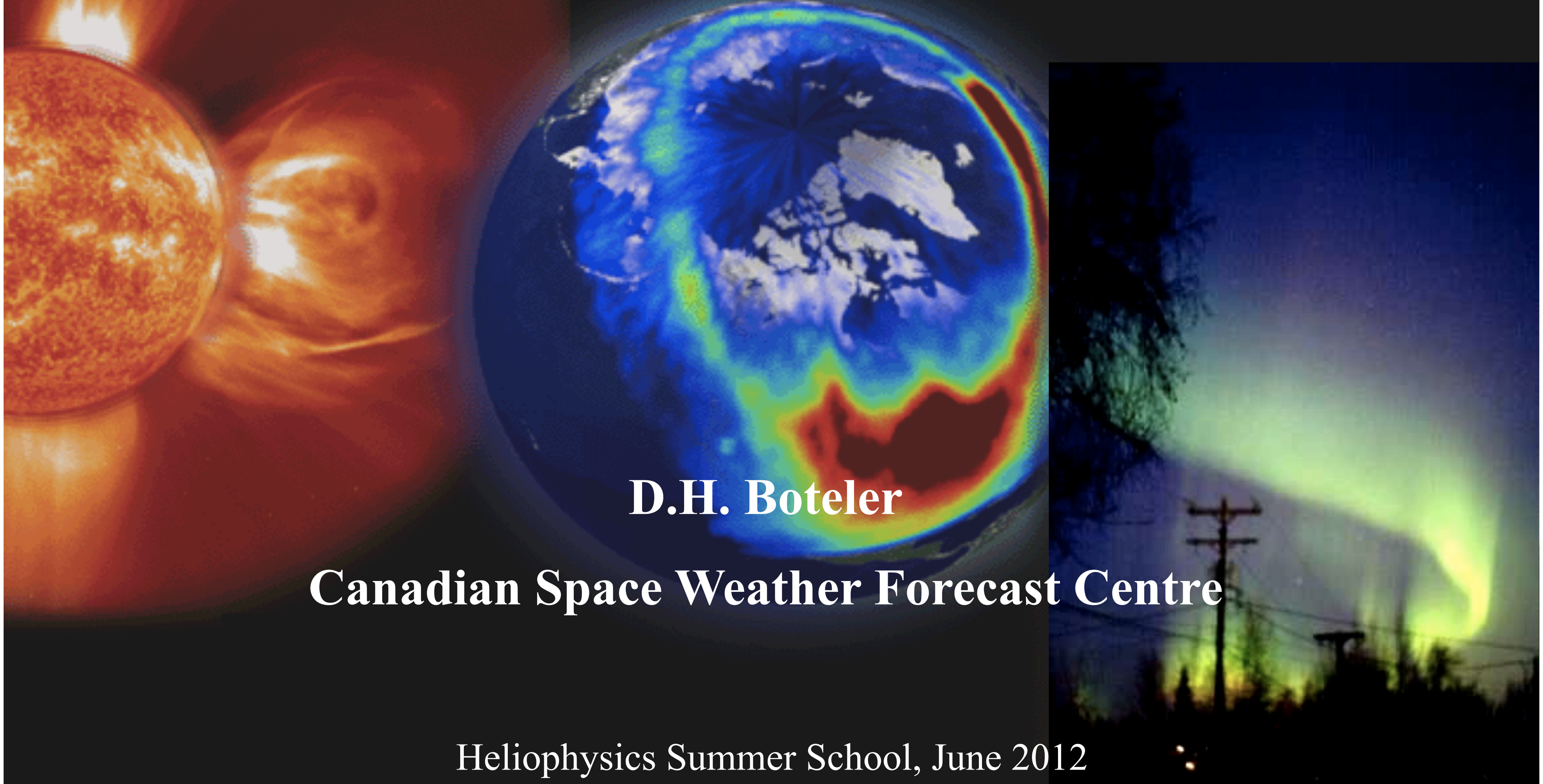
# The Impact of Space Weather on the Electric Power Grid




**D.H. Boteler**

**Canadian Space Weather Forecast Centre**

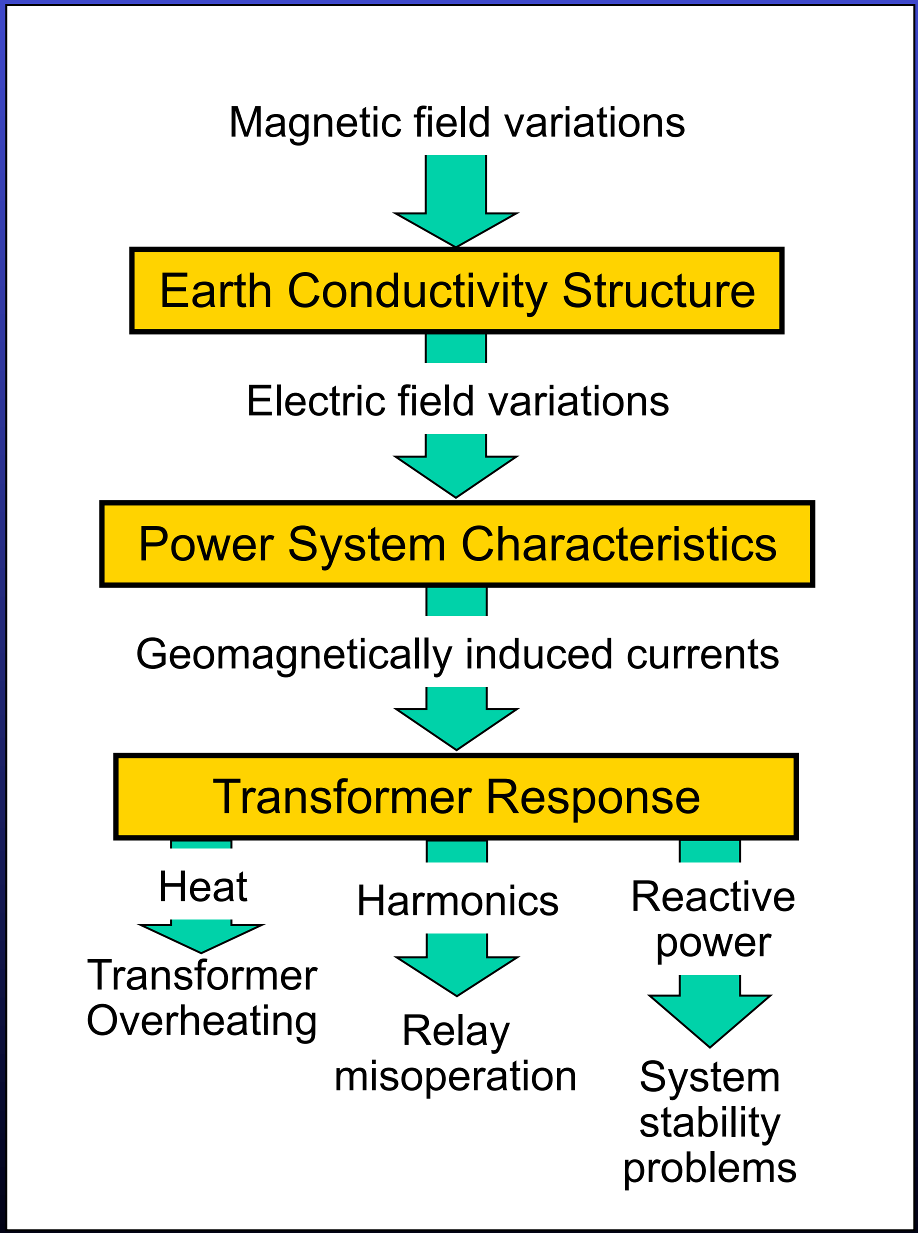

Heliophysics Summer School, June 2012

# Hazard Assessment and Real-Time Simulation of Geomagnetically Induced Currents

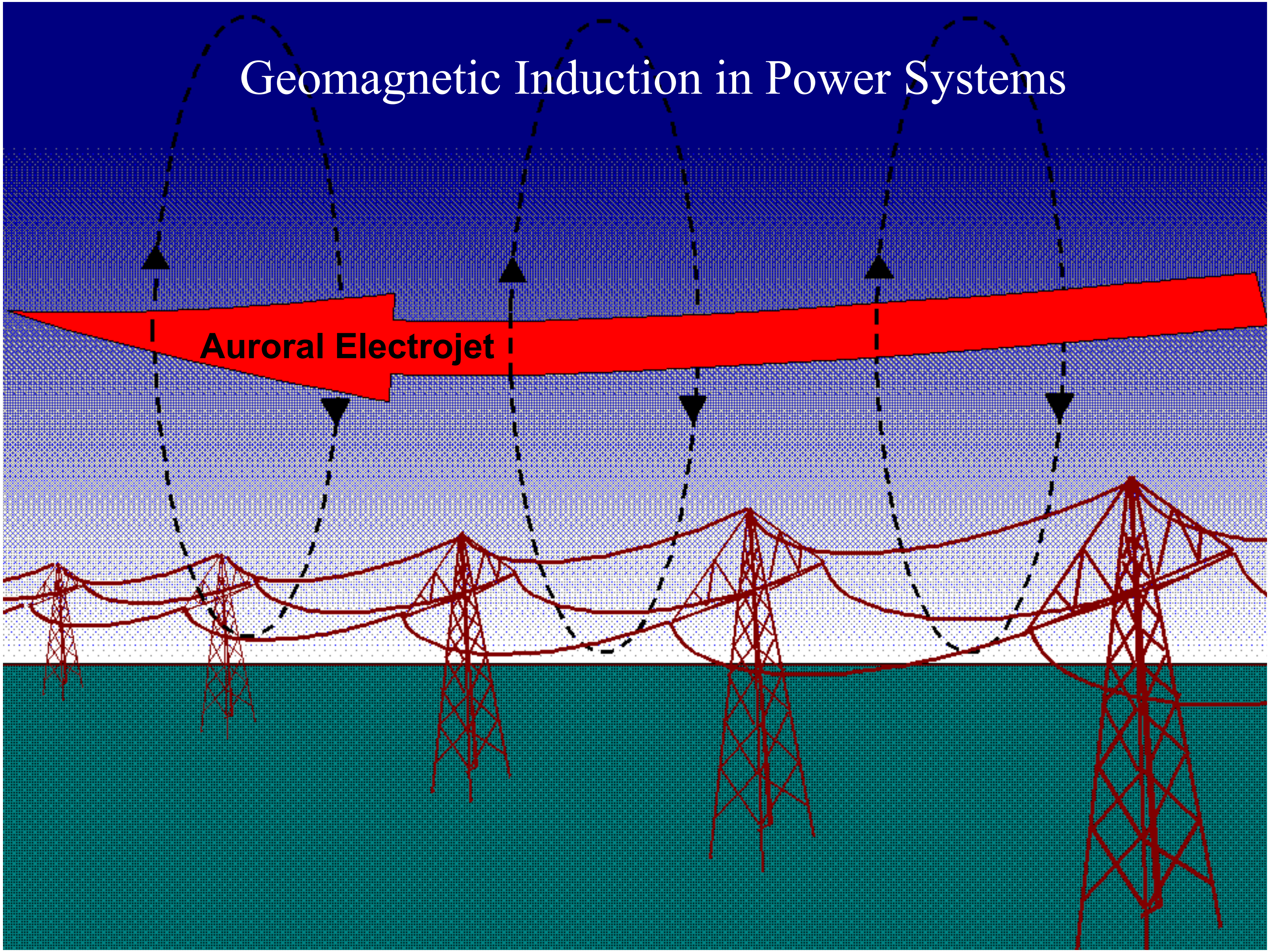
**D.H. Boteler**

**Geomagnetic Laboratory, Natural Resources Canada**

# Outline


Magnetic field variations
Earth Conductivity Structure
Electric field variations
Power System Characteristics
Geomagnetically induced currents
Transformer Response
Heat
Transformer Overheating
Harmonics
Relay misoperation
Reactive power
System stability problems

