

Power Quality Assessment via Physically Based Modeling



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PSERC Seminar
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Sakis
Meliopoulos
Georgia
Institute of
Technology
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Power Quality



Disturbances

Lightning

Switching

Power Faults

Feeder Energization inrush currents, Motor Start

Loading imbalance

Harmonics, Resonance

EMI

Impact on End User

Voltage Distortion, Sags, Swells, Outages, Imbalances, Neutral Voltage, Stray Voltages, Resonance

Design Options

Configuration

Grounding

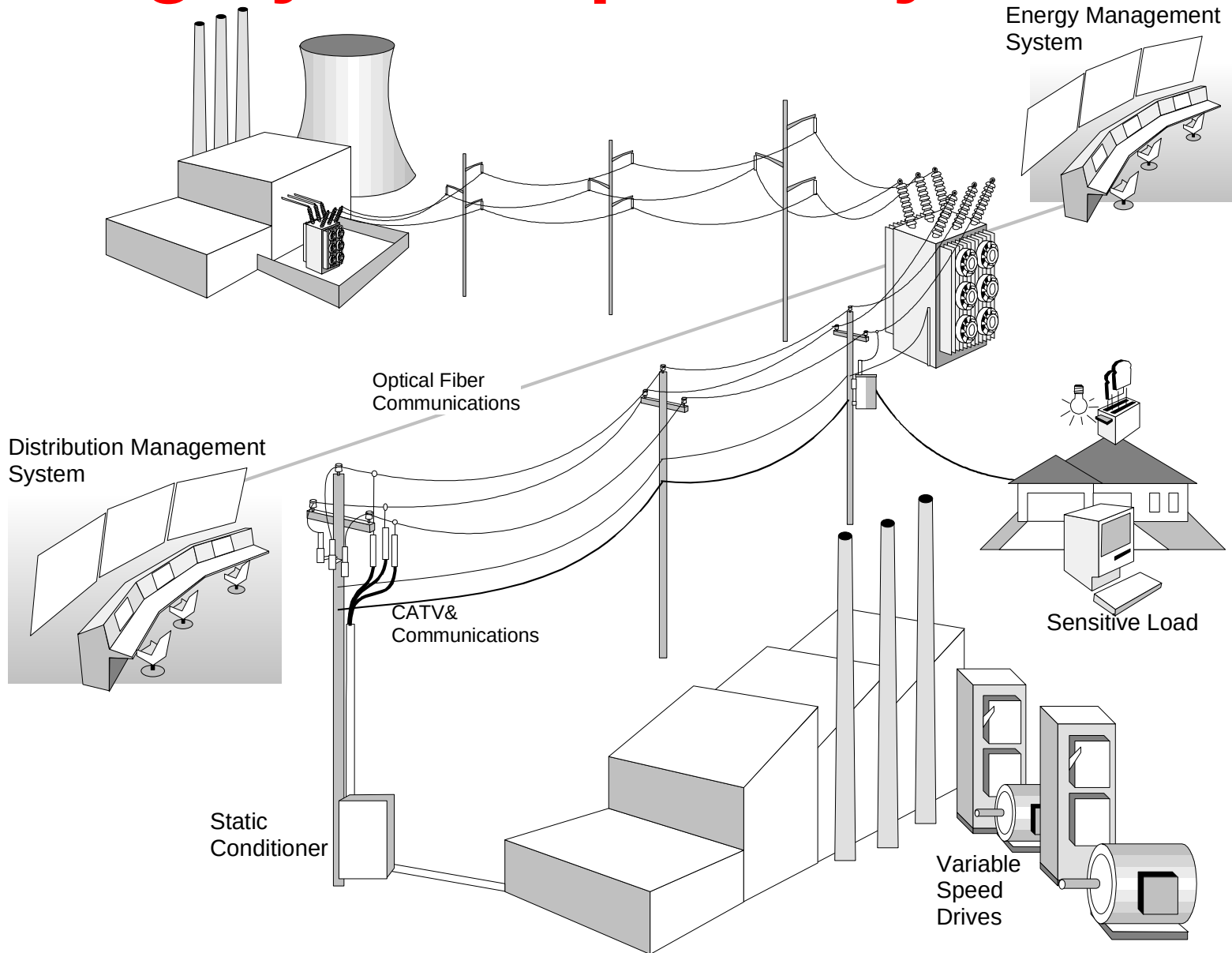
Overvoltage Protection (arresters), Fault Protection

Use of Steel/Aluminum conduit, Etc.

Highly Susceptible System



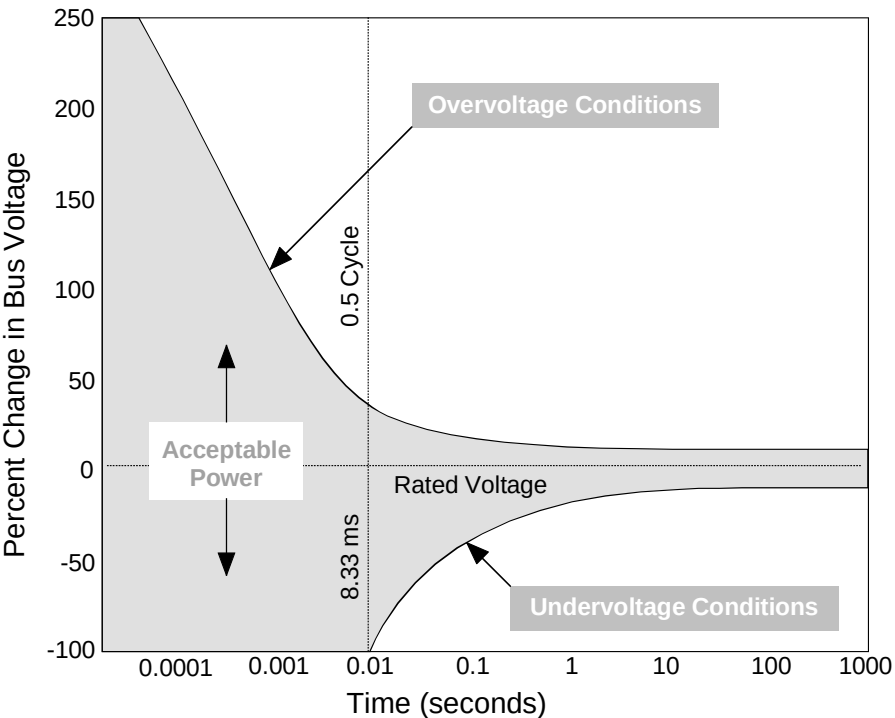
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Power Quality is Defined in Terms Of Problems at the End Use

Electric Power Quality Definition
Ability of the system to

- (a) deliver electric power service of sufficiently high quality so that the end-use equipment will operate within their design specifications and
- (b) of sufficient reliability so that the operation of end-use equipment will be continuous.



