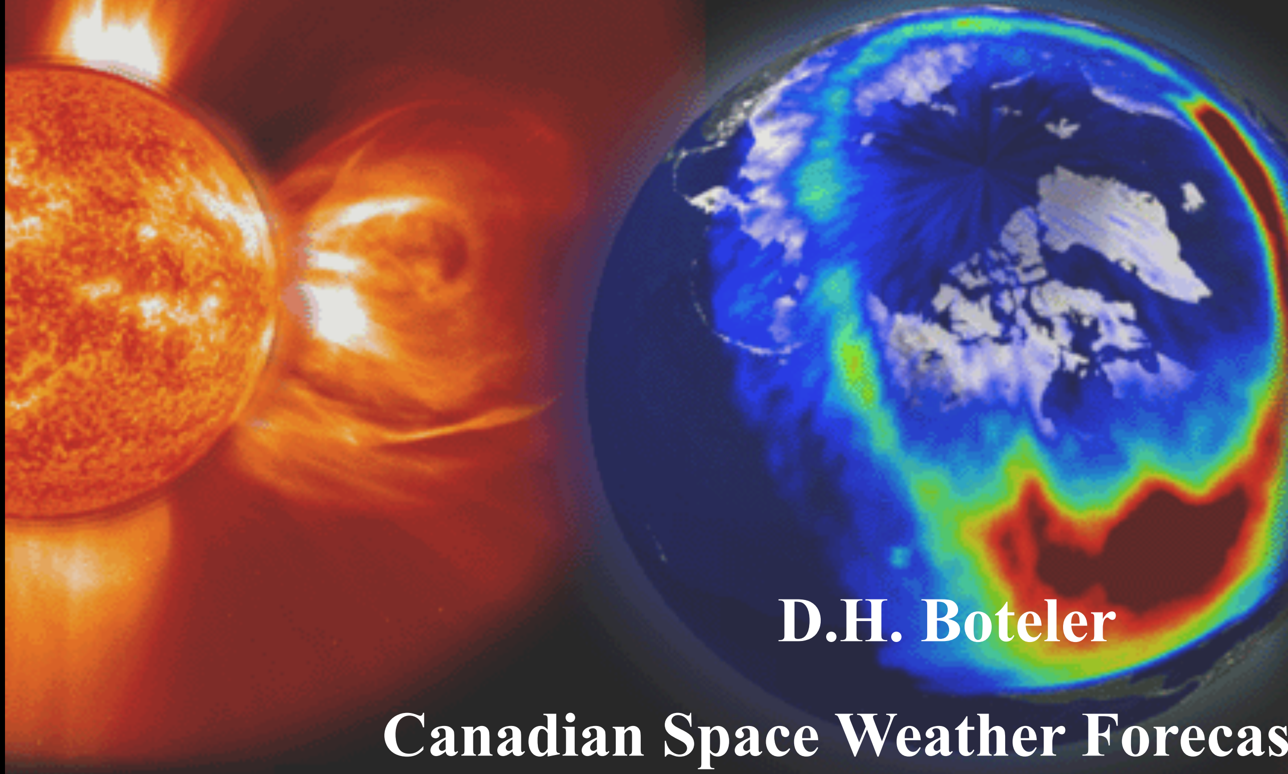
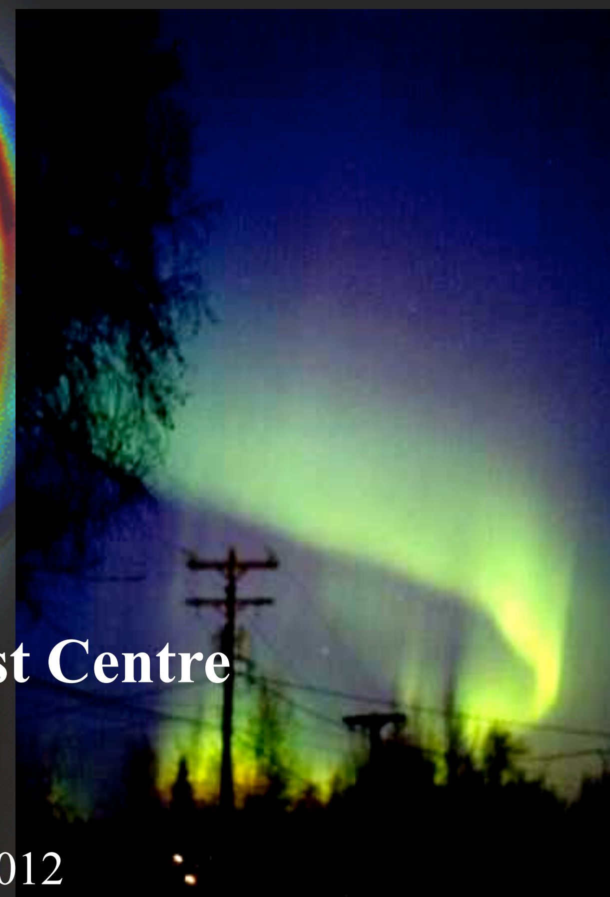
The Impact of Space Weather on the Electric Power Grid





D.H. Boteler

Canadian Space Weather Forecast Centre

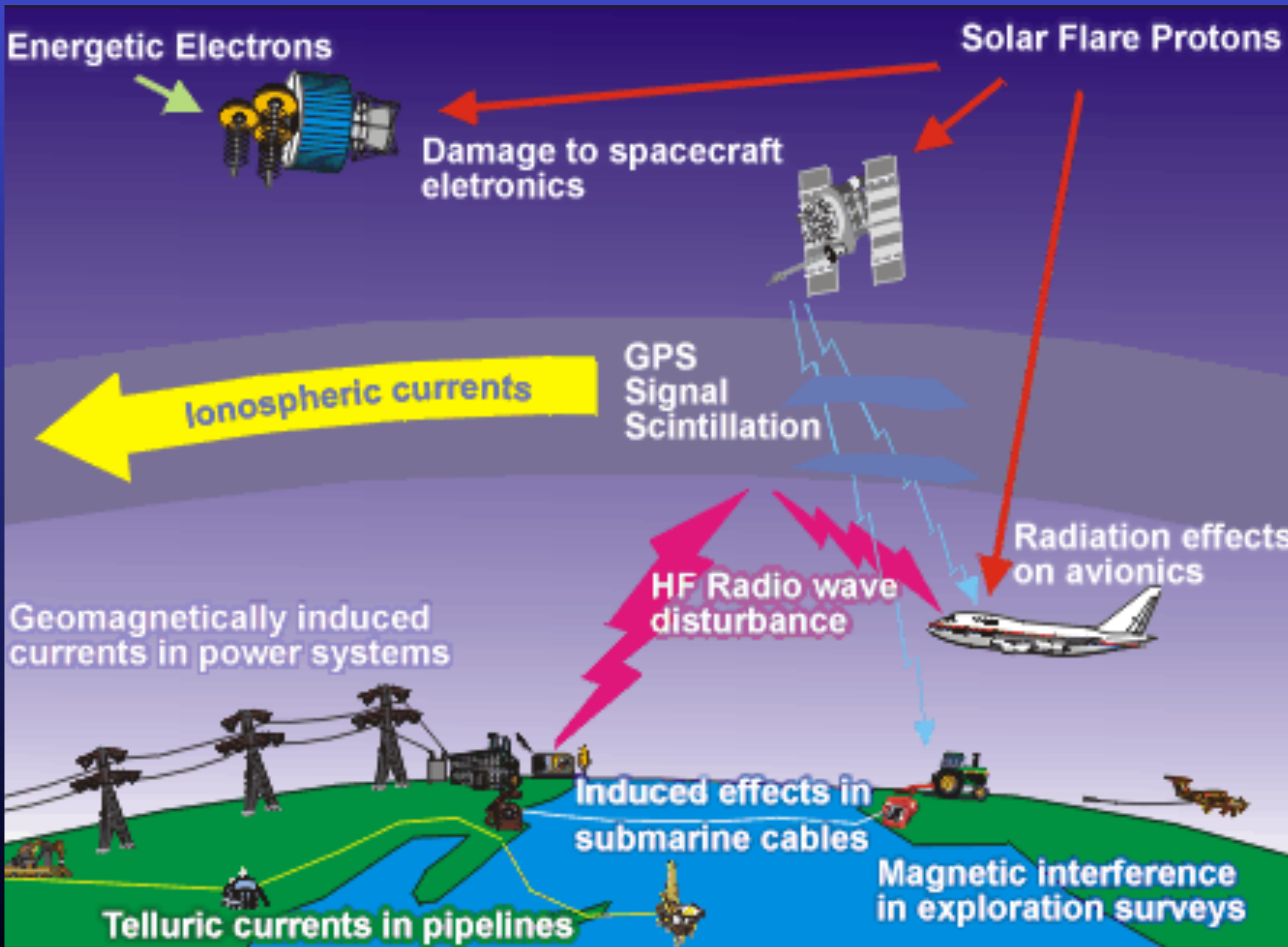
Heliophysics Summer School, June 2012

Outline

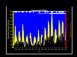
- What has happened
  - Telegraph
  - Power Systems
- How magnetic disturbances affect power systems
  - Characteristics of magnetic disturbances
  - Geomagnetic Induction
  - GIC flow through power systems
  - GIC impact
- What new knowledge is needed
  - "100 year" magnetic storm?
  - Limits to size of disturbances?
  - Improving predictions
- Assessing geomagnetic risk to power systems

Part 1. What has happened?

SPACE WEATHER EFFECTS ON MODERN TECHNOLOGY



Space Weather History



August 28-29, September 2, 1859

"I never witnessed anything like the extraordinary effect of the aurora borealis, between Quebec and Father's Point, last night. . . . so completely were the wires under the influence of the aurora borealis, that it was found utterly impossible to communicate between the telegraph stations, and the line was closed for the night."

Mr O. S. Wood, Superintendent of the Canadian Telegraph
(Prescott, 1866)

Observations made at Washington, D.C.,

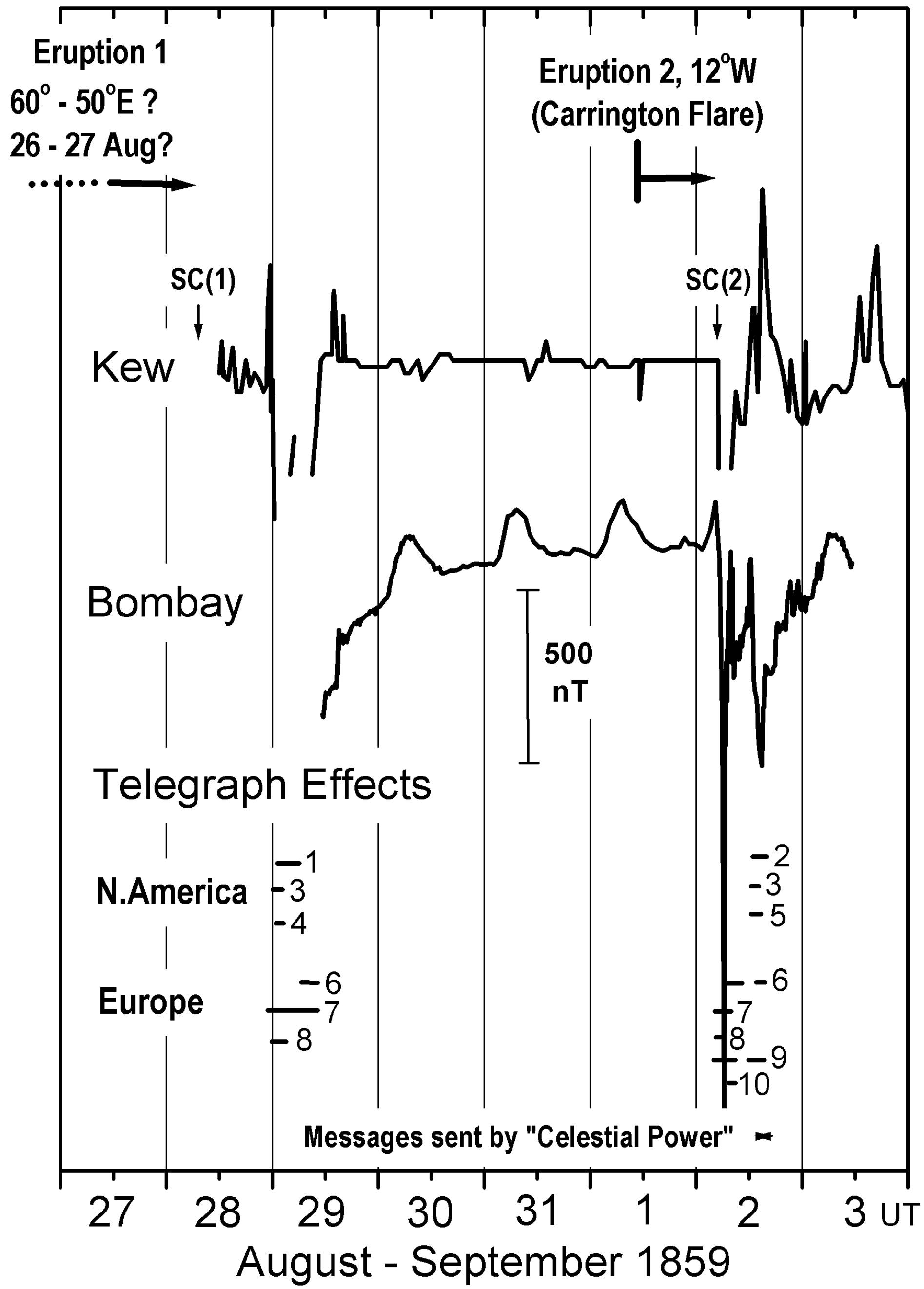
by FREDERICK W. ROYCE, *Telegraph operator.*

On the evening of Aug. 28th I had great difficulty in working the line to Richmond, Va. Happening to lean towards the sounder, my forehead grazed a ground wire. Immediately I received a very severe electric shock, which stunned me for an instant. An old man who was sitting facing me, and but a few feet distant, said that he saw a spark of fire jump from my forehead to the sounder.