# Geomagnetic Induction in Power Systems



# Geomagnetic Induction

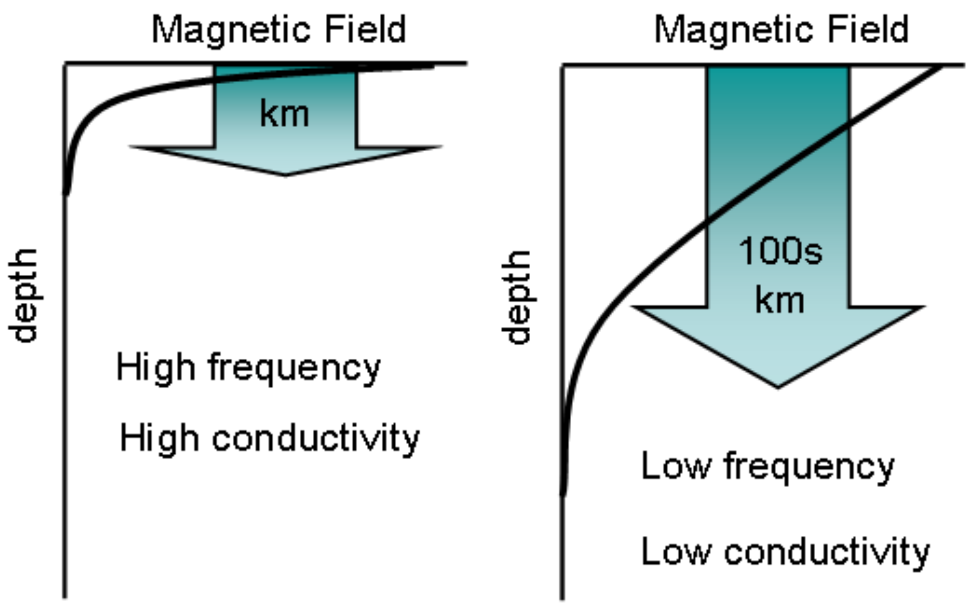
$E \neq dB/dt$

Induced currents create magnetic fields

Self-consistent solution where induced currents tend to cancel inducing magnetic field

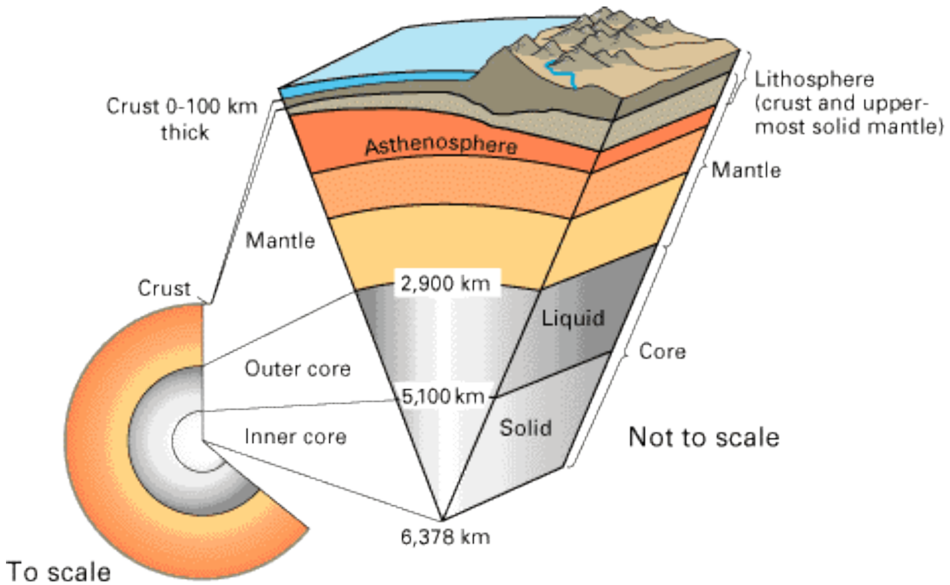
Skin depth

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

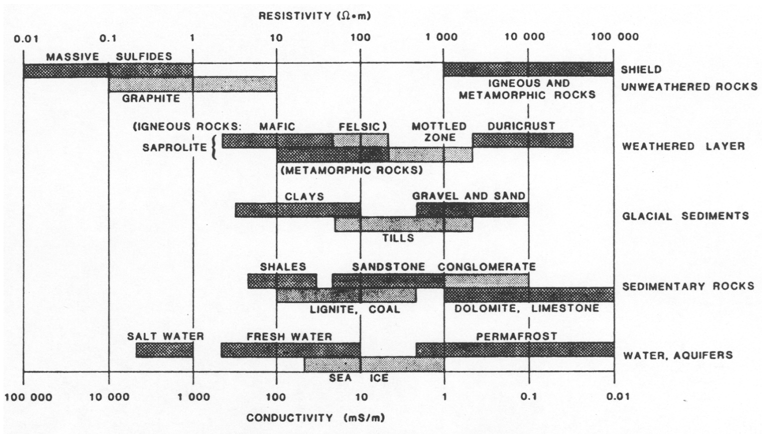


# Earth Conductivity Structure

## Earth Structure

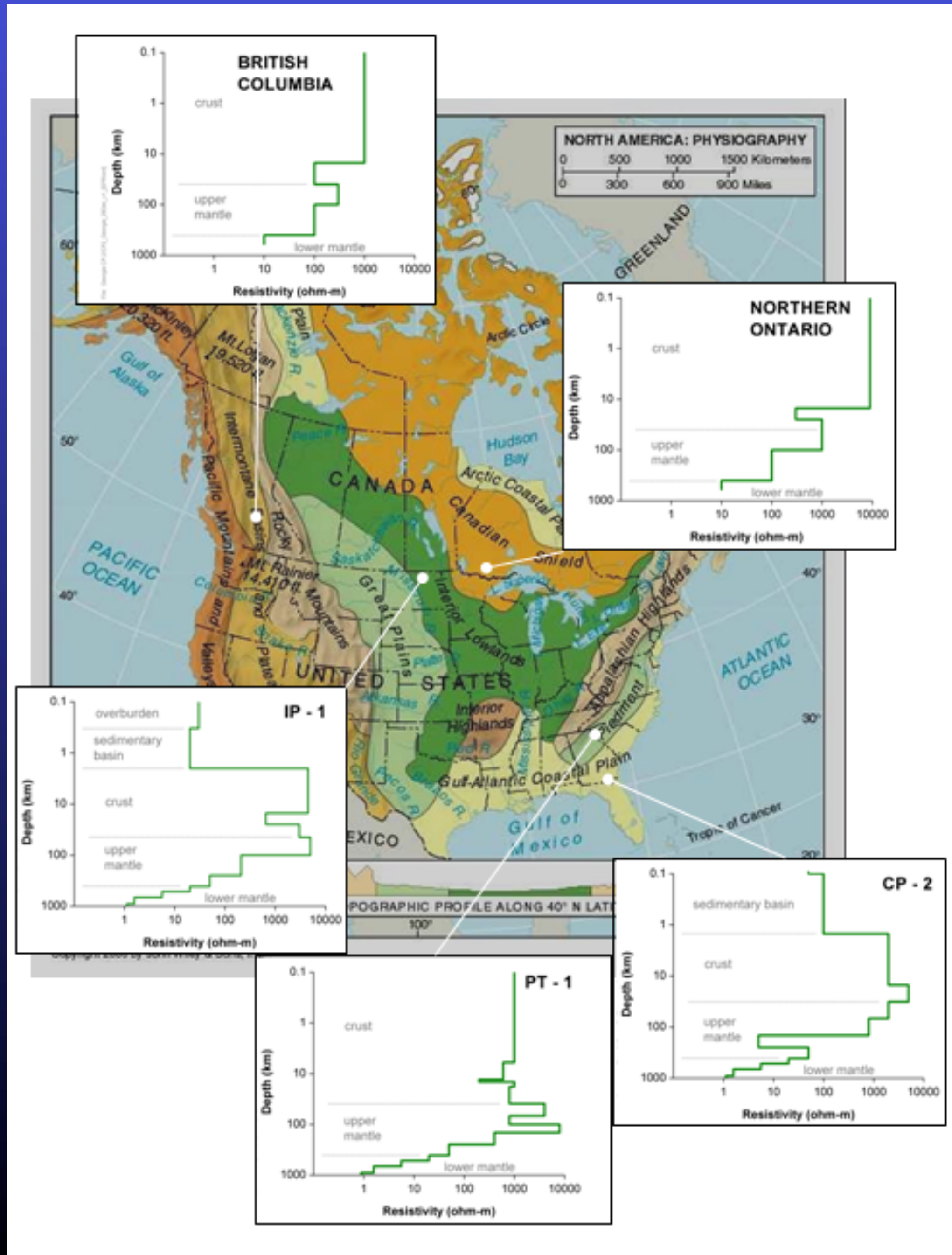



## Rock Resistivities

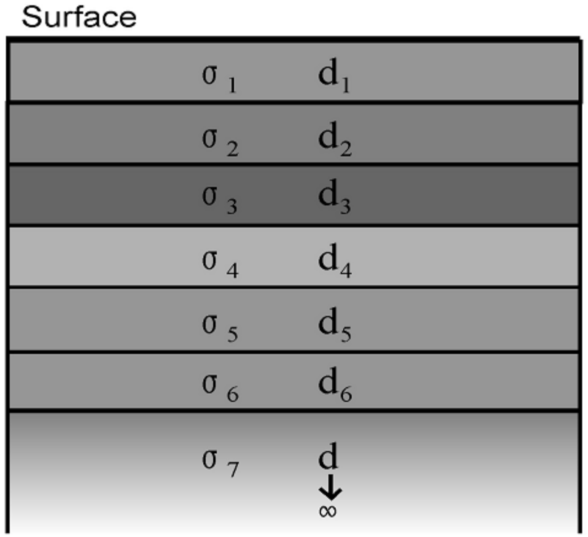


# Earth Models

Examples of 1-D Conductivity Models



# Calculate Earth Response




Recurrence Relation

$$Z_n = i\omega\mu\left(\frac{1 - r_n e^{-2k_n d_n}}{k_n(1 + r_n e^{-2k_n d_n})}\right)$$

$$r_n = \frac{1 - k_n \dfrac{Z_{n-1}}{i\omega\mu}}{1 + k_n \dfrac{Z_{n-1}}{i\omega\mu}} \qquad k_n = \sqrt{i\omega\mu\sigma_n}$$