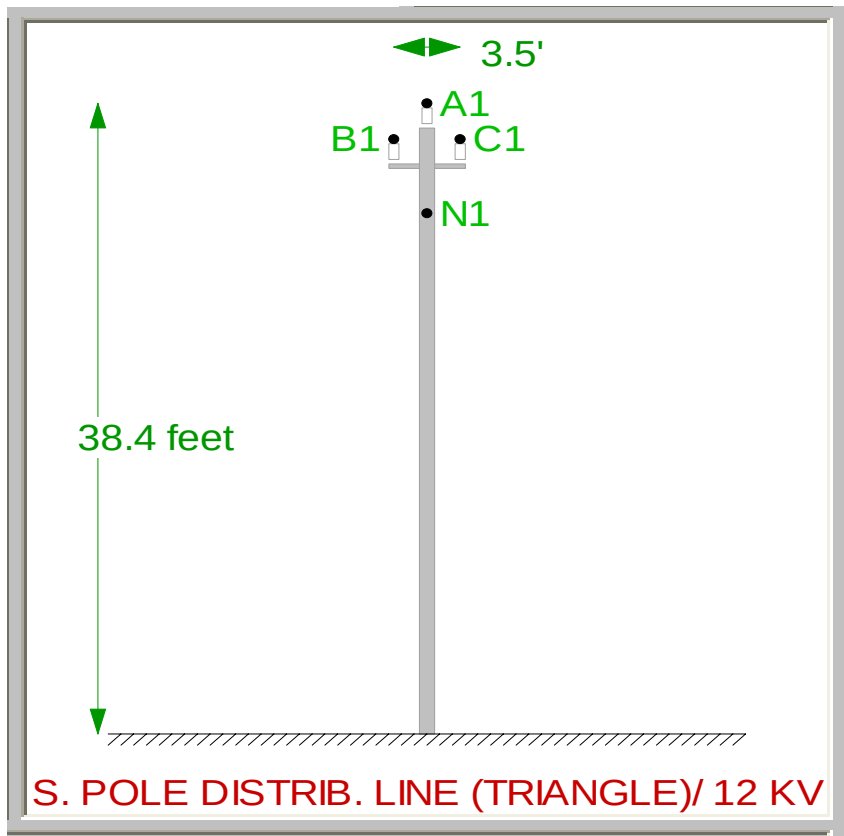
Physically Based Models

Example: Three Phase Power Line

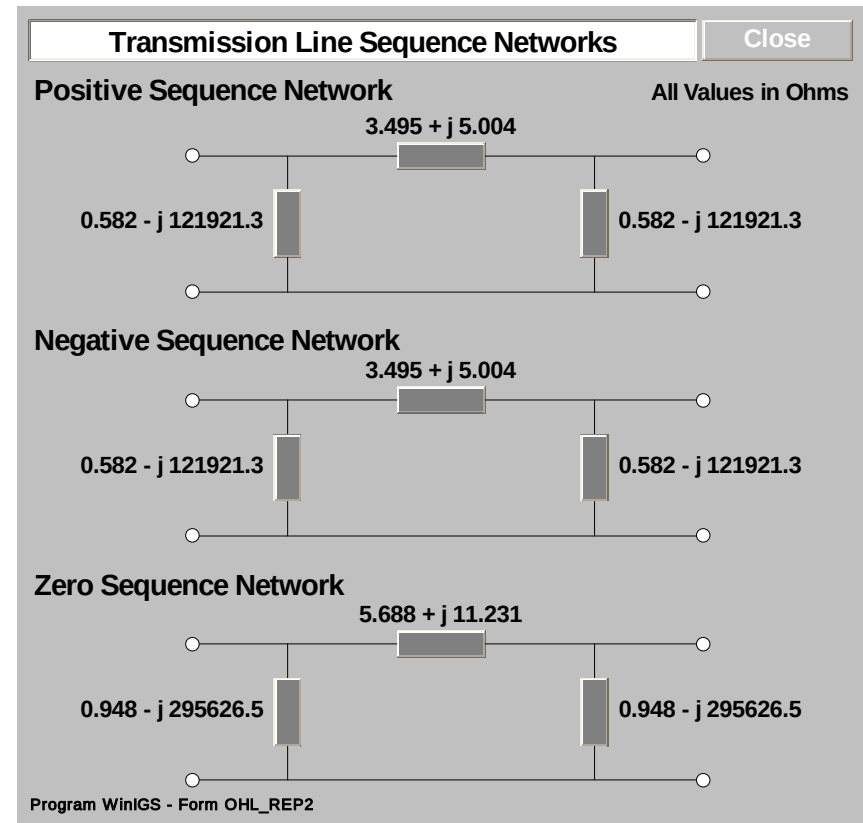


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Physically Based Model



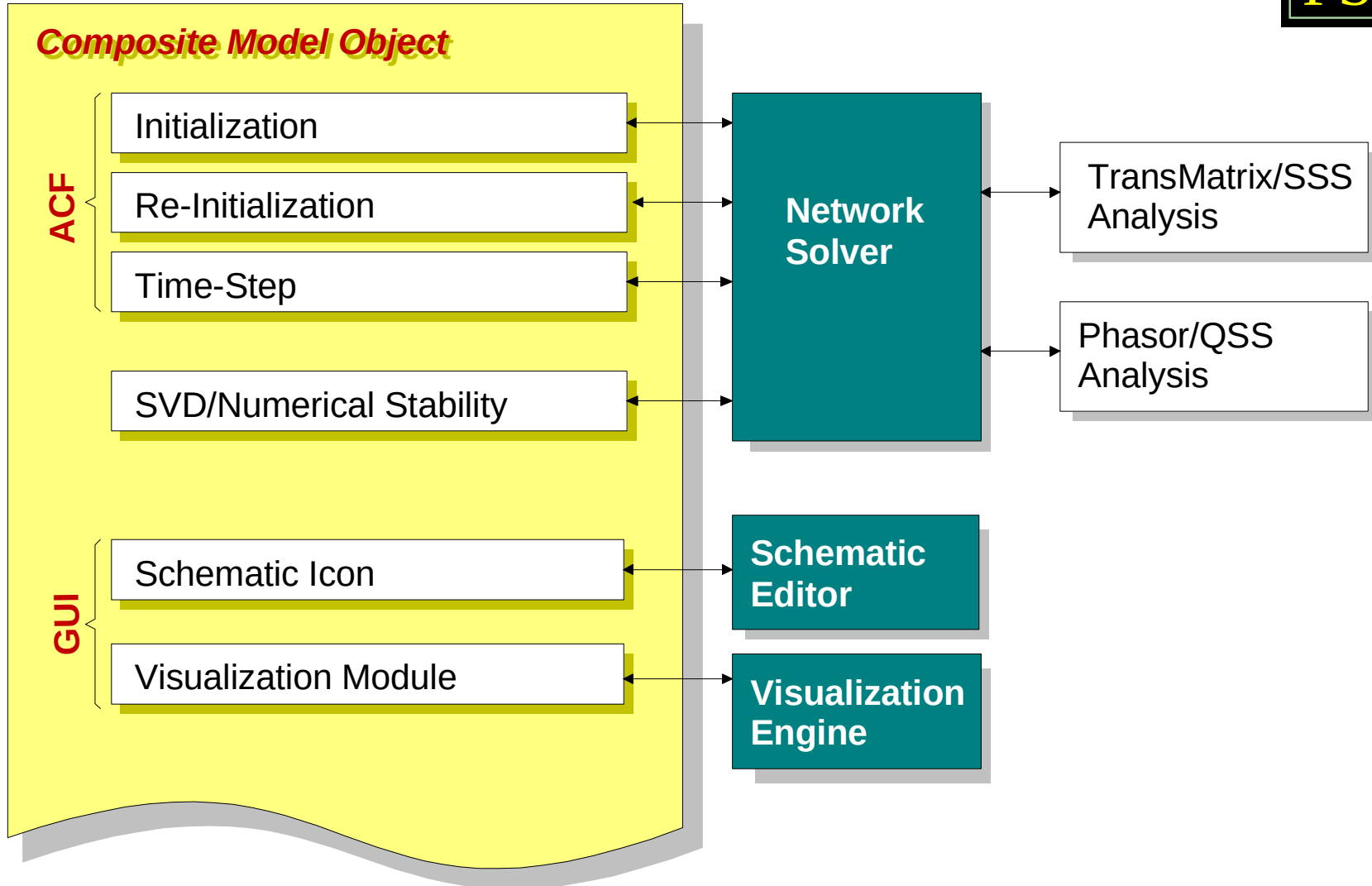
Sequence Parameter Model



Power System Simulator with “Physical” Models



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Universal Component Model Form --- ACF



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$$\begin{bmatrix} i \\ 0 \end{bmatrix} = \begin{bmatrix} f_1(\dot{v}, \dot{y}, v, y, u) \\ f_2(\dot{v}, \dot{y}, v, y, u) \end{bmatrix}$$

$$z(t) = g_0(v, y, u, t)$$

i Through Variables - Dependent Variables
 v Across Variables - External States
 y Internal State Variables
 u Controls - Independent
 $z(t)$ Observation functions

**Numerical
Integration**

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} \text{diag}(v(t), y(t))F_1 \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} \\ \text{diag}(v(t), y(t))F_2 \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} \\ \vdots \end{bmatrix} + \begin{bmatrix} b_1(t-h) \\ b_2(t-h) \end{bmatrix}$$

Simultaneous Solution - Time Interval (t-h,t)



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Component Model

$$\begin{bmatrix} i(t) \\ 0 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} \text{diag}(v(t), y(t)) F_1 \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} \\ \text{diag}(v(t), y(t)) F_2 \begin{bmatrix} v(t) \\ y(t) \end{bmatrix} \\ \vdots \end{bmatrix} + \begin{bmatrix} b_1(t-h) \\ b_2(t-h) \end{bmatrix}$$

**Connectivity
Constraints**

$$Ax(t) + \begin{bmatrix} \text{diag}(x(t)B_1(t)x(t) \\ \text{diag}(x(t)B_2(t)x(t) \\ \vdots \end{bmatrix} + b(t-h) = 0$$

**Newton's
Method**

$x(t)$

Universal Quadratic Component Model



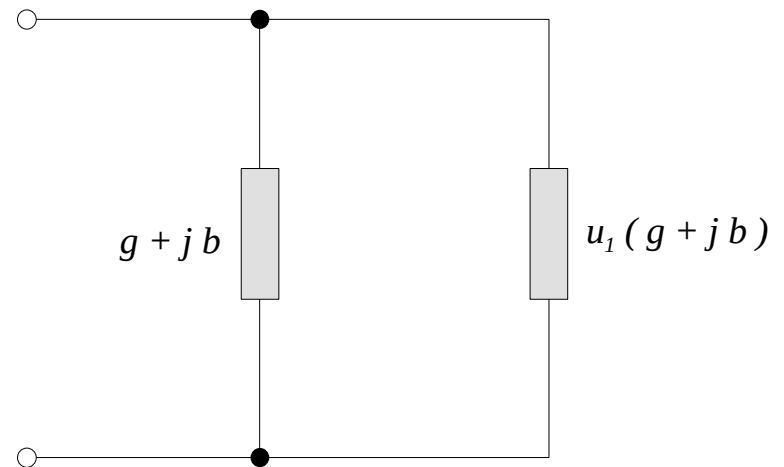
Frequency Domain Example:

Single Phase Constant Power Load

$$\tilde{I}_{dk} = (g + jb)\tilde{V}_k + u_1(g + jb)\tilde{V}_k$$

$$0 = gu_2 + gu_1u_2 - P_{dk}$$

$$0 = u_2 - V_k^2$$



Universal Quadratic Component Model



Time Domain Example:
Saturable Inductor Model

$$i(t) = i_0 \left(\frac{\lambda(t)}{\lambda_0} \right)^7$$

$$v(t) = \frac{d\lambda(t)}{dt}$$

Universal Quadratic Component Model



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Time Domain Example:

