Prospects for Novel Detection of Water Trees or Other Cable Faults

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EECS Dept and Berkeley Sensor & Actuator Center (BSAC)

Technology Team Goals

To assess cable integrity from in-service or out-of-service measurements involving **small sensors** that require minimal disturbance of the cable,

or using **transmission lines** that are adjacent or integral to the power cable that require minimal disturbance of the cable and distribution circuits.

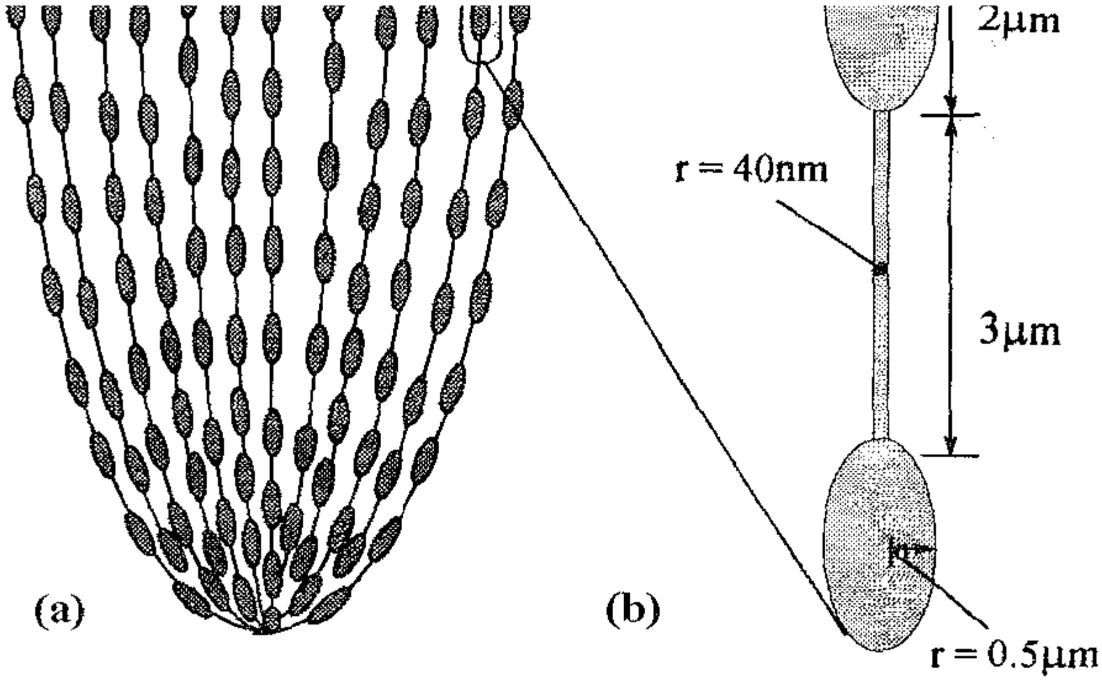
Roadmap

1. Proposed Model of Water Treeing Leading to Nonlinearity (Hvidsten *et al*.)
2. Nonlinearity as Function of Applied Voltage
3. Five Proposed Methods for Cable Assessment
4. Proposed Experiments and Analysis
5. Swedish Group's Approach
6. Conclusions, and Questions *from* You
7. Questions *for* You

1. Water Tree Mechanism Leading to Nonlinearity

(Hvidsten et al., *IEEE Trans. Dielectrics and Electrical Insulation* 5(5) 754-760, October 1999)

1. At low applied voltage the water treed region is characterized by micro-voids partially filled with water and separated by nanometer-sized channels
2. Increasing the test voltage will result in Maxwell mechanical stresses strong enough to elongate the water droplets
3. This causes crazes in insulator to open up and water to penetrate into the crazing zones
4. Thus, electrical contact will be established between the enclosed water droplets, **subsequently resulting in higher permittivity and electric loss**



Simplified sketch of water-treed region with elipsoidally shaped cavities (1 micron minor diameter) forming a “string of pearls” interconnected by 40nm-high channels of crazed insulation