Last layer: $Z_N = \dfrac{i\omega\mu}{k_N}$

μ – permeability

ω – frequency

$Z_n$ – impedance in layer n

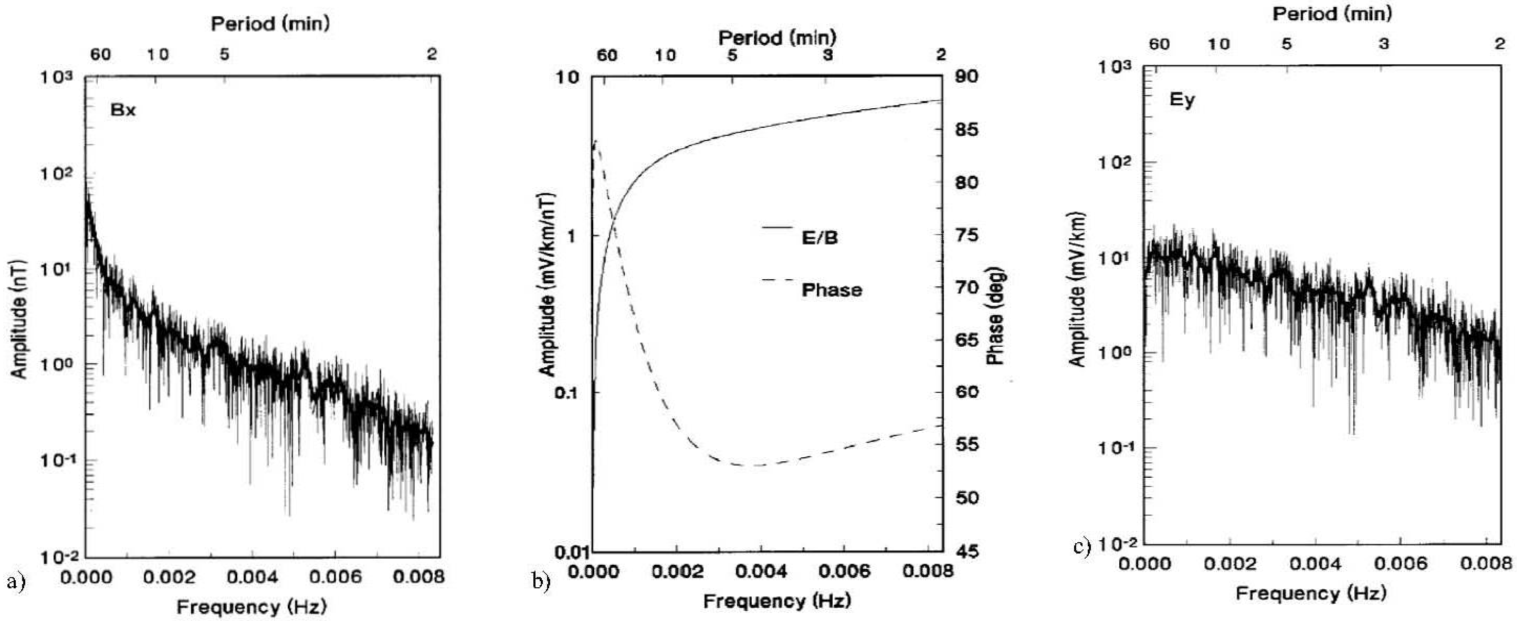
$\sigma_n$ – conductivity layer n

$d_n$ – depth of layer n

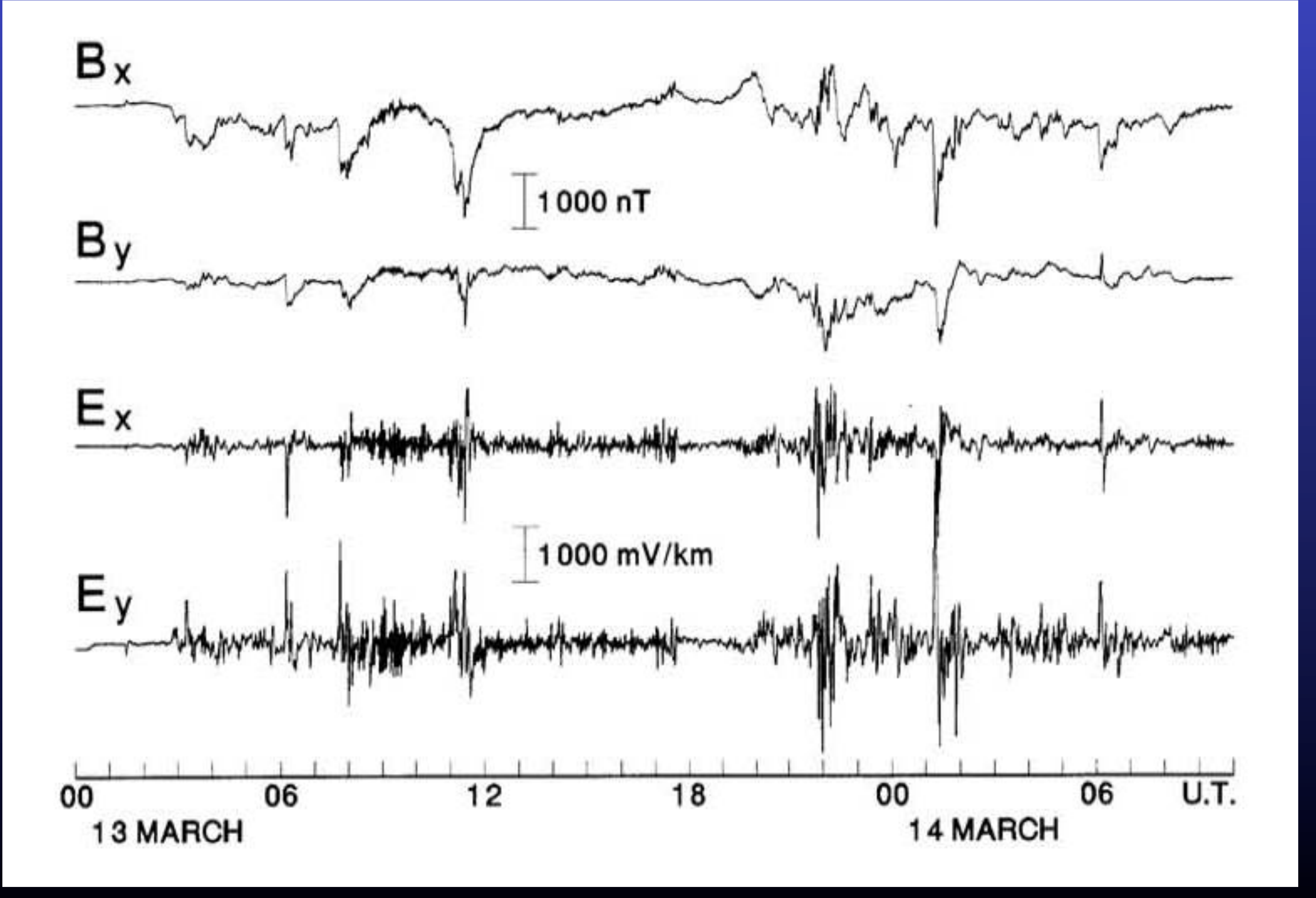
$k_n$ – propagation constant for layer n

# Electric Field Calculation

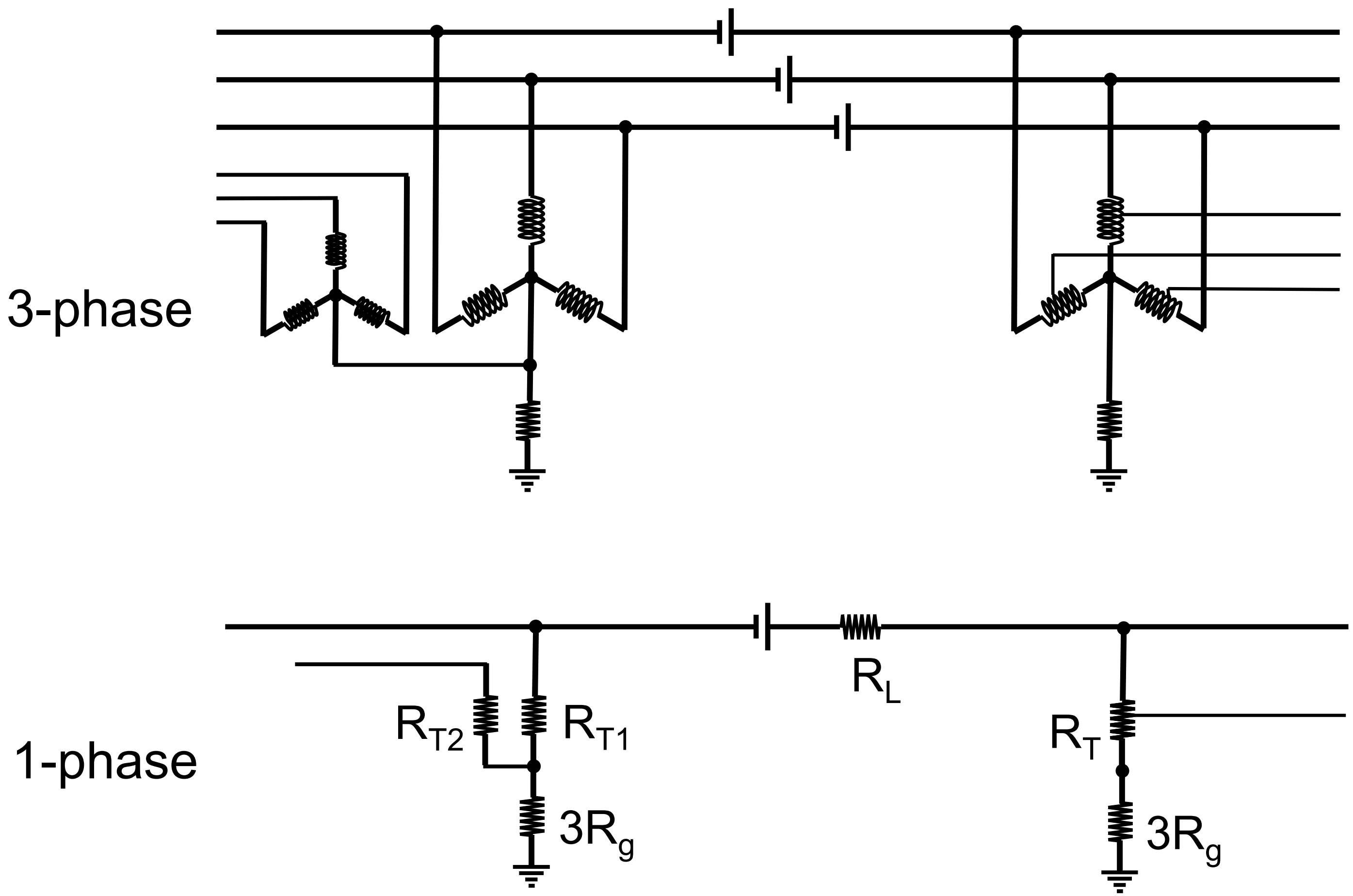
Magnetic Field → **FFT** → $E(\omega) = Z(\omega)H(\omega)$ → **IFFT** → Electric Field



