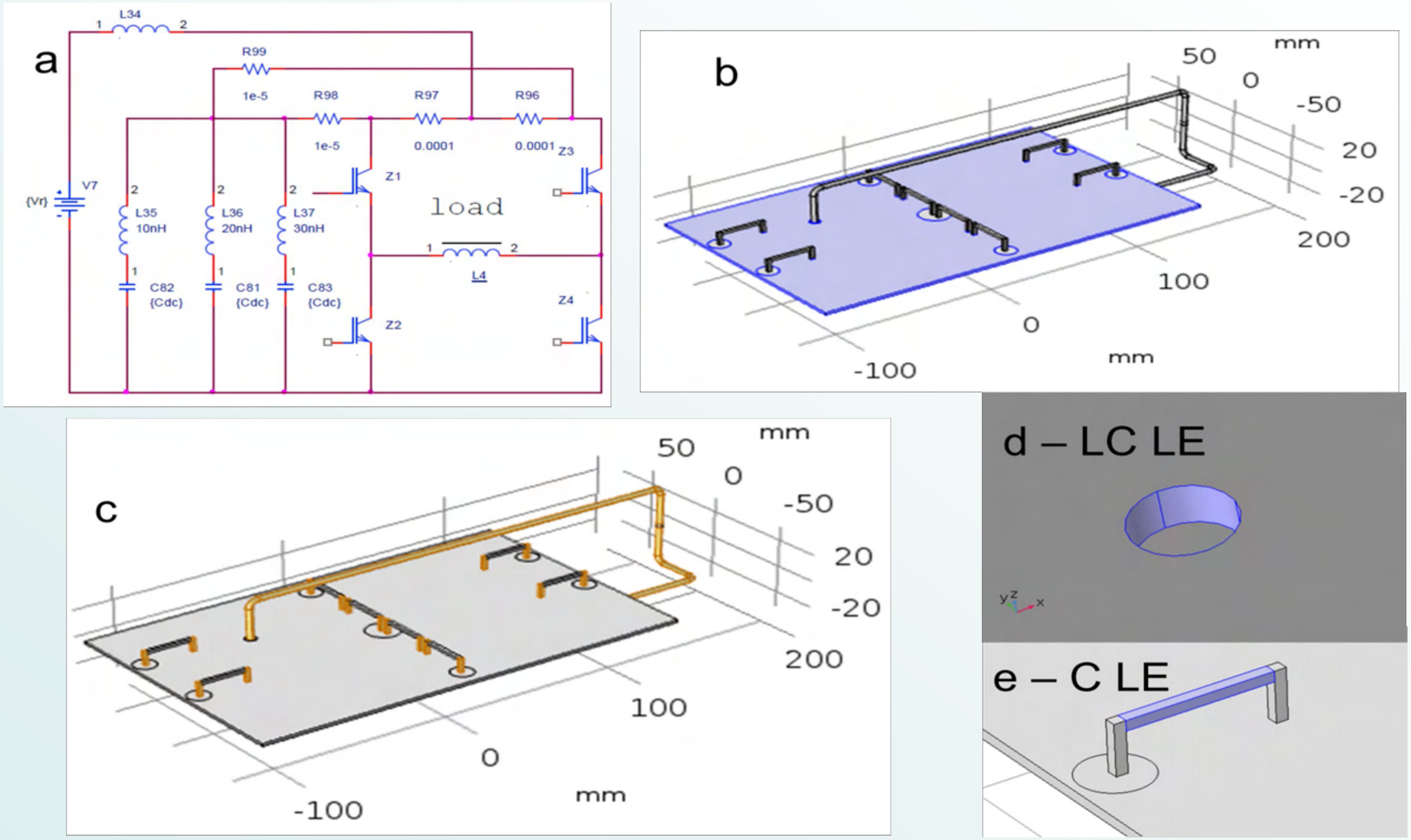






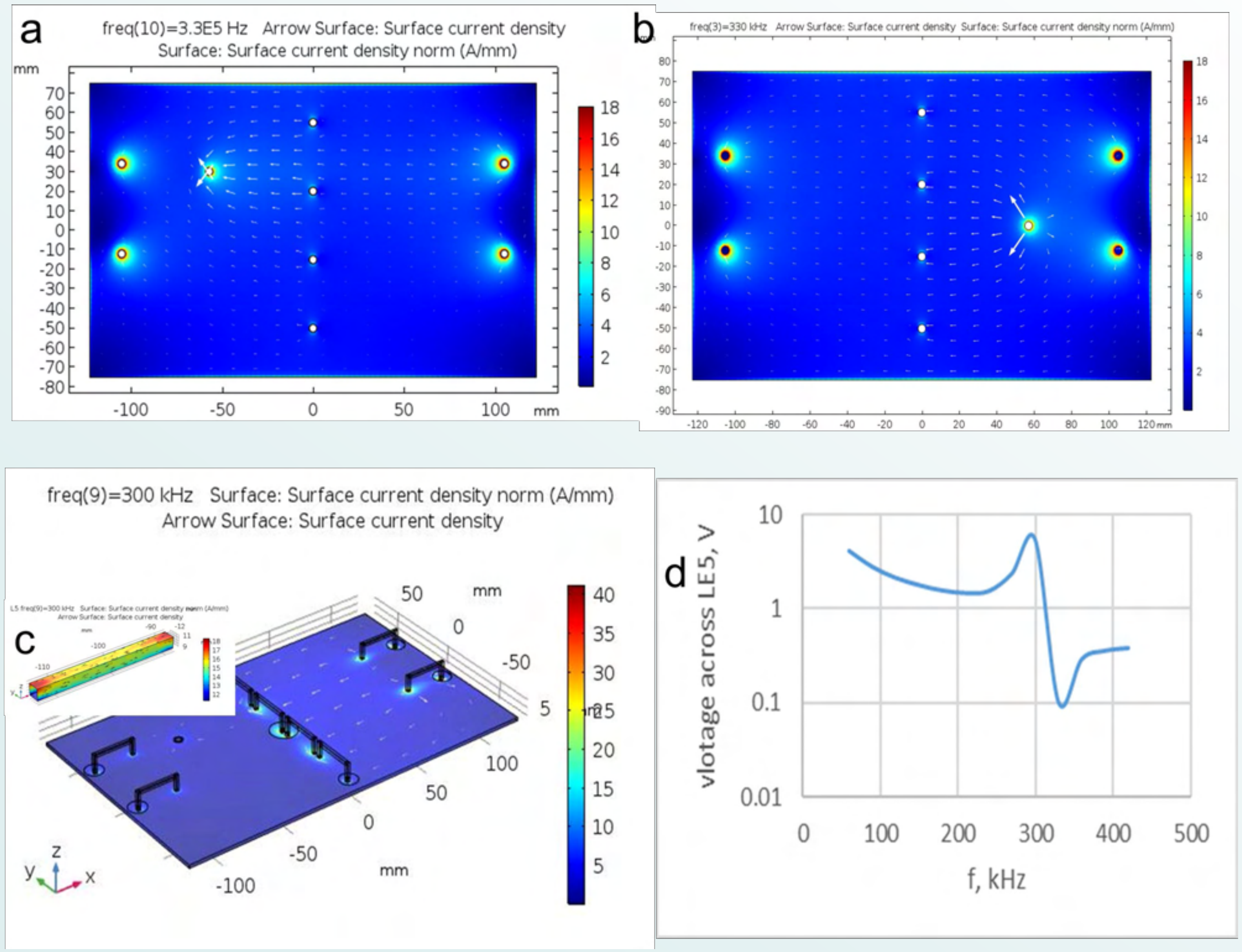
Pokryvailo, A., “Analyzing Electromagnetic Modes of Integrated Busbars implemented as Printed Circuit Boards (PCB)”, *Proc. COMSOL Conference 2018,* Boston MA, 2018, 7pp. Also, internal reports.

Modeling approach



a - H-bridge simulation circuit (simplified), b - TBC; c - IBC, d, e –each capacitor pair modeled by cylindrical Lumped Element (LE5 shown), and in volume, pitch 27.5mm (same LE5 shown), respectively. Current fed via Lumped Port.

Results



a, b – surface current density of top and bottom plates, respectively, at 330 kHz (LC-LE).

c - surface current density C-LE.

d - voltage across LE5 vs frequency.