Saturable Inductor Model

$$i(t) = i_0 \left(\frac{\lambda(t)}{\lambda_0} \right)^7 \quad v(t) = \frac{d\lambda(t)}{dt}$$

$$\rightarrow i(t) = i_0 \left(\frac{\lambda(t)}{\lambda_0} \right) (y_1(t))$$

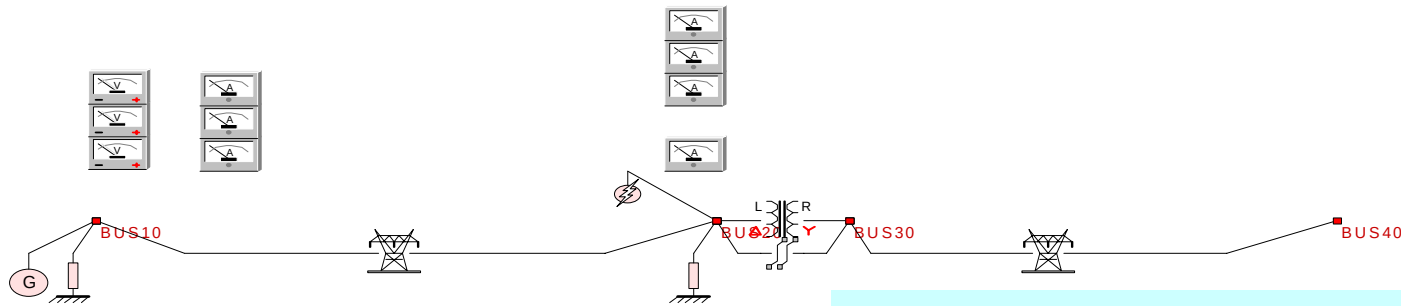
$$y_1(t) = y_2(t) \left(\frac{\lambda(t)}{\lambda_0} \right)$$

$$y_2(t) = y_3(t) \left(\frac{\lambda(t)}{\lambda_0} \right)$$

$$y_3(t) = y_4(t) \left(\frac{\lambda(t)}{\lambda_0} \right)$$

$$y_4(t) = y_5(t) \left(\frac{\lambda(t)}{\lambda_0} \right)$$

$$y_5(t) = \left(\frac{\lambda(t)}{\lambda_0} \right) \left(\frac{\lambda(t)}{\lambda_0} \right)$$



Important Issues

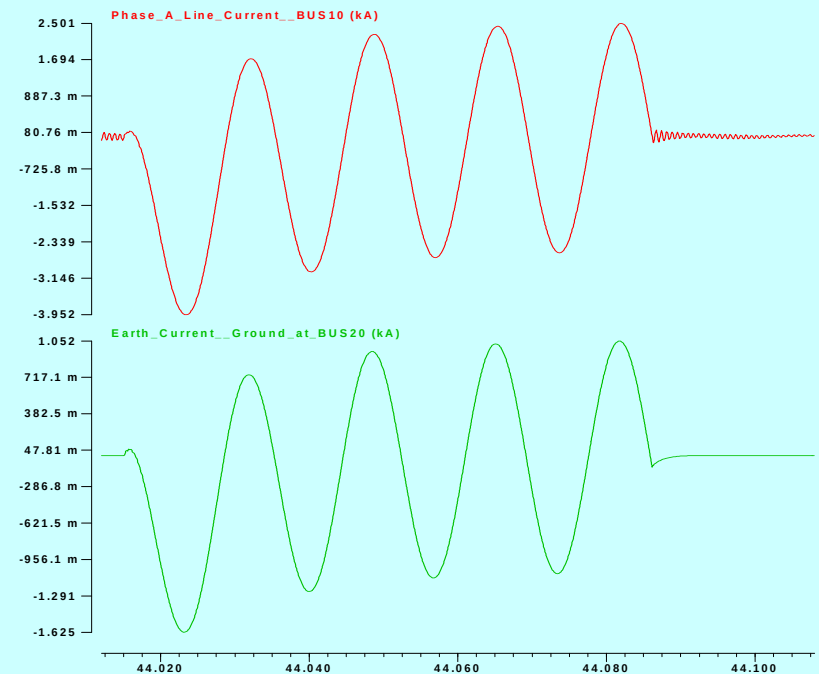
Ground Potential Rise Changes
Neutral Voltage

Customer Voltage is Proportional
To Phase to Neutral Voltage

Grounding and Bonding
Single Ground/Multi Ground
Transmission Interconnection

Program XFM - Page 1 of 1

c:\lwm\master\lg\ldata\lgpr_ex01 - May 14, 2000, 01:51:44.000000 - 200000.0 samples/sec - 24000 Samples