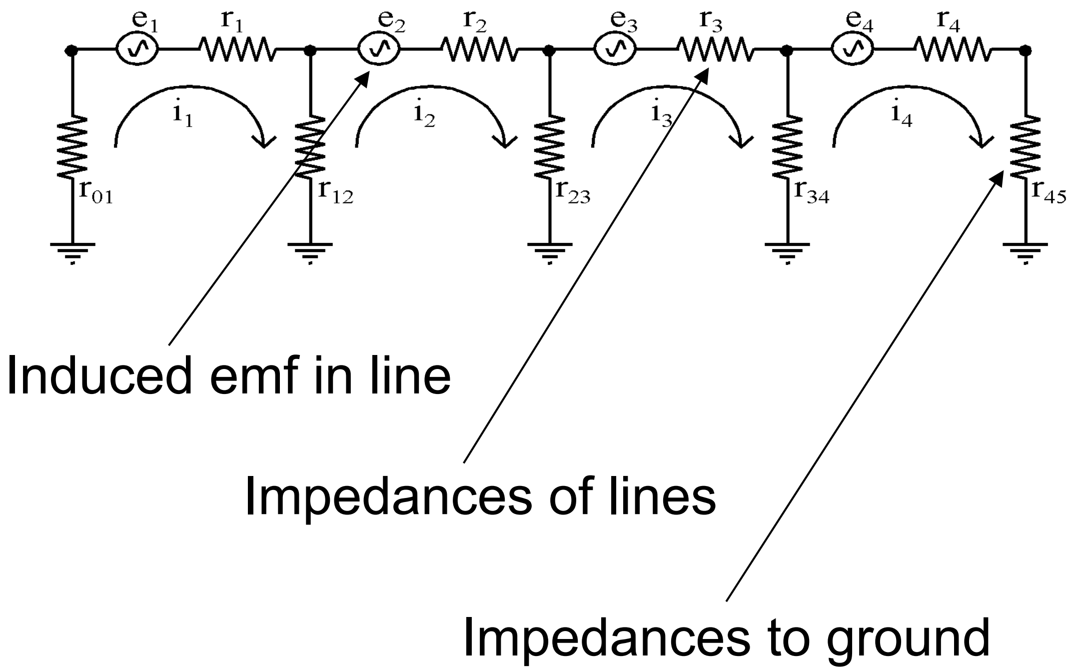
# Electric Field Calculation (Plane Wave)



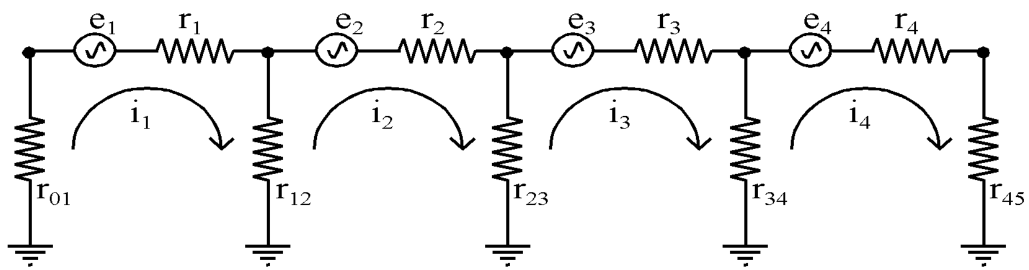
# Modelling Process: Basic Network



# Modelling Process: Basic Network




# 1. Modelling Process: Mesh Impedance Method




Using Kirchoff's voltage law we can write equations for each loop

$$r_{01}i_1 + r_1 i_1 + r_{12}(i_1 - i_2) = e_1$$

$$r_{12}(i_2 - i_1) + r_2 i_2 + r_{23}(i_2 - i_3) = e_2$$

$$r_{23}(i_3 - i_2) + r_3 i_3 + r_{34}(i_3 - i_4) = e_3$$

$$r_{34}(i_4 - i_3) + r_4 i_4 + r_{45} i_4 = e_4$$

# 1. Modelling Process: Mesh Impedance Method

Collecting terms in $i_1$ $i_2$ etc gives

$$(r_{01}+r_1+r_{12})i_1 - r_{12}i_2 = e_1$$

$$-r_{12}i_1 + (r_{12}+r_2+r_{23})i_2 - r_{23}i_3 = e_2$$

$$-r_{23}i_2 + (r_{23}+r_3+r_{34})i_3 - r_{34}i_4 = e_3$$

$$-r_{34}i_3 + (r_{34}+r_4+r_{45})i_4 = e_4$$

$$\begin{bmatrix} r_{01}+r_1+r_{12} & -r_{12} & -r_{23} & 0 \\ -r_{12} & r_{12}+r_2+r_{23} & 0 & 0 \\ 0 & -r_{23} & r_{23}+r_3+r_{34} & -r_{34} \\ 0 & 0 & -r_{34} & r_{34}+r_4+r_{45} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \end{bmatrix} = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \end{bmatrix}$$

# 1. Modelling Process: Mesh Impedance Method

Thus the equations can be written in matrix form

$$[Z][I]=[E]$$

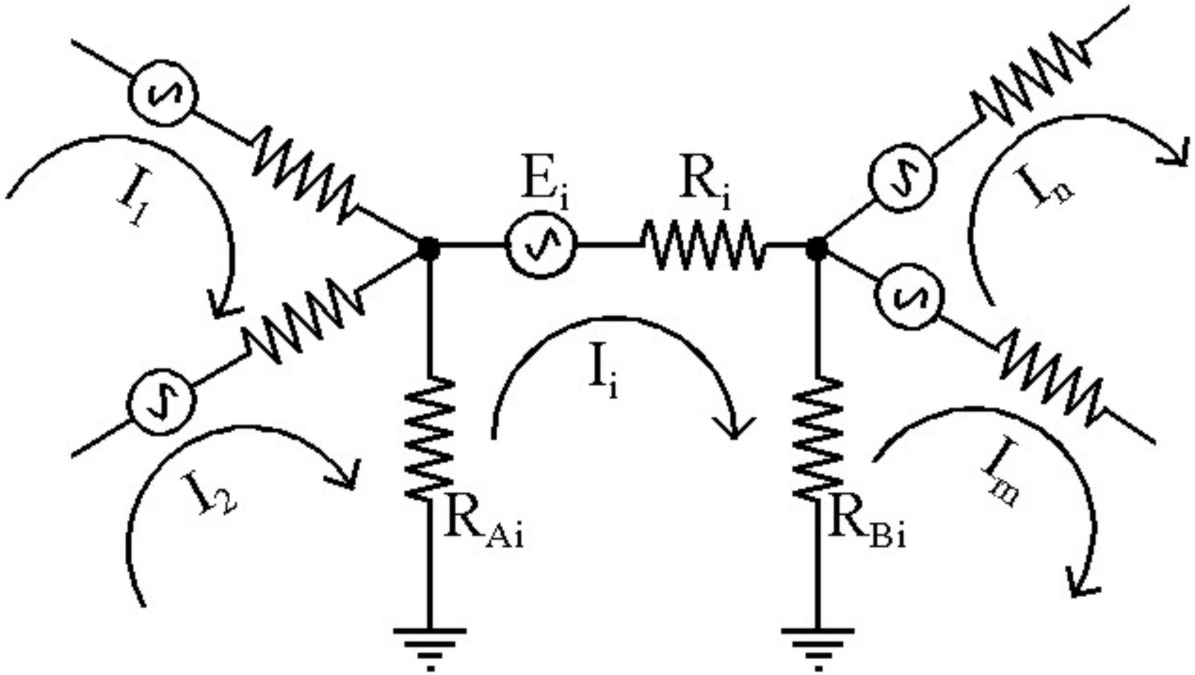
Matrix inversion then gives the expression for the currents