Thermal and CFD simulations

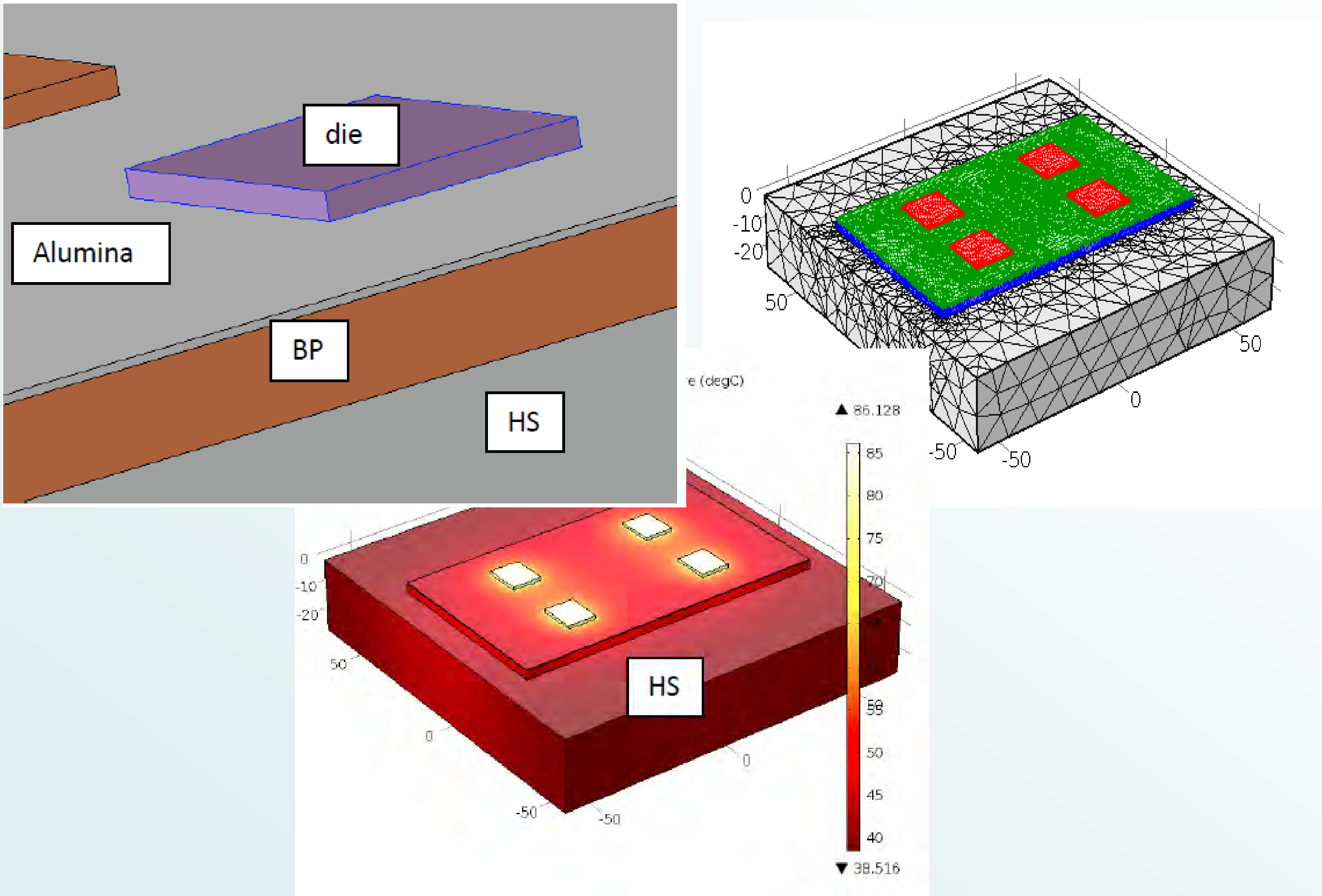
- Heat transfer in solids (simplest)
- Heat transfer in fluids
- Conjugate heat transfer
- Multiphysics (e.g., electrostatic forces and heat sources moving liquid, EM heating, etc.)