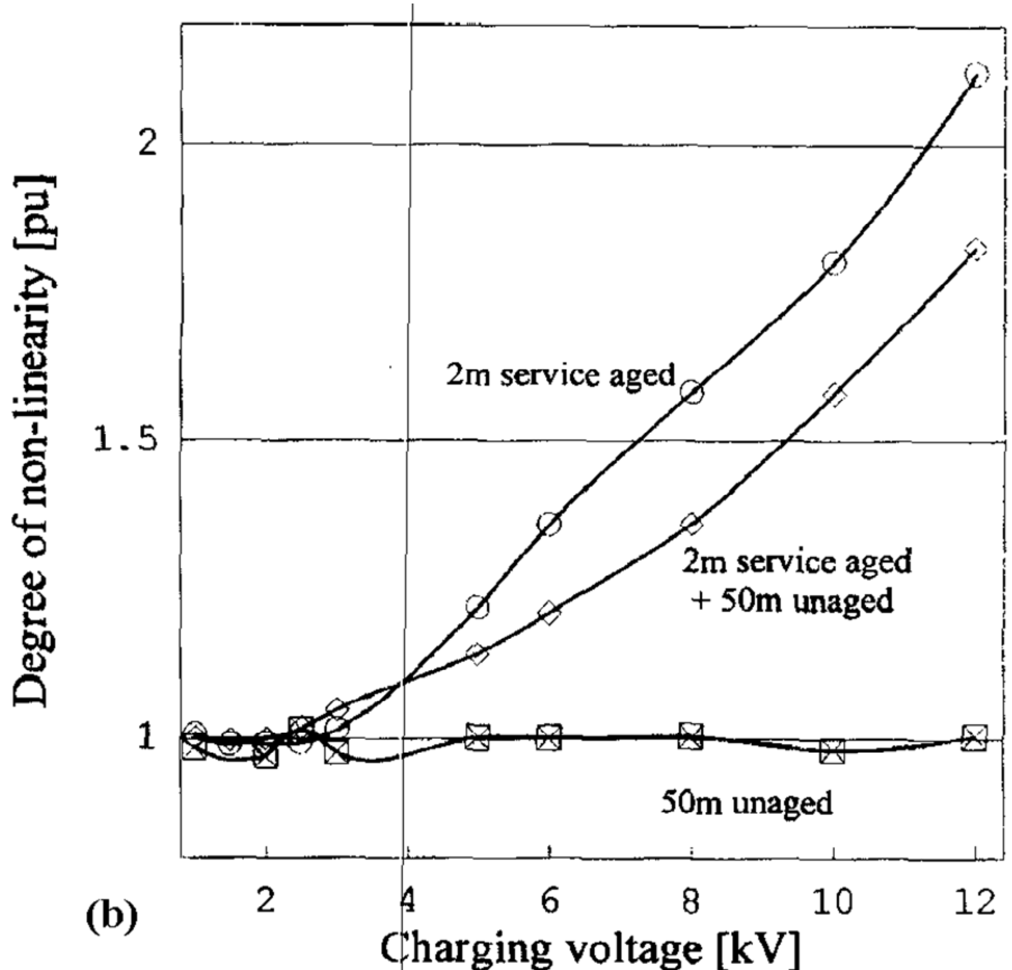
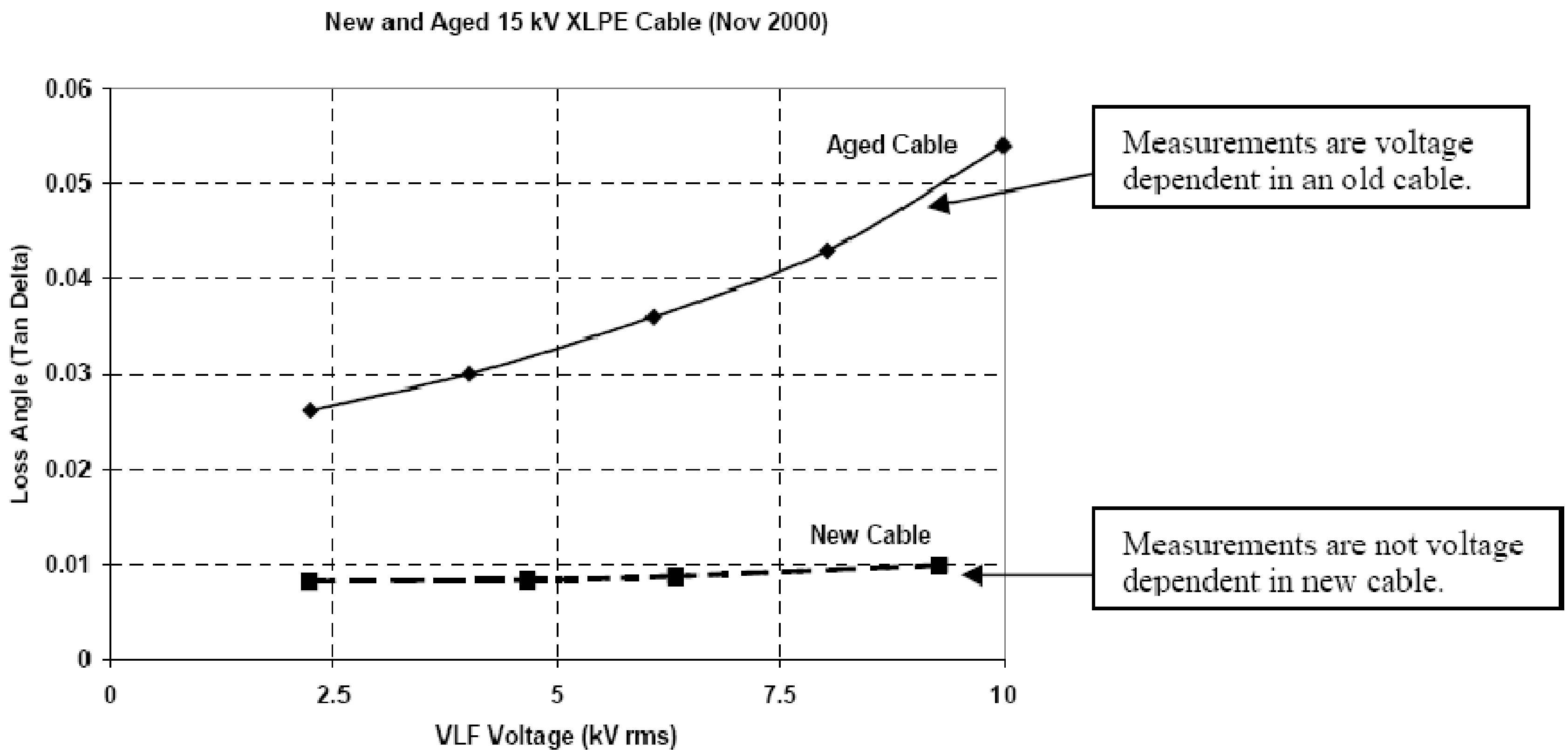


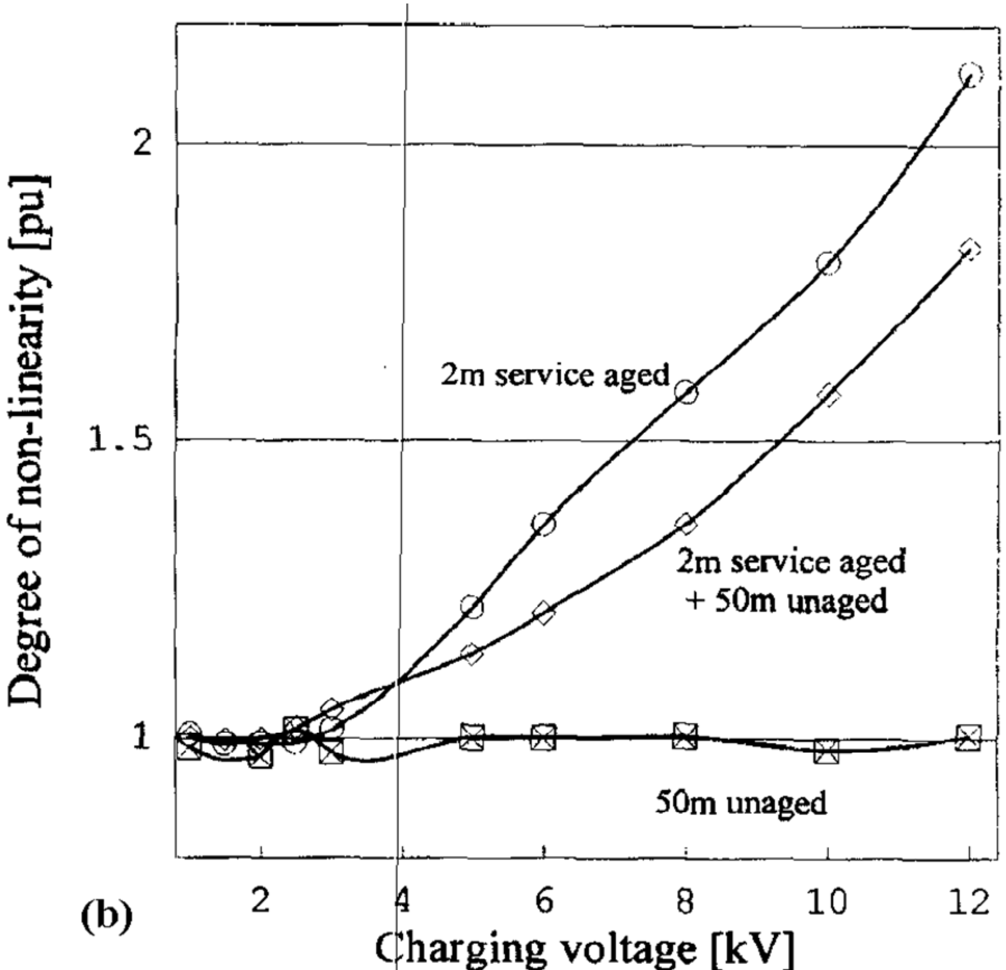
Figure 1. (a) Dielectric loss factor ($\tan\delta$) values of service and unaged XLPE 24 kV cables deduced from depolarized current measurements using Fourier transformation, and (b) degree of nonlinearity η as a function of applied voltage $\eta = \tan\delta(V) / \tan\delta|_{1kV}$ [7].