$$[I]=[Z]^{-1}[E]$$

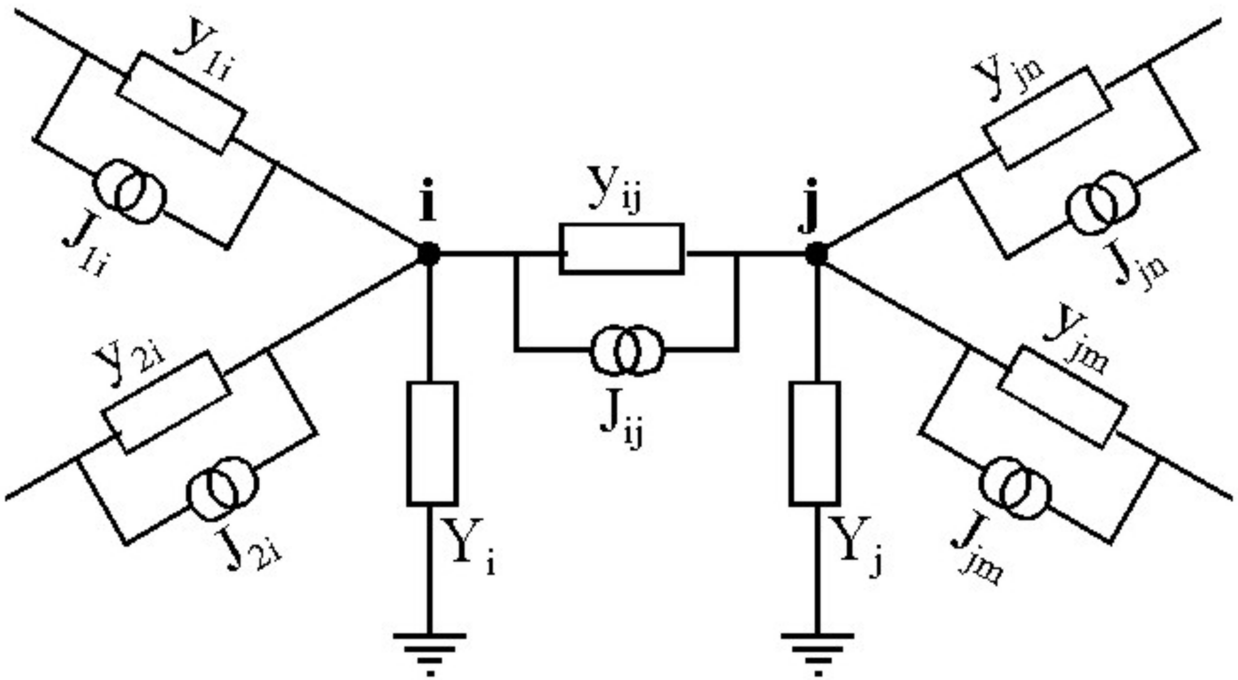
# General Modelling Methods

- Mesh Impedance Matrix Method
- Nodal Admittance Matrix Method
- Lehtinen-Pirjola Method

