Fundamentals of Insulation Design

Transformer Concepts & Applications Seminar

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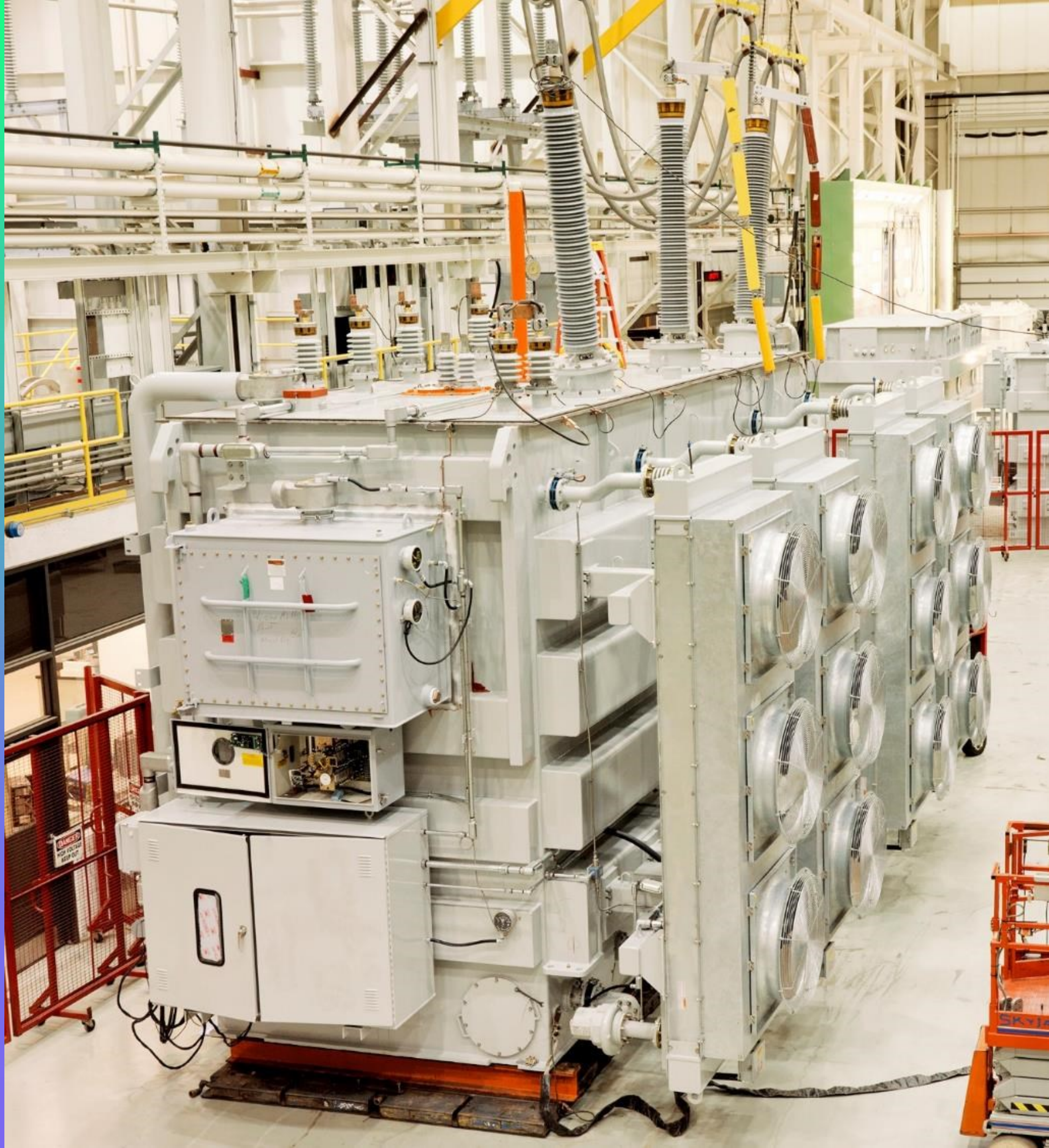


Agenda

- Insulation Materials
- Design Margins
- Insulation Design Method
- Impulse Voltage Distribution

Insulation Materials

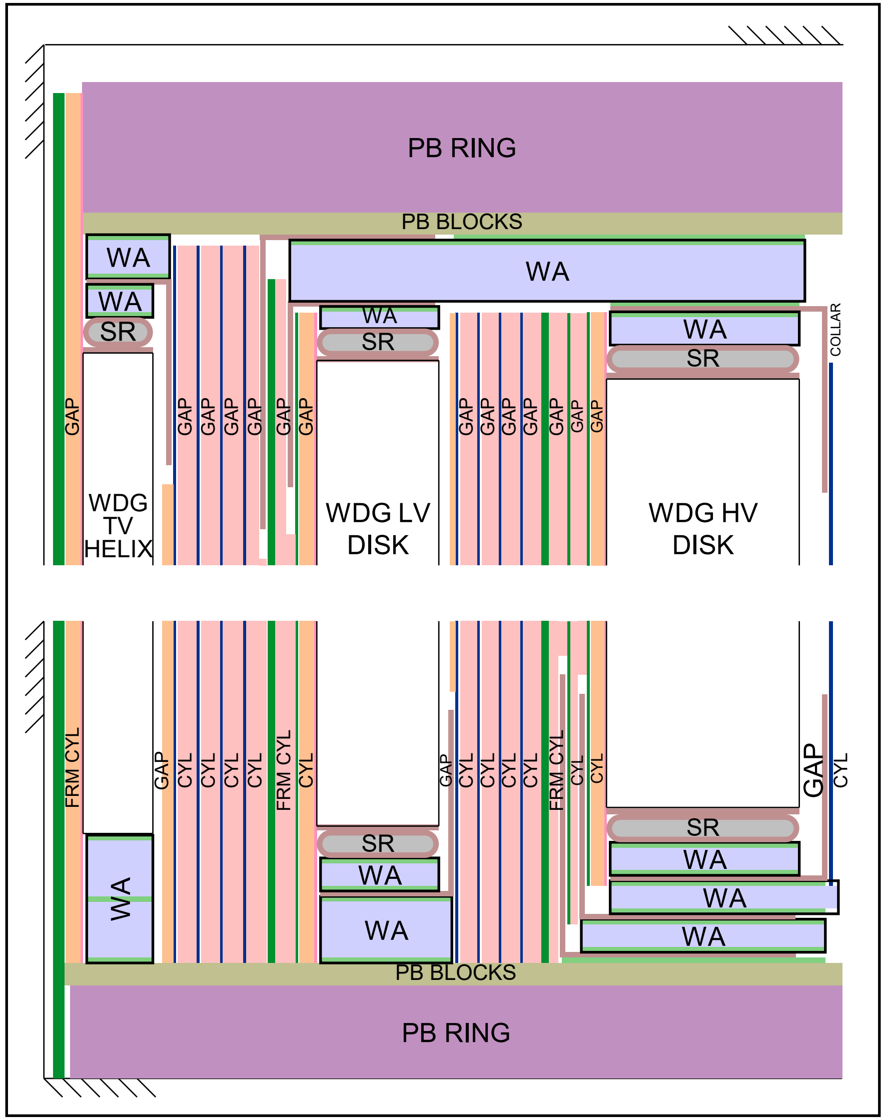
Insulation Materials

Major Insulation

Insulation of windings to ground, core, other windings within the phase and to other phases

Materials

- **Pressboard (cellulose)**
  - **High density (TIV)** – cylinders
  - **Medium density (Hi-Val)** – collars
  - **Layered TIV (TX2)** – rings, washers
- **Nomex** – for higher temperatures
- **Laminated Wood** – rings
- **Kraft Paper (cellulose)** – leads
- **Copaco (cotton based paper)** – leads
- **Resin/epoxy materials** – on metal parts



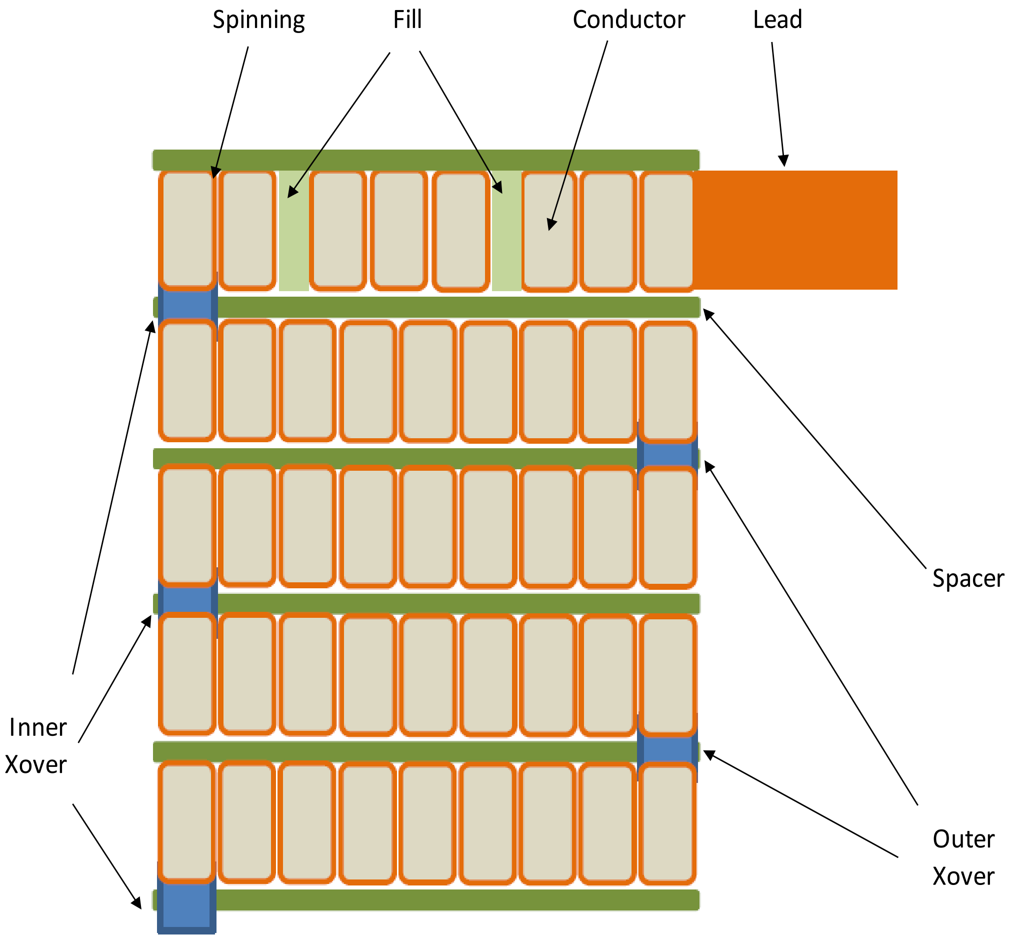
Insulation Materials

Minor Insulation

- Insulation between different parts of one winding – between turns, stands of conductors, discs or layers

Materials

- **Kraft Paper** – conductor insulation/spinning
- **Nomex** – spinning, spacers
- **Formvar** – conductor insulation
- **Epoxy (CTC)** – conductor insulation
- **Copaco (cotton based paper)** – leads
- **Pressboard**
  - **High density (T4)** – spacers
  - **Medium density (Hi-Val)** – collars, etc.
  - **Layered TIV (TX2)** – structural parts



Insulation Materials

Insulating Fluids

- Mineral Oil
- Natural Ester (FR3)

Advantages of Natural Ester

- Slows aging of cellulose (equiv. to roughly 10 ˚C lower winding rise)
- Higher Flashpoint (330˚C vs 140˚C)
- Environmental advantage/containment

Drawbacks:

- Cost
- Higher viscosity
- Solidifies below -20˚C

Other Materials

Lead Insulation

- Kraft Paper
- Copaco
- Nomex
- Pressboard

Lead Supports

- Maple
- Laminated Wood
- TX2

Bushings, Insulators

- Resin/epoxy materials
- Porcelain

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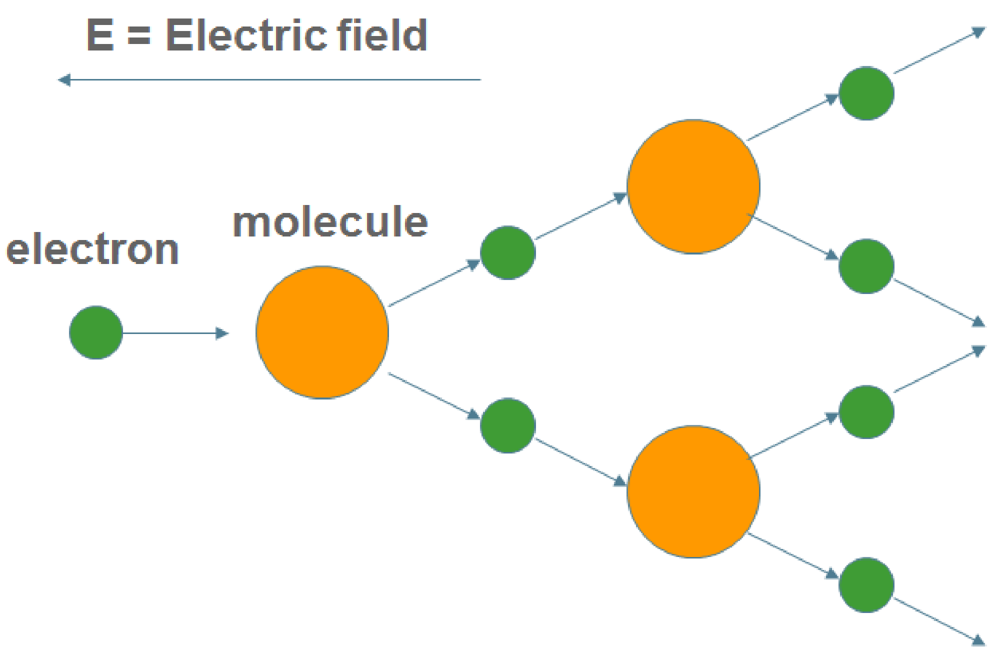
Design Margins

Design Margins



Townsend Mechanism

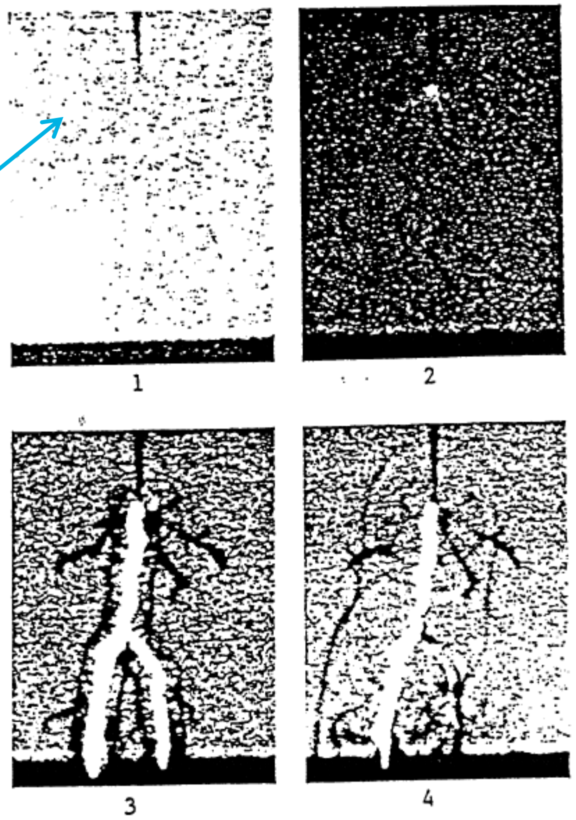
Avalanche Breakdown

- This type of breakdown applies to gases and results in a breakdown voltage which depends on distance

A similar mechanism operates in oil and breakdown voltage versus gap thickness curves are used

Design Margins

An ionized streamer starting out will propagate very fast, breaking down the oil at its tip.

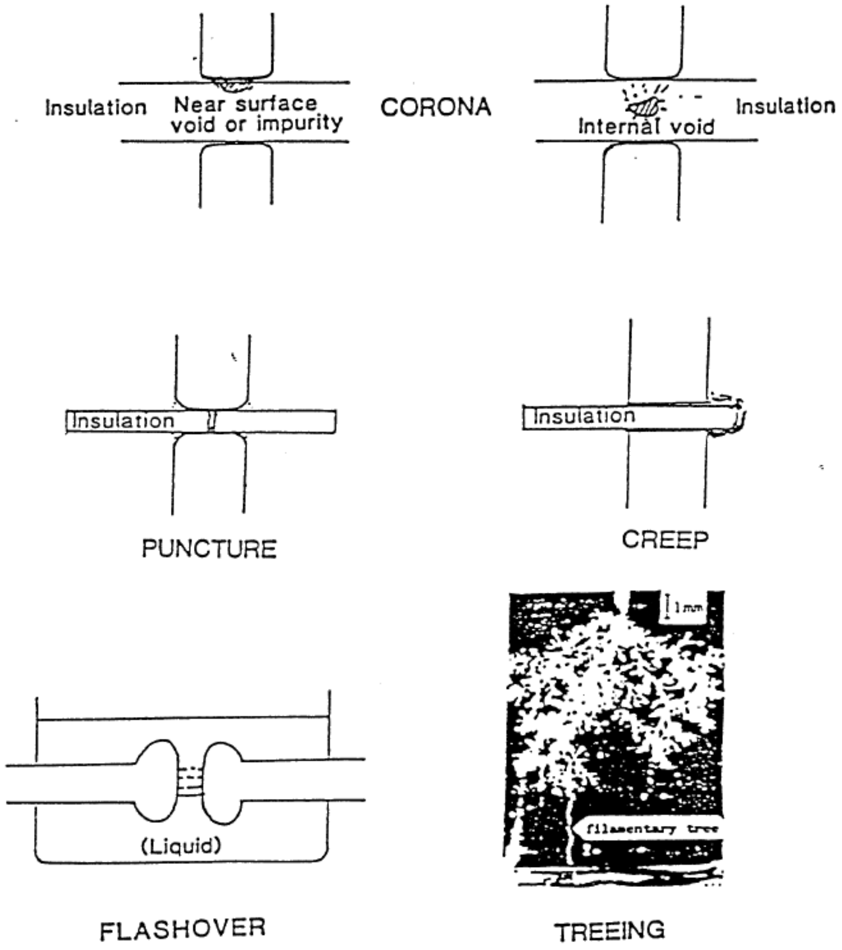


A positive streamer development (50 kV, 4 mm gap, 0.1 μs exposure time, 0.4 μs between frames). The first frame is taken 0.4 μs before the leading edge of voltage pulse.

The oil gaps are generally the weak link in the insulation system

4 mm Oil gap breaking down in 1 /1,000,000 of second

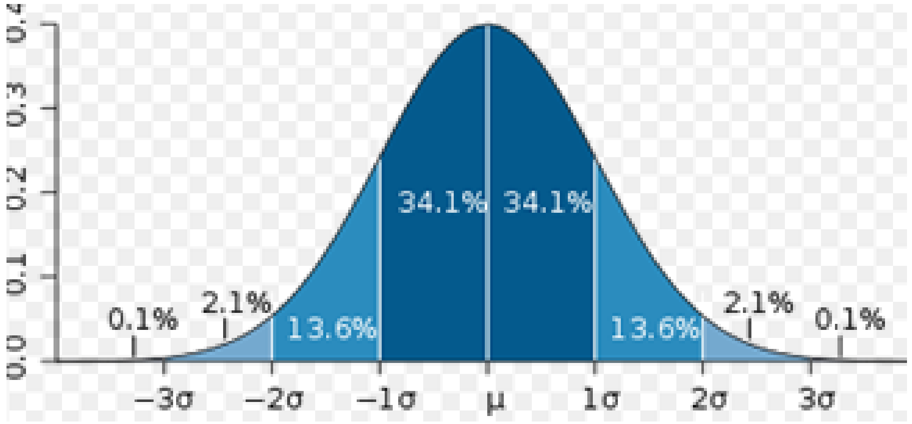
Design Margins



Dielectric Breakdown Types

Design Margins

3 σ chance of test failure = 0.15%



Dielectric Breakdowns Follow Normal Distribution

Typical Design Level: Mean Breakdown– 3 σ = 70% of Average Breakdown
σ = 10% is typical for oil breakdown

Design Margin	**(Definition A)**	**1-Design/Breakdown**	**30% is appropriate**
Design Margin	**(Definition B)**	**Breakdown/Design – 1**	**43% is appropriate**

Note σ is not always 10%. Using barriers reduces scatter, 'open' systems such as lead cables have higher σ.
Solid puncture has a much smaller sigma than oil breakdown (2% is typical).

Using PDI (partial discharge inception): Use 80% of PDI level
(PD starts at about 80% of breakdown level)

Insulation Design Method

Insulation Design Method

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1) **Establish Voltage between parts**
   Use Volts per turn for AC, transient calculations for impulse type Voltages.

2) **Localized Stress Check**
   Find stress through Finite Element methods, compare with allowable limits. Use Stressed Oil Volume or test models to arrive at design stress levels by using appropriate margin.

3) **Oil duct stress limits**
   Check average stress in oil ducts vs size of duct, apply appropriate margin.

4) **Creep Stress Analysis**
   Compare creep stress path against Weidmann creep curve

Localized Stress

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- Evaluating 300 kV (AC 1 min) Cable Clearance to Ground

Analyzing Localized Stress

Localized Stress (FEA analysis)