Grounding & Power Quality

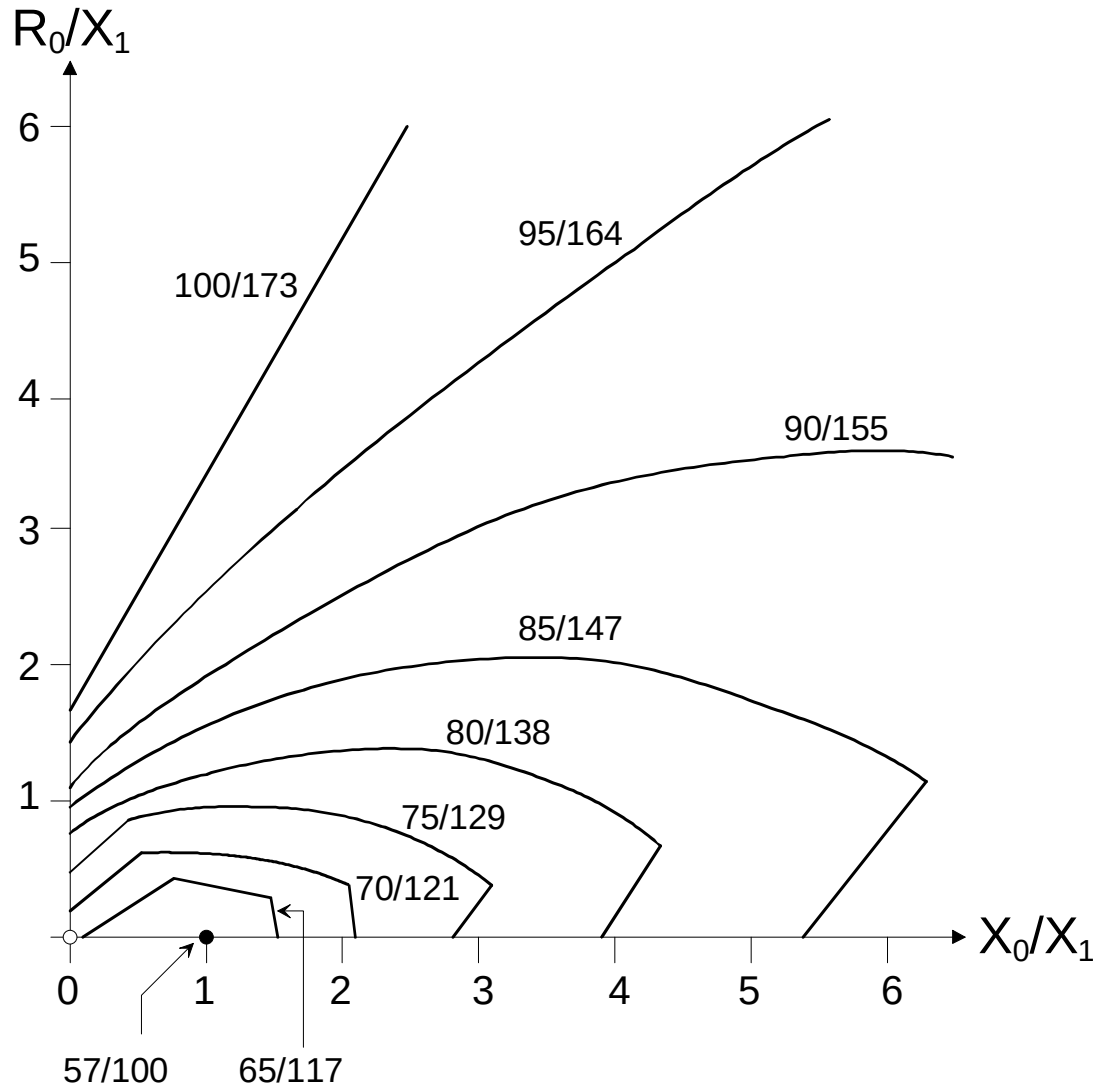
Example: Voltage Sags & Swells



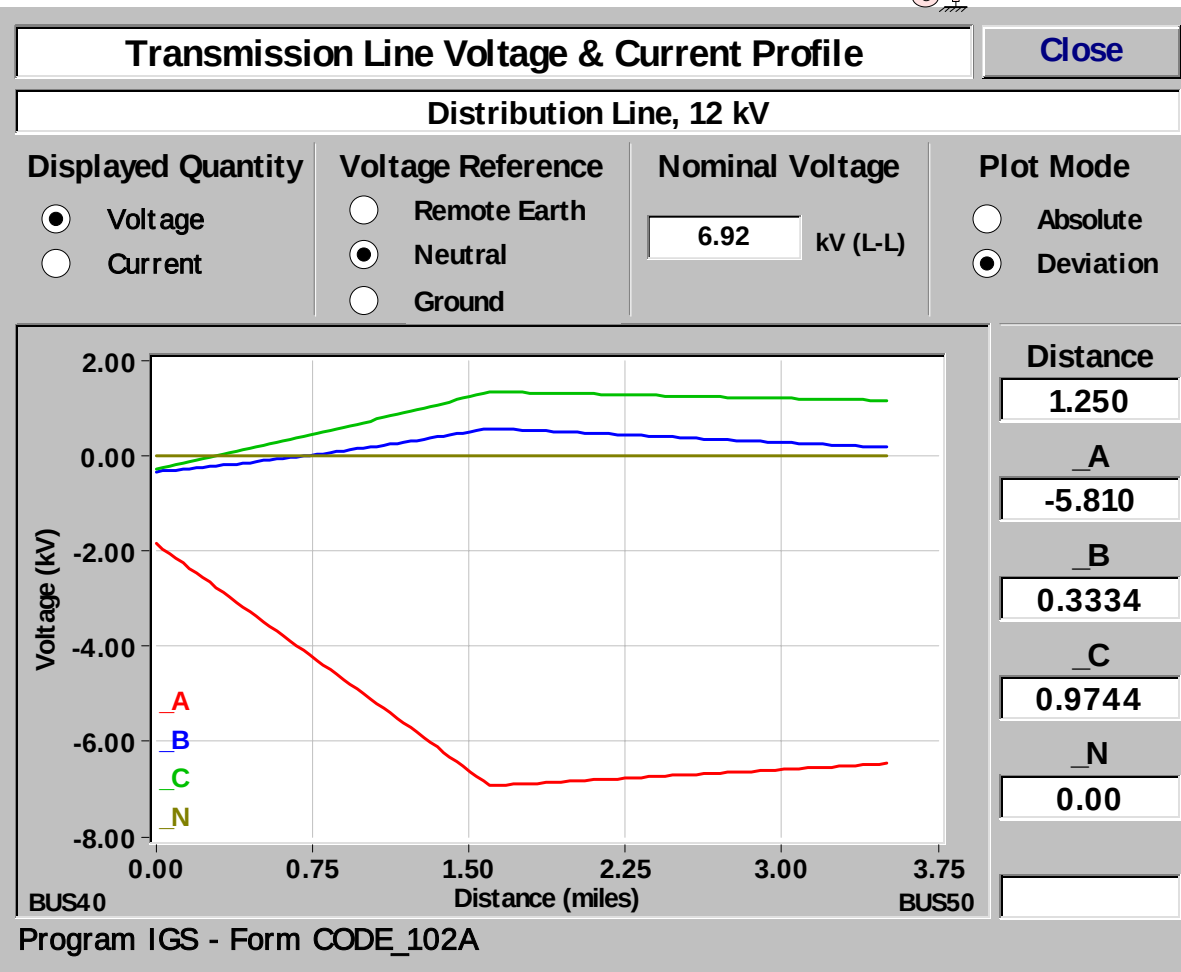
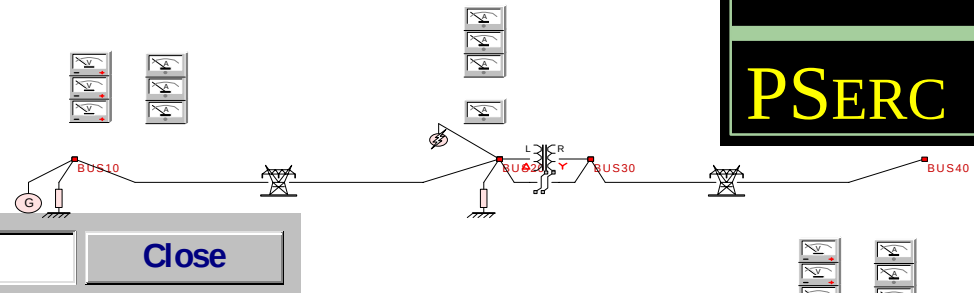
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Coefficient of
Grounding

$$C_g = \frac{V_{LG}^{actual}}{V_{LG}^{no\ min\ al}}$$



Voltage Sags & Swells During a Ground Fault



Comments

The Graph Illustrates Voltage Sags and Swells During a Phase A to Ground Fault at Mile Post 1.6 of the Line.

Data of the Figure can be used to generate nomograms and statistical distributions of voltage sags and swells for a specific location (IEEE P1346)

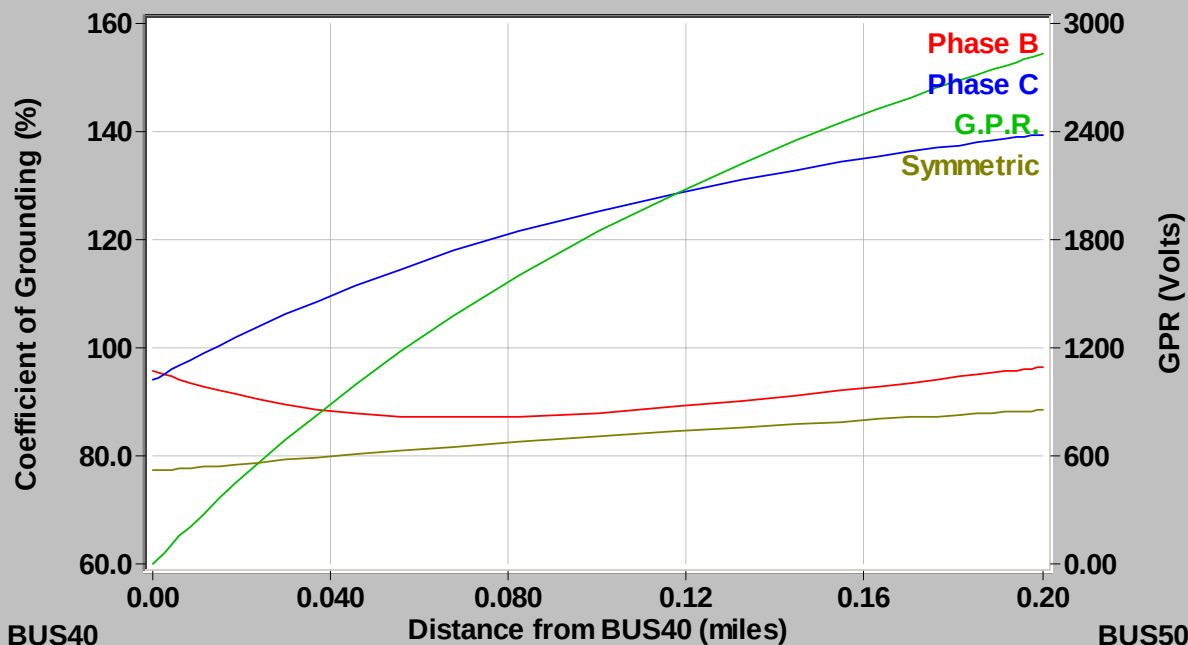
Voltage Sags and Swells Are Dependent on Design Parameters (Neutral Size, Grounds, etc.)

Coefficient of Grounding for Ground Faults Along the Line



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Coefficient of Grounding



Close

Distance

0.1000

Coefficient of
Grounding
Phase B

87.98

Coefficient of
Grounding
Phase C

125.3

GPR

1844

Symmetric Coeff.
of Grounding

83.47

Update

Comments

The Graph
Illustrates the
Coefficient of
Grounding Using
Physically Based
Modeling

Note Each Phase is
Experiencing a
Different
Overvoltage
(Symmetrical
Components Predict
Identical
Overvoltages)

Circuit

Circuit #

1

Nominal L-L Voltage (kV)

12.0

Distribution Line, 12 kV

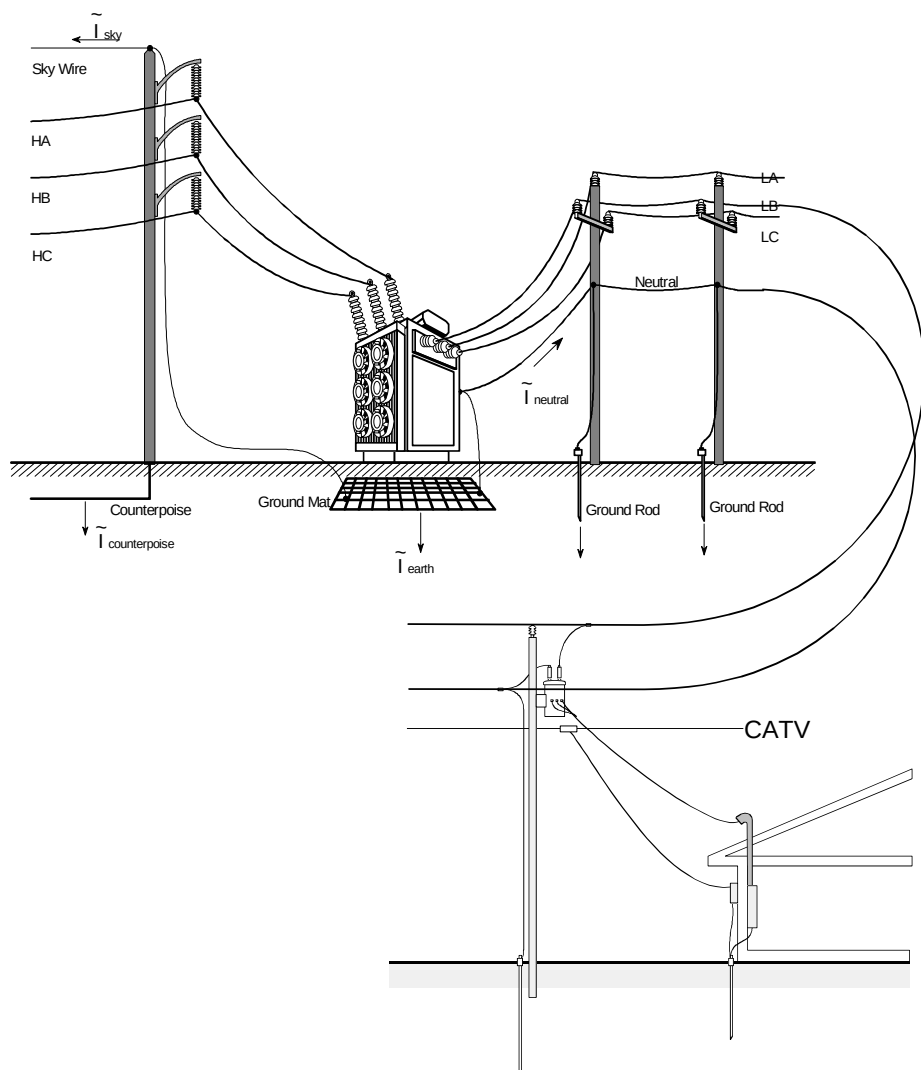
Fault Type ☒ L-N ☐ L-G

Faulted Phase ☒ A ☐ B ☐ C

Definition of Unfaulted Phase Voltage ☒ L-N ☐ L-G ☐ Absolute

Program WinIGS - Form COEF_GR

Stray Voltages and Currents



Comments

Single Phase Loads Generate Current Flow in the Parallel Path of Neutral and Soil/Grounds