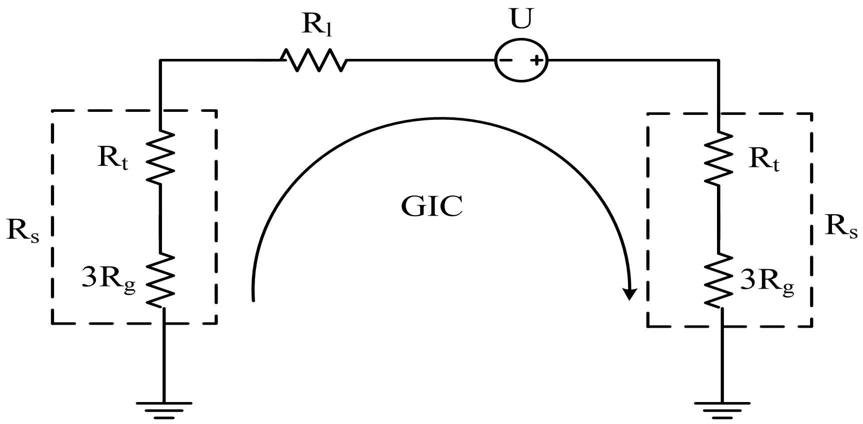
# Mesh Impedance Matrix Method



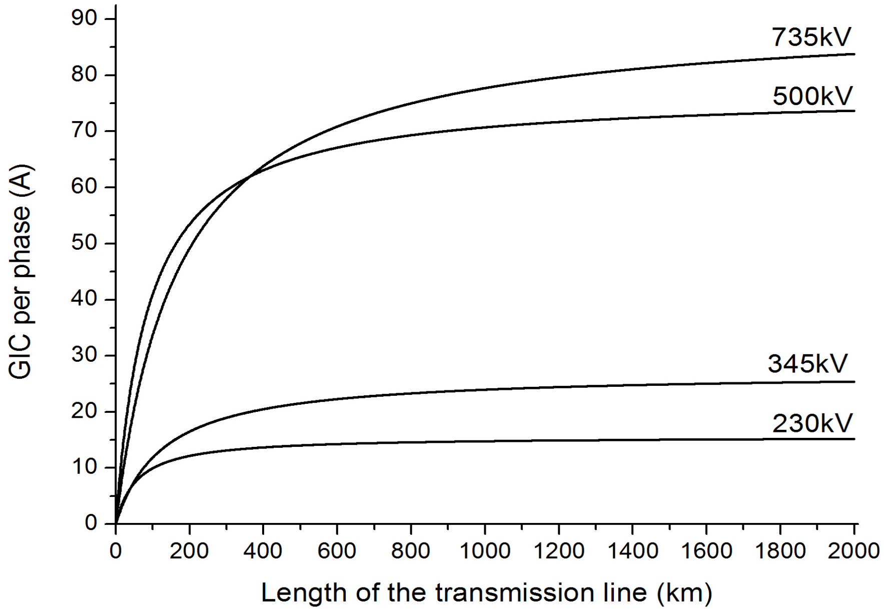
# Nodal Admittance Matrix Method



# Effect of Line Length



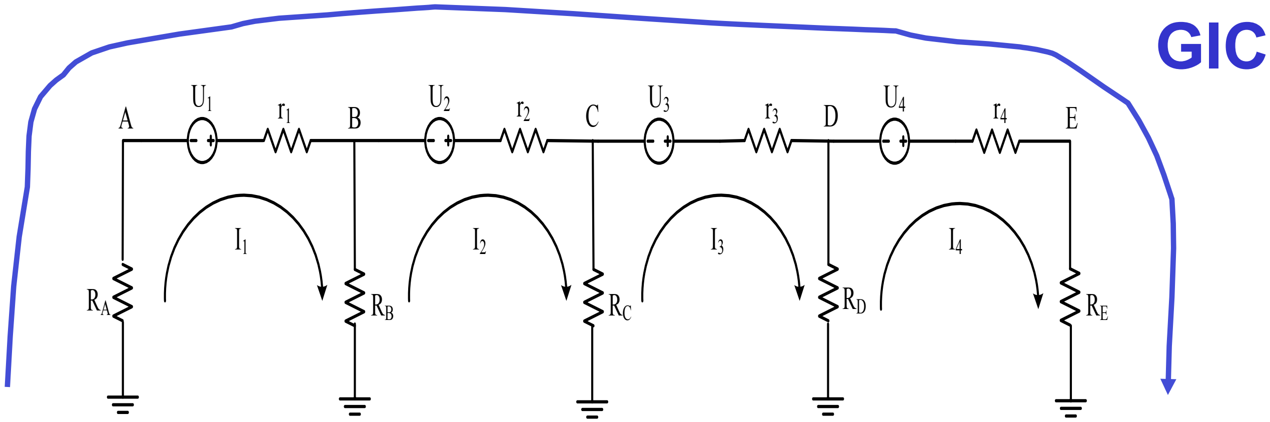

$$GIC = \frac{U}{R_l + 2R_s} = \frac{E_l \cdot l}{r \cdot l + 2R_s}$$




Maximum GIC

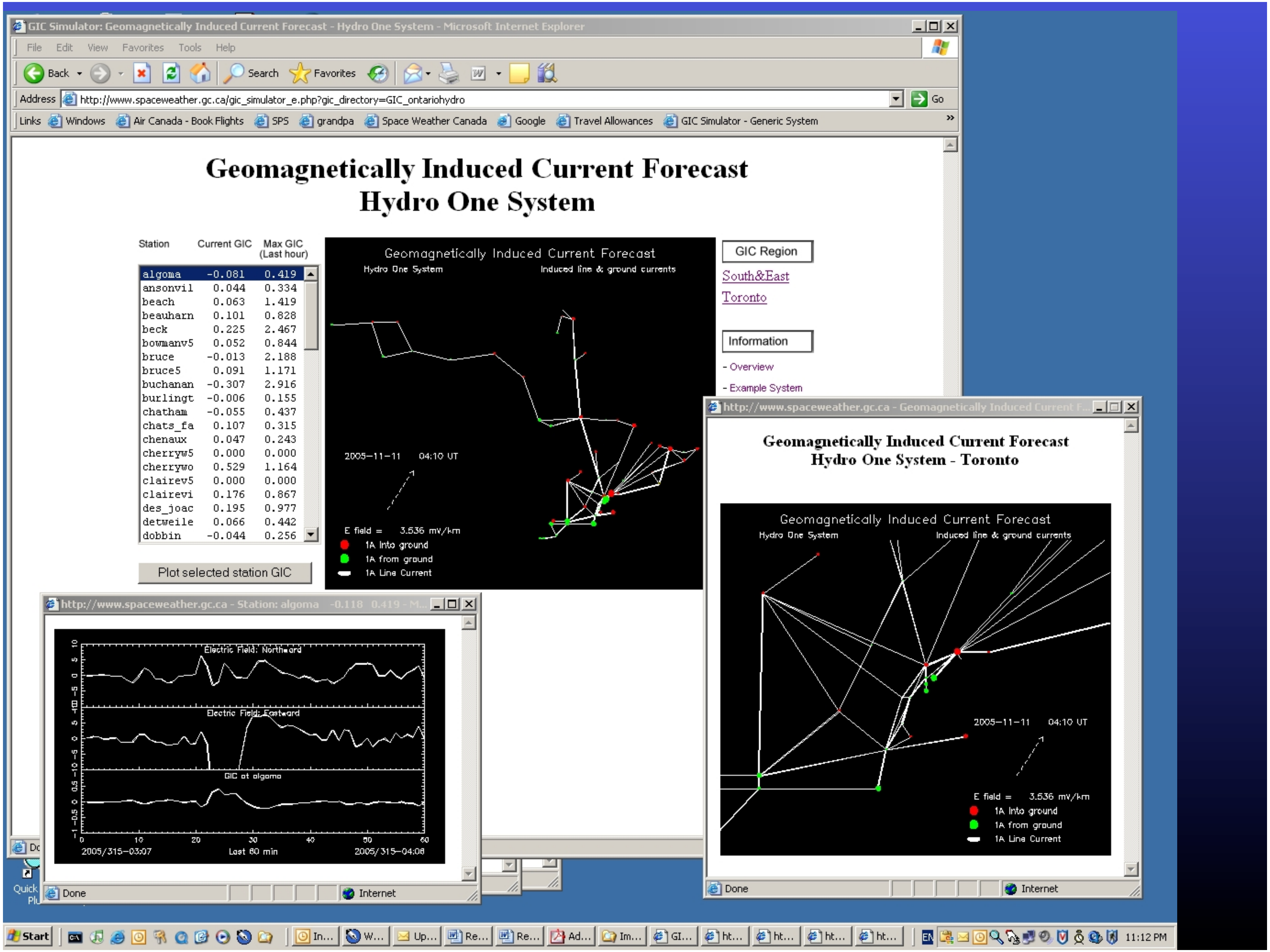
$$GIC_{\max} = \frac{E_l}{r}$$

# Edge Effect




GIC flows from one edge of the network to the other

GIC flows past substations in the middle of the network


GIC Simulator: Geomagnetically Induced Current Forecast - Hydro One System - Microsoft Internet Explorer
http://www.spaceweather.gc.ca/gic_simulator_e.php?gic_directory=GIC_ontariohydro
Geomagnetically Induced Current Forecast
Hydro One System
Station
Current GIC
Max GIC (Last hour)
algoma -0.081 0.419
ansonvil 0.044 0.334
beach 0.063 1.419
beauharn 0.101 0.828
beck 0.225 2.467
bowmanv5 0.052 0.844
bruce -0.013 2.188
bruce5 0.091 1.171
buchanan -0.307 2.916
burlingt -0.006 0.155
chatham -0.055 0.437
chats_fa 0.107 0.315
chenaux 0.047 0.243
cherryw5 0.000 0.000
cherrywo 0.529 1.164
clairev5 0.000 0.000
clairevi 0.176 0.867
des_joac 0.195 0.977
detweile 0.066 0.442
dobbin -0.044 0.256
Plot selected station GIC
Geomagnetically Induced Current Forecast
Hydro One System
Induced line & ground currents
2005-11-11 04:10 UT
E field = 3.536 mV/km
1A Into ground
1A from ground
1A Line Current
GIC Region
South&East
Toronto
Information
- Overview
- Example System
http://www.spaceweather.gc.ca - Station: algoma
Electric Field: Northward
Electric Field: Eastward
GIC at algoma
2005/315-03:07
Last 60 min
2005/315-04:08
http://www.spaceweather.gc.ca - Geomagnetically Induced Current F...
Geomagnetically Induced Current Forecast
Hydro One System - Toronto
Geomagnetically Induced Current Forecast
Hydro One System
Induced line & ground currents
2005-11-11 04:10 UT
E field = 3.536 mV/km
1A Into ground
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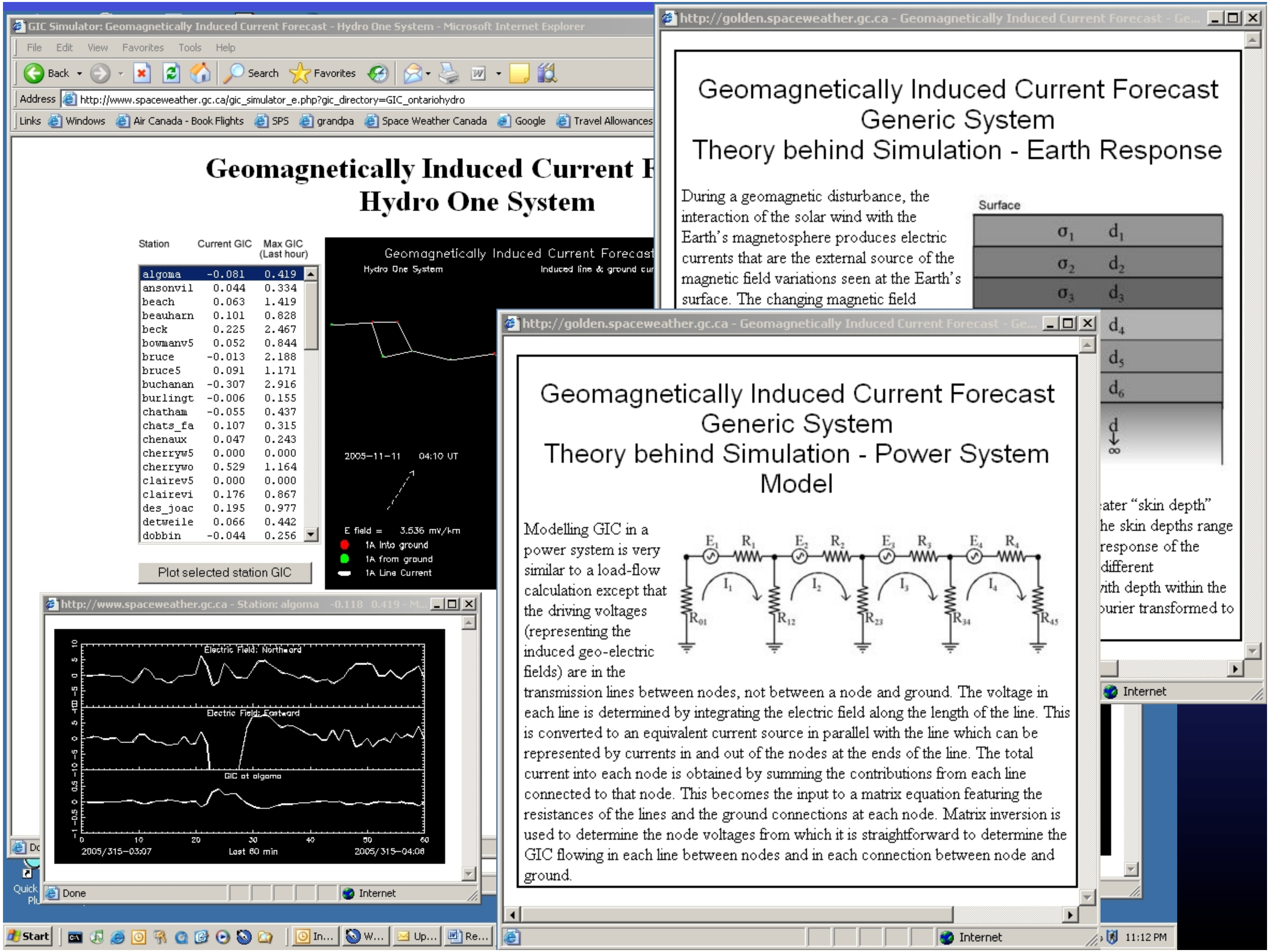
1A Line Current