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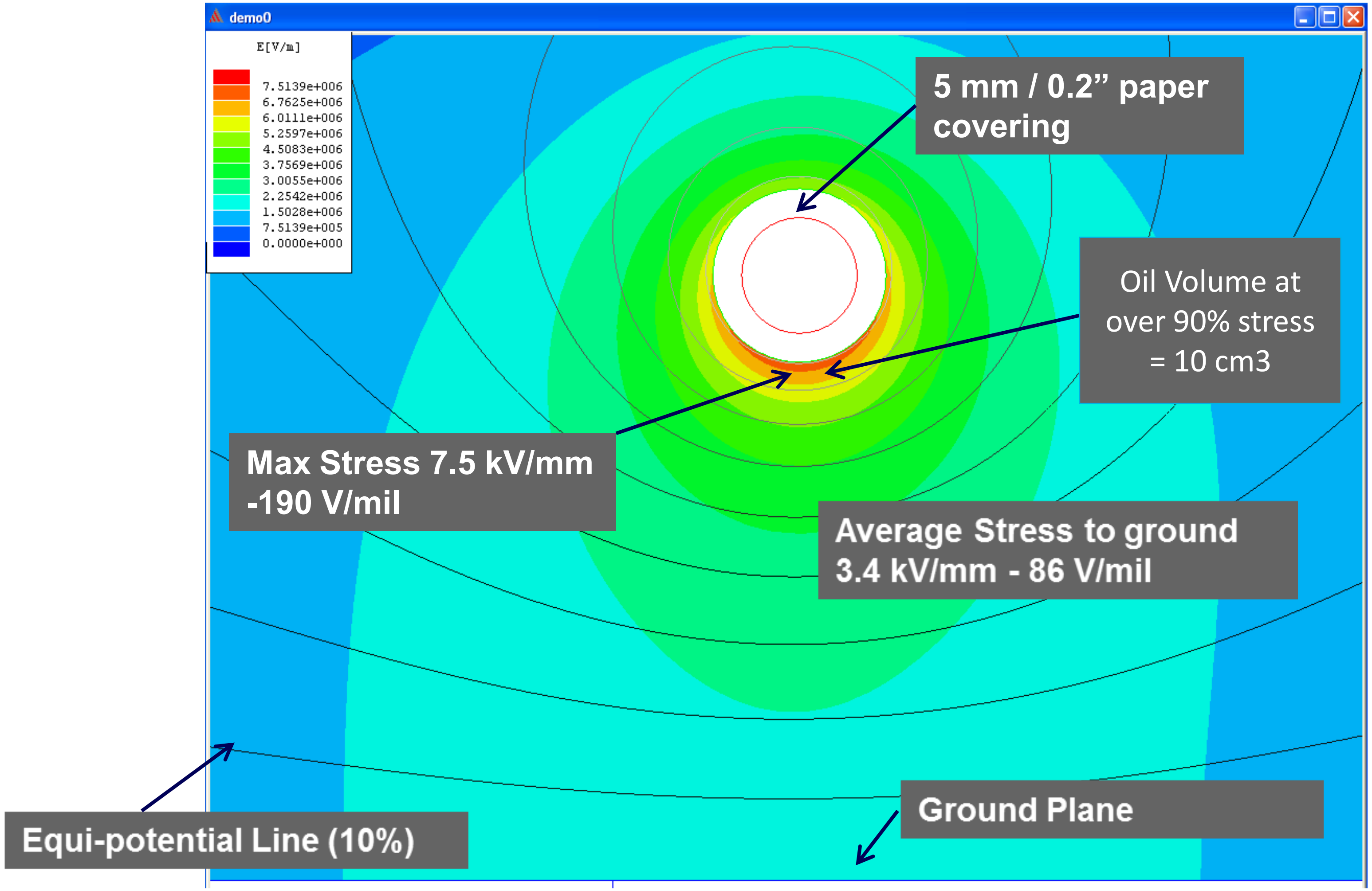
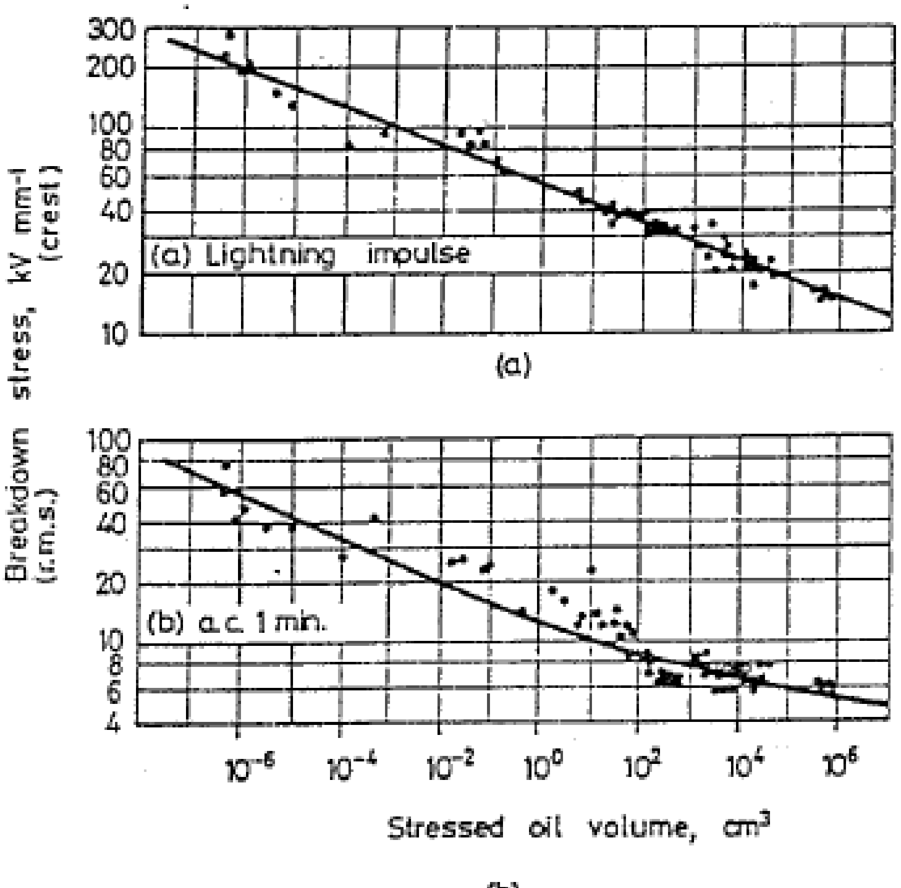


Field (FEA) Plot of Cable with 89 mm/3.5” strike to Ground

Localized Stress



Breakdown voltage of oil as a function of oil volume examined

- 10 cubic cm of SOV gives predicted AC average breakdown of 10.3 kV/mm AC (260 V/mil)
- Use 60% of breakdown level (cables have large breakdown level scatter)
- Max stress allowed for the cable example is 10.3 kV/mm * 0.6 = 6.2 kV/mm /157 V/mil

Applying Stressed Oil Volume

Localized Stress (FEA Analysis)

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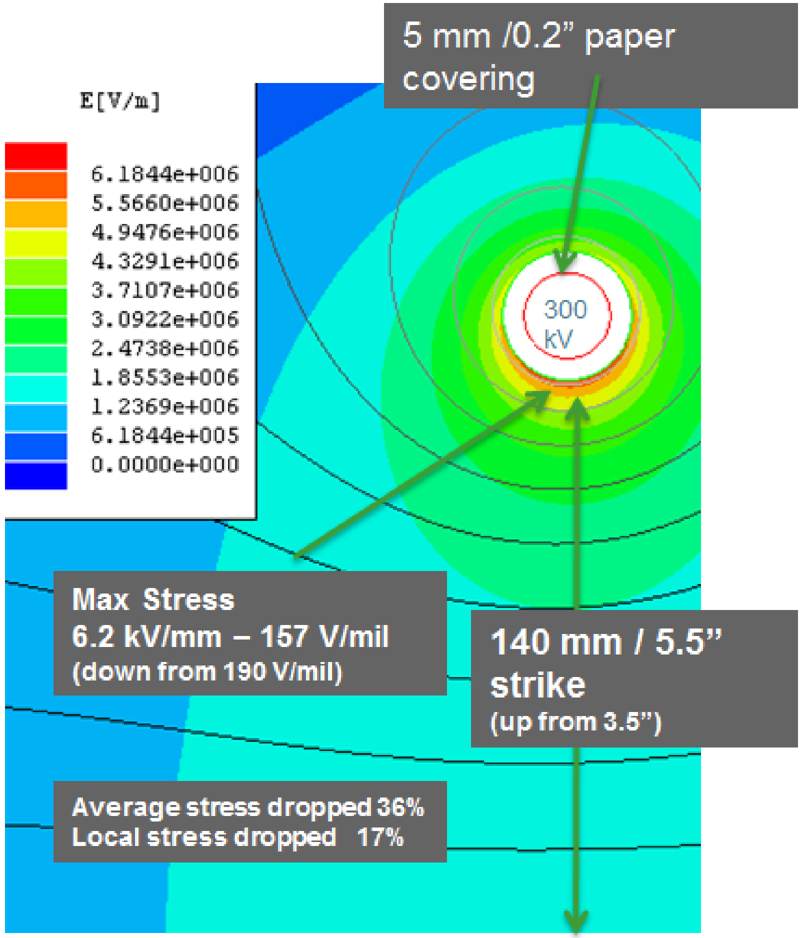
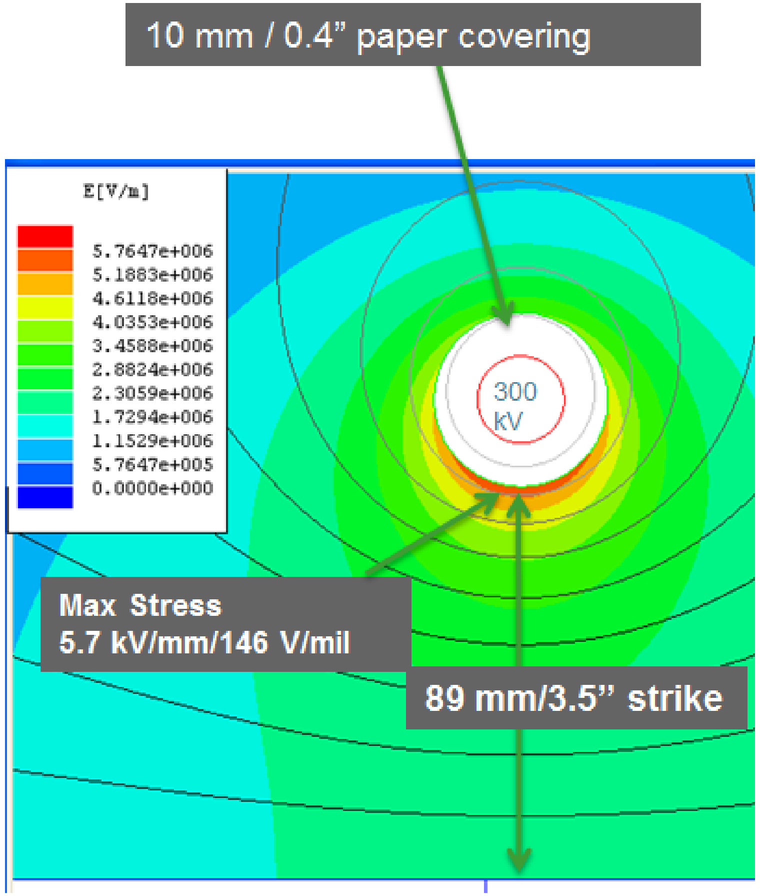
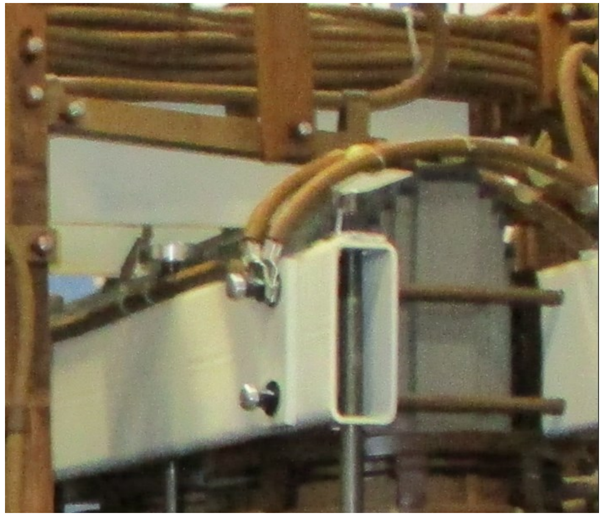