Observations at Christiania, Norway,

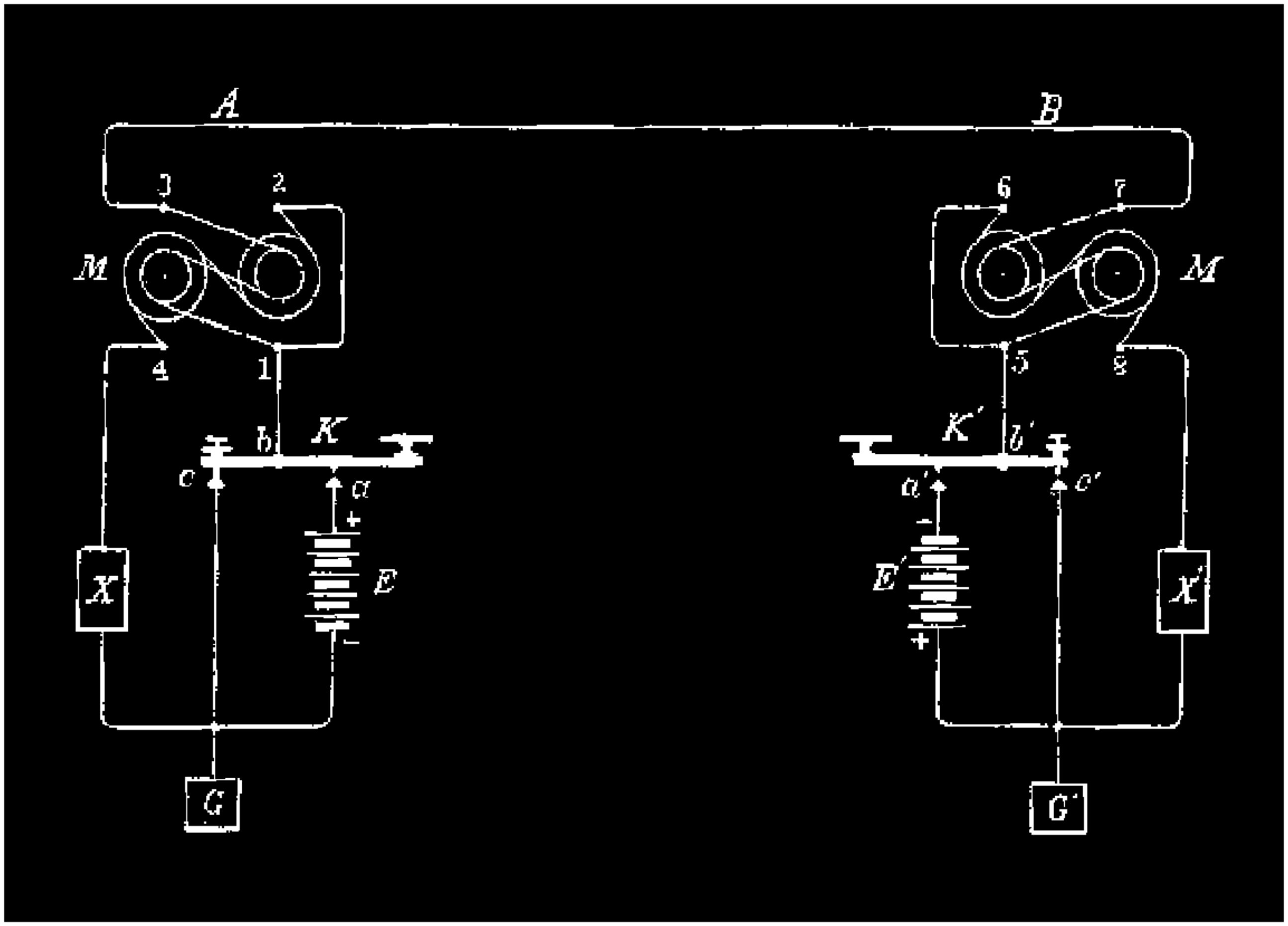
by Prof. CHRISTOPH HANSTEEN

The effect of this aurora upon the telegraph lines in Norway was much greater than in France and Germany. The effect was noticed from the opening of the stations at 7 A.M. On the 29th communication was interrupted till 11 A.M. on almost all the lines; and likewise Sept. 2d, but with a long repetition after 2 P.M.



Eruption 1
60° - 50°E ?
26 - 27 Aug?
Eruption 2, 12°W
(Carrington Flare)
SC(1)
SC(2)
Kew
Bombay
500
nT
Telegraph Effects
N.America
Europe
1
3
4
6
7
8
2
3
5
6
7
8
9
10
Messages sent by "Celestial Power"
27
28
29
30
31
1
2
3 UT
August - September 1859

Effects on the Telegraph System

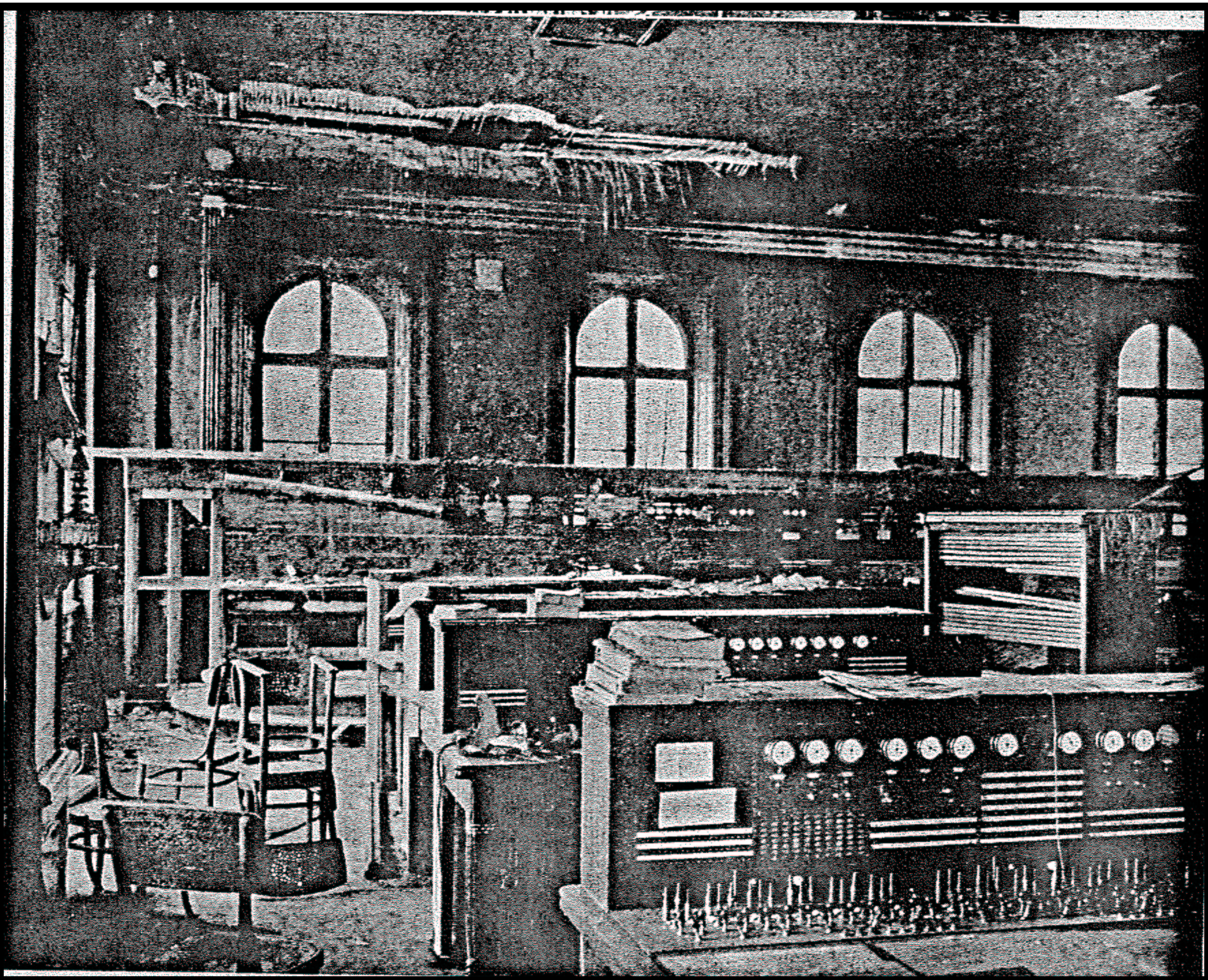


October 31, 1903

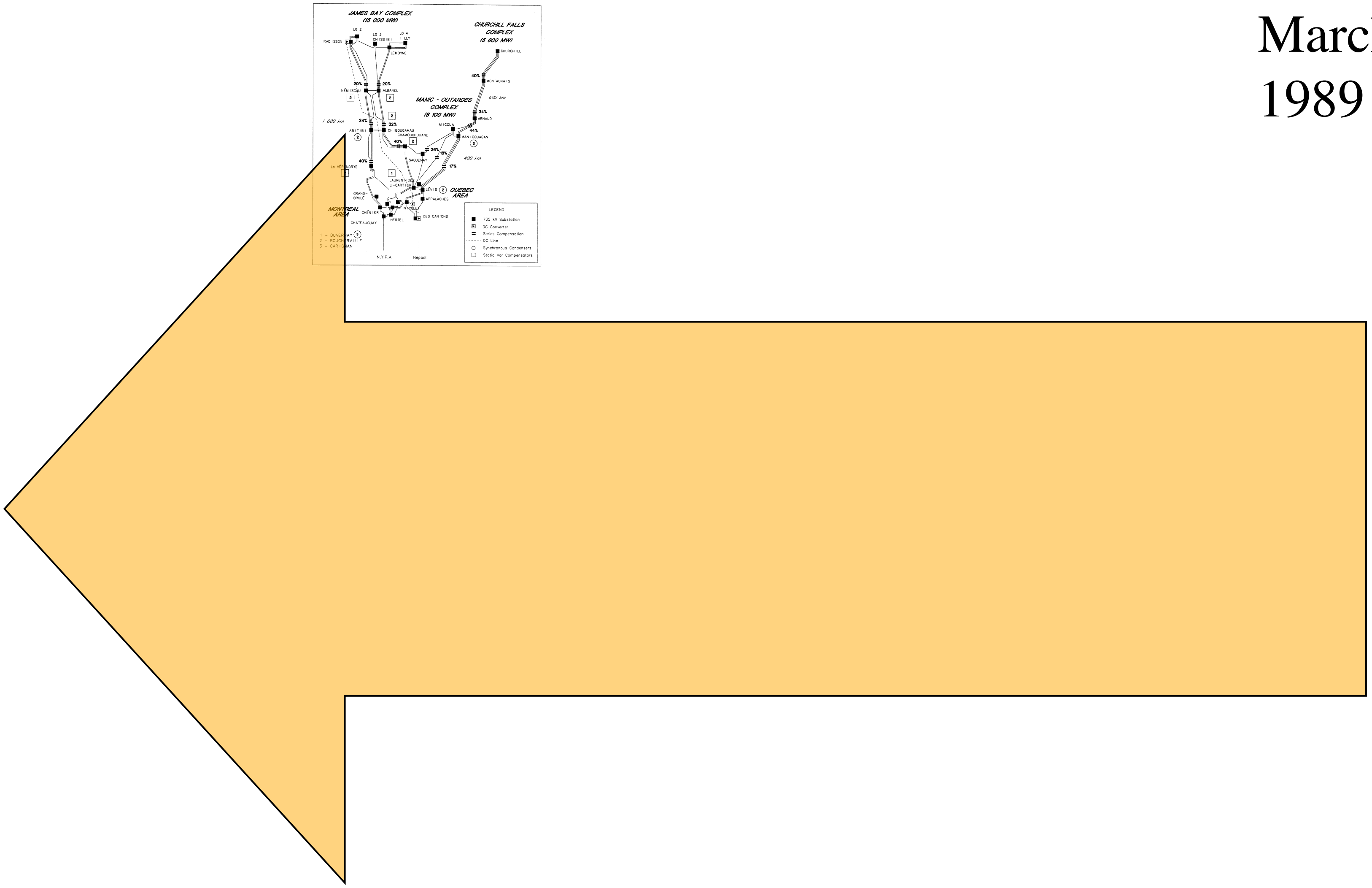
Lockyer (1903) reports that on October 31 practically the world's whole telegraph system was upset.

The book by V.V. Ryumin 'Talks on magnetizm' (Petrograd, 1925) comments on the strength of the storm in Russia and says:

> " … it even stopped the tram traffic."