All three mechanisms, in all combinations, of heat transfer can be modeled

Planning thermal tests
For instance - *how long can one run IGBT/FET w/o blowing it?*

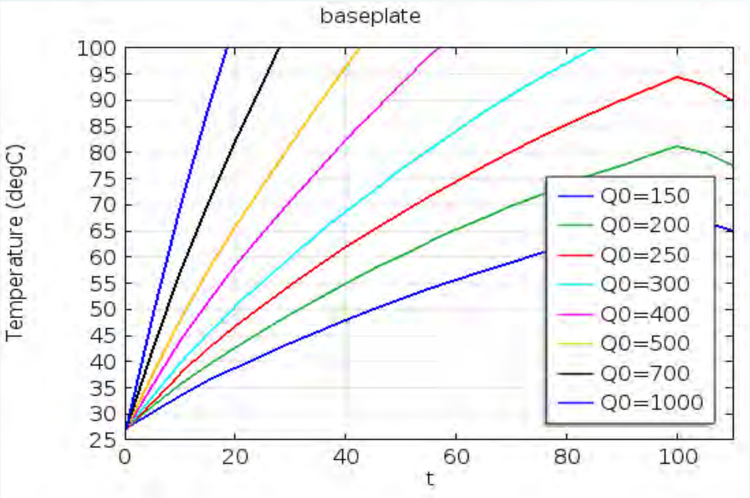
- Determining losses with circuit analysis/experiment comes first
- Manufacturer info:
  - Materials' properties
  - IGBT Geometry

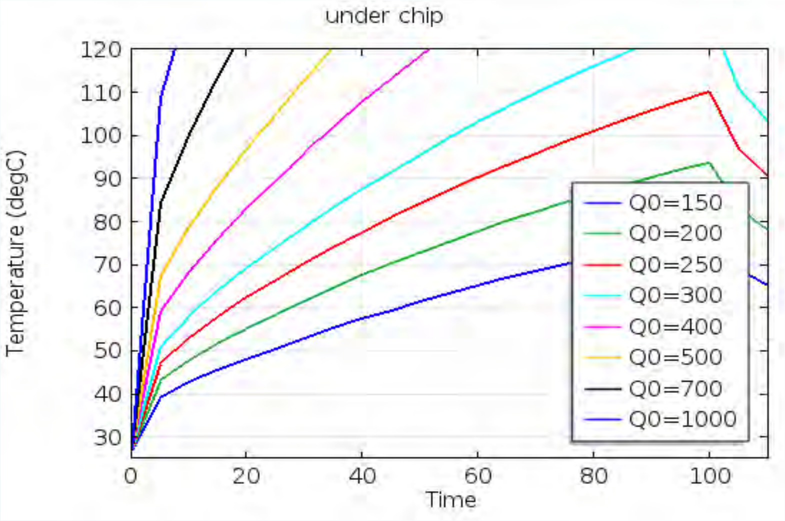
Model of IGBT on heatsink

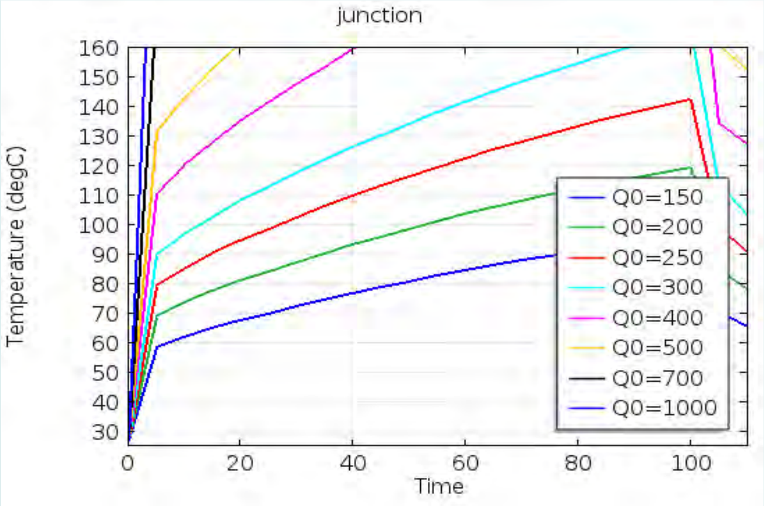


IGBT heating – results

1200V@300A IGBT on HS baseplate 1”. Q0 is loss per chip, so transistor loss is 2xQ0.