Controlling localized stress

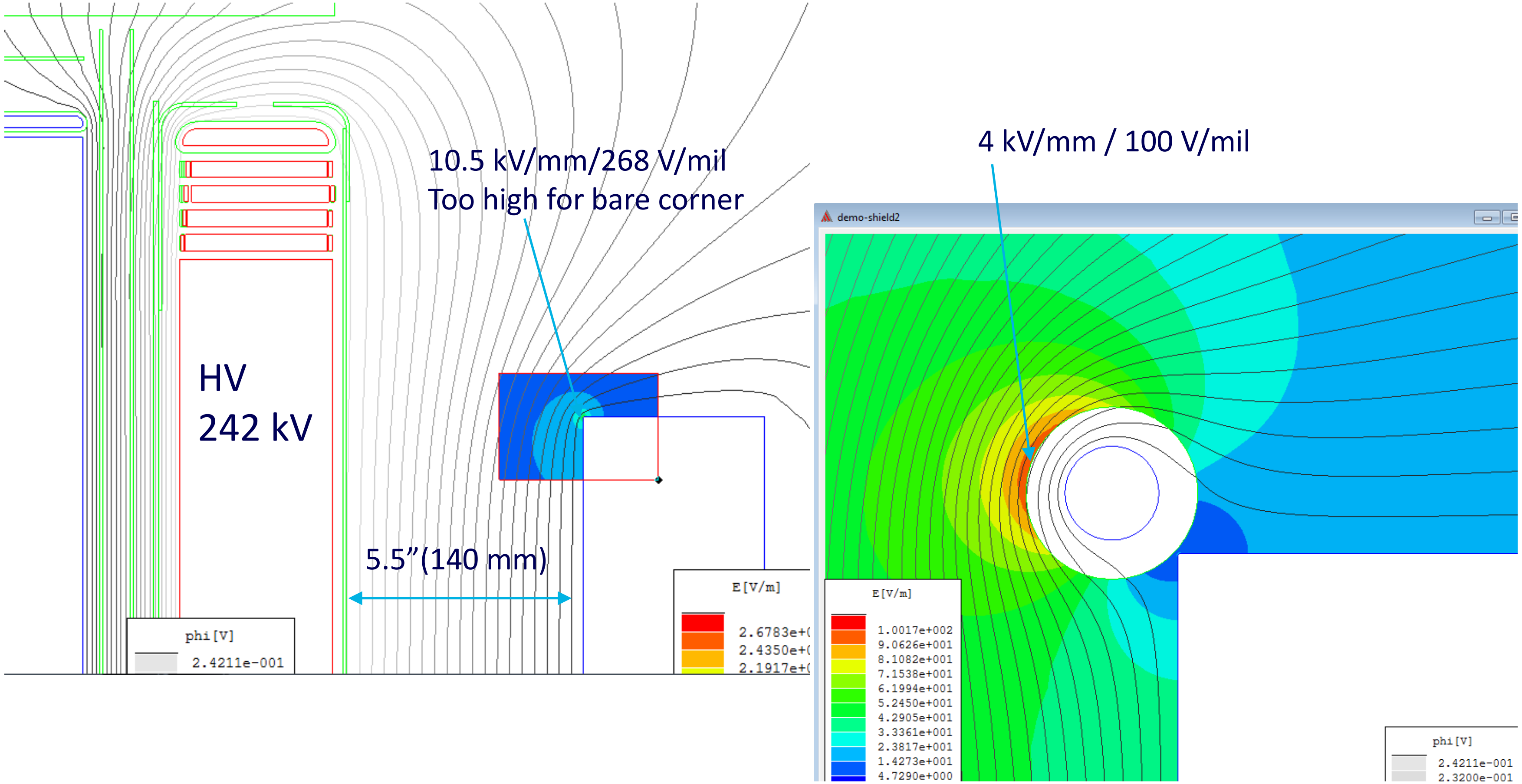
Localized Stress Control



- Shielding of sharp points with corona rings and cable shields

Controlling localized stress

Localized Stress

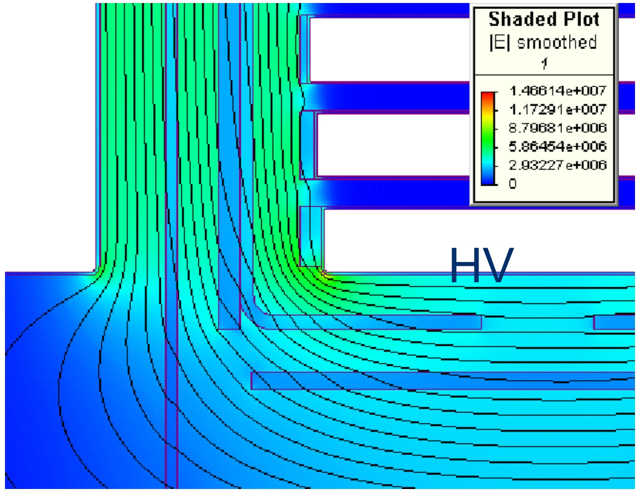


- Cable shield reduces local stress down to 38% of previous

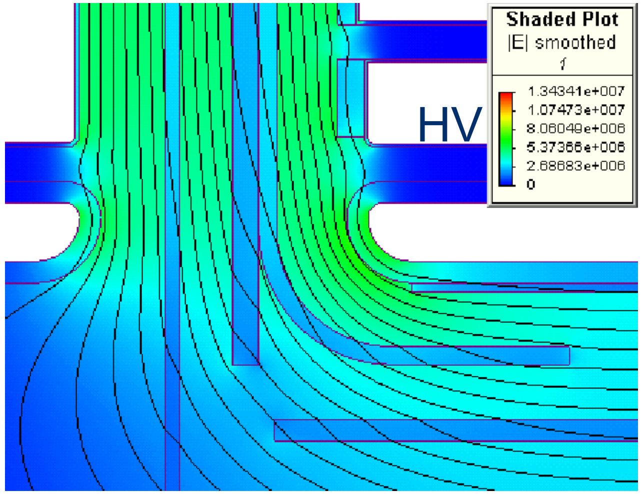
Controlling localized stress

Localized Stress

- Charge piles up on the sharp edges of conductors.
- w/o static ring = 12.5 kV/mm (318 V/mil)
- Exceeds recommended Weidmann design level of 12 kV/mm



- To lower the stress, we shield the conductor edge w/ static ring 7.7 kV/mm (196 V/mil)



Using static rings to control localized stress

Oil Duct Stress

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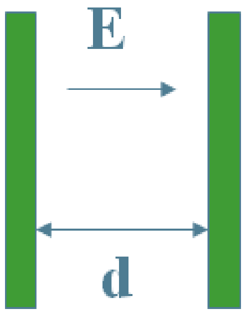
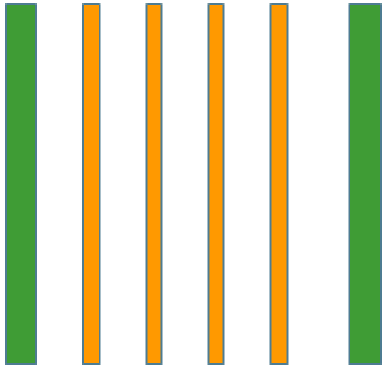


uniform field gap



Gaps are subdivided with pressboard barriers

- Weidmann's Partial discharge inception curves for 1 minute a.c. voltages - d in mm
  Design for max 80% of P.D.I. (20% margin)
- Appropriate margin from PDI is lower than from breakdown

		Metric
WETI Creep Line:	Obsolete	$\frac{kV}{mm} = 16.7 * d^{-0.46}$
WETAG Creep Line:	(pressboard)	$\frac{kV}{mm} = 15.0 * d^{-0.37}$
WETAG Degassed Non-insulated Electrode:		$\frac{kV}{mm} = 17.5 * d^{-0.37}$
WETAG Gas Saturated Non-insulated Electrode:		$\frac{kV}{mm} = 14.0 * d^{-0.37}$
WETAG Degassed Insulated Electrode:		$\frac{kV}{mm} = 21.5 * d^{-0.37}$
WETAG Gas Saturated Insulated Electrode:		$\frac{kV}{mm} = 18.5 * d^{-0.37}$
Note: d = gap or creep path distance		d in mm

Oil Duct Stress

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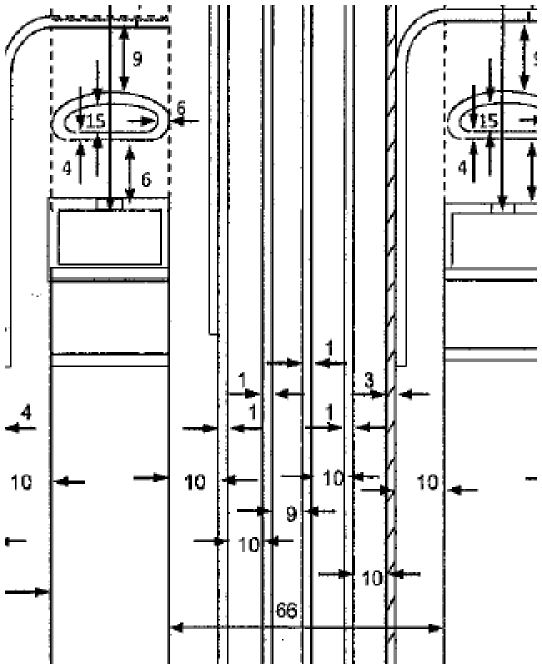
- Use degassed oil non insulated for duct next to winding (<0.5 mm ins.wall)
- Use insulated case for center ducts

$$E_{pb,ac} = (kV_{rms}/mm) = 17.5 * d^{-0.37}$$

80% of PD Inception			
mm	inch	kV/mm	V/mil
6	0.24	7.2	183
8	0.31	6.5	165
10	0.39	6.0	152
12	0.47	5.6	142
14	0.55	5.3	134
16	0.63	5.0	127



Equiv. oil gap = 59 (oil) + 7 (pb) * 2.2/4.4 = 62.5 mm

Stress at 1st duct= 345 kV / 62.5 mm x

ave/min. gap radius = 6.0 kV/mm

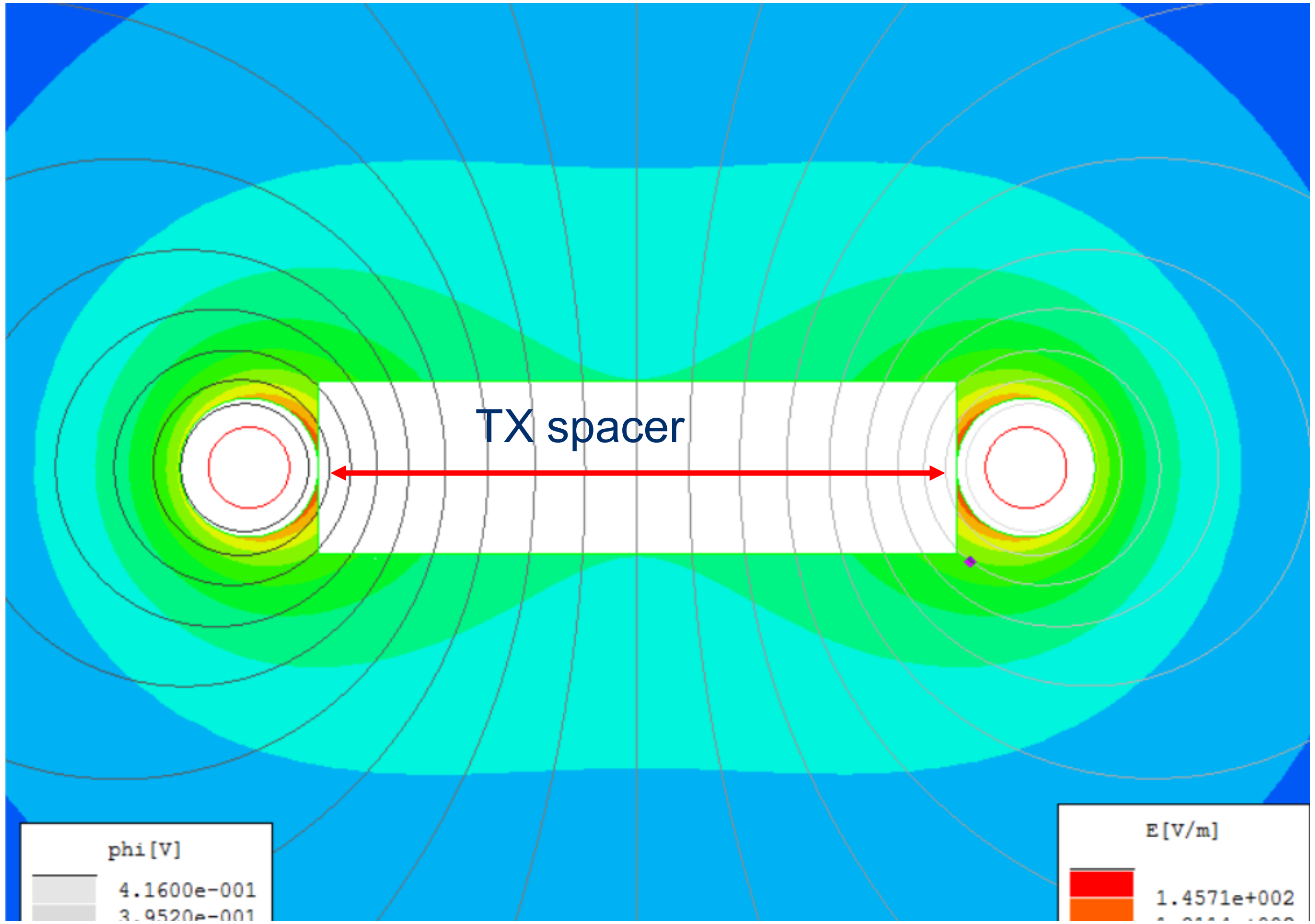
This is less than the 6.0 kV/mm design limit - OK

345 kV hipot test
(230 kV class unit)

Dielectric constants
Oil = 2.2, Pressboard=4.4

Applying oil duct stress in hi-lo gaps between windings.