Effects on Systems on the Ground



March 13, 1989

EARLY ED
The Gazette
MONTREAL

"Do not wait for extraordinary circumstances to do good; try to use ordinary situations."

We're sorry for the delay

Yesterday's power failure may have delayed delivery of your paper. We're sorry.

Before the blackout hit at 2:45 a.m., *The Gazette* had printed 125,000 copies. After power returned at 1:30 p.m., another 60,000 copies containing coverage of the blackout were printed for delivery to homes and stores.

About 70 per cent of subscribers received their copies in the morning as usual.

Hydro will

By SARAH SCOTT
Gazette Quebec Bureau

QUEBEC — The government will keep Hydro-Québec on a short leash, Premier Robert Bourassa said yesterday after calling in officials of the giant utility to account for the second province-wide blackout in a year.

Hydro will have to report monthly to the province on the progress of its $2-billion plan to halve the number of yearly blackouts by 1995, Bourassa said.

And the utility will have to speed up its plan to make the system more reliable, he

Hydro blames

Francine Perreault serves coffee by candlelight at L'Express D

Stocks plun

By JAY BRYAN
of The Gazette

North American stock markets plunged yesterday as inflation rates jumped, and economists quickly warned that more bad news is on the way in the form of higher interest rates.

Jittery investors dumped their stocks, causing the Dow Jones industrial average to plummet 48.57 points to 2292.14, its biggest drop in 11 months. The Toronto Stock Exchange's 300 index fell by 37.34 points to close at 3614.32.

At the same time, a round of hikes in mortgage rates spread to two more major banks yester one-year mo half a point t level in five y

Economists ness and cons

In Canada, was up by 0.7 ing the infla months to 4.6 since July 19 rate was 4.3

But observ reacting mos announceme Producer Pri

Consumers fear Hy

PRISONERS OF POWER

ROBERT BOURASSA
To keep utility on short leash

By PEGGY CURRAN
of The Gazette

From his office atop Complexe Desjardins, John Ciaccia has a bird's-eye view of Hydro-Québec's green fortress on René Lévesque Blvd.

The energy minister jokes about keeping a telescope by his desk to peer through the windows of the troubled utility, to see what it's up to.

But after two provincewide blackouts in less than a year, frustrated customers and energy critics aren't laughing. And they're frankly skeptical of Ciaccia's — or anyone else's — ability to rein in the mammoth power company, the second largest industrial employer in the province behind BCE Inc. and ahead of Stein-

Greenhouse effect

SATURDAY
The Gazette

"The real price of everything is the toil trouble of acquiring it"

SECTION C
The Gazette BUSINESS
MONTREAL, TUESDAY, MARCH 14, 1989

Maine won't reconsider Quebec power

By SHIRLEY WON
of The Gazette

The Maine Public Utilities Commission yesterday turned down a petition to reconsider its decision against the purchase of $4 billion of power from Hydro-Quebec.

The petition was made last month by Maine's public advocate, Stephen Ward, who represents consumers in state proceedings on utility issues. Ward could not be reached for comment.

The Maine utilities commission in January rejected the contract, which was signed between Central Maine Power Co. and Hydro-Québec for the sale of 300 megawatts of power.

Jacques Guevremont, executive-vice-president of external sales for Hydro-Québec, said he is disappointed by the decision but stressed in a telephone interview yesterday that the "deal is not dead yet."

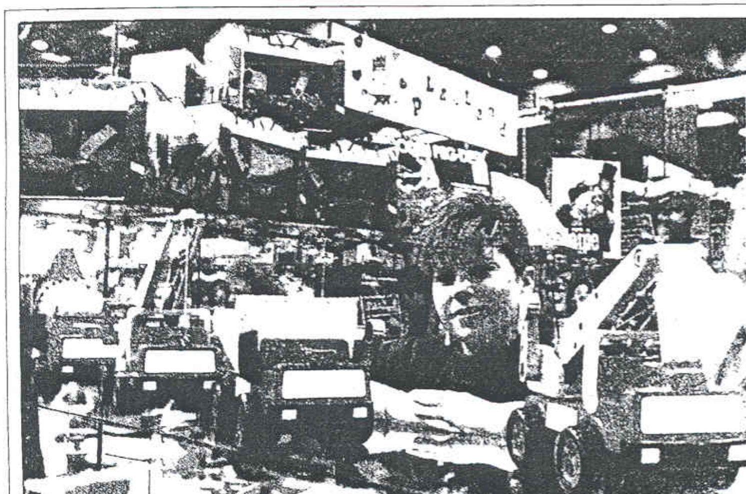
Guevremont said there can still be appeals to the Maine Supreme Court by parties involved in the original hearings, or possibly a new petition by Central Maine Power to the commission.

In voting down the contract two months ago, the commission said the state's largest utility had not adequately explored alternative energy sources — such as cogeneration or small power plants — and energy savings from conservation.

Charles Jacobs, administrative director for the commission, said the decision to reject reconsideration was 2-to-1, the same margin as the January vote. He said reasons for the rejection will be issued later.

The Maine power contract, signed last July, could have been worth up to $15 billion for Hydro-Québec if Central Maine exercised options to buy more power over 29 years.

The Maine contract — along with contracts with utilities in Vermont and New York — helped to trigger last spring's announcement by Premier Robert Bourassa of the second phase of the James Bay La Grande hydro complex.



Gazette

Robin Levinson of R.F. Enterprises works at one of the booths at Spring Gift Show at Place Bonaventure.

Jumbo colored blocks are hot in toyland

By JAN RAVENSBERGEN
of The Gazette

Robin Levinson let out a groan yesterday afternoon as the lights went out at the Montreal Spring Gift Show at Place Bonaventure.

But just as quickly they came on and it was back to business for Levinson and the more than 1,000 others handling the roughly 325 booths at the trade-only gift show, which continues until tomorrow at 5 p.m.

Levinson's enthusiasm was undimmed. The fast-talking administrative co-ordinator for Montreal toy importer and wholesaler R.F. Enterprises Inc. quickly resumed her explanation of why she's so certain her employer's sales will more than double this year.

"Eighty per cent of our toys are made in East Germany. People hear it's East German, they won't go there for their summer vacation.

"But they'll buy the little workbench for $7.90" wholesale from R.F. — and sell it in Baie Comeau, Winnipeg and points between for $12.99 retail, or perhaps lower.

"Jumbo colored blocks. Everybody wants them," Levinson asserted. "Anything in wood is hot, very hot." Much of it, the wooden stuff from R.F. anyway, is now imported from Chile and Brazil.

"On price point, we can beat Taiwan any day," chimed in R.F. sales representative Femiria Nanni. "They might be able to knock us off ... a year or two down the line ... but "we'll find something else."

After a quick phone call to "Elizabeth in the office" to see how far she could go on numbers, Levinson confided that "last year was good. We did over a million dollars in sales. I know we're gonna double that this year."

Even triple ... interjected Nanni, "with all the majors" the company has been signing up ... ing Zellers Inc.

Companies tally the cost of blackout

By FRANÇOIS SHALOM and CRAIG TOOMEY
of The Gazette

Stalled production, idled workers and spoiled products caused by yesterday's province-wide blackout cost Quebec businesses at least tens of millions of dollars.

The power failure also slashed trading volume at the Montreal Exchange, prevented brokerage firms from operating normally and shut down automated banking machines and bank branches across the province for most of the morning.

The General Motors car-assembly plant in Boisbriand lost production of $6.4 million worth of automobiles, company official Paulette Charbonneau estimated.

"You're talking about 356 cars (built during an eight-hour shift) at about $18,000 each," Charbonneau said.

"And this doesn't include the salaries of the people we sent home," she said.

With average wages at about $16 an hour, those 1,750 workers collected some $224,000 in pay.

The Montreal Exchange, located in Place Victoria, was forced to operate on emergency power until regular power was restored at about 1:15 p.m. Until then, most trades had to be completed manually, prompting many local brokerage firms to divert as many transactions as possible to the rival Toronto Stock Exchange.

By the end of the trading session, only 1.8 million shares traded hands on the exchange floor, about a third the normal number. ME official Marcel Barthe couldn't provide an estimate on the damages, but noted the ME breaks even at around the 5-million-share mark.

"We're surprised we were one of the latest (buildings) to be back on track," said an exasperated Barthe, suggesting the ME might have a word with Hydro-Québec about its priorities for restoring power.

'Day was writeoff'

David Bérubé, a broker at Dean Witter Reynolds (Canada) Inc., described the day as "somewhat of a writeoff." Computers giving up-to-date stock quotations were out of commission at brokerage firms across the city, forcing brokers to obtain prices by telephone.

Sidbec-Dosco Inc., a Quebec-owned owned steel company with three plants in the province, said it will probably lose more money than million. "All the steel that was ready on the line in the hot rolli mills is now scrap," LeBoutill said. "It's gone."

Dale Coffin, an official of mini giant Noranda Minerals Inc., said t power failure would cost Norand copper factory in Montreal's ea end between $200,000 and $300,00

He said the disruption also "hac major impact on our (zinc produ ing) operations in Valleyfield" b couldn't provide an estimate losses. Three of four roasters where zinc concentrate is heated 1,800 degrees to extract impurit are down in Valleyfield and sta ing them up again will take ab three days, Coffin said.

Michael Provencher, an offic for Cascades Inc., a pulp and pa company based in Kingsey Fal said the power shutdown would c his company between $200,000 a $300,000. He noted the amou doesn't include salaries.

Backup generators

Agropur, Quebec's biggest dai co-operative, said backup generat maintained normal operations at 26 Quebec plants, which produce variety of milk, cheese, yogurt a ice cream. "If we didn't have eme gency power we would have lost lot of money," said relieved co-op ficial Ken McCaughey.

But Molson Breweries of Cana Ltd. wasn't as fortunate. Robe Presseau, vice-president of produ tion, said the bottling line at t company's Notre Dame St. plant w paralysed until about 1:15 p.m. during the day's output by an es mated 50,000 cases of beer.

But Presseau said there's no d ger of a beer shortage because shortfall will be made up by add extra shifts during the next f days.

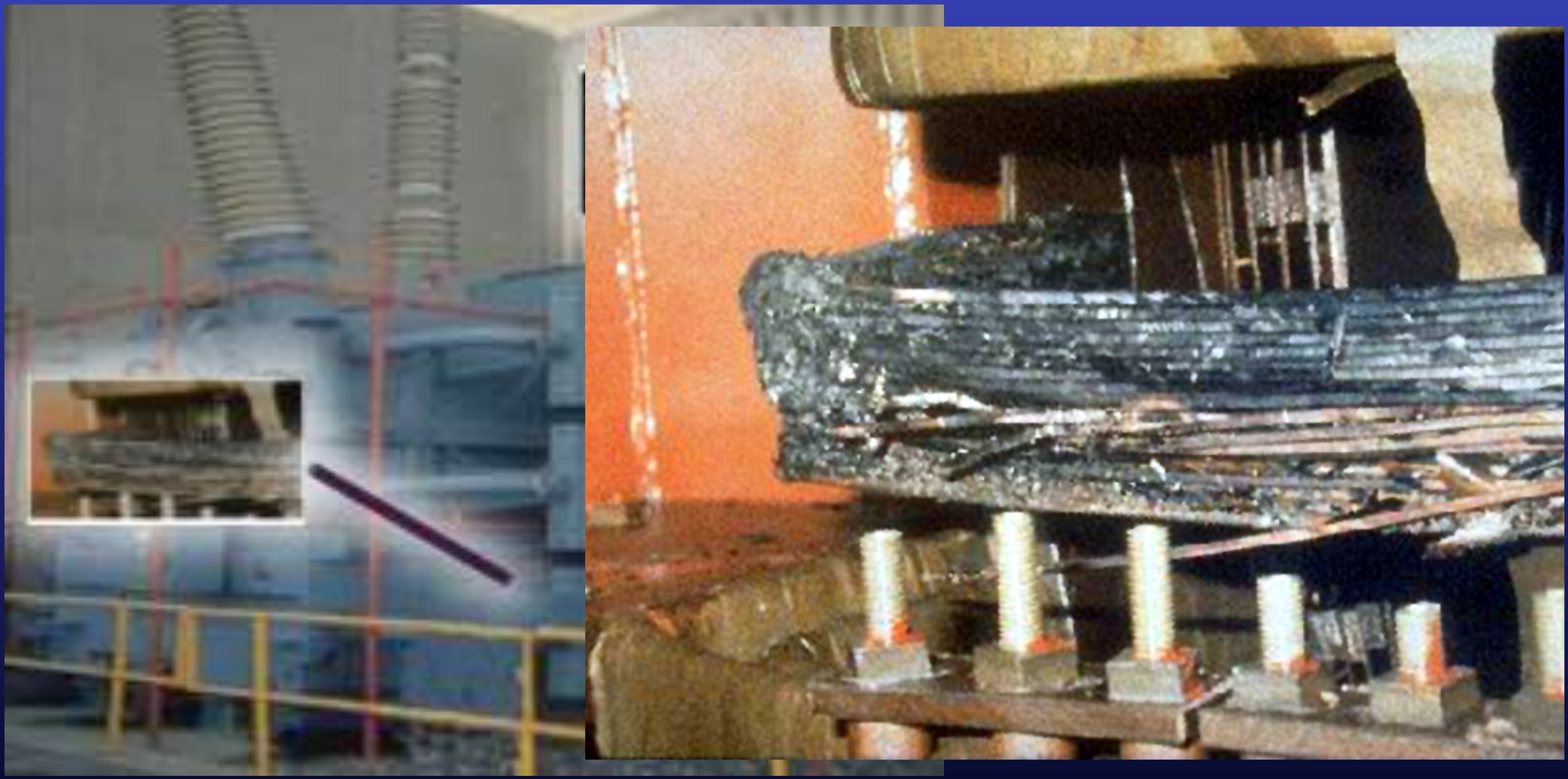
Patrice Bourgeois, president aluminum consortium Aluminerie Bécancour Inc. near Trois Rivier said the company had lost two ho of production time. The alumin industry is humming at 97-per-c capacity, and lost production can be made up.