[Hvidsten et al., 1998]



Data from High Voltage Engineering, Inc.

2. Nonlinearity as Function of Applied Voltage



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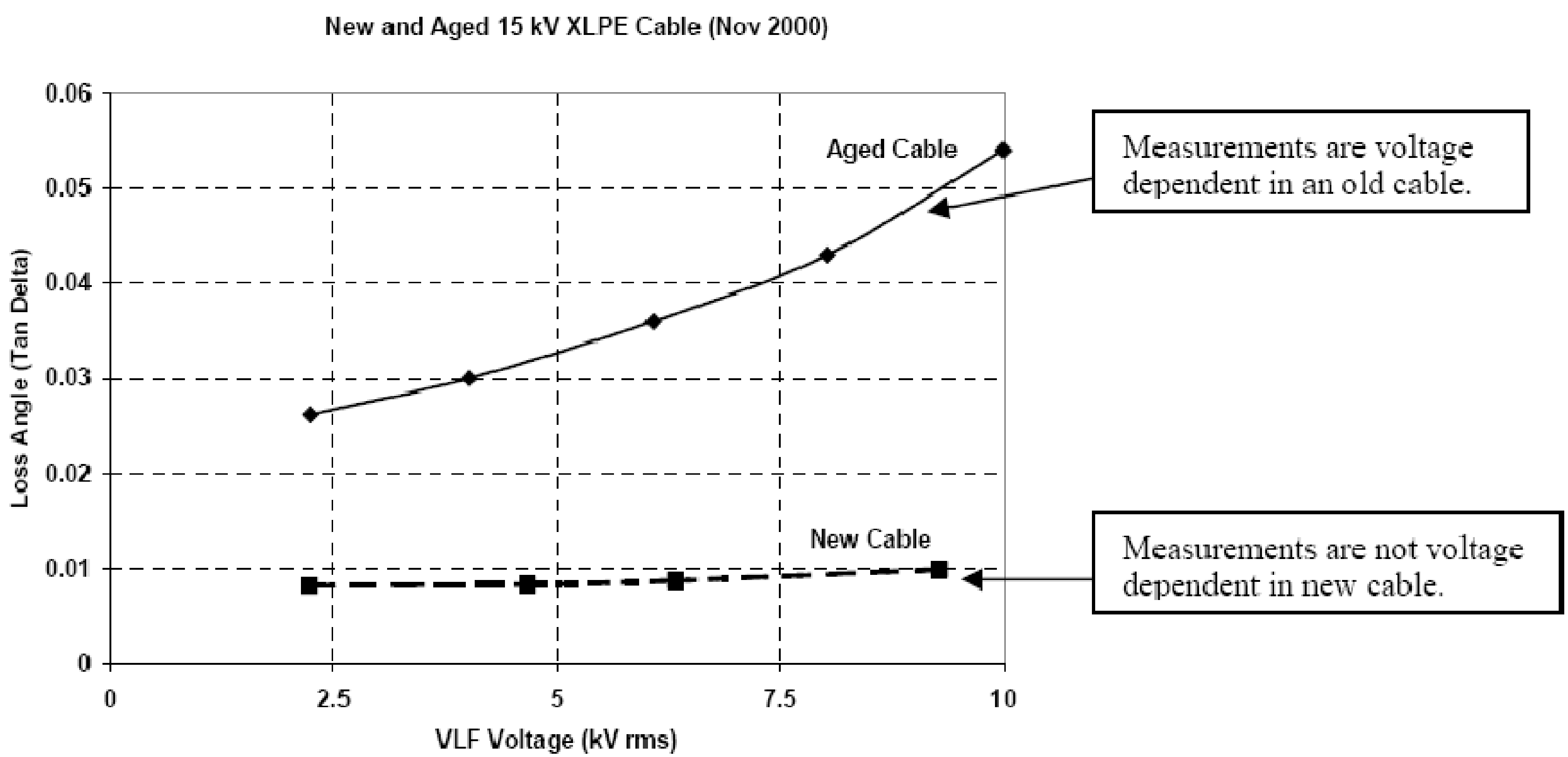

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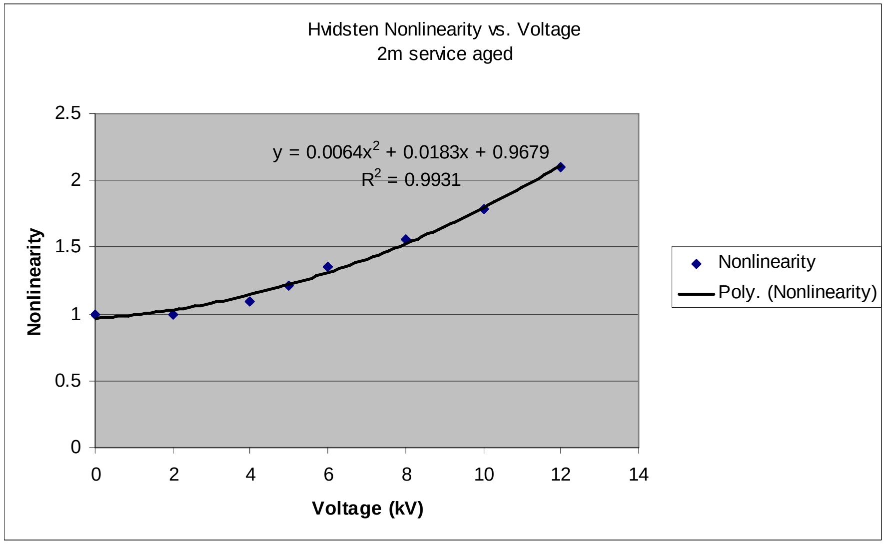