Creep Stress

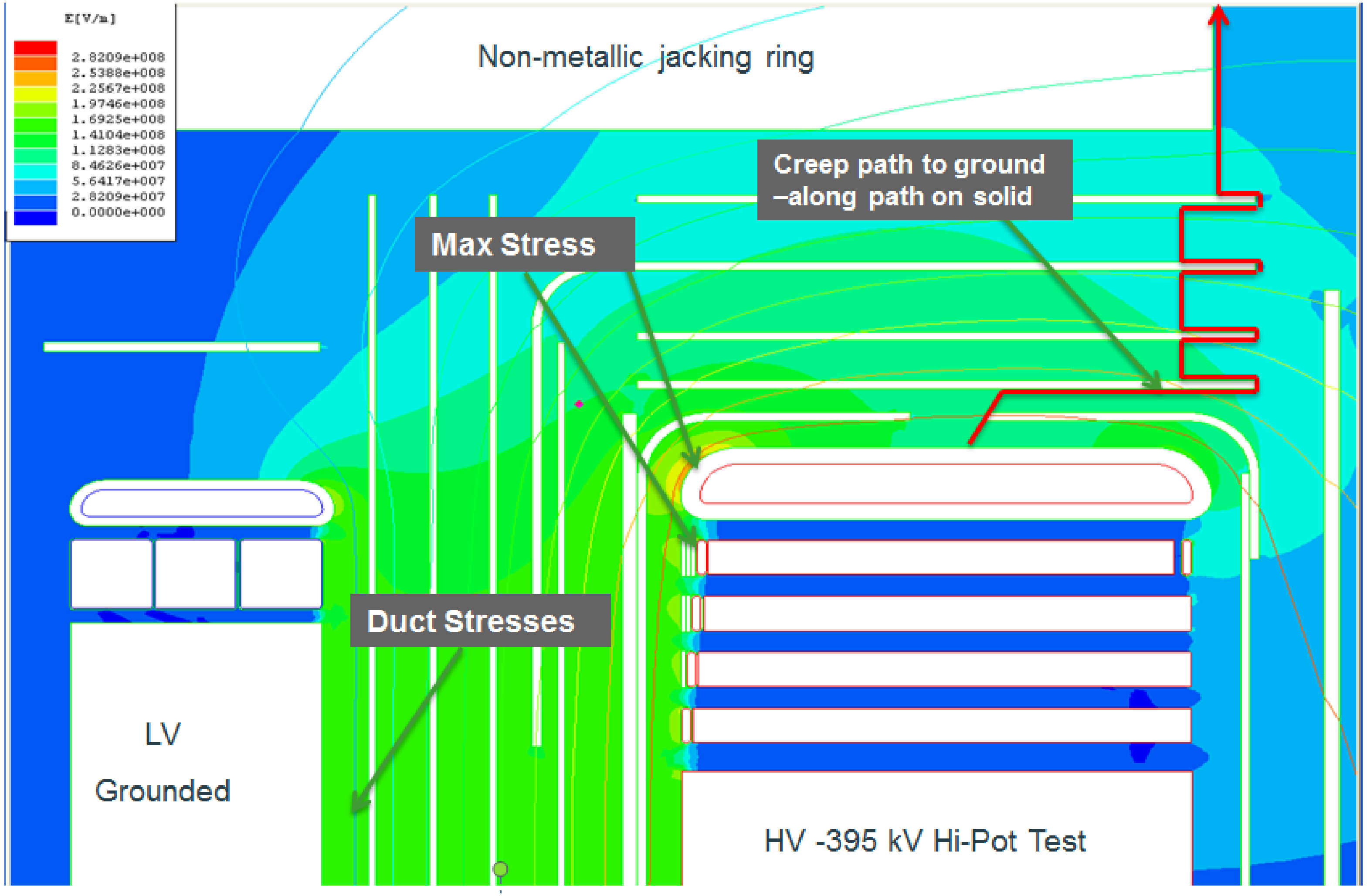


Local stress is 5.7 kV/mm (146 V/mil) – ok
Average creep stress is 0.85 x 416 kV / 140 mm = 2.5 kV/mm
Allowable = 0.8 x 15 x 140 ^(- .37) = 1.92 kV/mm
Creep stress limit is exceeded!

Phase to phase 416 kV enhanced test cable to cable 5.5” (140 mm separation)

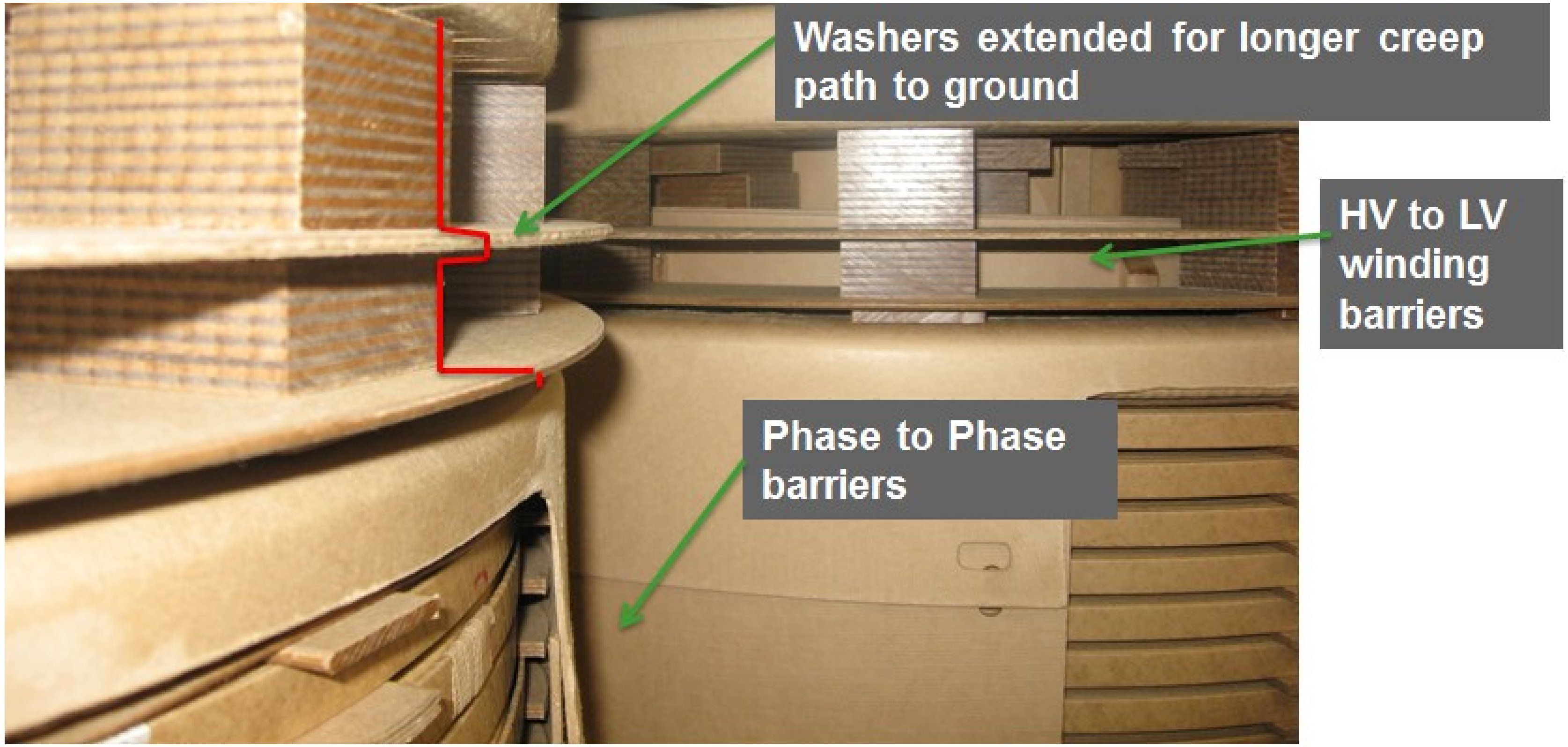
Creep Stress along cable separator

Insulation Design Method



Check for local stress, oil duct stress vs duct size and creep stress

Insulation Design Method

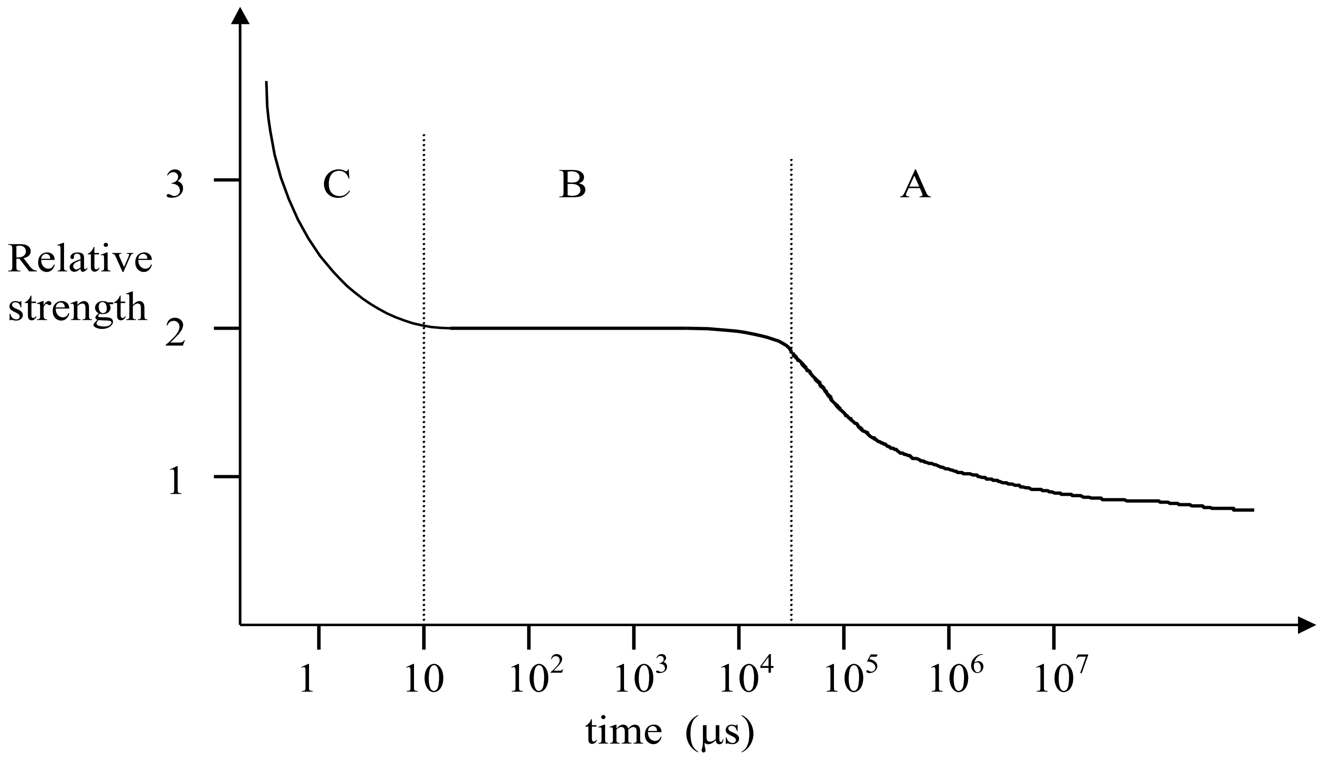


Barriers and extended creep paths

Insulation Coordination

Insulation Coordination

- Transformer oil / pressboard insulation can withstand higher voltages for shorter periods of time