Montreal-based Alcan Alumini Ltd. was minimally affected by disruption, said official Fernand Clerc. Alcan produces 2,000 m gawatts of electricity for its own in the Lac St. Jean region, said Clerc.

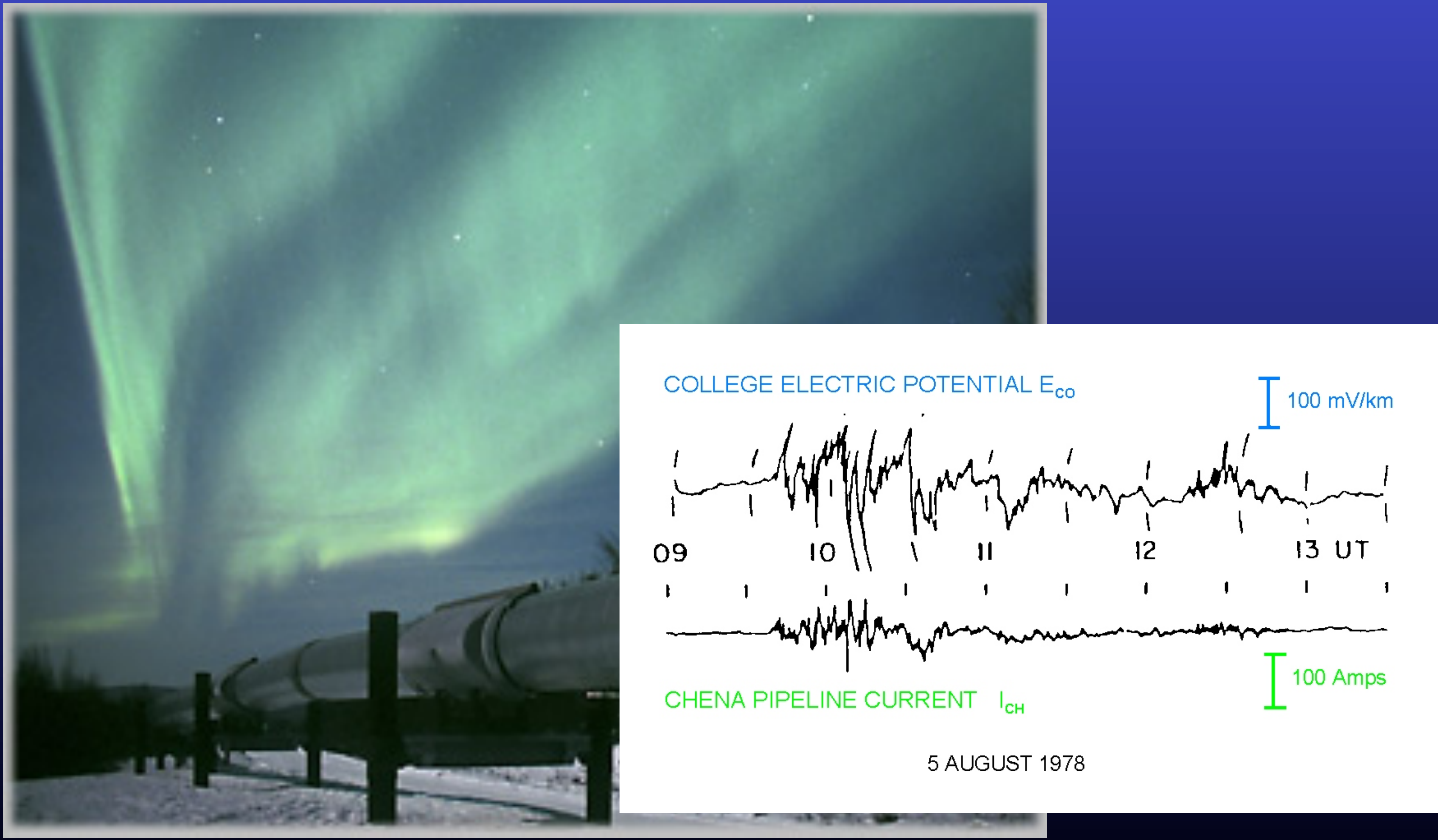
In fact, Alcan has an agreem with Hydro-Quebec to provide provincial utility with any surp

Ottawa lifts ban on some Chilean

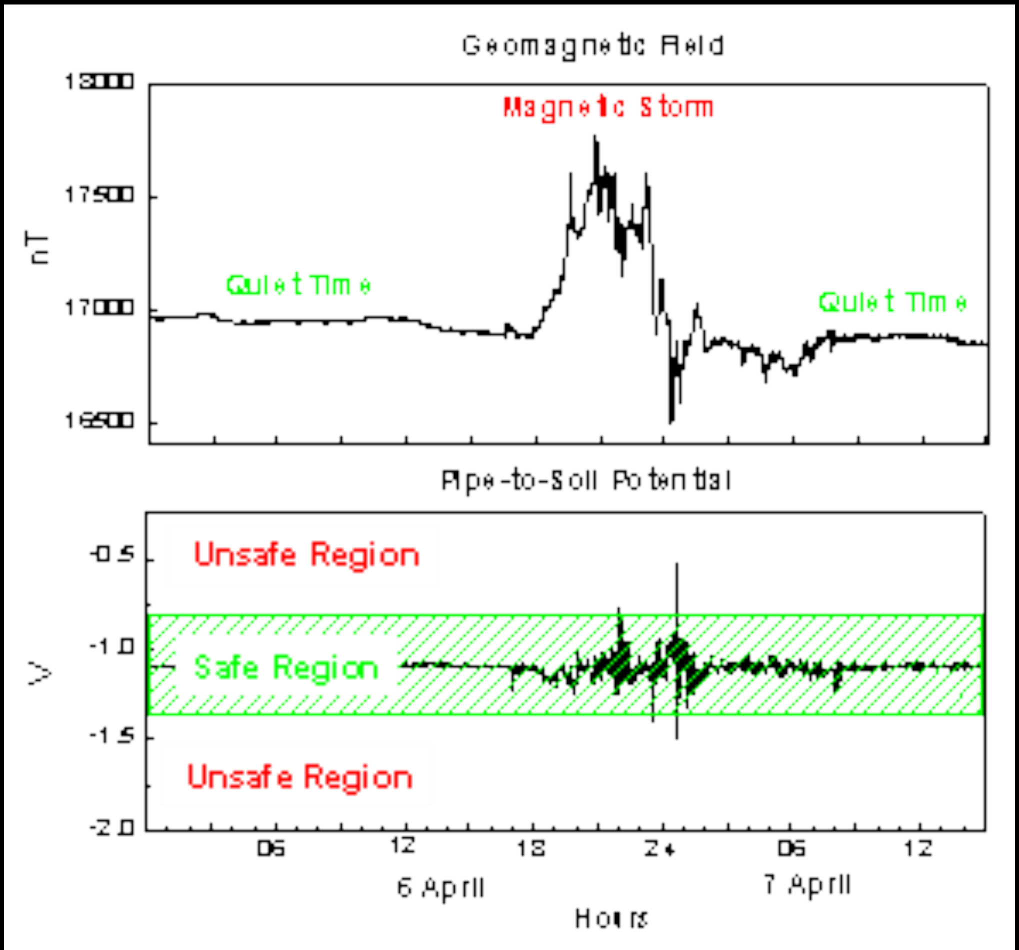
Transformer damage in USA



Geomagnetic effects on pipelines



Geomagnetic effects on pipelines

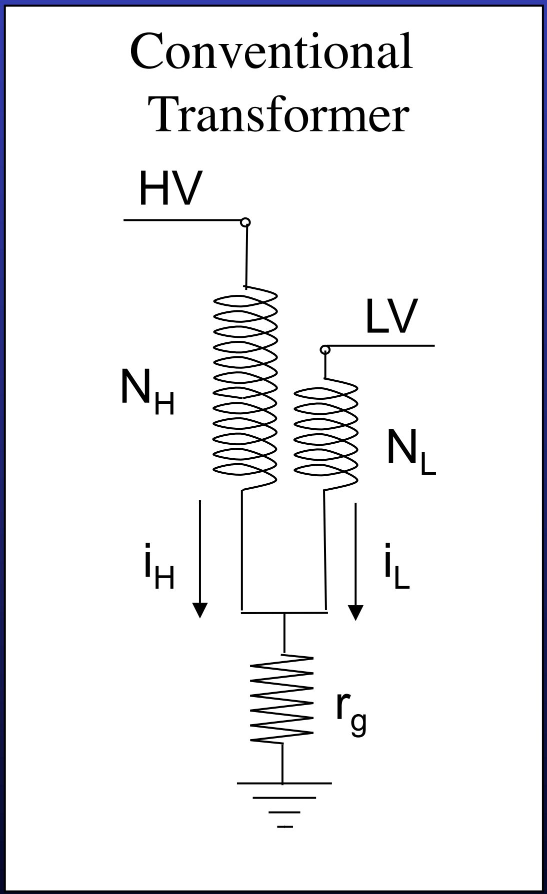


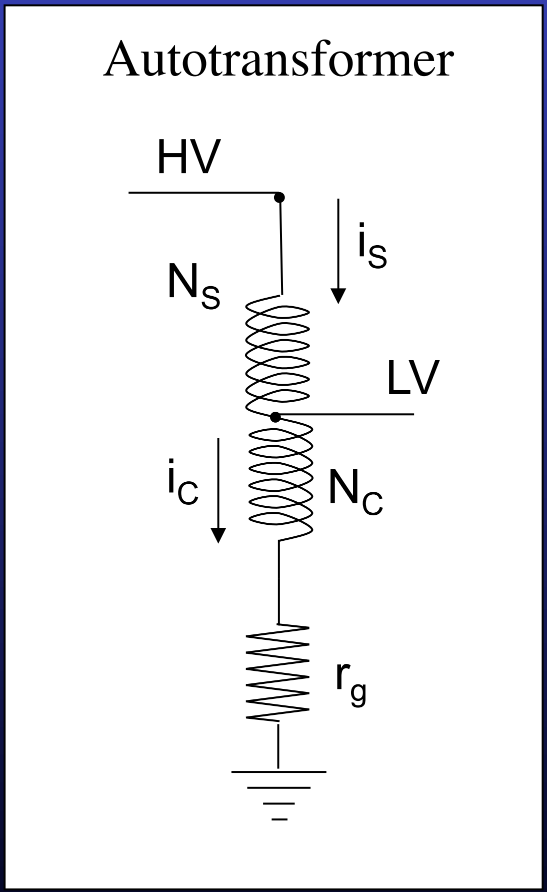
Seager, after tests on 522 km cathodically protected pipeline in Canada, 1986

"telluric related corrosion can override any standard corrosion prevention system and cause pipe perforation in unacceptably short periods of time"

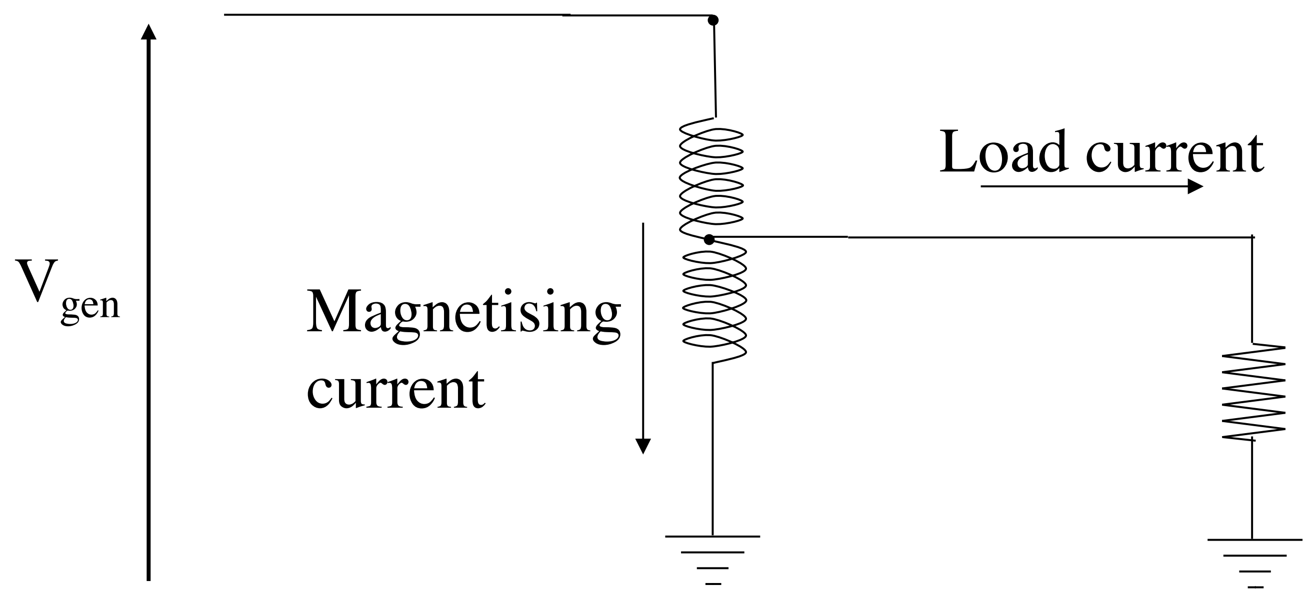

Part 2. How magnetic disturbances
affect power systems

Why do power systems use transformers?