GIC Simulator: Geomagnetically Induced Current Forecast - Hydro One System - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Back Search Favorites
Address http://www.spaceweather.gc.ca/gic_simulator_e.php?gic_directory=GIC_ontariohydro
Links Windows Air Canada - Book Flights SPS grandpa Space Weather Canada Google Travel Allowances
Geomagnetically Induced Current F
Hydro One System
Station Current GIC Max GIC (Last hour)
algoma -0.081 0.419
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2005-11-11 04:10 UT
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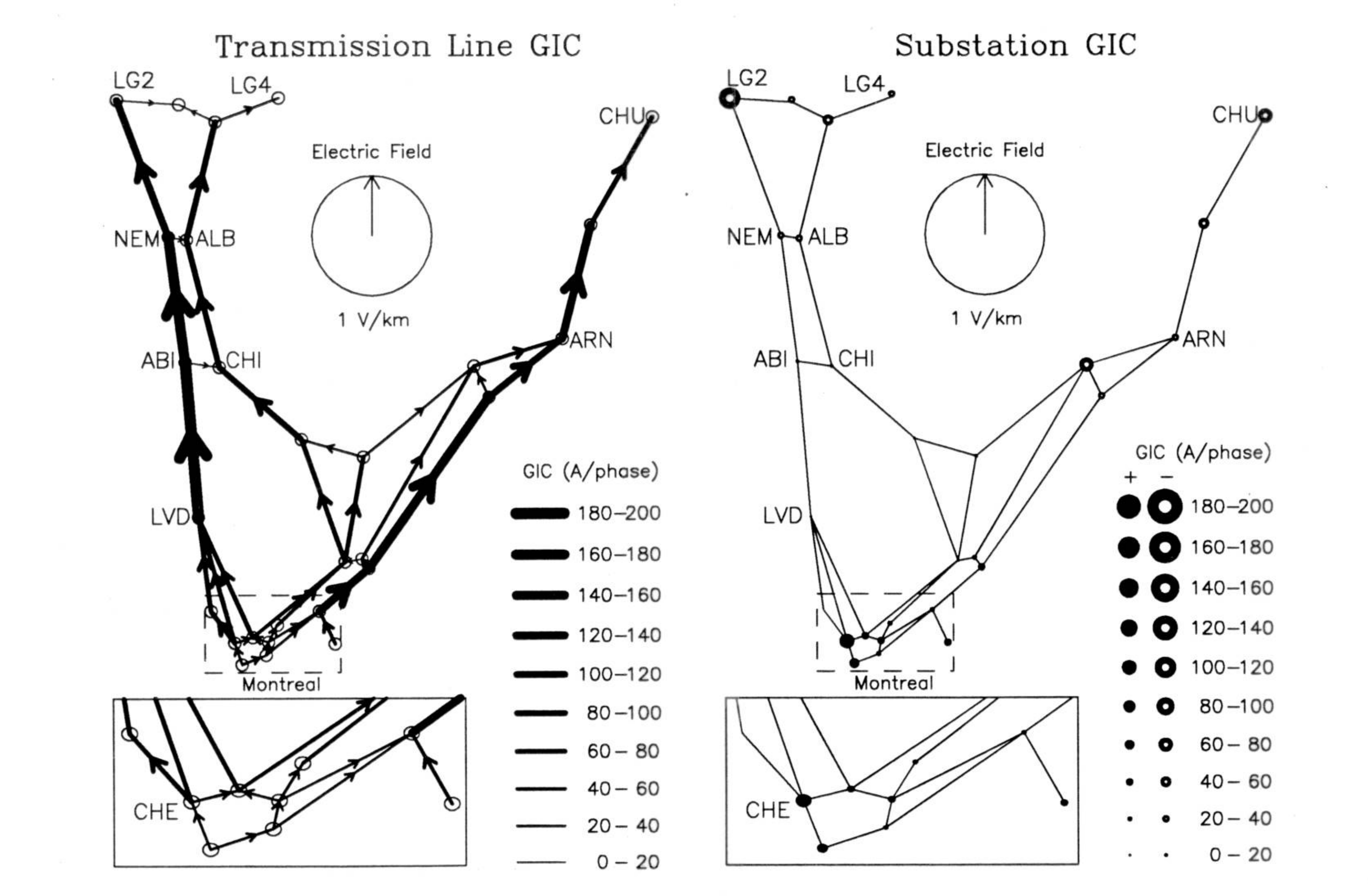
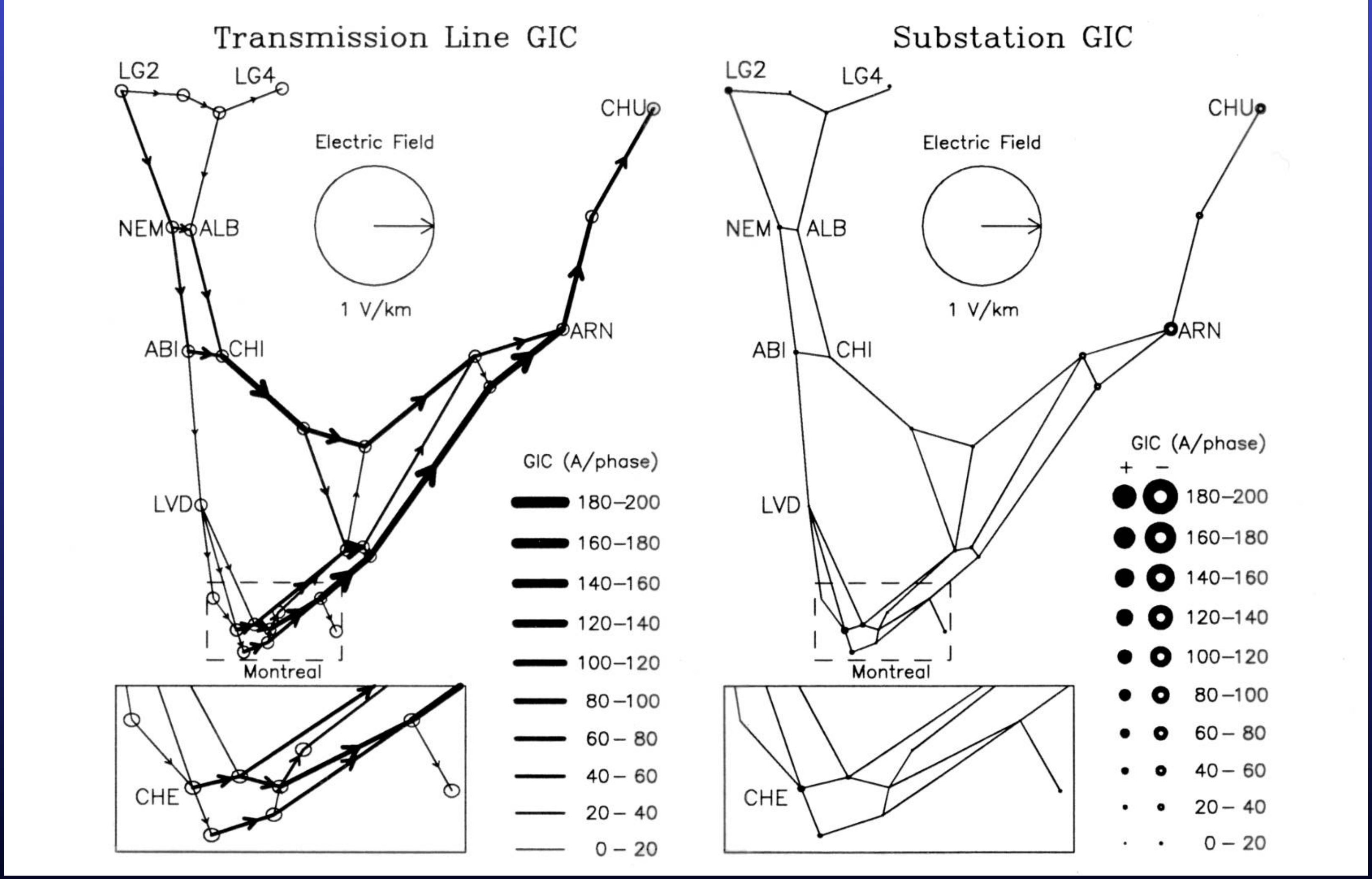
1A Into ground
1A from ground
1A Line Current
http://www.spaceweather.gc.ca - Station: algoma
Electric Field: Northward
Electric Field: Eastward
GIC at algoma
2005/315-03:07
Last 60 min
2005/315-04:08
Done
Internet
http://golden.spaceweather.gc.ca - Geomagnetically Induced Current Forecast - Ge...
Geomagnetically Induced Current Forecast
Generic System
Theory behind Simulation - Earth Response
During a geomagnetic disturbance, the interaction of the solar wind with the Earth's magnetosphere produces electric currents that are the external source of the magnetic field variations seen at the Earth's surface. The changing magnetic field
Surface
ater "skin depth"
he skin depths range
response of the
different
vith depth within the
ourier transformed to
Internet
http://golden.spaceweather.gc.ca - Geomagnetically Induced Current Forecast - Ge...
Geomagnetically Induced Current Forecast
Generic System
Theory behind Simulation - Power System Model
Modelling GIC in a power system is very similar to a load-flow calculation except that the driving voltages (representing the induced geo-electric fields) are in the transmission lines between nodes, not between a node and ground. The voltage in each line is determined by integrating the electric field along the length of the line. This is converted to an equivalent current source in parallel with the line which can be represented by currents in and out of the nodes at the ends of the line. The total current into each node is obtained by summing the contributions from each line connected to that node. This becomes the input to a matrix equation featuring the resistances of the lines and the ground connections at each node. Matrix inversion is used to determine the node voltages from which it is straightforward to determine the GIC flowing in each line between nodes and in each connection between node and ground.
Internet
Start
11:12 PM