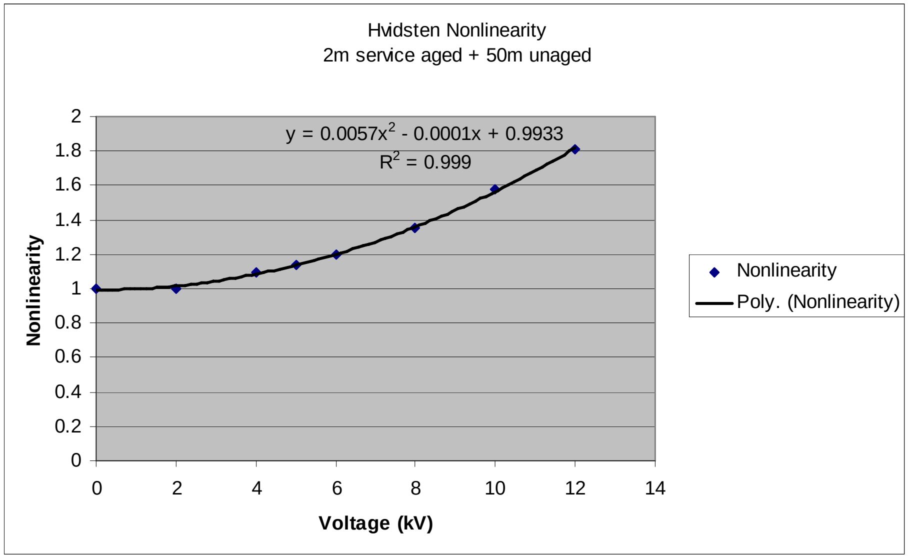

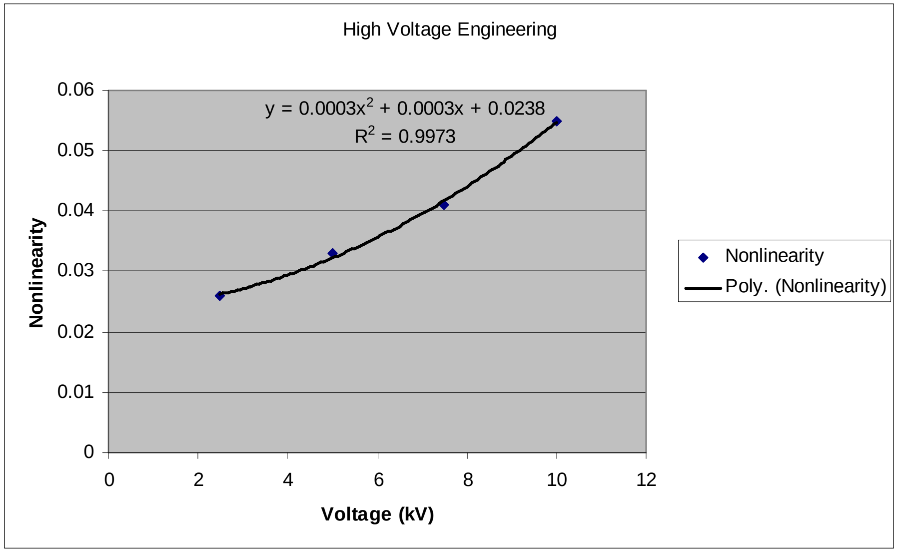

Degree of nonlinearity often defined as

$\eta(V) = \tan\delta(V) / \tan\delta(V_{reference})$

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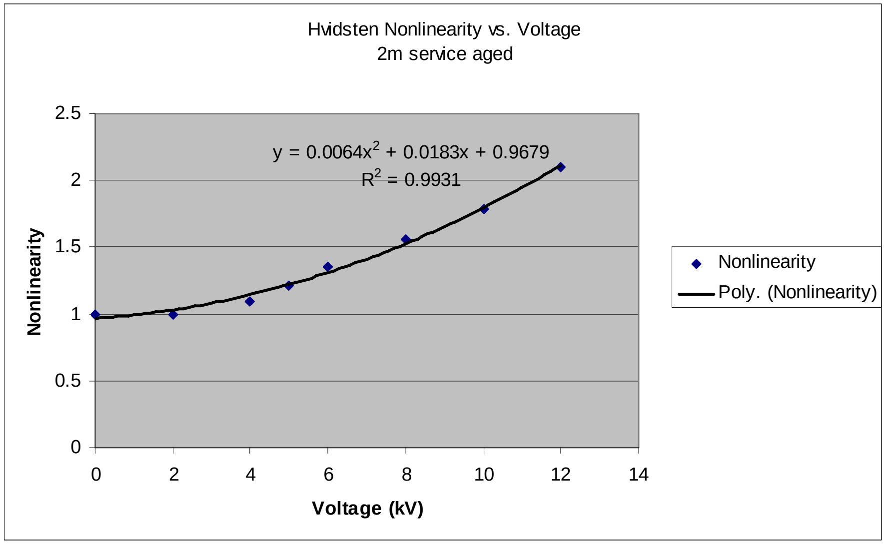
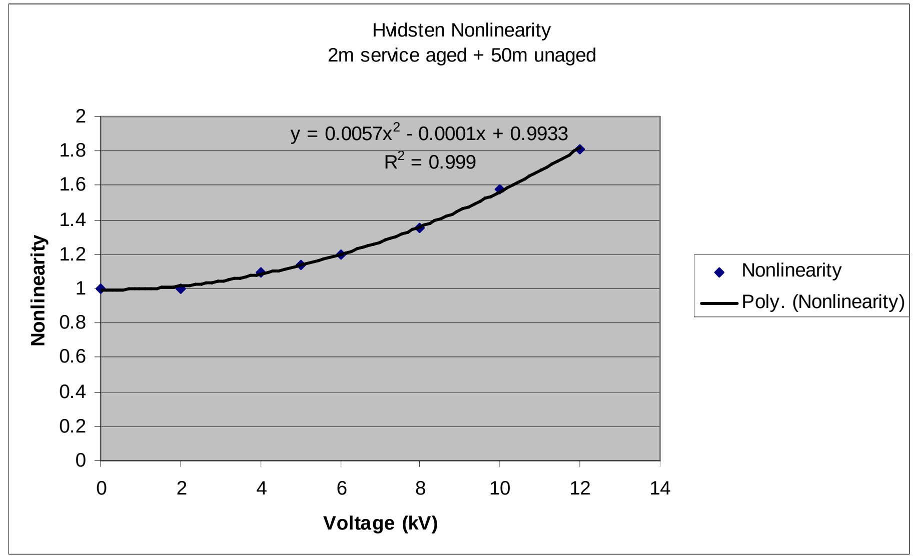
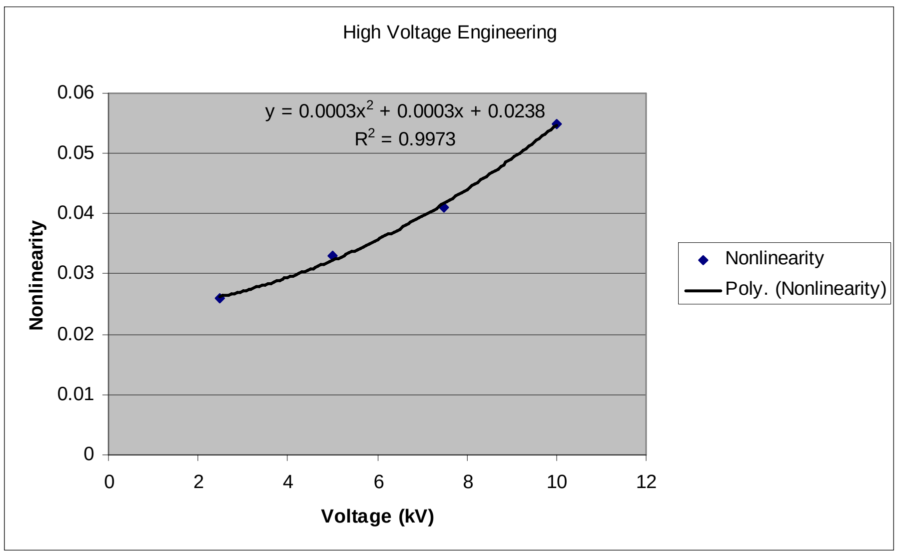
2. Nonlinearity as Function of Applied Voltage