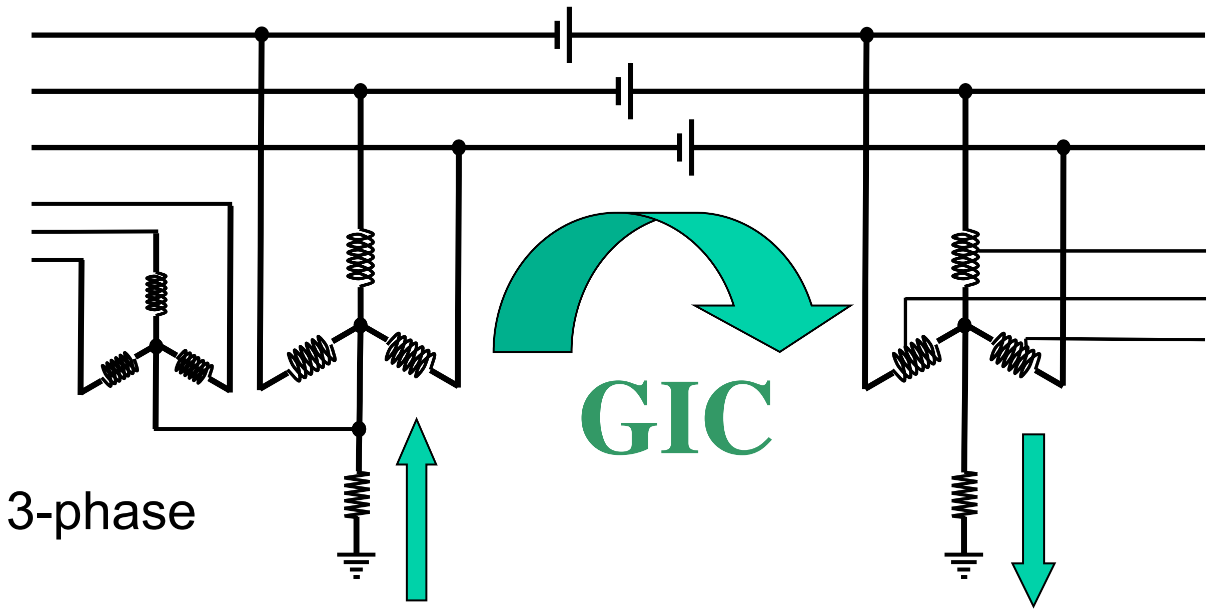
Real Power and Reactive Power



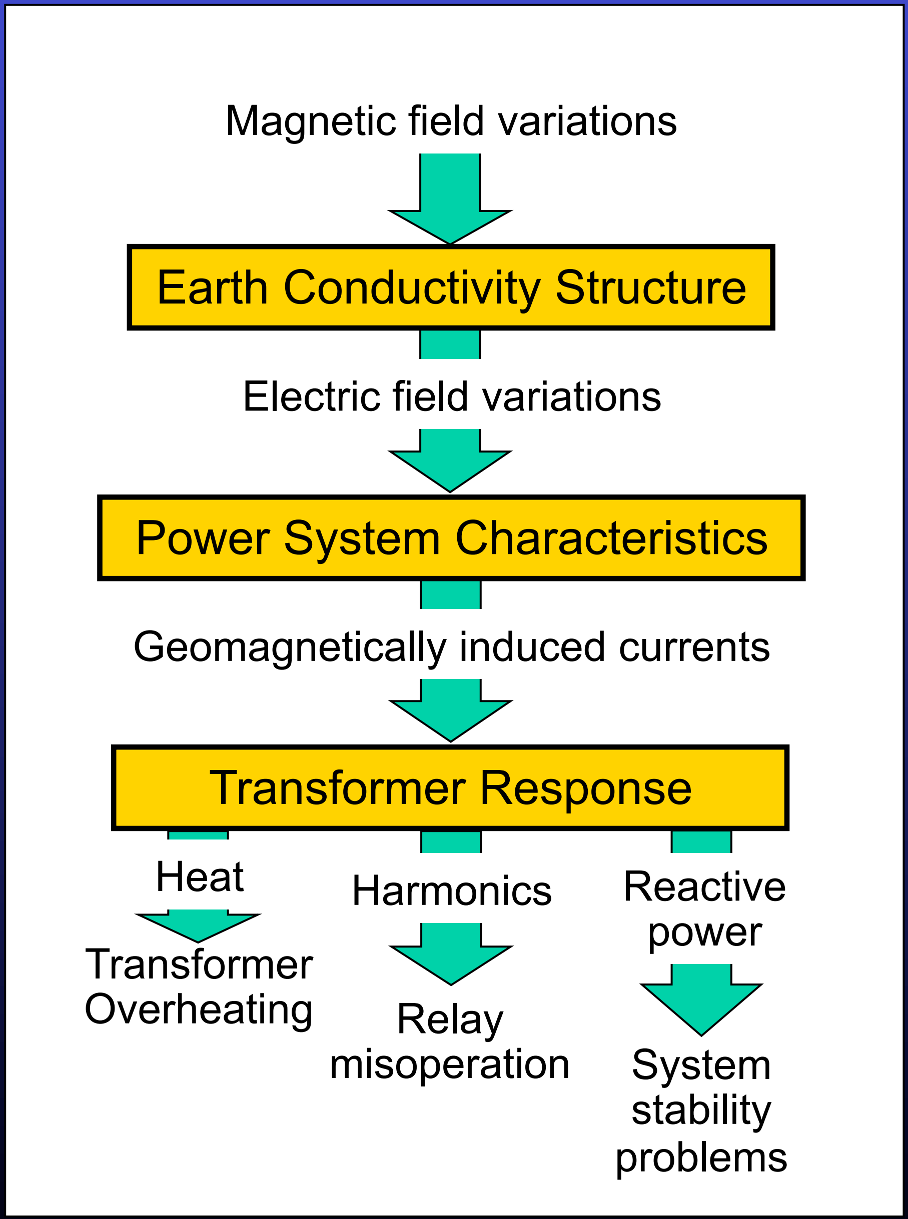
$W = V.I_{load}$

$VAR = V.I_{mag}$

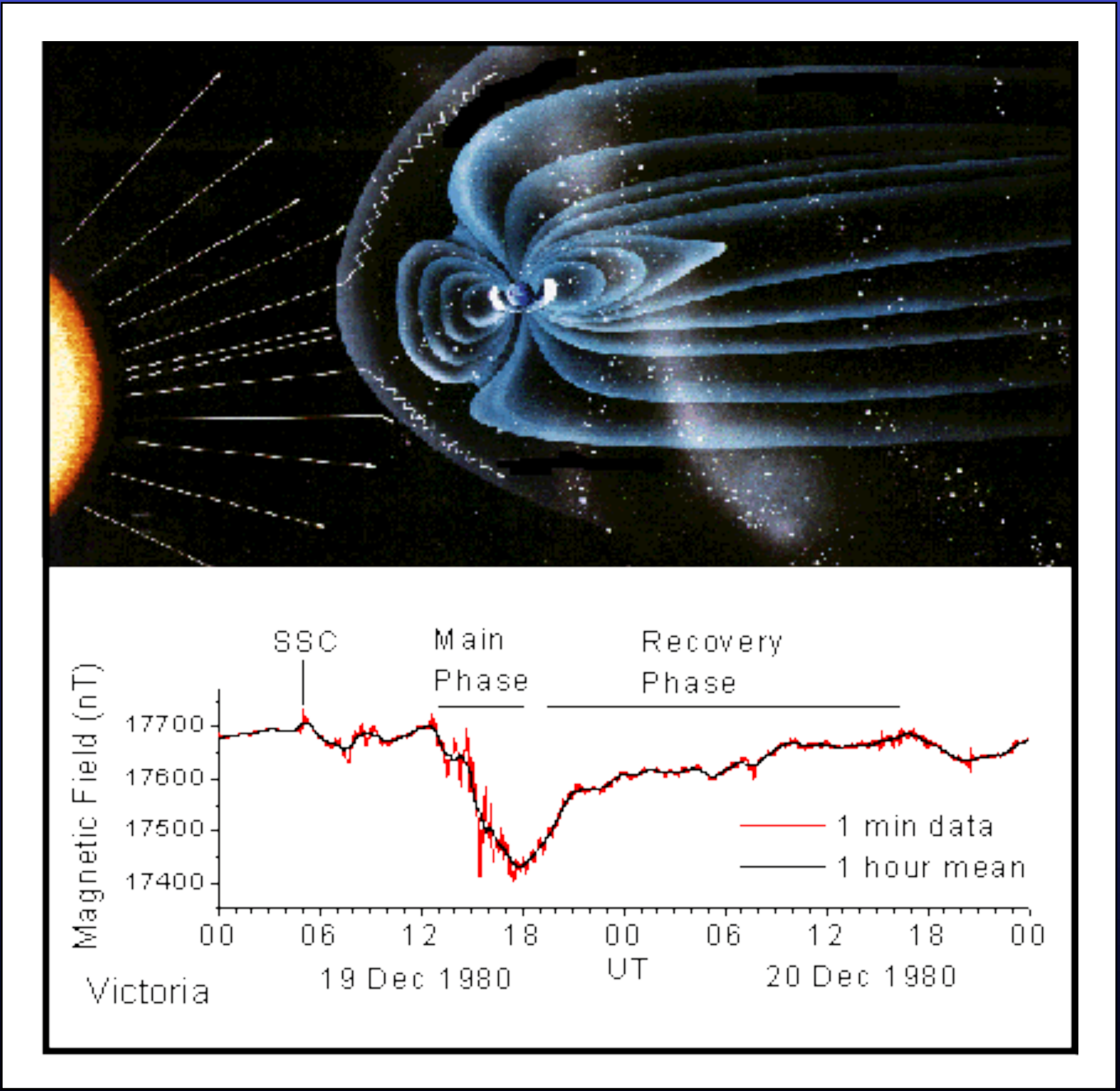
Power Systems use 3-phase Alternating Currents



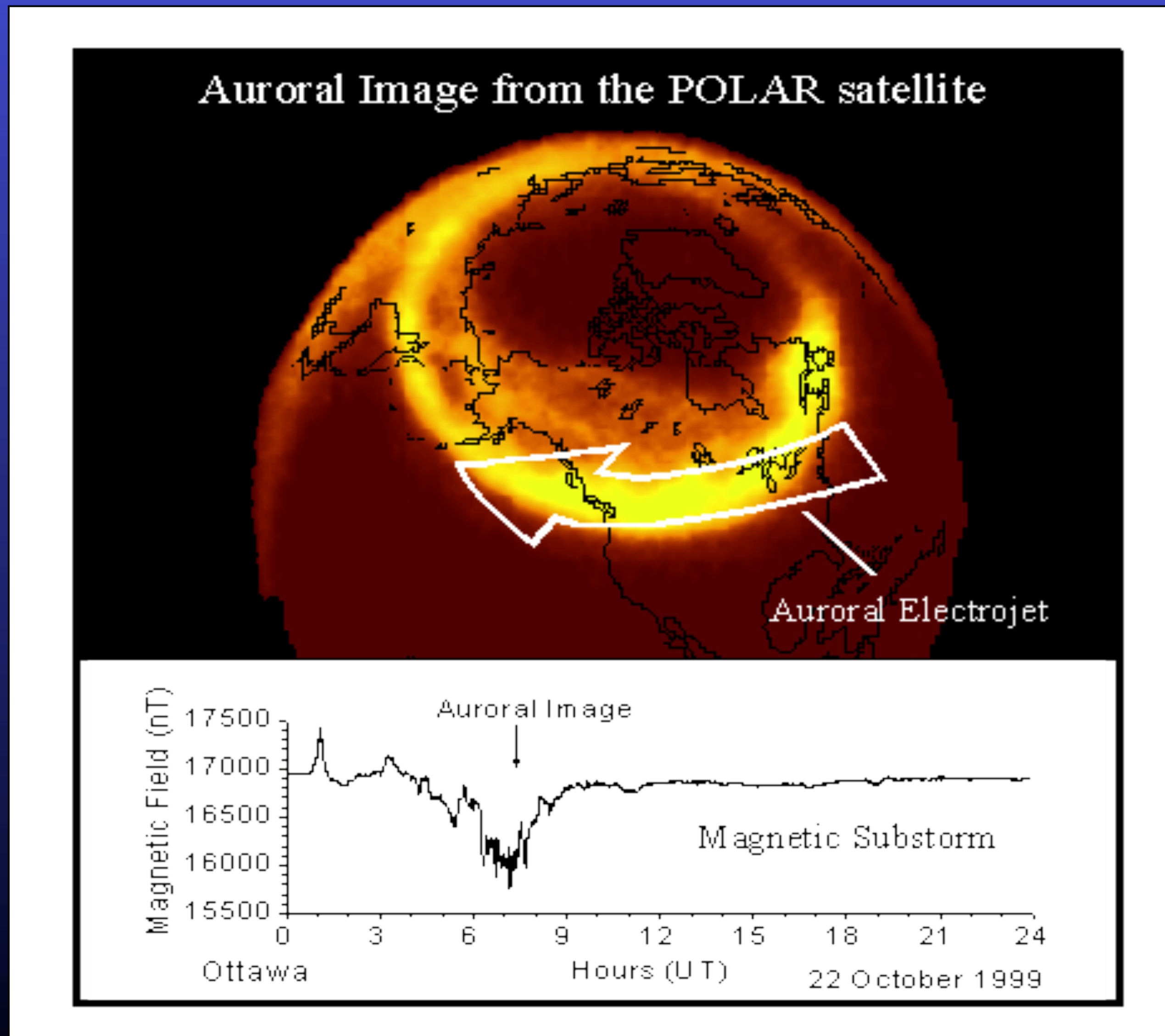
How magnetic disturbances affect power systems