Oil or pressboard breakdown relative strength vs time - schematic

Volt/Time curve

Insulation Coordination

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Impulse: Short term, high Voltage

- Impulse breakdown strength is
- 2.1-4.0 times the 1 min 60Hz strength

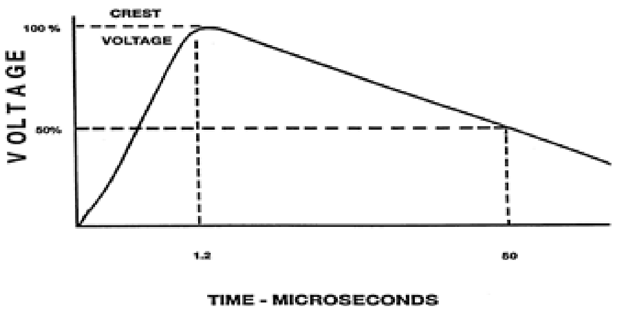
Types of Impulse Tests

- Full Wave Level = BIL
- Chopped Wave = 1.10 x BIL
- Switching Surge = 0.83 x BIL

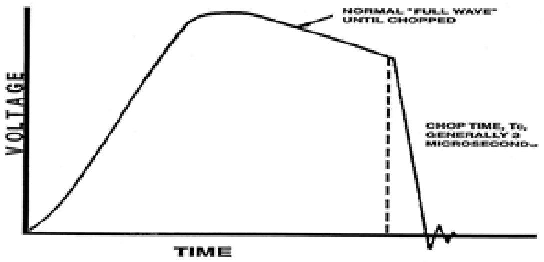
a, b: lightning simulation

c: breaker simulation

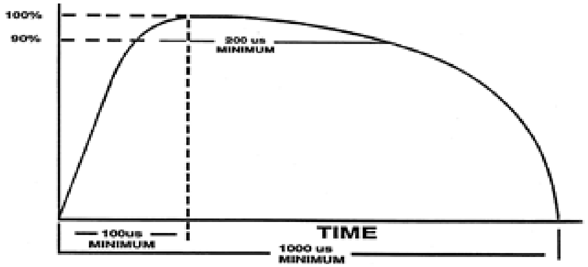
a) Full Wave



b) Chopped Wave



c) Switching Surge



Impulse Wave Shapes

Insulation Coordination

EXAMPLE: 230 kV transformer, 900 kV BIL			
	Voltage to Ground kV	Volt-Time Correction	Equivalent AC Test kV
Operating	133	0.5	266
Applied	345	1.0	345
One Hour Induced	210	0.85	247
7200 Cycle Induced	240	1.0	240
Switching Surge	745	2.1	355
Full Wave	900	2.50	360
Chopped Wave	990	2.75	360

- The voltages from line to ground can be said to be equivalent to a short term applied test.
  Also called DIL (design insulation level)
- The voltages within the transformer will not be distributed the same way for each test
- Impulse voltage distribution is very non-linear and varies through the duration of the impulse
- The highest equivalent voltage between the parts of the transformer being analyzed must be identified for each case – the full range of tests must be considered
- The voltage distribution between parts under impulse can be measured with low voltage impulse method before the unit is tanked to verify the voltage between parts is as calculated

Converting to Equivalent AC (1 min) - DIL

Impulse Voltage Distribution

Voltage Distribution – Capacitive Distribution

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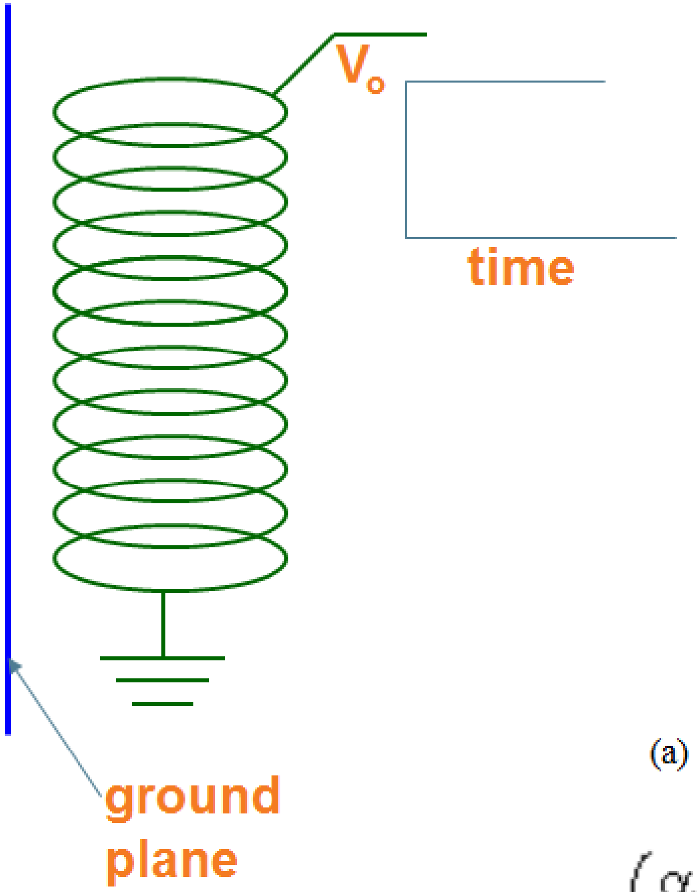
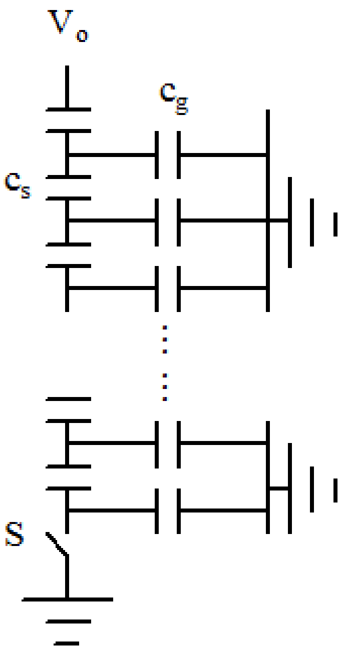
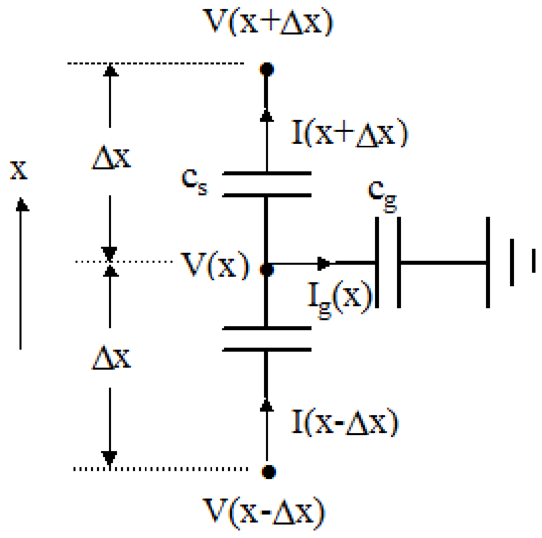




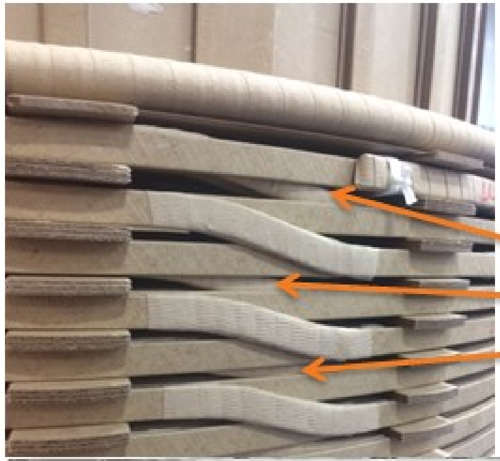
(a) Capacitive model of winding



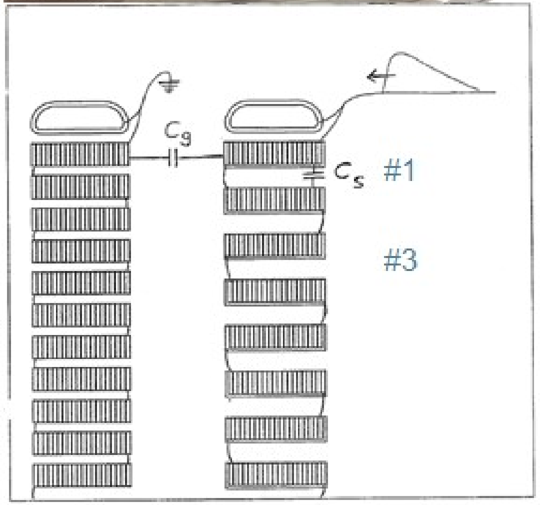
(b) Small section of winding used for analytical purposes

Solution: $$V(x) = V_o \frac{\sinh\left(\frac{\alpha}{L}x\right)}{\sinh \alpha}$$ **where** $$\alpha = \sqrt{\frac{C_g}{C_s}}$$ **is the distribution constant**

Impulse Distribution (Initial Voltage Distribution)

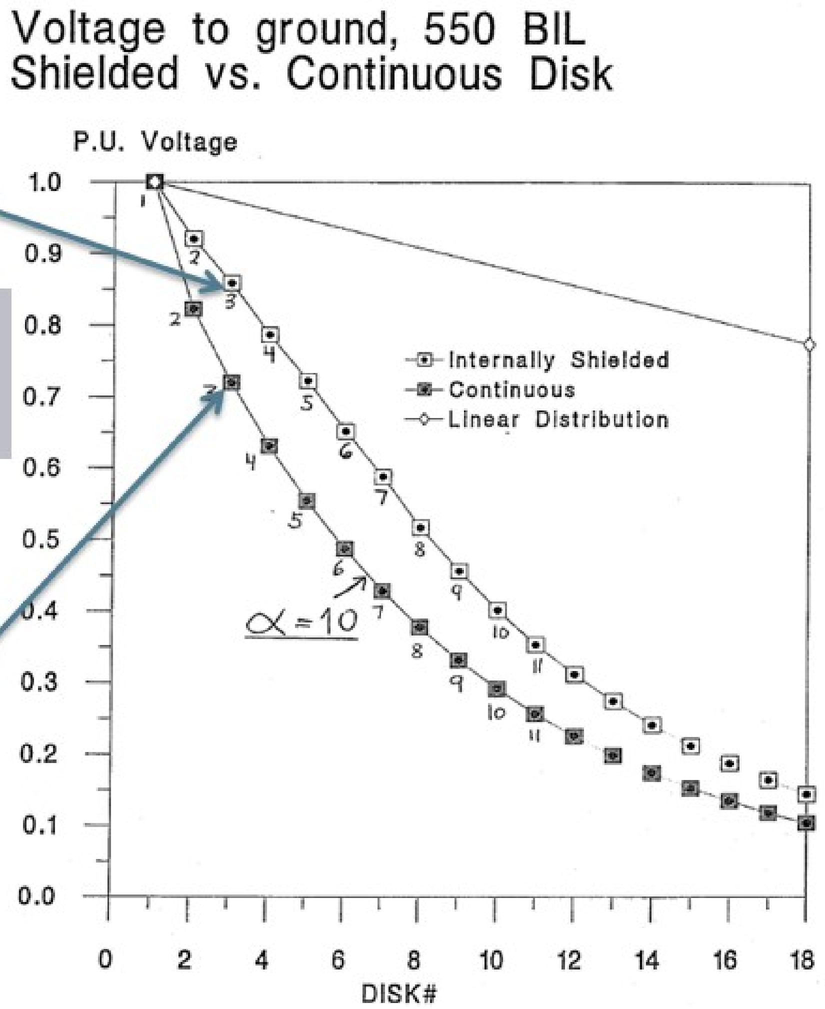


Floating internal shields wound into discs for added series capacitance (Cs)