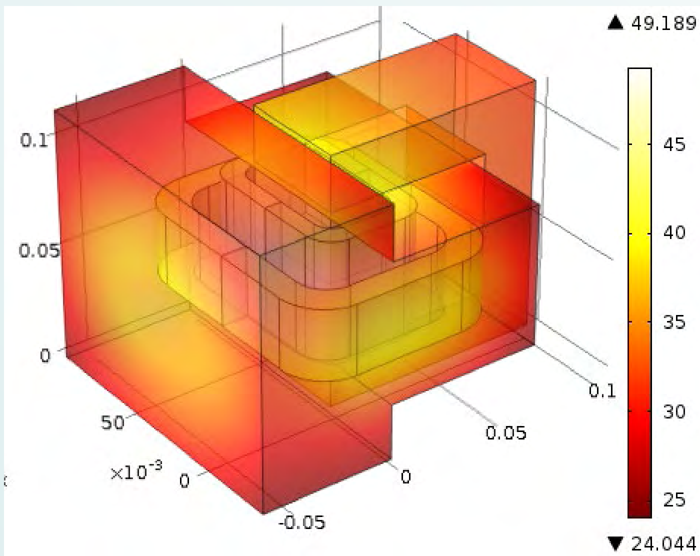




Thermocouples placed on baseplate and/or under chip to determine time to reach specified junction T.

Thermals –repetitive operation

of a potted HV transformer



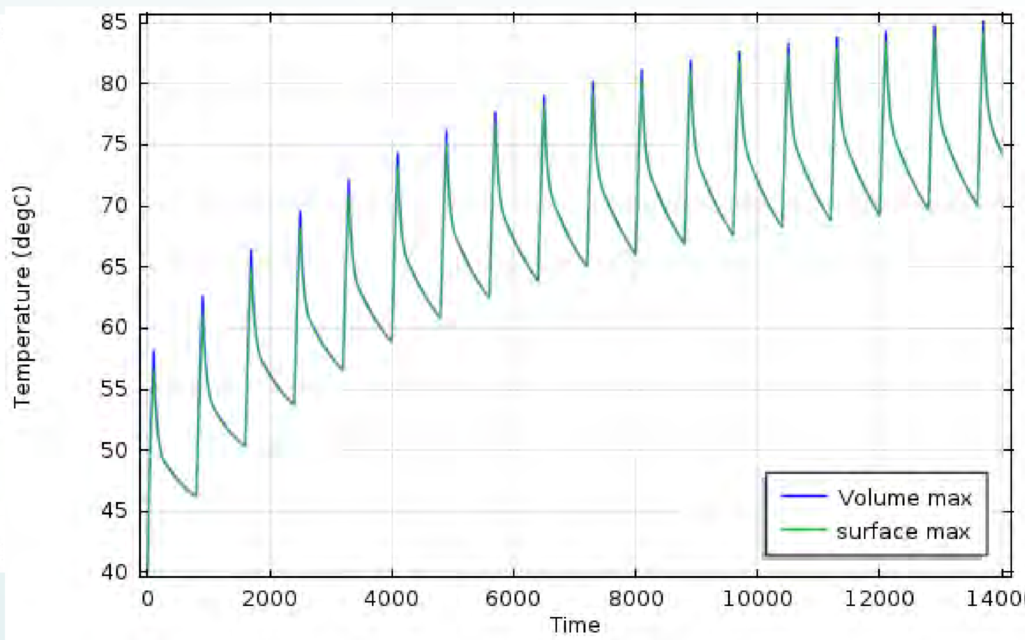


Figure 39. 50kW 100s on 700s off. T0=40degC.

Electroconvection and heat transfer in oil

$$(2) \qquad f = \frac{(\varepsilon_r - 1)\varepsilon_0}{2} \nabla E^2 \; [\mathrm{N/m^3}].$$

Electroconvection can occur in absence of charged species!

1) Pokryvailo, A., "Impact of Electro-Convection (EC) on Heat Transfer in Liquid-Filled Containers", *Proc. Comsol Conf. 2015,* Boston MA, 7-9 October 2015. Available at Comsol site.

2) Pokryvailo, A., "Electro-Convection in Liquids in Absence of Ionization", Proc. 2016 IEEE Power Modulator and High Voltage Conf., 2016.

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} =$$

$$\nabla \cdot \left[-p\mathbf{I} + \mu\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right)\right] + \mathbf{F}$$

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot (\mathbf{u}) = 0$$

where

- $\mathbf{u}$ is the velocity vector;
- p is the pressure (SI unit: Pa);
- $\mathbf{F}$ is the body force vector (SI unit: N/m3).

Heat transfer is defined by the equation

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q + Q_{vd} + Q_p$$

where

- C_p is the specific heat capacity at constant pressure;
- T is the absolute temperature;
- k is thermal conductivity
- Q's are heat sources.