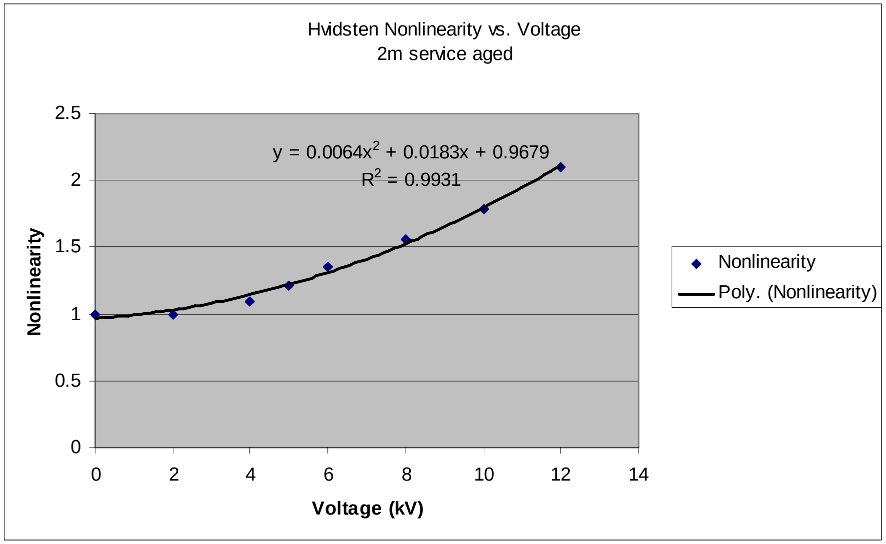


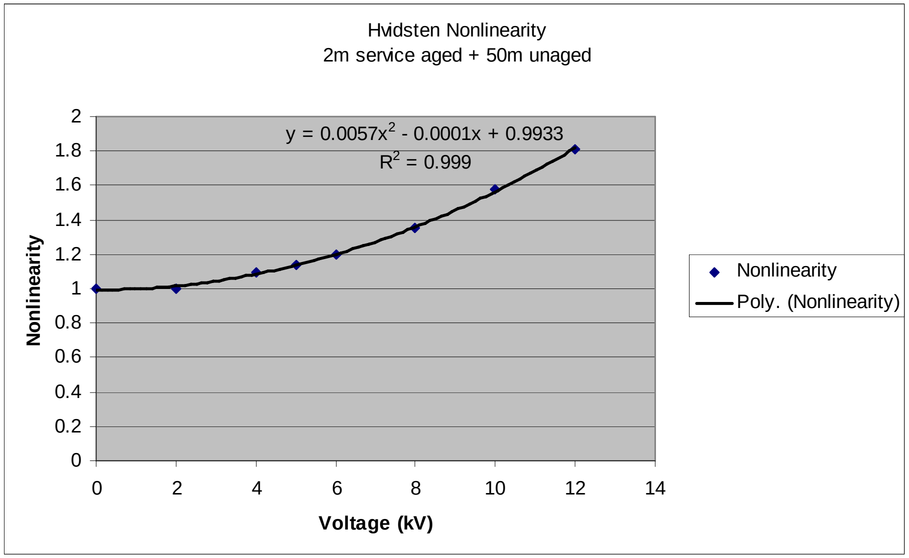


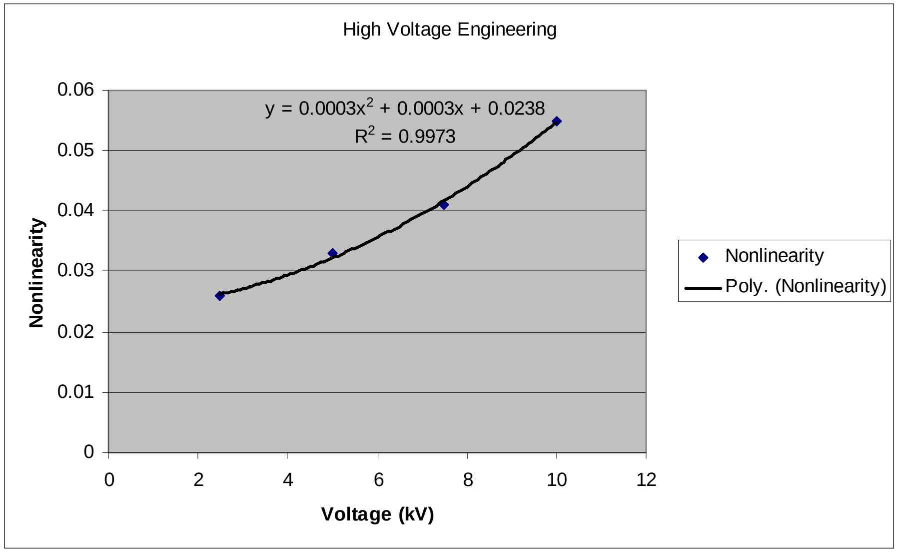
Very large R^2 values (good polynomial fits)

Nonlinearity varies essentially as voltage-squared since squared term is dominant at high voltages

2. Nonlinearity as Function of Applied Voltage







Note that electro-mechanical forces -- Maxwell stress, dielectrophoretic force -- vary as (Electric field)^2 and hence as (Voltage)^2 – coincidental or causal?

How large an increase in permittivity with voltage is there?

Could we detect it experimentally?