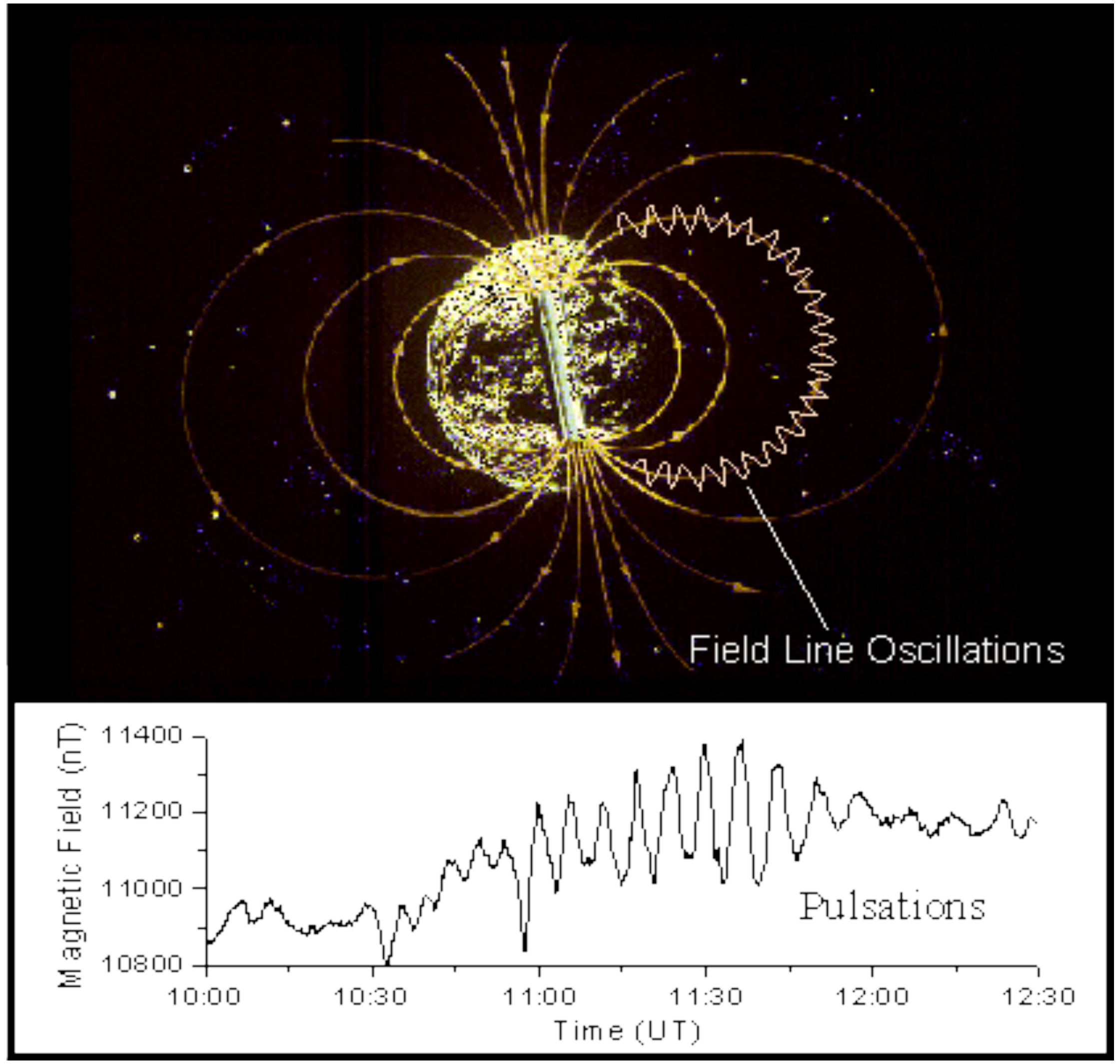
Magnetic Storms

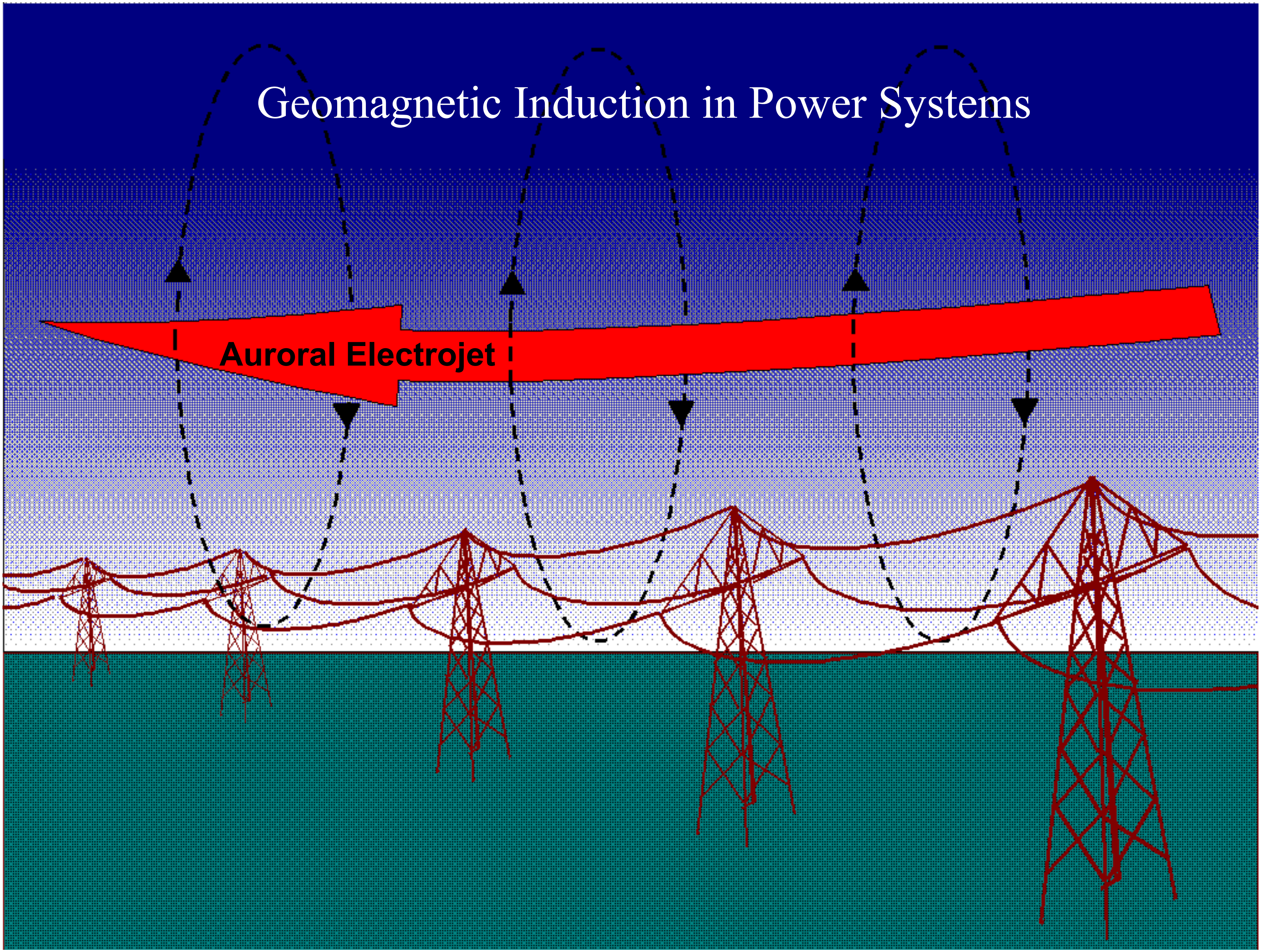


Substorms

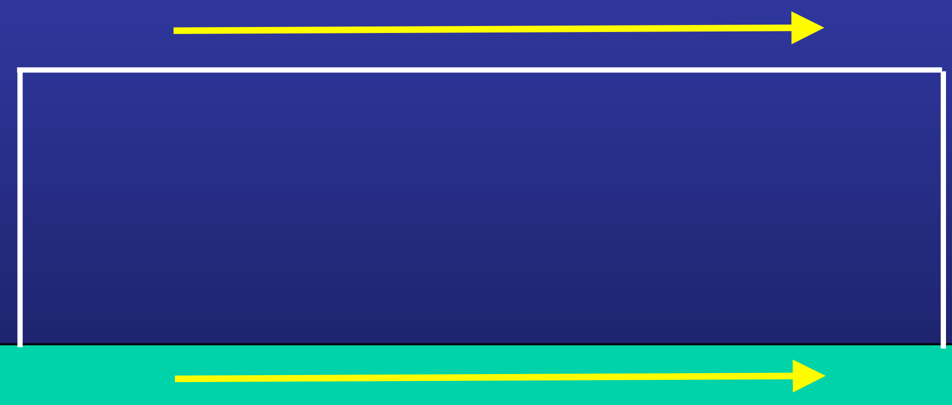

Auroral Image from the POLAR satellite
Auroral Electrojet
Auroral Image
Magnetic Field (nT)
17500
17000
16500
16000
15500
0
3
6
9
12
15
18
21
24
Magnetic Substorm
Ottawa
Hours (UT)
22 October 1999

Pulsations


Field Line Oscillations
Magnetic Field (nT)
11400
11200
11000
10800
10:00
10:30
11:00
11:30
12:00
12:30
Time (UT)
Pulsations