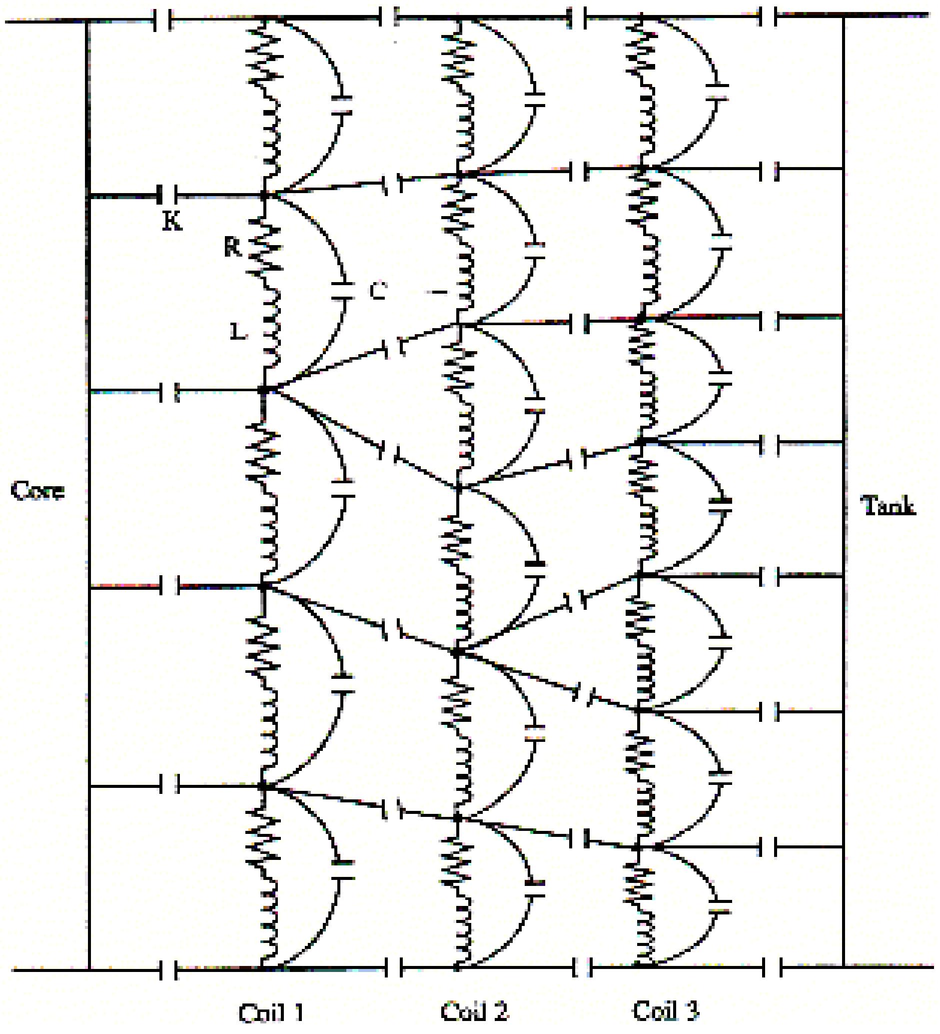
14% Voltage drop (77 kV)

28% Voltage drop (154 kV)



Improving initial impulse distribution with internal shields

Impulse Voltage Distribution – Building a Circuit Model



- The number of coil subdivisions is arbitrary. Can make finer subdivisions where voltages are critical.

Impulse Voltage Distribution – Circuit Model

- Inductances and mutual inductances are calculated for all the coil subdivisions of the same or different coils, taking the core and yokes into account.

- Resistances of the coils is included. Windings can be grounded directly or through resistors included in the model, including their frequency dependence

- Different nodes in the model can be connected directly or through resistors, varistors or inductors.

- Disk-disk capacitances can include the effects of wound-in-shields.

Features of Circuit Model

Impulse Voltage Distribution – Circuit Model

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Current equations can be put in the form:

$$M \frac{dI}{dt} = BV - RI$$

M is an inductance-mutual inductance matrix,
R is a resistance matrix, and *B* is a matrix of ± 1's and 0's.

Voltage equations can be put in the form:

$$C \frac{dV}{dt} = AI$$

C is a capacitance matrix and A is a matrix of ± 1's and 0's.

The standard impulse full waveshape is represented mathematically by:

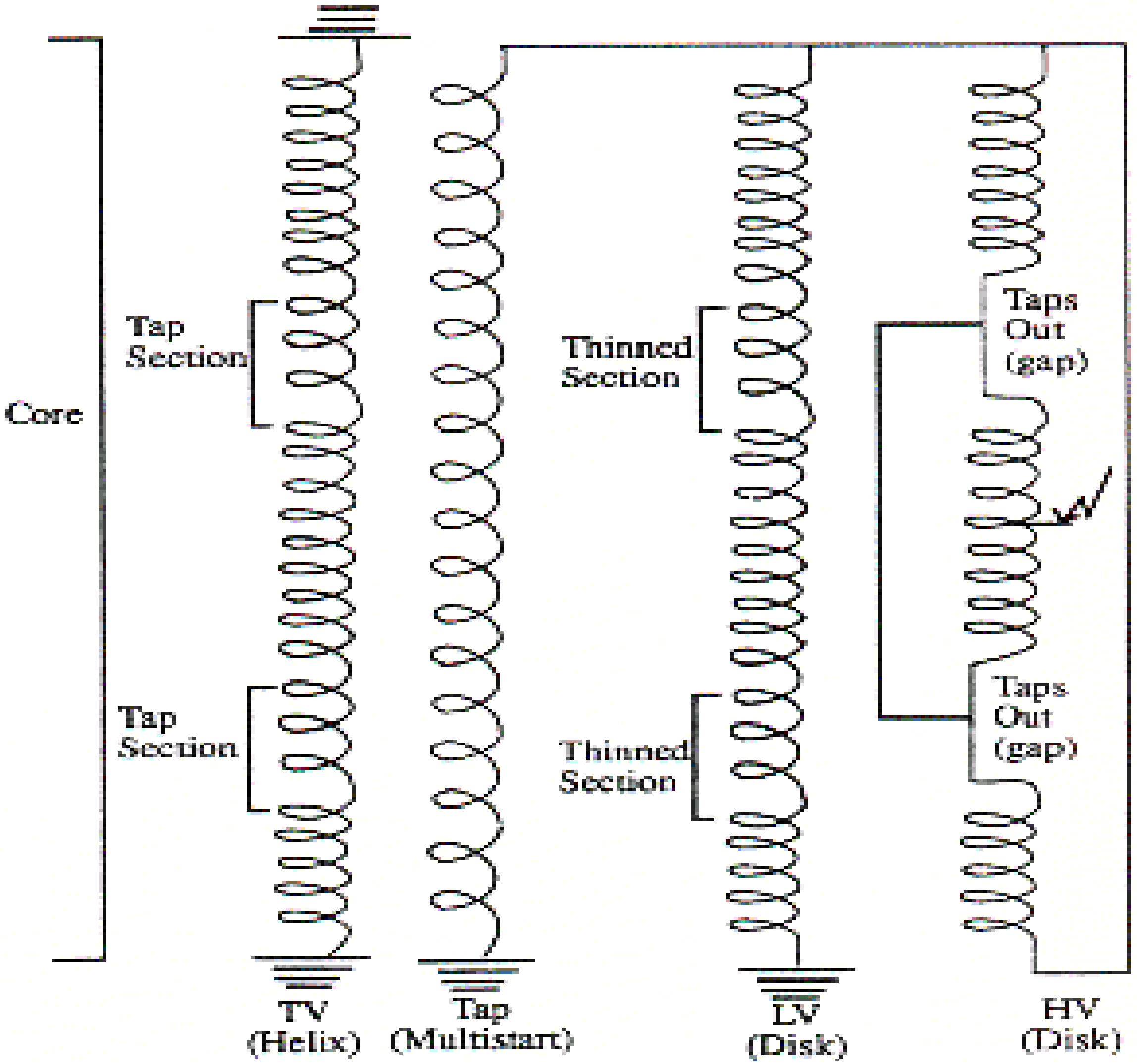
$$V_s(t) = V_o(e^{-k_1 t} - e^{-k_2 t})$$

The chopped wave has this shape up until the chop. Then the voltage drops to zero and some undershoot and ringing are included.

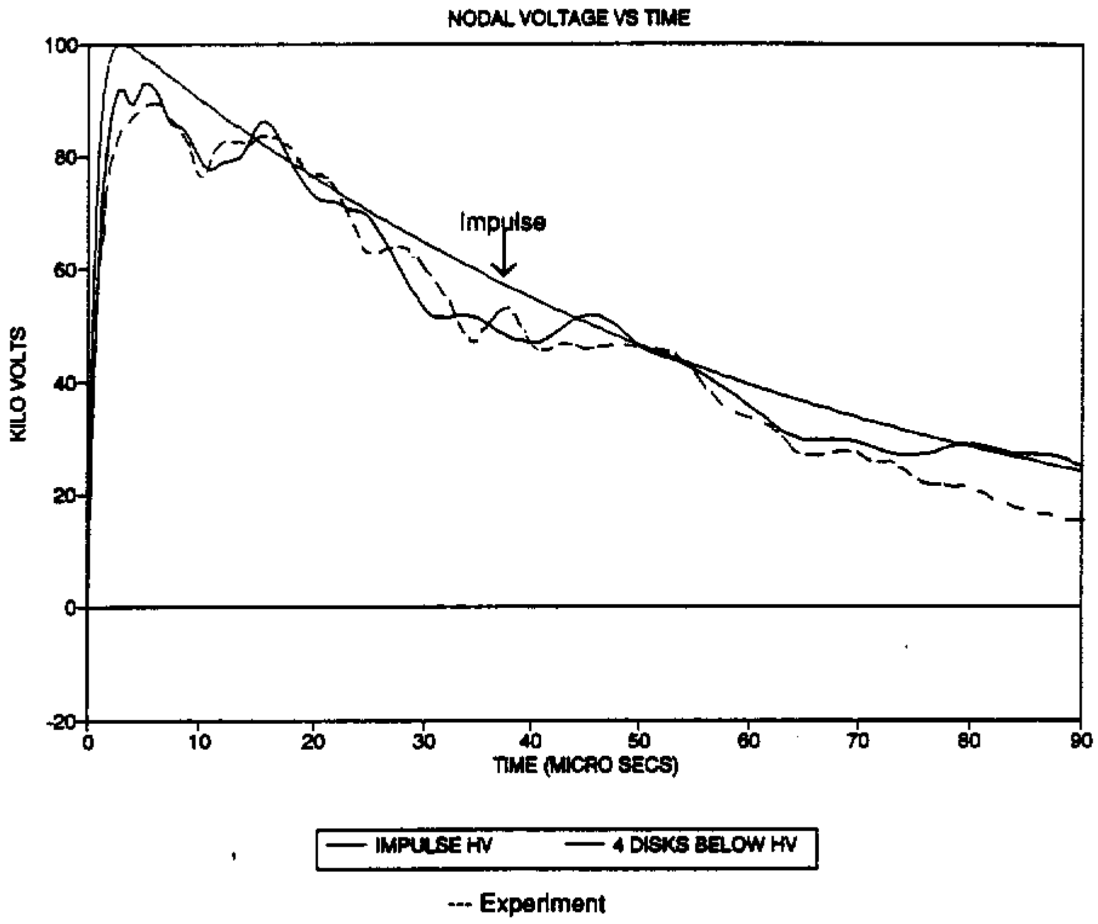
These equations are solved by means of a Runge-Kutta algorithm, which is a transient time-stepping method.