3. Five Methods for Studying In-Service Cables

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1. Measure, with small probe, dependence on instantaneous applied voltage of permittivity of cable insulator, and determine nonlinearity

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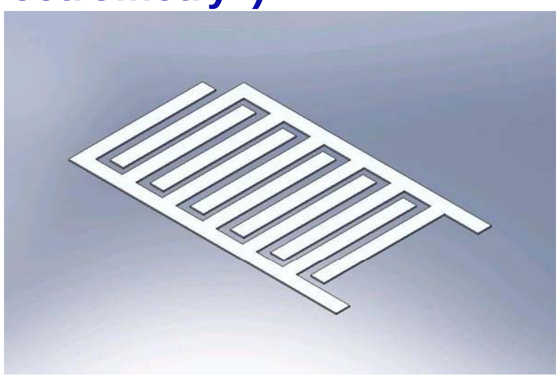
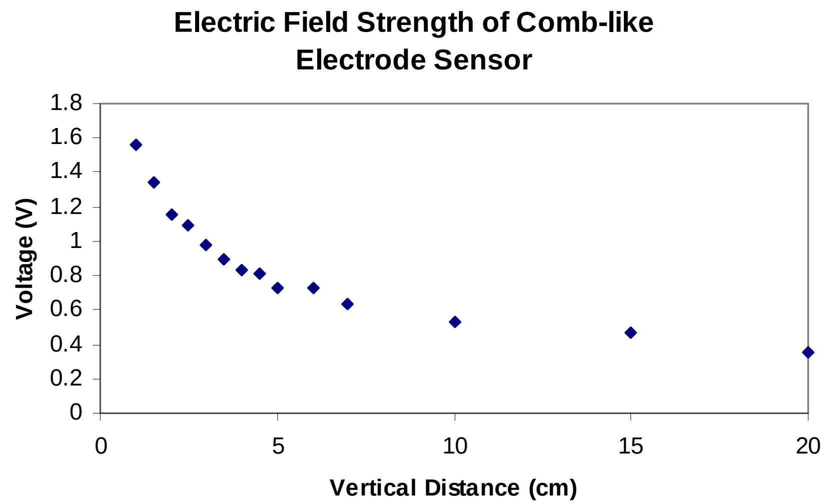
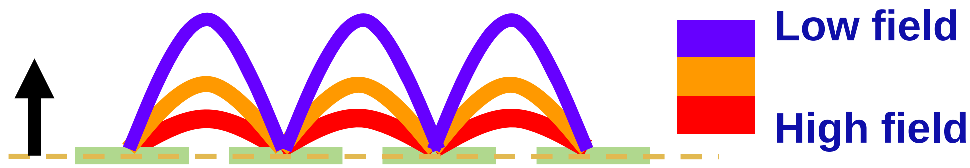
AC driven interdigitated electrodes contacting jacket between CNs produce quasi-static electric fields that penetrate dielectric to measure its permittivity ("interdigital dielectrometry")







Interdigitated electrodes beneath dielectric

Giovanni Gonzalez, Michael Seidel

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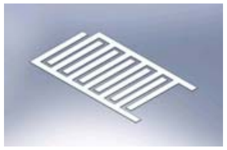
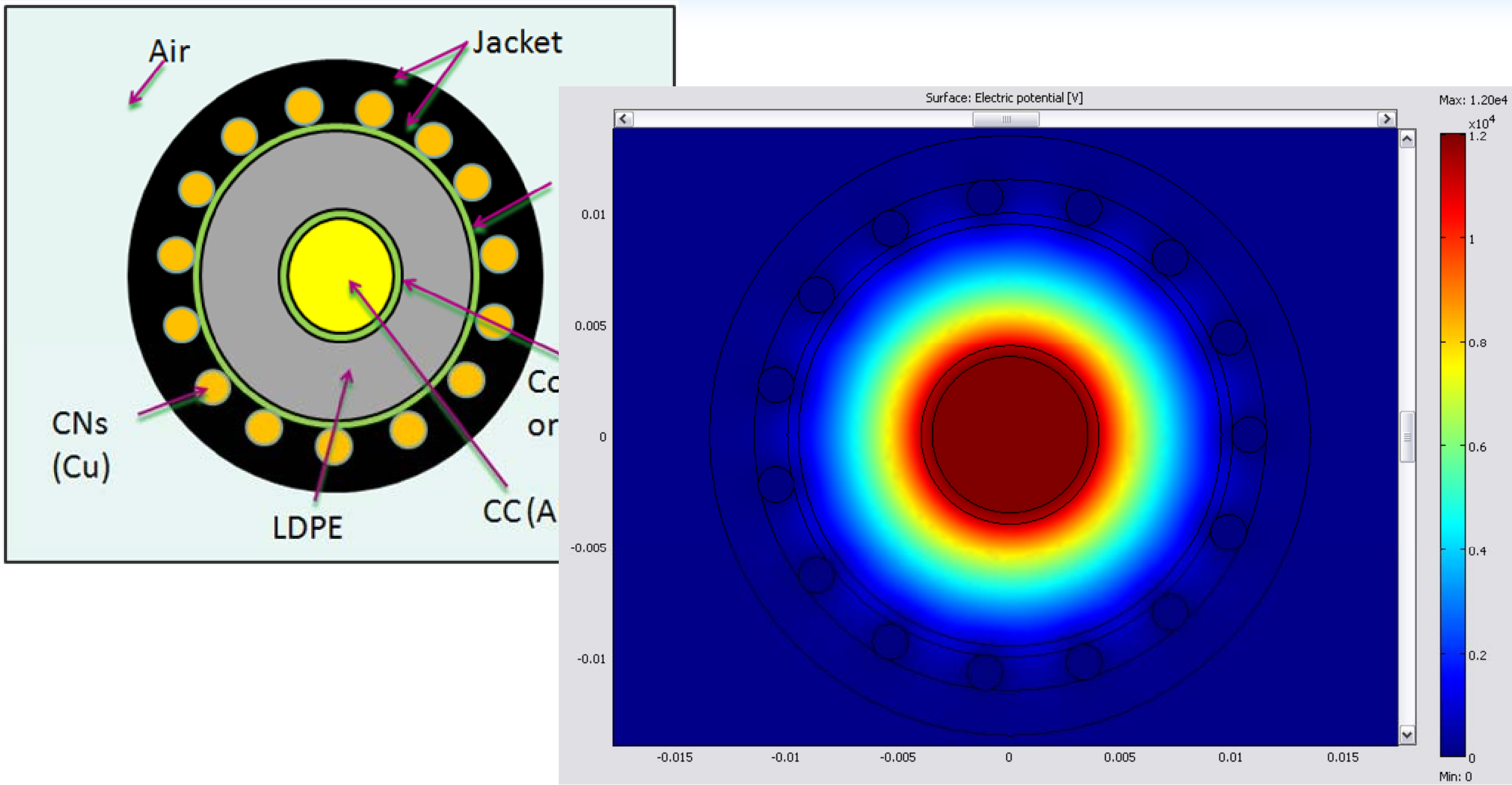


2. Probe electric fields or potentials just outside cable to infer insulator permittivity, and determine nonlinearity as applied voltage changes



COMSOL simulation (by Piero Marcolongo, Prof. Evans student) of electric potential shows substantial AC potential exists just outside jacket between adjacent concentric neutrals, and that its amplitude is affected by permittivity of insulator there. Will attempt with a properly shielded microsensor to detect this potential to measure insulator properties at different times in applied voltage cycle looking for nonlinearity.