Typical Distribution 50-70% in Neutral, 50-30% in Soil/Grounds

Neutral Voltage Typically 2 to 12 Volts

Properly Designed Systems can Practically Eliminate Stray Voltages and Currents



Example Parameters Affecting Stray Voltages

Case/ Neutral Point	XFMR2_N	POLE2_N	XFMRA_N	XFMR9_N	XFMR5_N	XFMR3_N
25,1/3,N,N	3.1 V	2.1 V	2.8 V	4.0 V	4.3 V	3.7 V
25,1/3,N,Y	2.2 V	1.1 V	1.9 V	3.1 V	3.4 V	2.7 V
25,1/3,Y,N	1.5 V	1.3 V	1.5 V	1.8 V	1.8 V	1.7 V
25,1/3,Y,Y	1.0 V	0.7 V	0.9 V	1.2 V	1.3 V	1.1 V
25,1/2,N,N	2.9 V	2.2 V	2.7 V	3.5 V	3.6 V	3.2 V
25,1/2,Y,N	1.9 V	1.2 V	1.7 V	2.5 V	2.7 V	2.3 V
25,1/2,N,Y	1.5 V	1.3 V	1.5 V	1.7 V	1.8 V	1.6 V
25,1/2,Y,Y	1.0 V	0.7 V	0.9 V	1.2 V	1.2 V	2.8 V
25,F,N,N	2.6 V	2.3 V	2.6 V	2.9 V	3.0 V	2.8 V
25,F,N,Y	1.6 V	1.3 V	1.5 V	1.9 V	2.0 V	1.8 V
25,F,Y,N	1.5 V	1.4 V	1.5 V	1.6 V	1.7 V	1.6 V
25,F,Y,Y	0.9 V	0.8 V	0.9 V	1.0 V	1.0 V	1.0 V

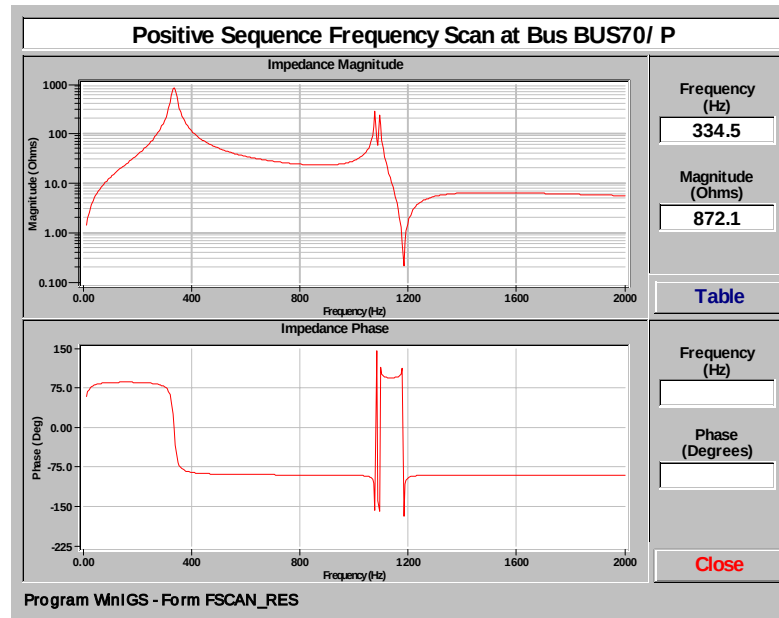
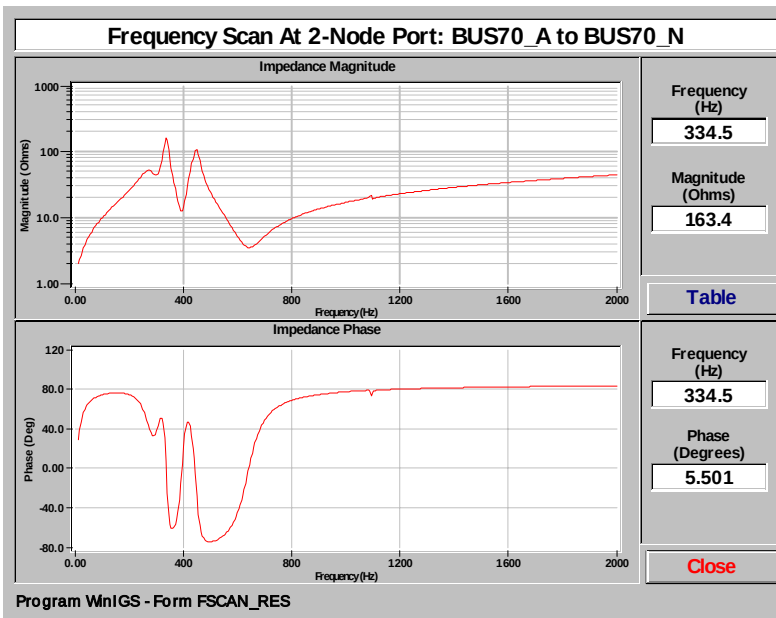
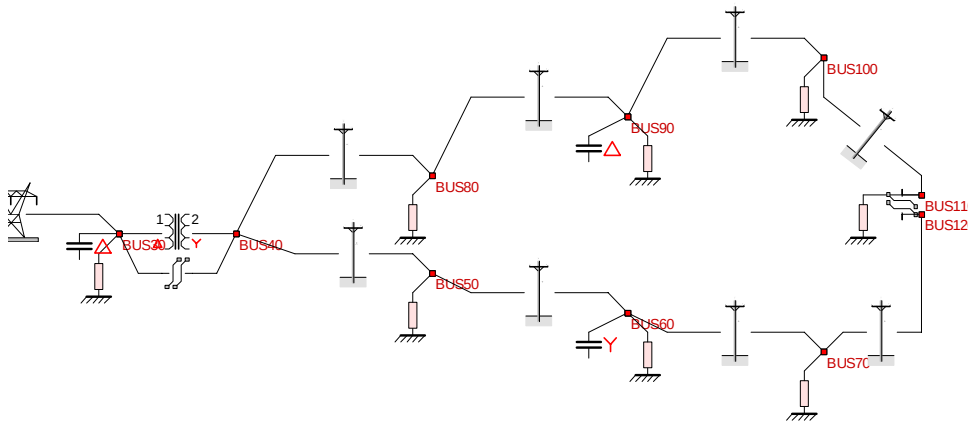
Harmonic Resonance

Comments

Harmonic Resonance Has Multiple Modes and Resonance Frequencies

System May Be Vulnerable When Resonance Coincides with a Harmonic Frequency

When Problem is Known, Solution is Very Simple - Detuning



Monte Carlo Simulation Effects Analysis



Select (at Random) a Set of Parameters

Perform Transient Analysis

Characterize “Power Quality” at Customer

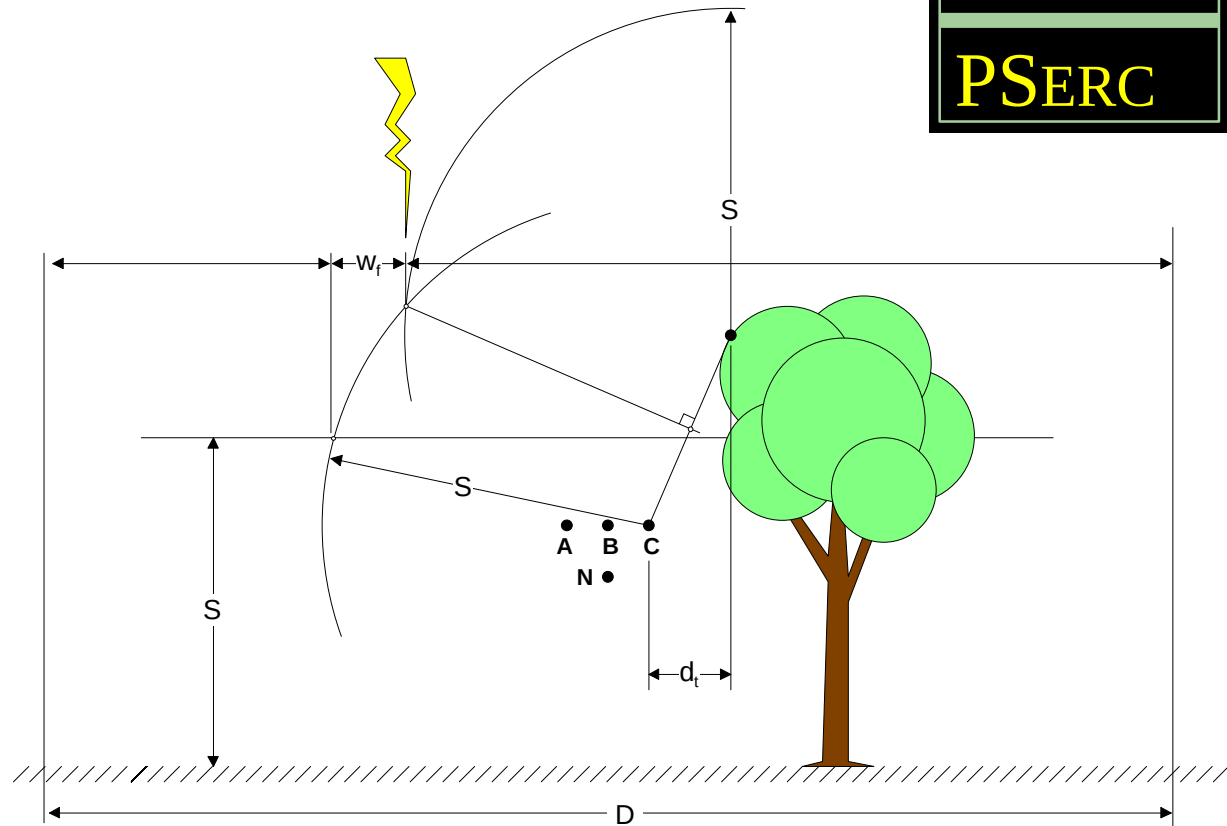
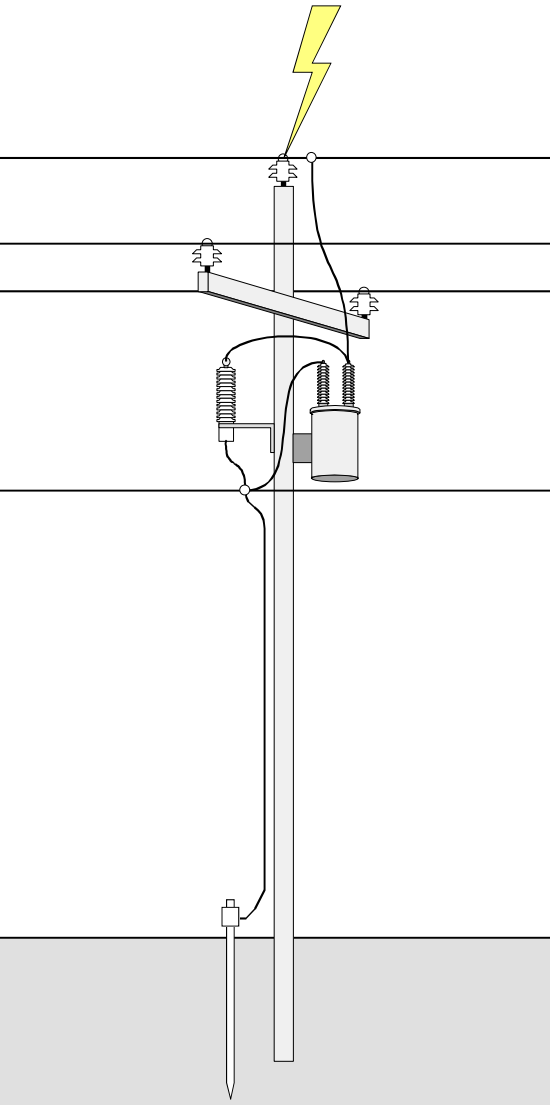
Evaluate the Effects