Geomagnetic Induction in Power Systems
Auroral Electrojet

Geomagnetic Induction in a Power System



$$\oint \mathbf{E} = \frac{d\mathbf{F}}{dt} = 0$$

Geomagnetic Induction

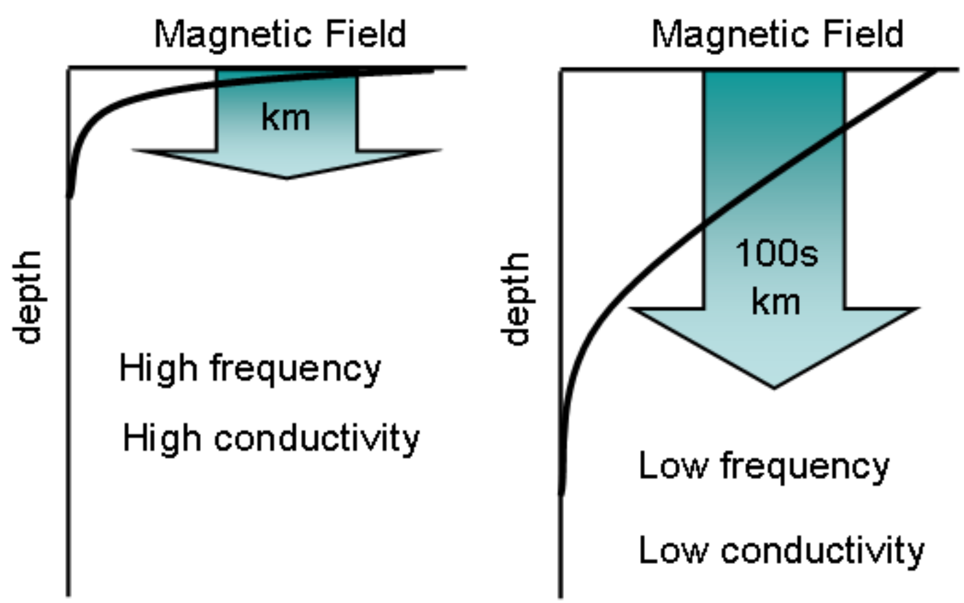
$E \neq dB/dt$

Induced currents create magnetic fields

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

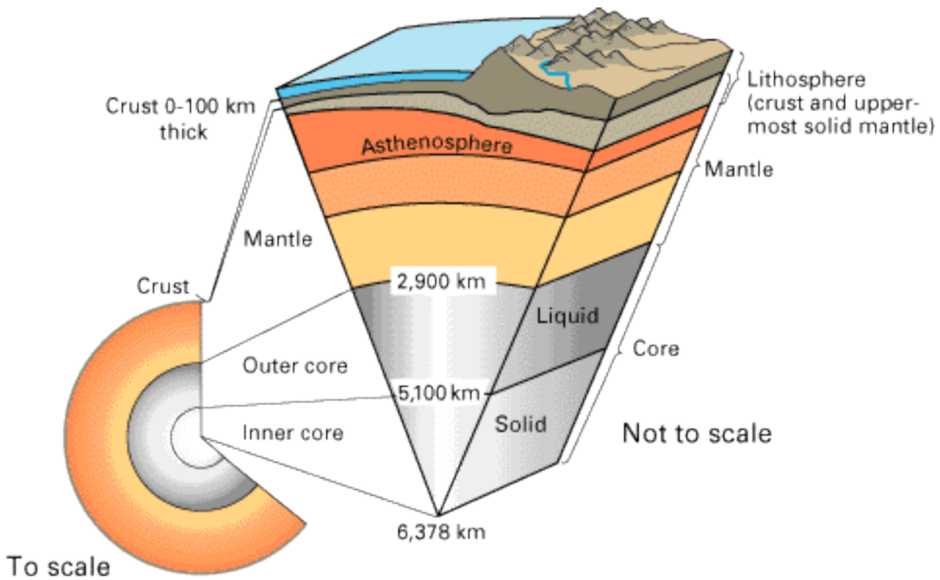
Skin depth

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

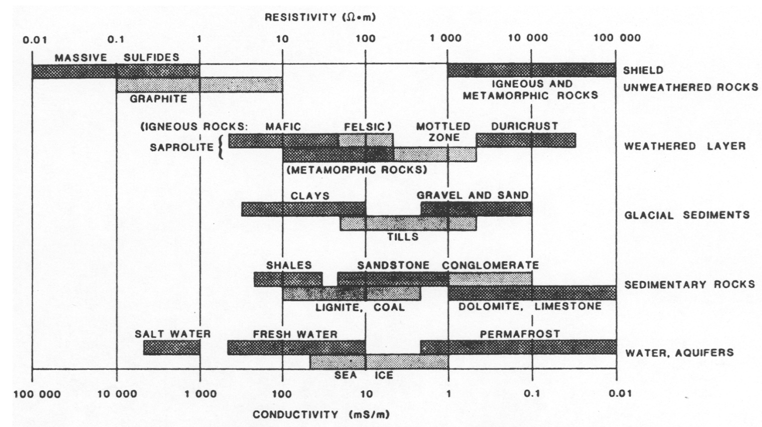


Earth Conductivity Structure

Earth Structure



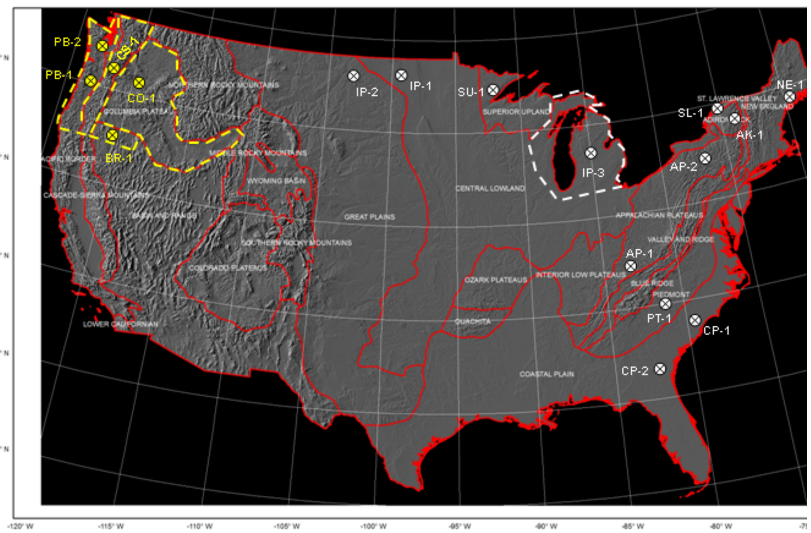
Rock Resistivities

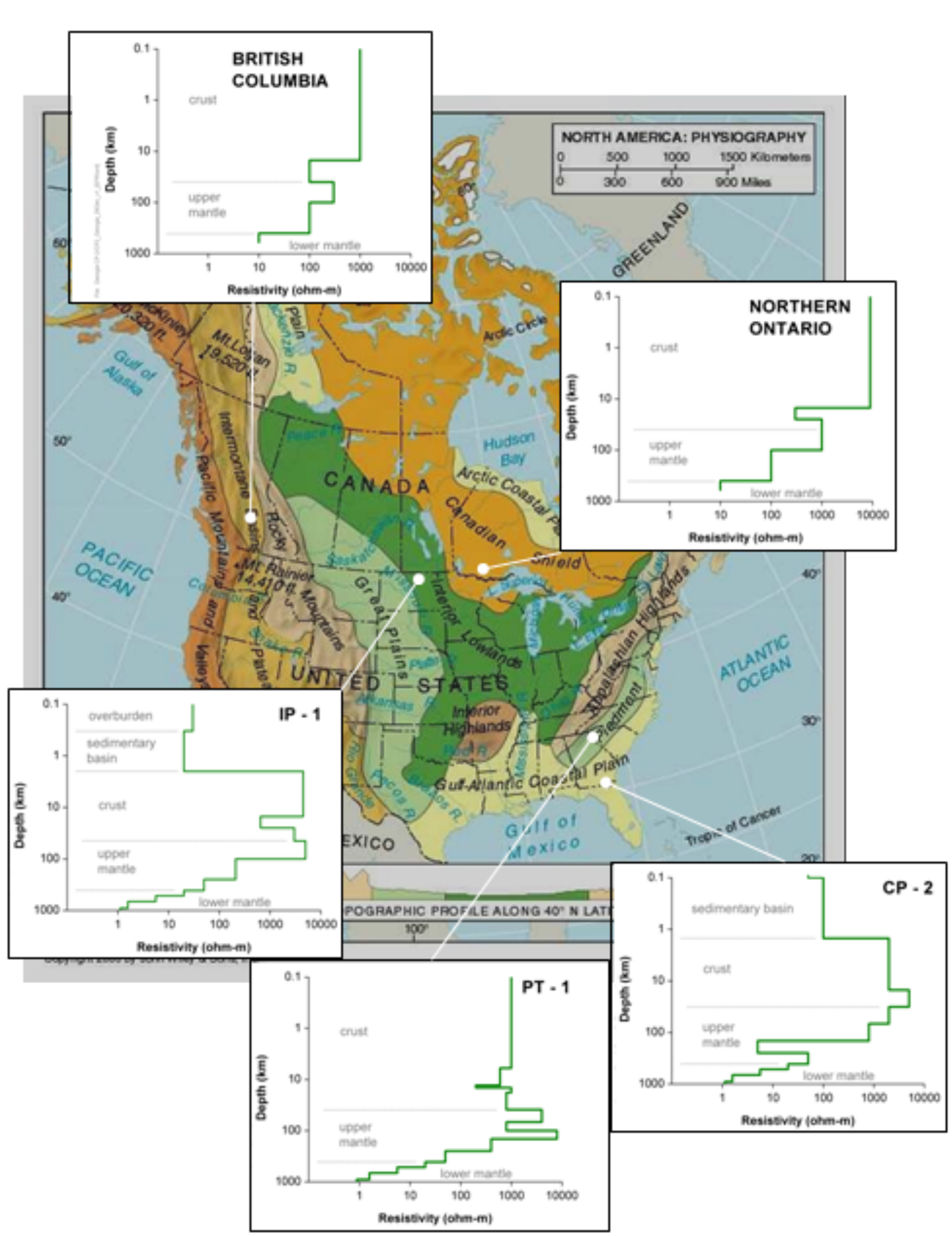


Earth Models

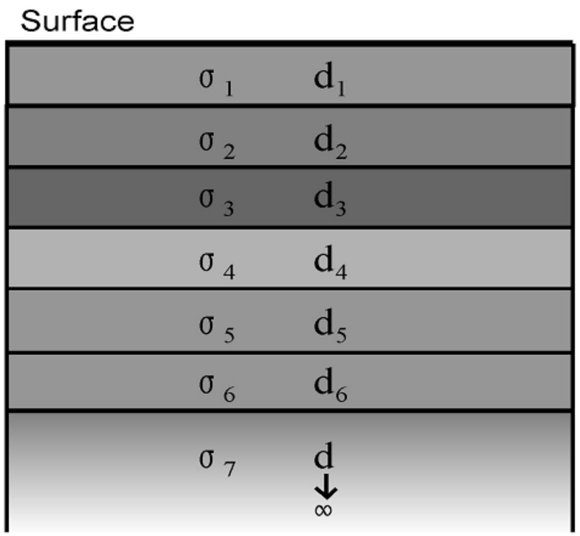
Examples of 1-D Conductivity Models

Location of 1D Earth Resistivity Models
with respect to Physiographic Regions of the USA





Calculate Earth Response



μ – permeability

ω – frequency

Z_n – impedance in layer n

σ_n – conductivity layer n

d_n – depth of layer n

k_n – propagation constant for layer n

Recurrence Relation

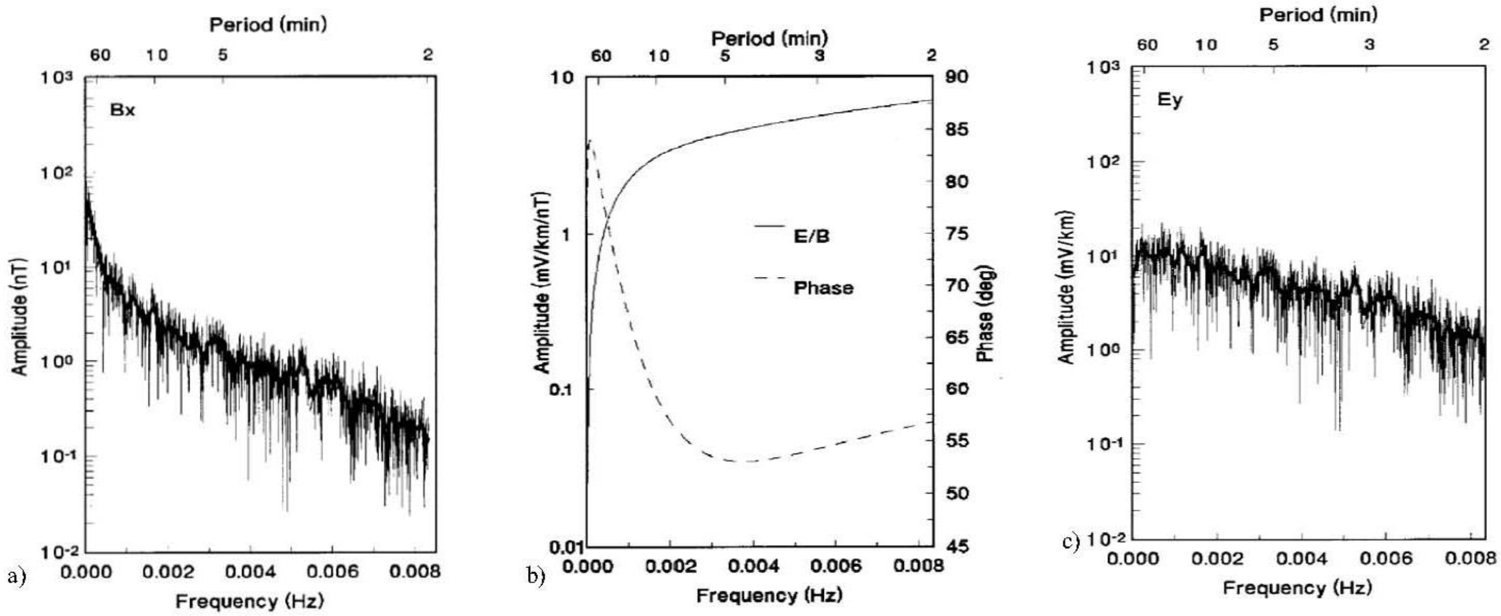
$$Z_n = i\omega\mu\left(\frac{1 - r_n e^{-2k_n d_n}}{k_n(1 + r_n e^{-2k_n d_n})}\right)$$