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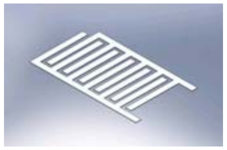

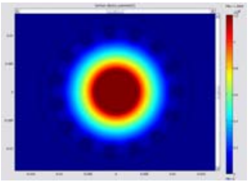

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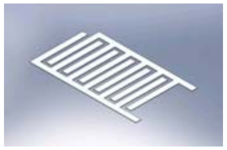

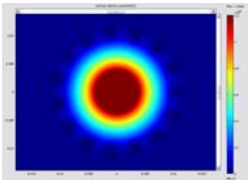

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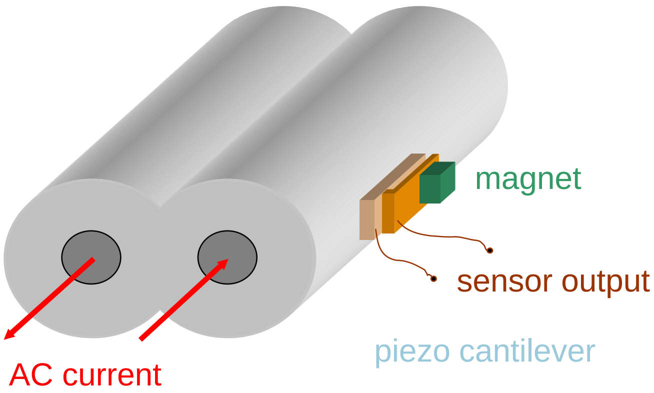

MEMS-based version of passive proximity AC current sensor. Permanent magnet couples to AC magnetic field to drive piezoelectric-coated cantilever and produce proportional AC voltage output

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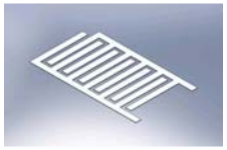

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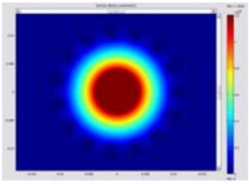

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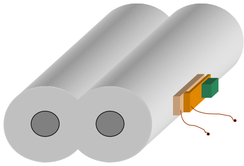

3. At cable end, measure currents in individual concentric neutrals to identify open concentric neutrals (no current) and asymmetry (detect possible degradation near concentric neutral wire)

4. Using pairs of concentric neutral wires as transmission line, from reflections and/or loss infer insulator permittivity and loss as function of instantaneous applied voltage to determine nonlinearity

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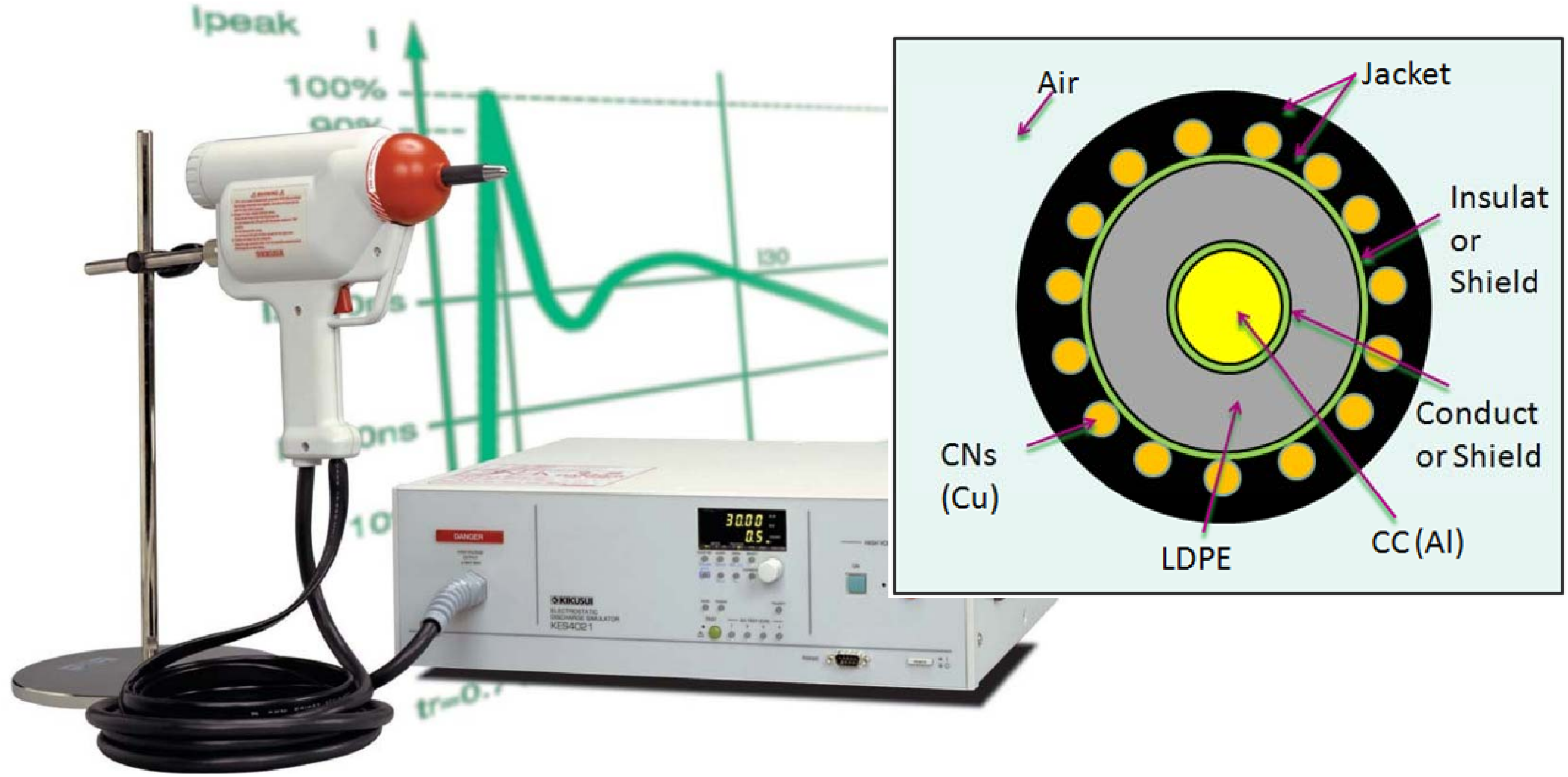

High-voltage pulsed source (electrostatic discharge tester, gift of Kikusui Corp.) might launch usable pulse through jacket non-destructively onto a concentric neutral wire transmission line. Source voltages adjustable from -30 kV to +30 kV, central spike 1 ns duration, pulse shoulder to 60 ns.