Repeat Process Many-Many Times

Lightning Caused Voltage Sags, Swells and Outages



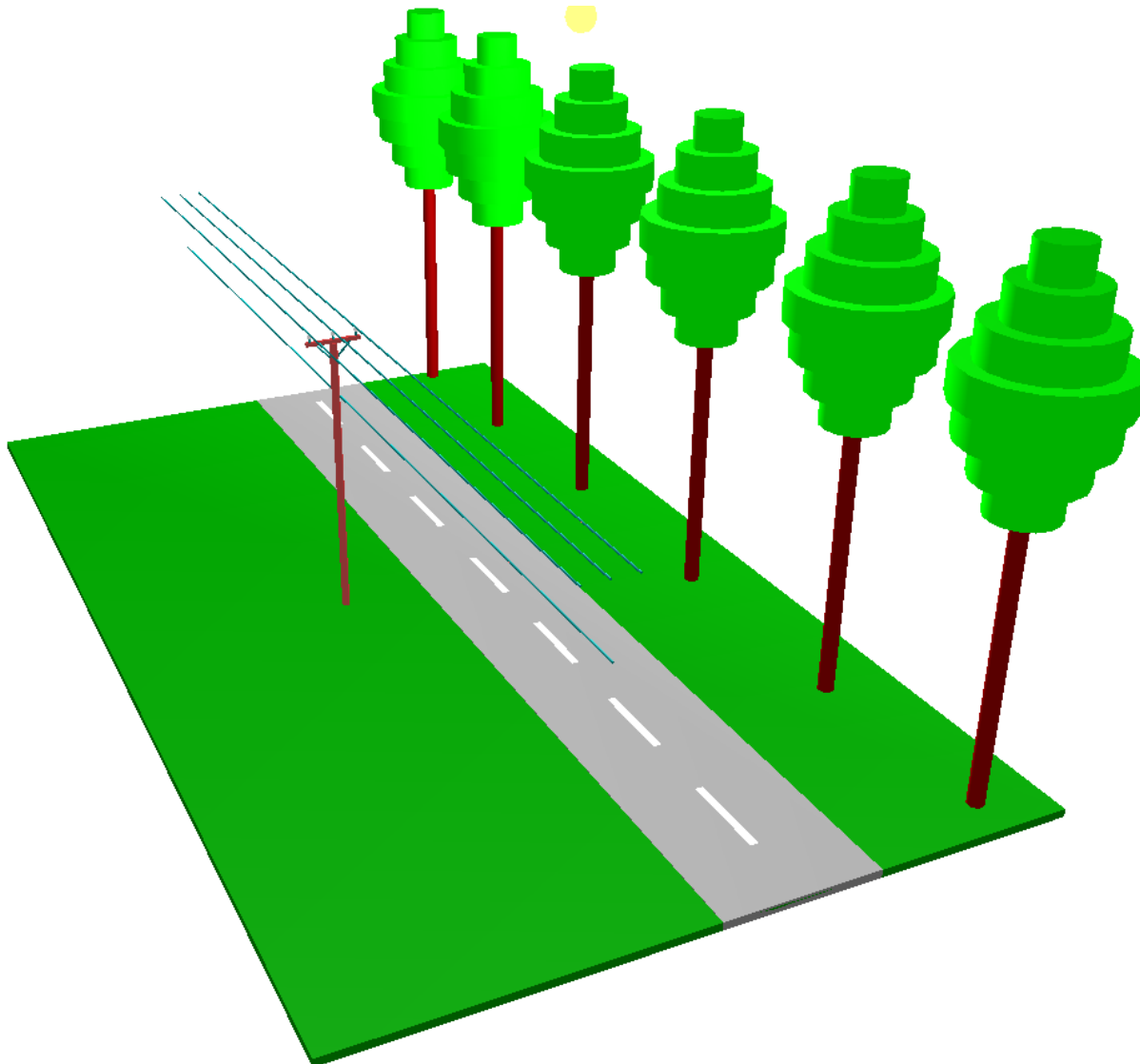
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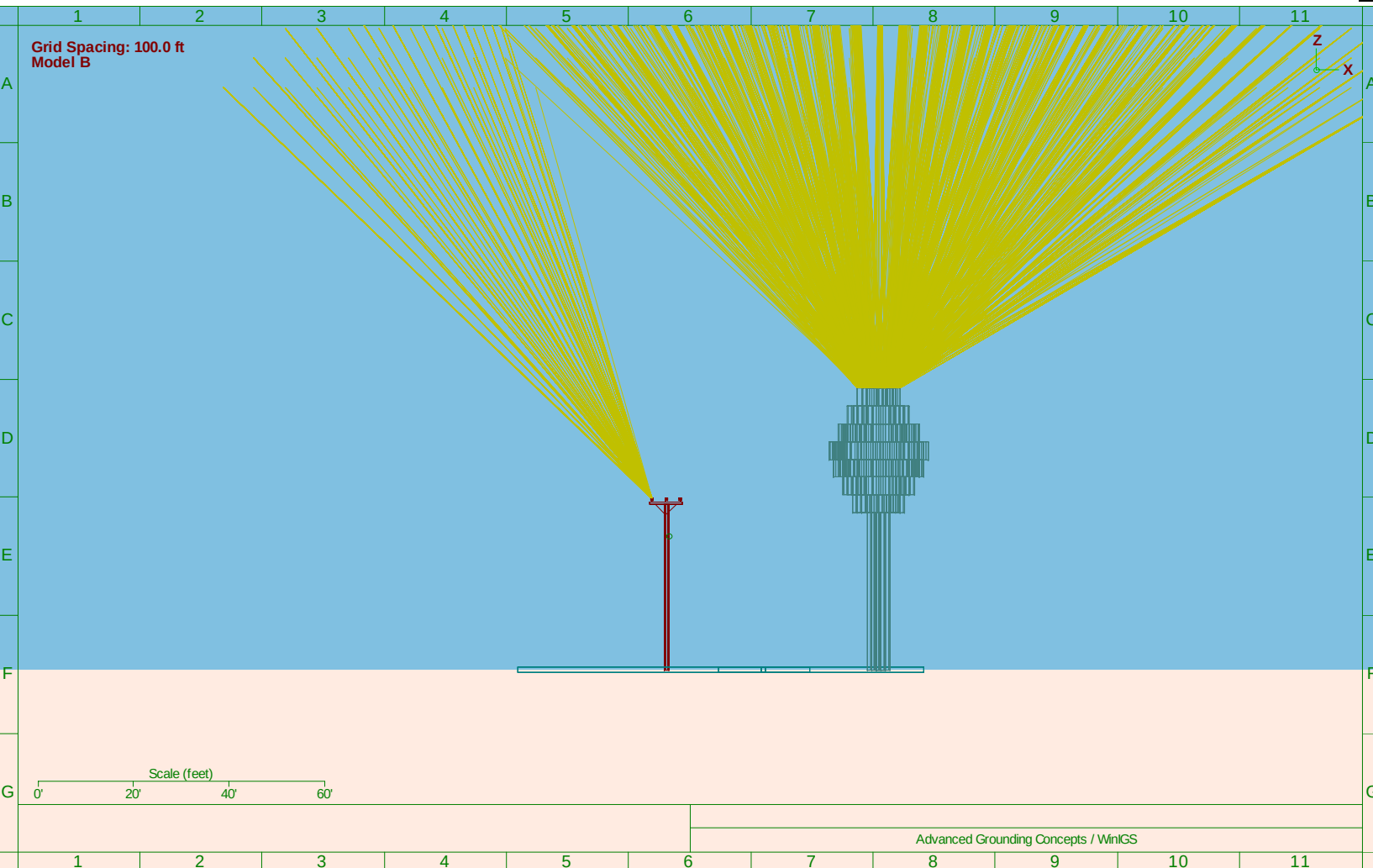
Physically Based Model of Distribution Line