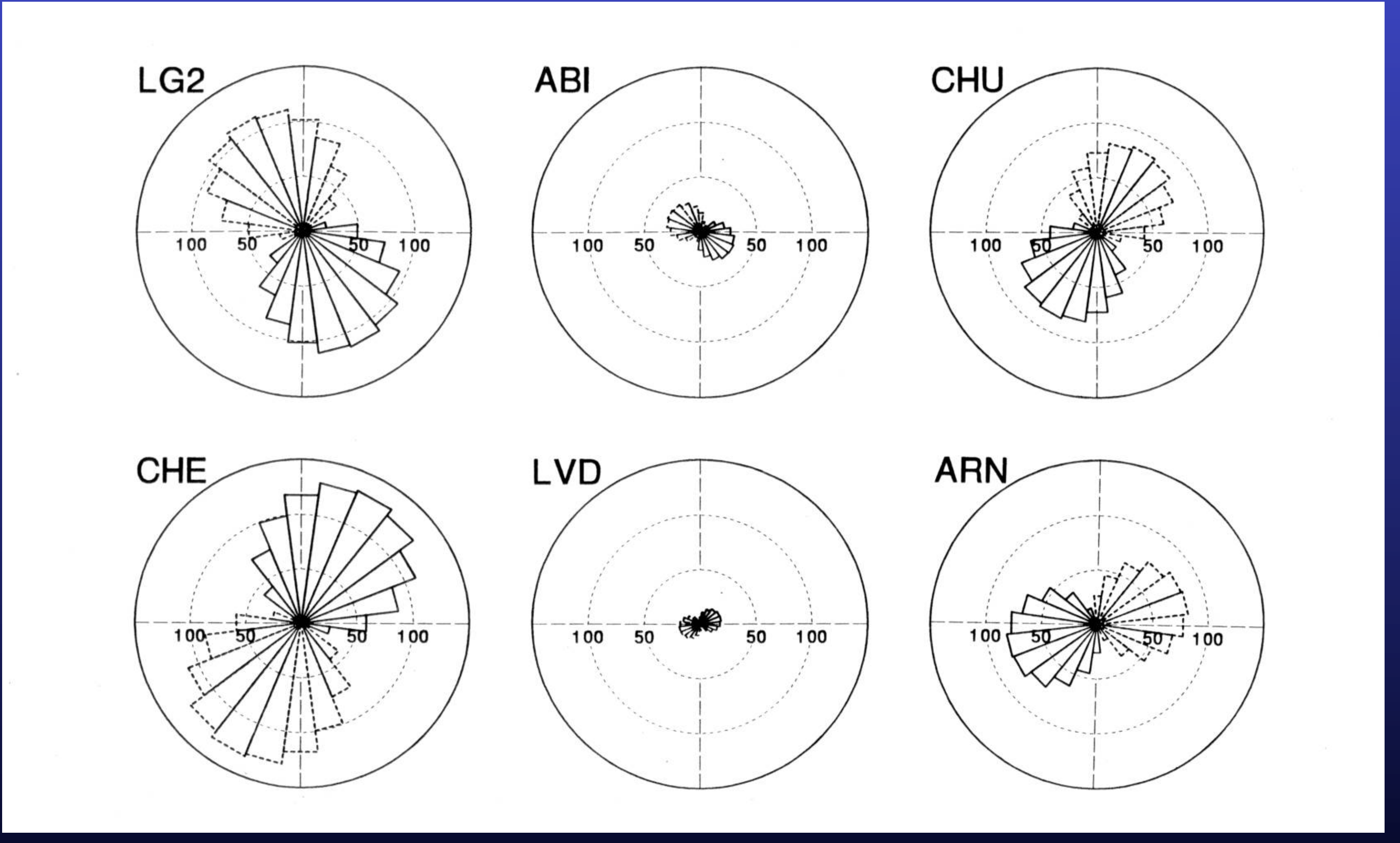
# GIC for Northward Electric Field



# GIC for Eastward Electric Field



# Directional Sensitivity



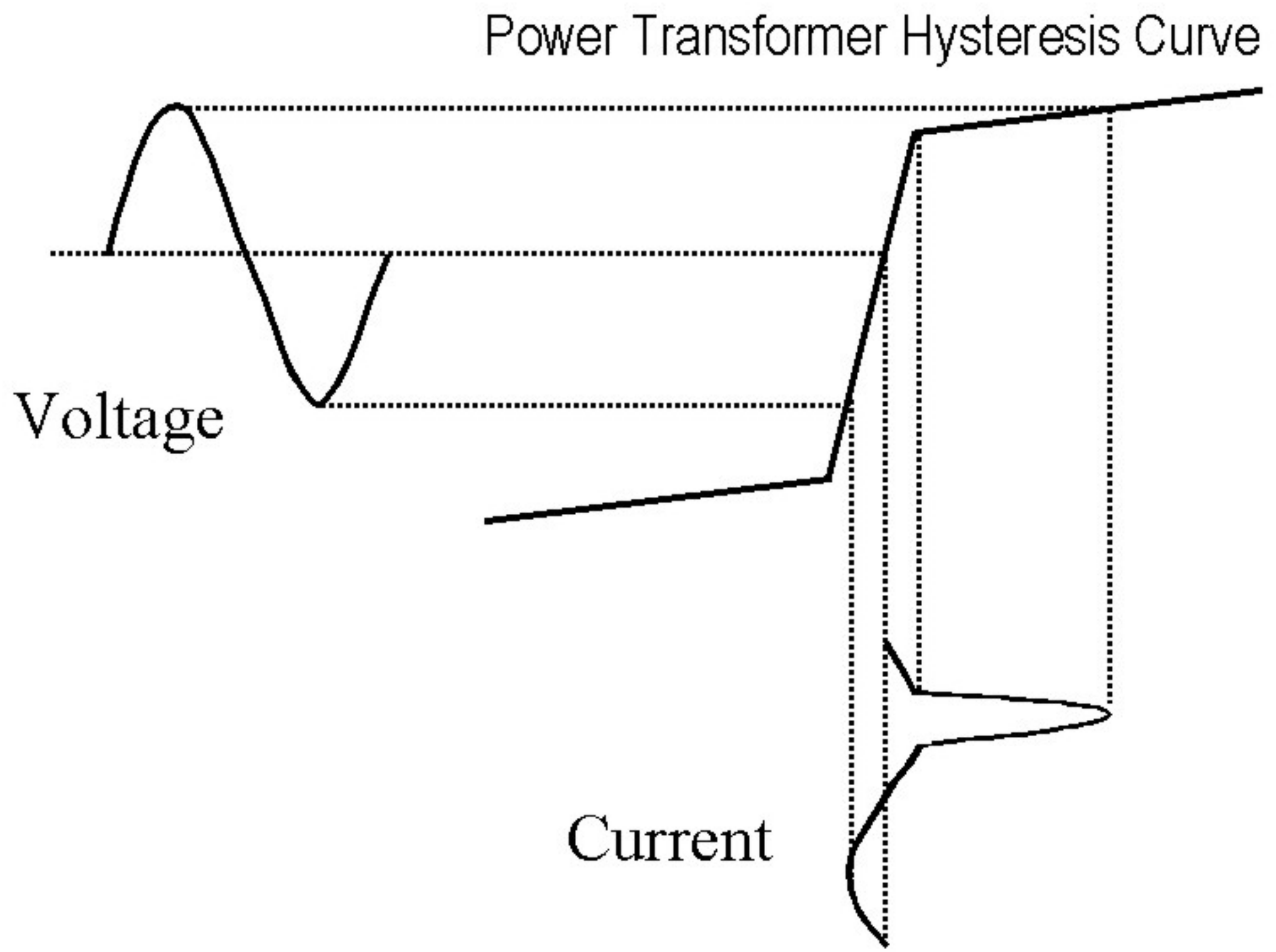
## Impacts on Power System

Spikey waveform → harmonics

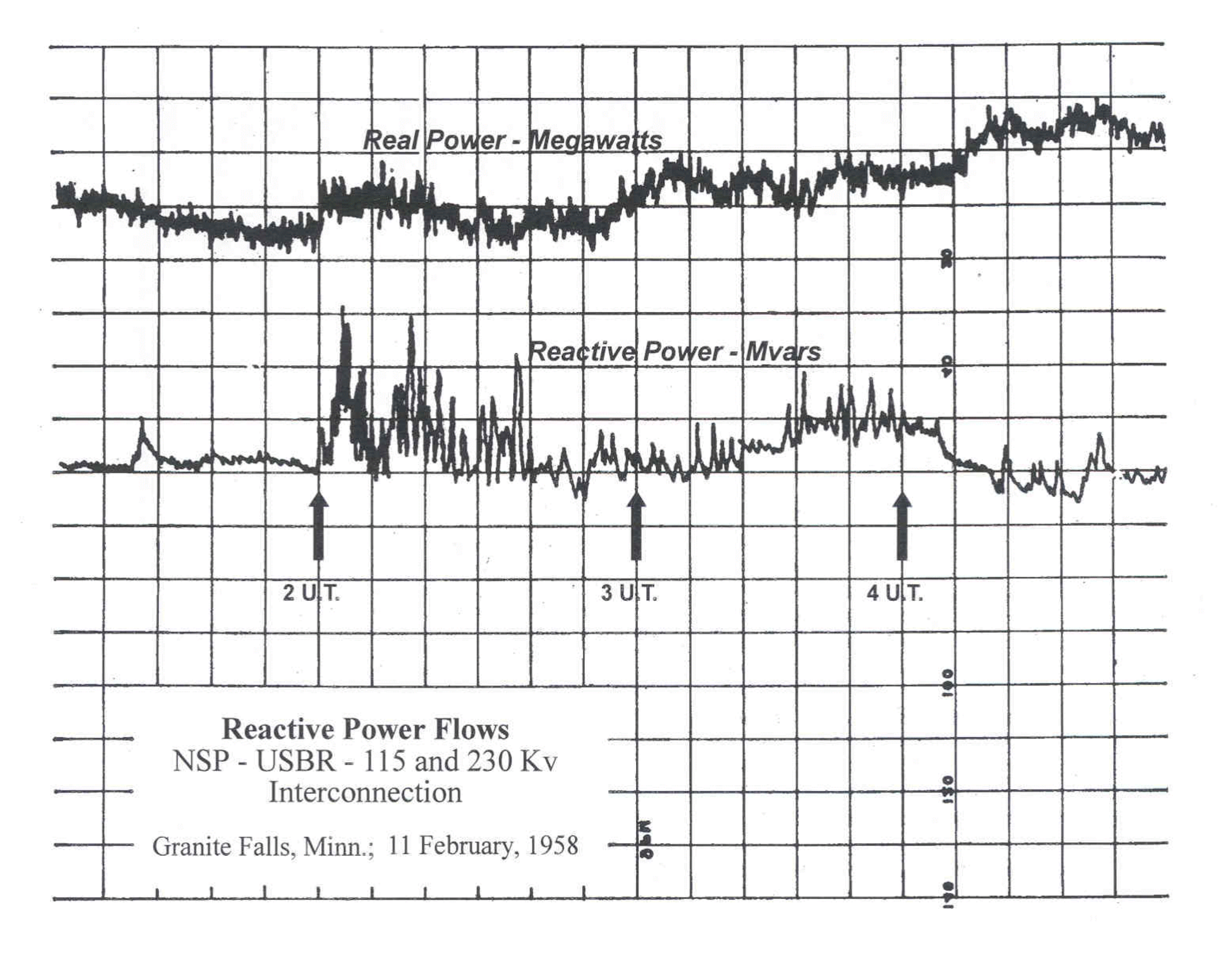
Harmonics cause misoperation of protective relays

Increased magnetising current → increased reactive power consumption

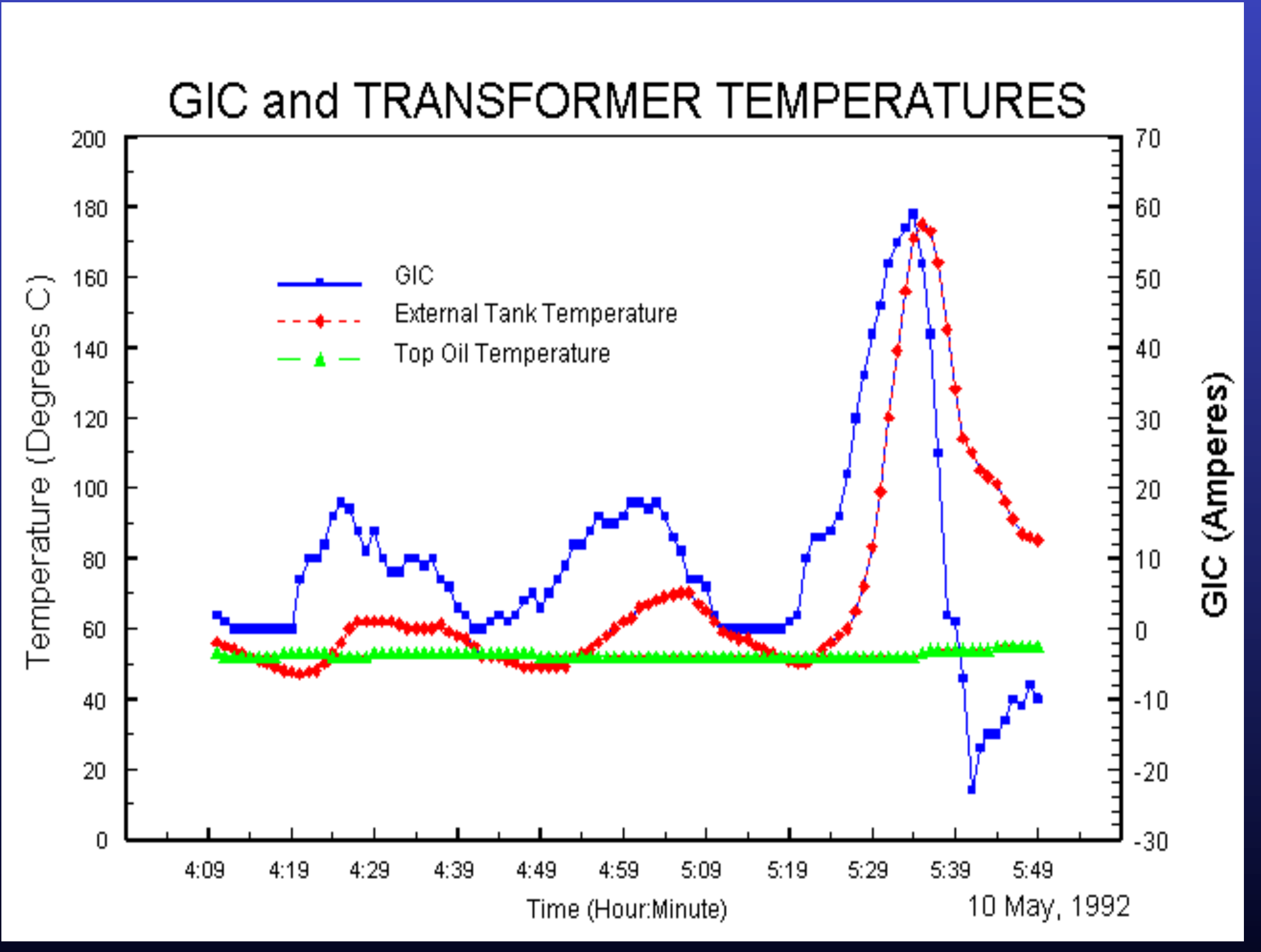
Lack of reactive power causes voltage collapse


Power Transformer Hysteresis Curve
Voltage
Current

# Increased Reactive Power Requirements



# Transformer Overheating



# Conclusions

- Calculation of GIC needs knowledge of
  geomagnetic disturbance,
  Earth conductivity,
  network impedances
- Simulation done assuming:
  uniform magnetic disturbance
  1-D Earth conductivity model
  resistive network
- Simulation use off-line for hazard assessment and in real-time for system monitoring


Thank you