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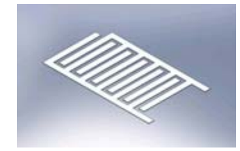

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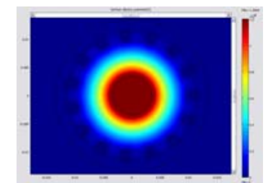

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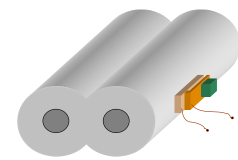

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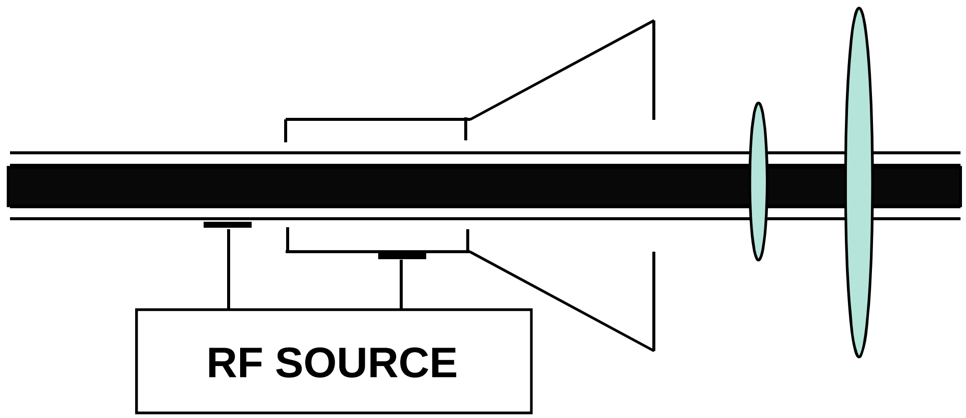

Surface wave RF transmission line with waves guided by dielectric coated conductor. Low loss at high frequencies (Goubau line). Conventional insulated distribution cable would guide it. Its propagation characteristics might be affected by dielectric nonuniformities in the cable insulator.

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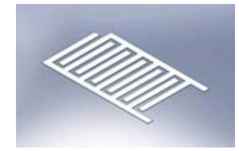

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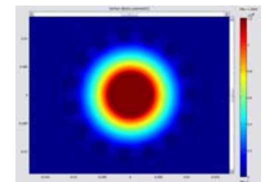

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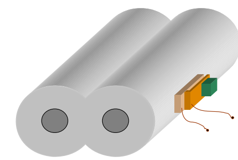

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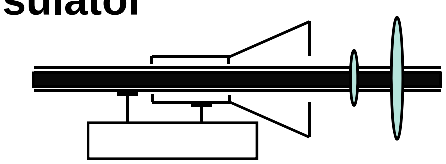
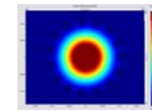


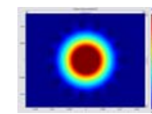
4. Planned Experiments

1. Test with standard cables our ability to measure permittivity using dielectric probes. Test ability to measure permittivity as function of applied voltage.

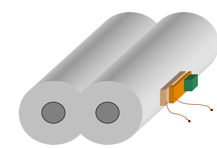
2. Test at UCB for electric fields or potentials just outside short length of new XLPE cable at up to 5 kV. Compare with simulations. Test with cable section dry and wet. Don't expect difference with new cable and at that low voltage.

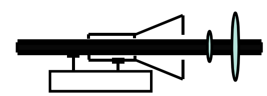


3. Test at UCB for electric fields and potentials using small sensor just outside short length of aged XLPE cable from 1970s at up to 5 kV with cable section dry and then wet. **C**ompare with simulations. Expect may see effect of moisture. Might not see nonlinearity because of relative low voltage.



4. Test short section of new cable driving currents in various concentric neutrals to determine sensitivity of available proximity current sensors. Determine how well can detect individual currents in concentric neutrals. Can one detect insulator nonuniformities?





5. Test cables at PG&E San Ramon facility at rated voltages with new and aged cables dry and wet looking for evidence of nonlinearity (exterior fields or potentials,non-uniform distributions of CN current distributions). **(ALL)**

4. (continued) Planned Analytical Studies

1. Further analysis of transmission line techniques to determine coupling of those lines to the cable's insulator and usefulness in assessing cable integrity (concentric-neutral line, surface-wave transmission line).

2. Disentangle permittivity and loss in tanδ testing to determine what components we can measure and extent of nonlinearity and its value in assessing cable integrity.

3. Analyze sensor responsivities.

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6. Swedish Group's In-Service Testing Techniques

From the literature: "On-line time domain reflectometry diagnostics of medium voltage XLPE power cables", Valentinas Dubickas, Licentiate Thesis, KTH (Kungl Tekniska Hogskolan), Stockholm, Sweden (2006), and related publications.

"On-voltage TDR": Tests performed on the cable disconnected from the grid.

"On-line TDR": Measurements performed on operating cable. Due to safety issues the cable is disconnected from the grid when the sensors are mounted; afterwards the diagnostics could be performed during several days or weeks.

(Example: measurements performed on about 2 km long, 24 kV rated, three-phase, second generation XLPE insulated power cable. Measurements performed every 2 hours over four-day measurement sequence. Look for evidence of nonlinearity as voltage-induced shift of reflection velocity at peaks of applied voltage cycle.)

Involves installation of capacitive strip sensors on the insulation screen of the cable or insertion of RF test signals on central conductor with high-voltage capacitors.

6. Conclusions

1. Seeking means for assessing integrity of (especially) in-service cables in tests with small sensors and/or transmission lines adjacent or integral to the distribution cable.

2. Focusing on nonlinearity as indicator of cable degradation

3. Five test methods described

4. Observed square-law dependence of nonlinearity on applied voltage. Explore for significance and applications.

Questions from You?

Some Questions *for* You

1. Does anyone have a sample of cable with a water tree at a known location that we could test here with our electric field or potential leakage probes, or sensors to measure currents in a nearby concentric neutral?

2. How fast can the insulator respond to voltage changes in aged cable?

3. Tan-delta testing measurement confounds change of permittivity and loss; Is there analysis or data that indicates how those two change separately?

4. Is finding open concentric neutrals a difficult or unsolved problem?

5. Are the ends of cable in vaults (for example, in sidewalks) often wet and therefore likely to contain water trees accessible for testing?

6. The Swedish group has demonstrated means for in-service cable assessment. Does that solve the cable problem?