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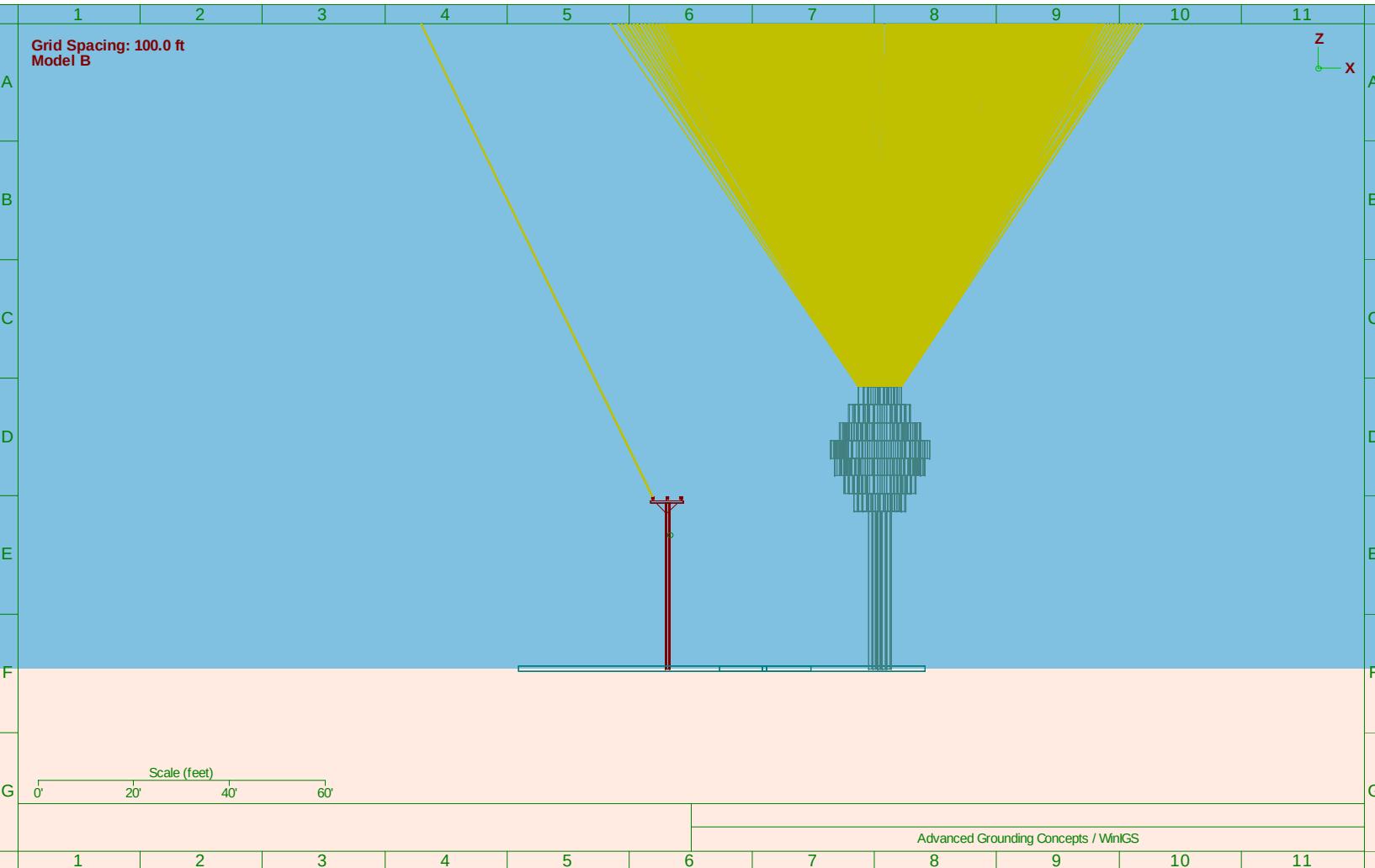
Lightning Shielding Analysis, 12 kA Crest





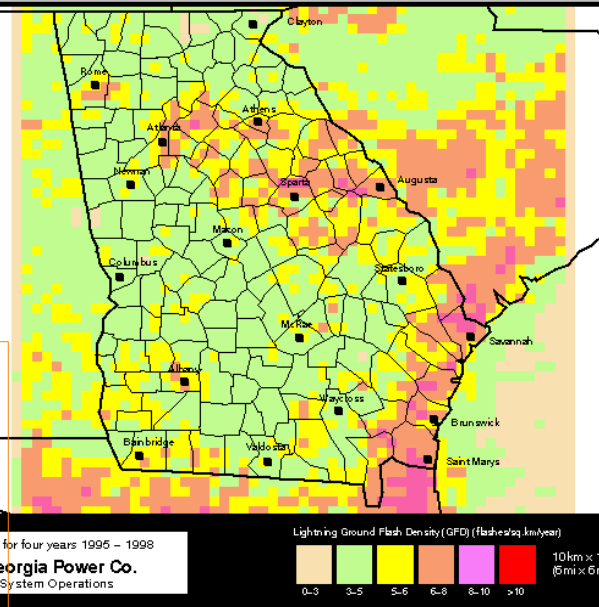
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Lightning Shielding Analysis, 45 kA Crest

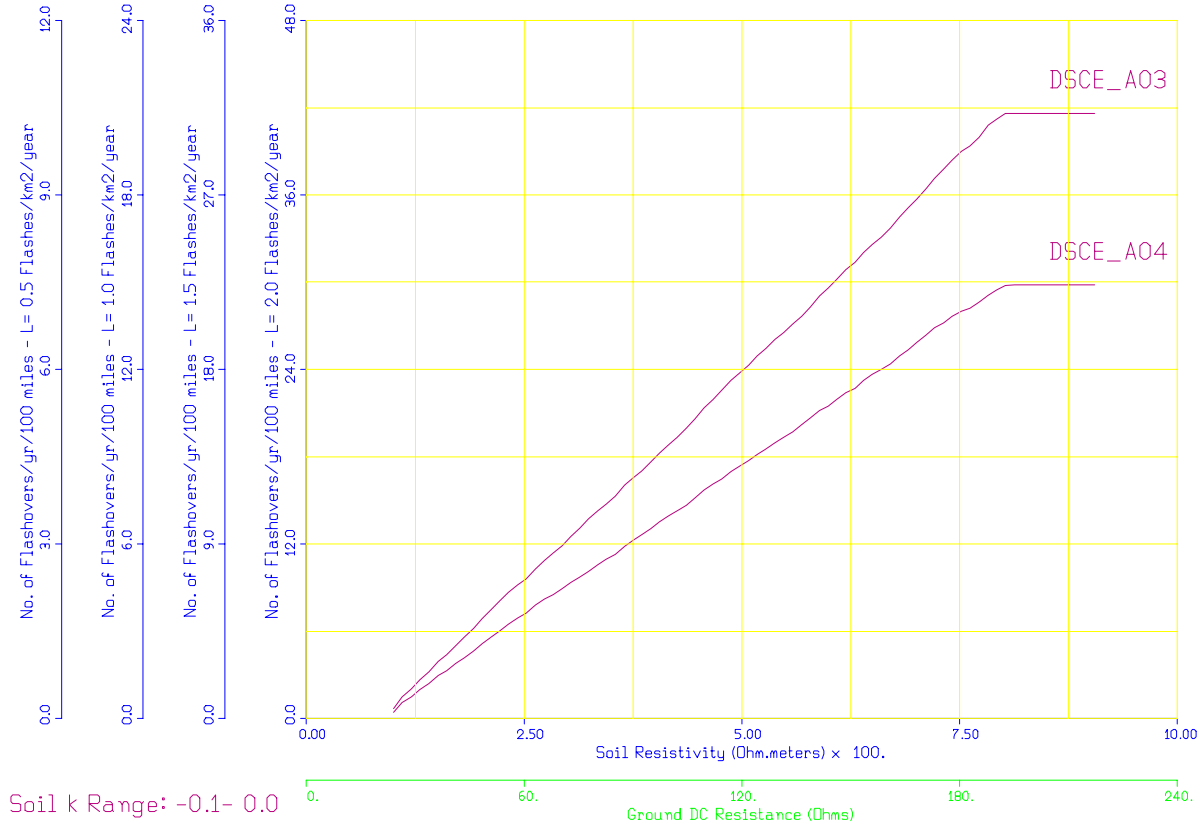


Lightning Caused Voltage Sags, Swells and Outages

Successful Arrester Operation is Counted as Success



DSCE_A03: SCE: 33/12kV,PELICAN,1#4,Post/pin,spaced,80',2400
DSCE_A04: SCE: 33/12kV,PELICAN,1#4,Post/pin,spaced,80',800