Impulse Voltage Distribution

- Comparison with Experiment Test of an Autotransformer

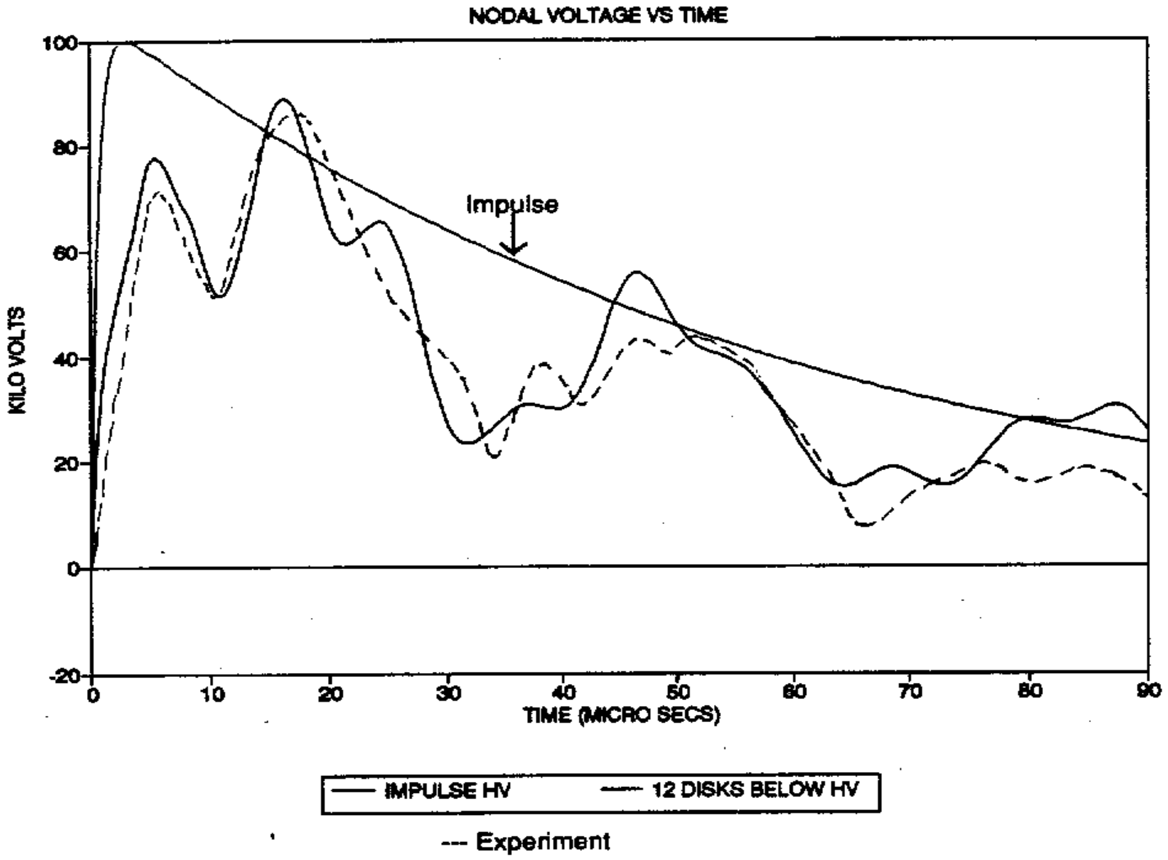


Impulse Voltage Distribution



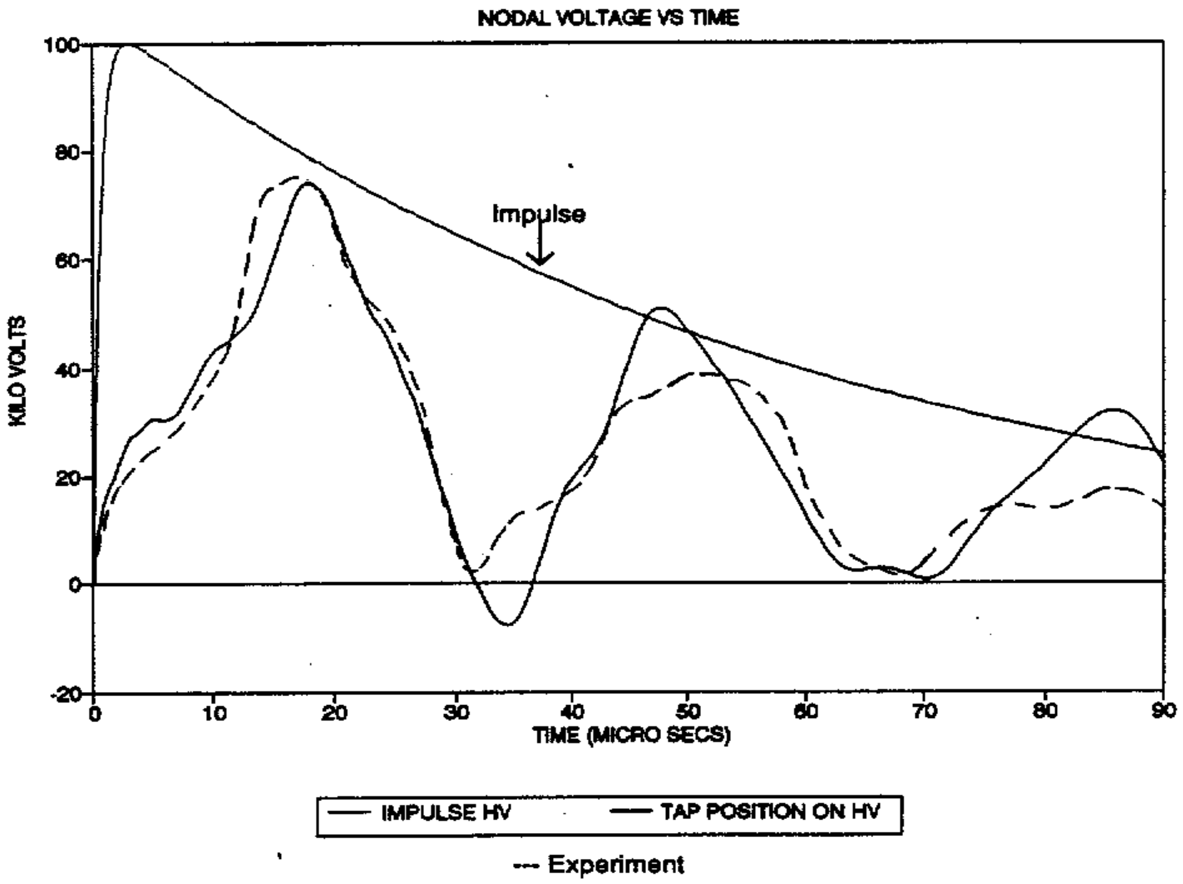
- 4 Disks Below the HV impulsed Terminal. Calculated vs measured Voltages to ground.
- The Voltage distribution was measured before tanking with a VD (RSO) test using recurring <100 V impulse waves.

Impulse Voltage Distribution



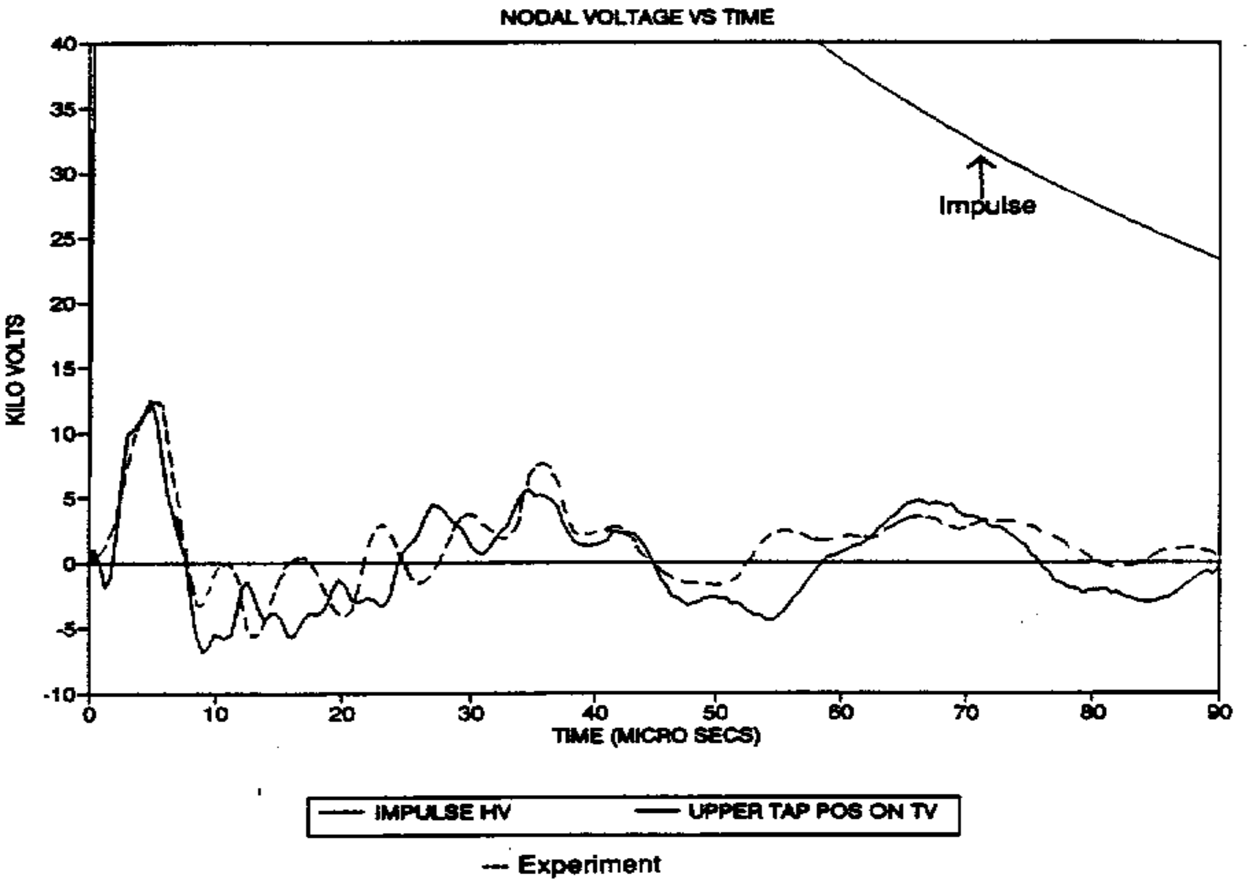
- 12 Disks Below the HV Impulsed Terminal
- Calculated vs measured Voltages to ground

Impulse Voltage Distribution



- Tap Position on the HV Winding, about 30 Disks below the Impulsed Terminal. Measured vs Calculated Voltages

Experimental and Calculated Voltages to Ground



- Center of the upper tap position on the TV Winding
- Calculated vs Measured Voltage

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