Effects of
Grounding
and
Protection

Program: PST4.1 12/98

Form Name: MC_REP04

Print

Alt P

Save

Alt S

Cost Benefit Analysis



EXAMPLE FEEDER

Feeder Length: 40 miles

Lightning Activity: 5 per sq. km

Feeder Design: 25 kV, Steel Arms, Arresters 1800ft

Pole Ground: Single Ground Rod

Soil: 500 ohm.meters, 20% variation

IMPROVEMENTS

Arresters: at 600 ft

Pole Ground: Two Ground Rods

PERFORMANCE

From 20 operations to 3

COST

Arresters: \$59,670

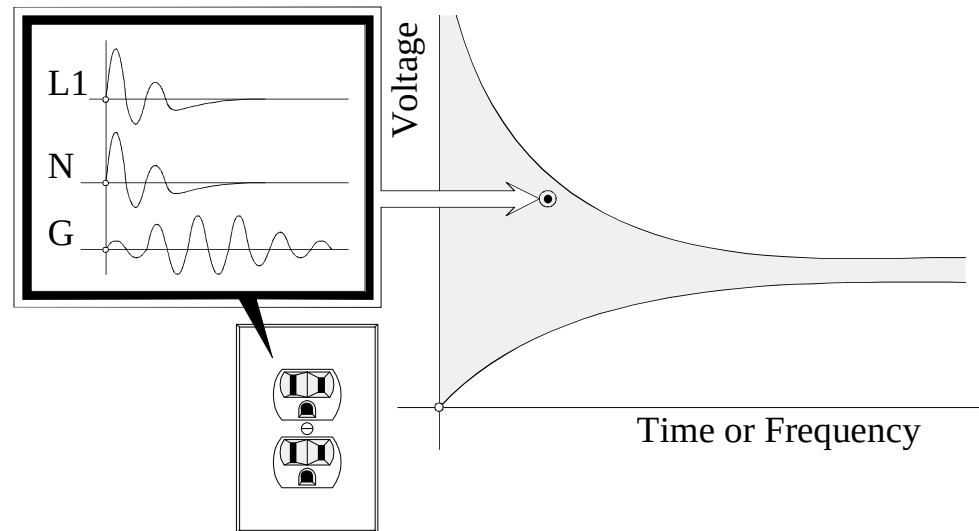
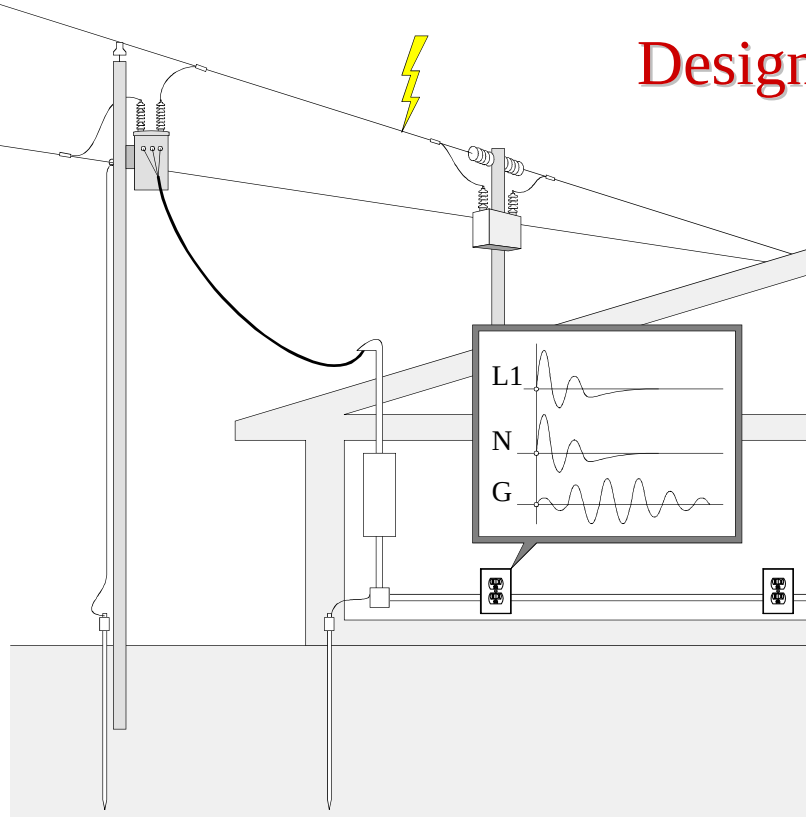
Grounds: \$29,484

Item	Cost of Material	Installation
Arrester	\$35	\$150 (per three phases)
Ground Rod	\$10	\$30
Ground Rod Coupler	\$2	-
Connector	\$3	-
Copper Conductor (#4 or #6)	\$2	\$1 per foot

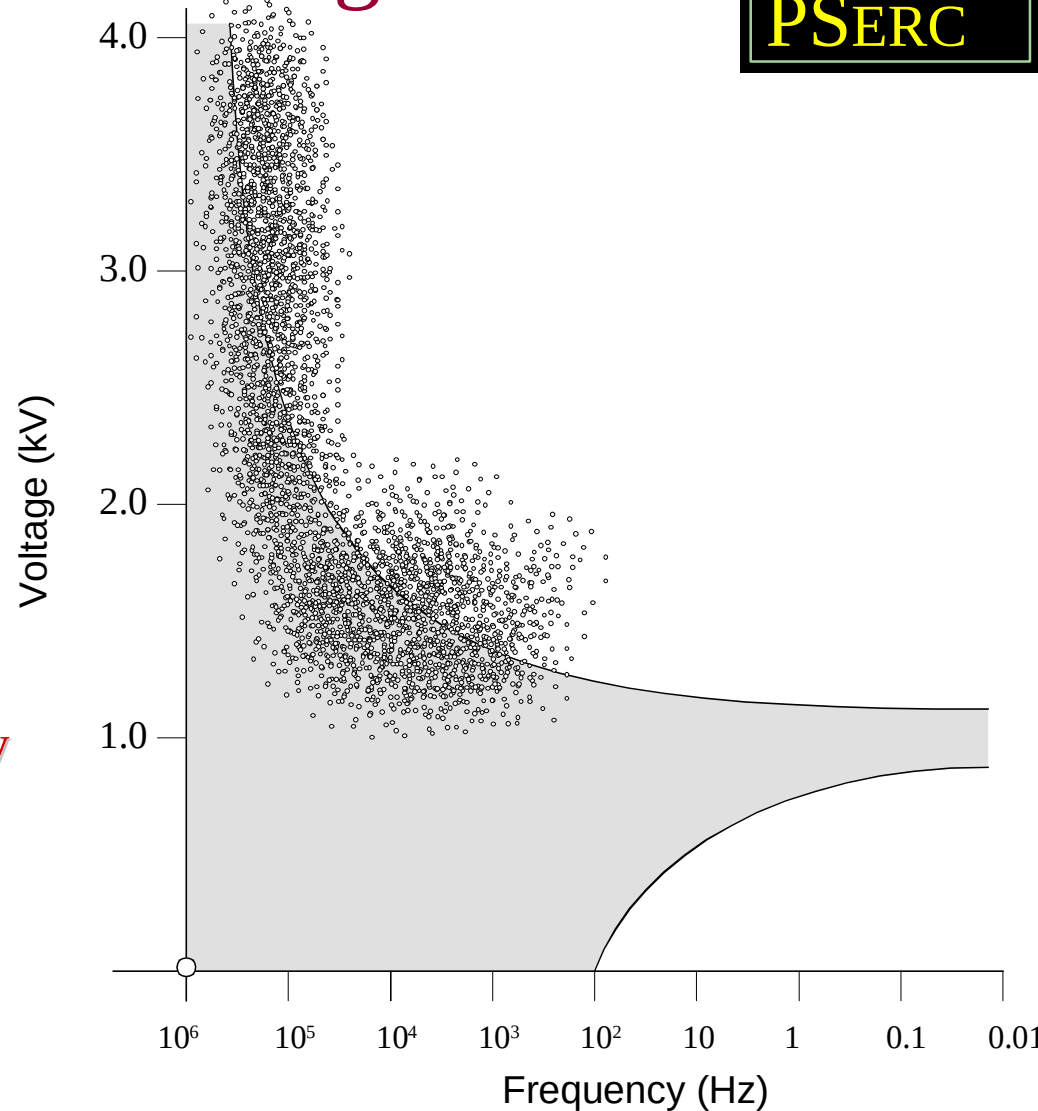
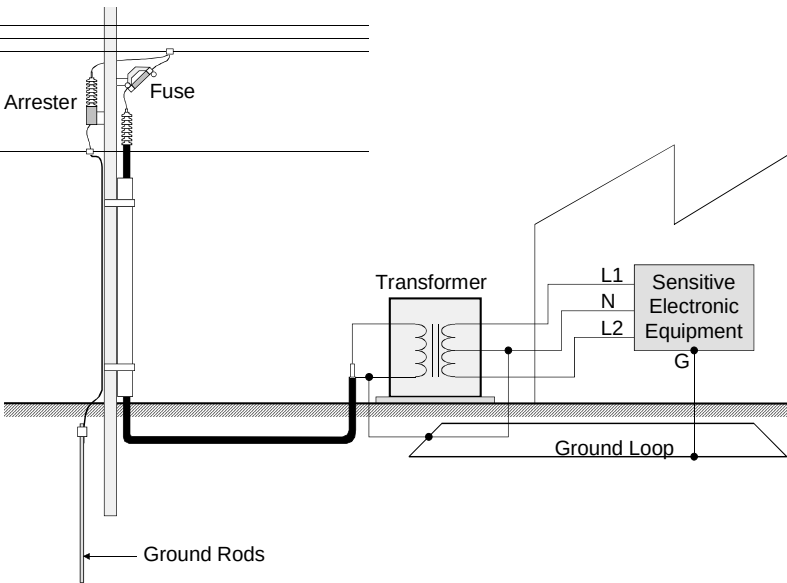
Physically Based Integrated Model Approach



Probabilistic Approach to Power Quality Analysis PQ Characterization Design Options for PQ Enhancement



Statistical Distribution of Voltage Sags/Swells



Probabilistic Approach to Power Quality Analysis

PQ Characterization

Design Options for PQ Enhancement

Conclusions

You Can Do a Lot More with Physically Based Modeling

Disadvantage: More Complex Models

Advantage: Provides the Interrelationship Between Design Parameters and Performance:

→ **Cost-Benefit Analysis**