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

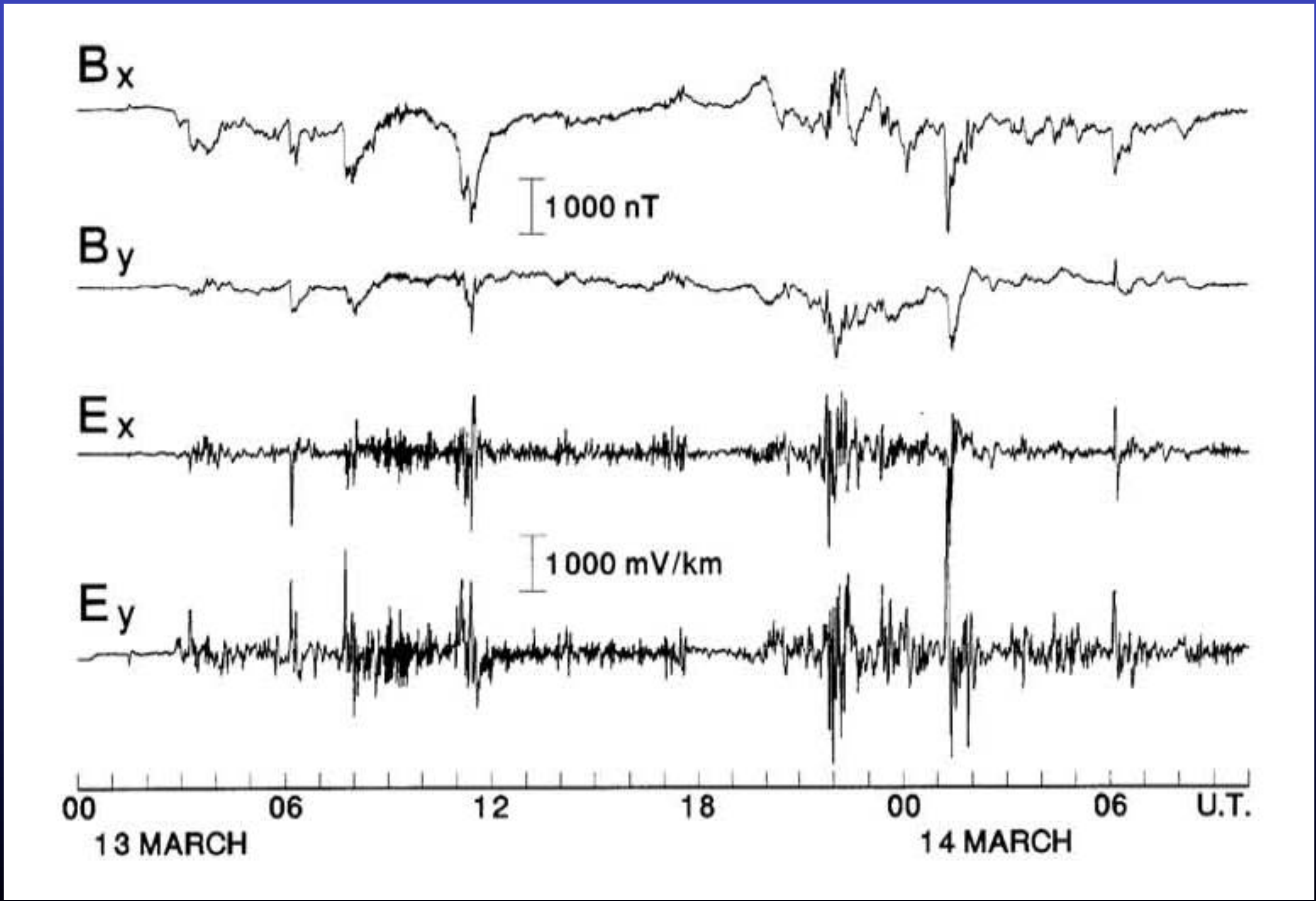
Last layer: $Z_N = \dfrac{i\omega\mu}{k_N}$

Electric Field Calculation

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



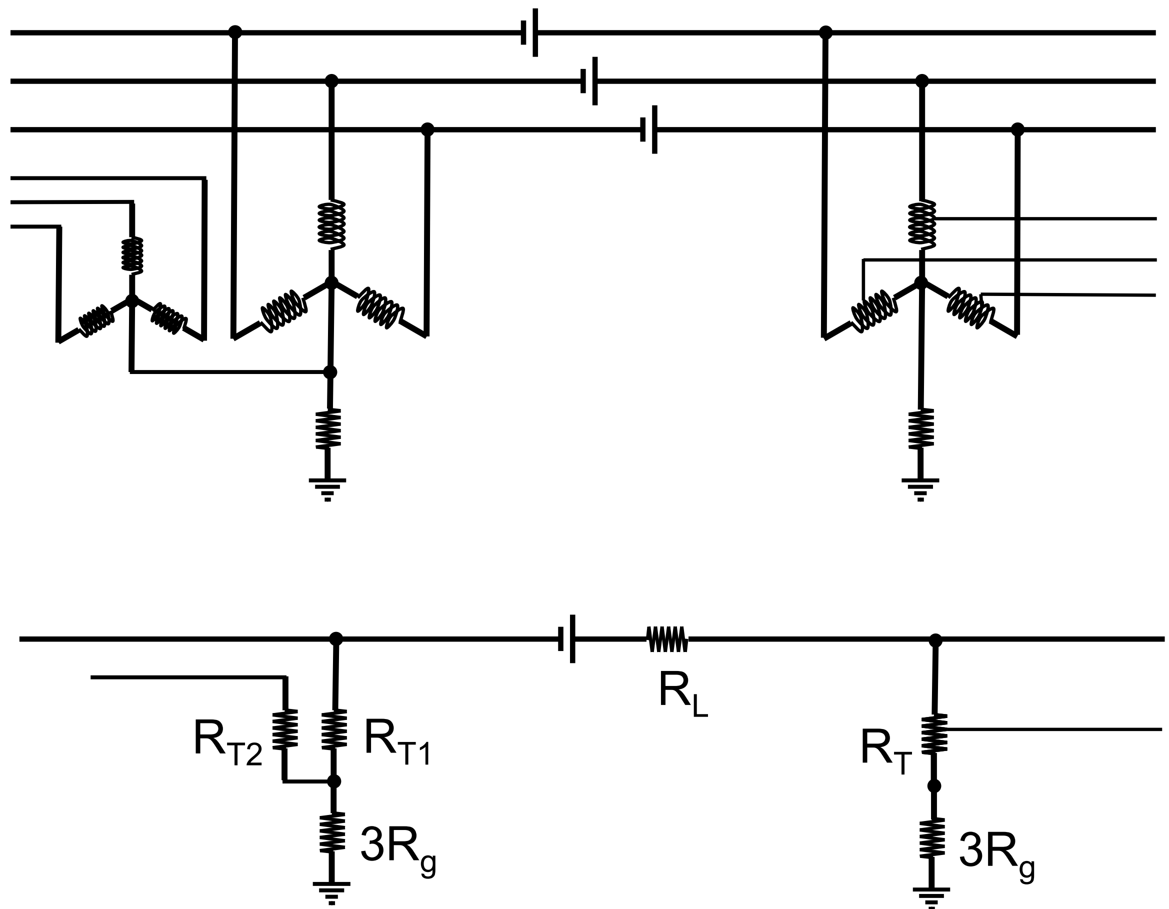
Electric Field Calculation (Plane Wave)



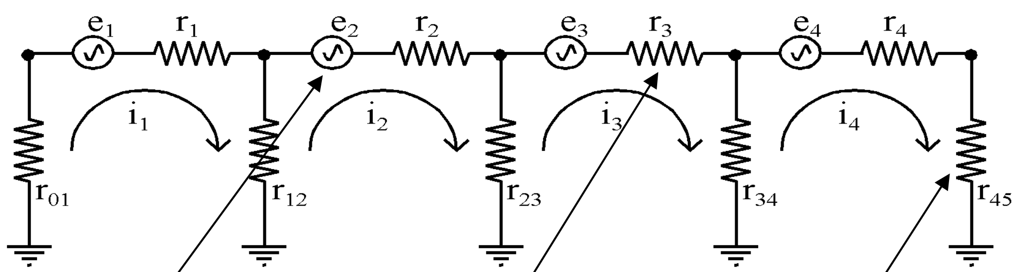
Modelling Process: Basic Network

3-phase

1-phase



Modelling Process: Basic Network

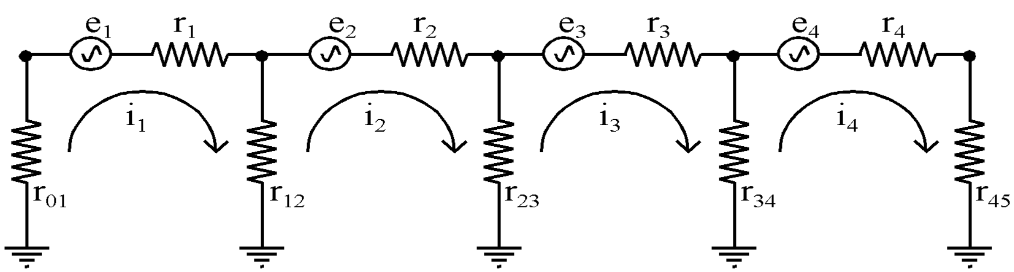


Induced emf in line

Impedances of lines

Impedances to ground

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

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

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

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

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

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

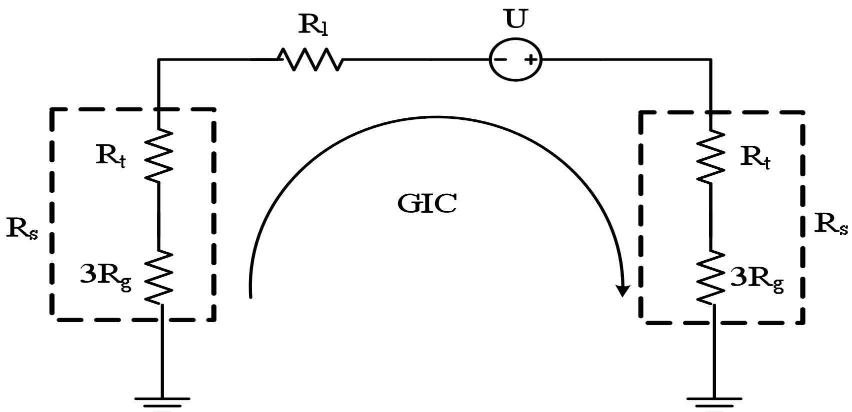
Thus the equations can be written in matrix form

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

Matrix inversion then gives the expression for the currents

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

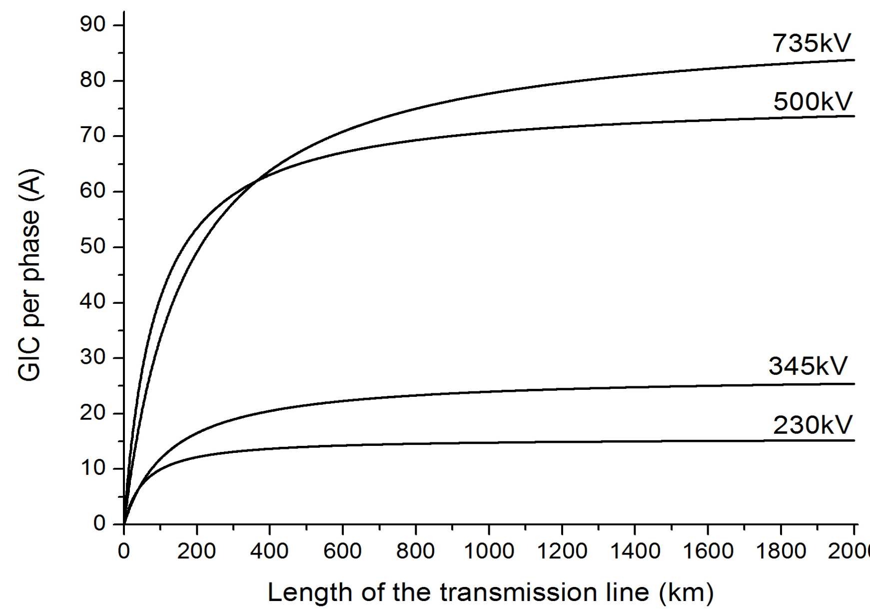
Effect of Line Length



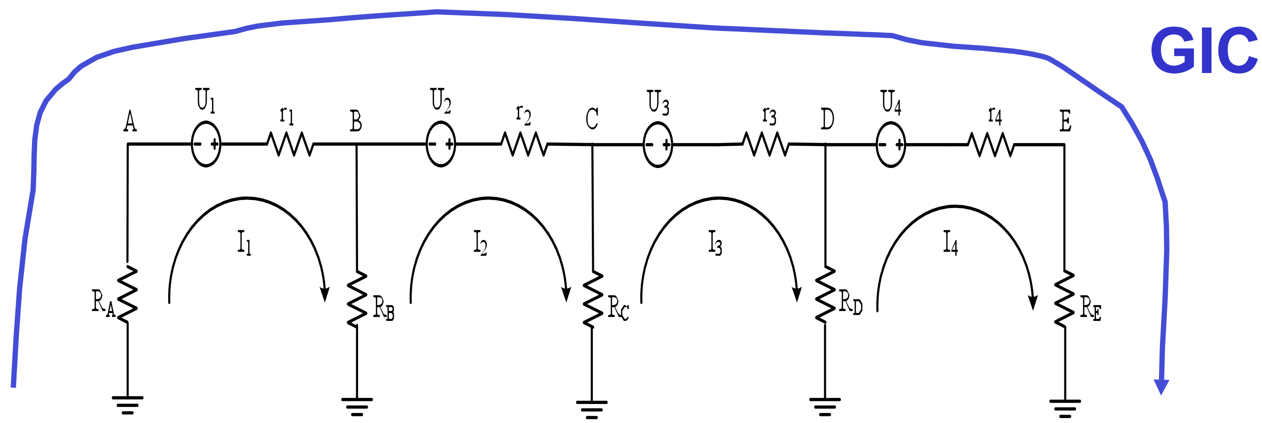
$$GIC = \frac{U}{R_l + 2R_s} = \frac{E_l \cdot l}{r \cdot l + 2R_s}$$

Maximum GIC

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

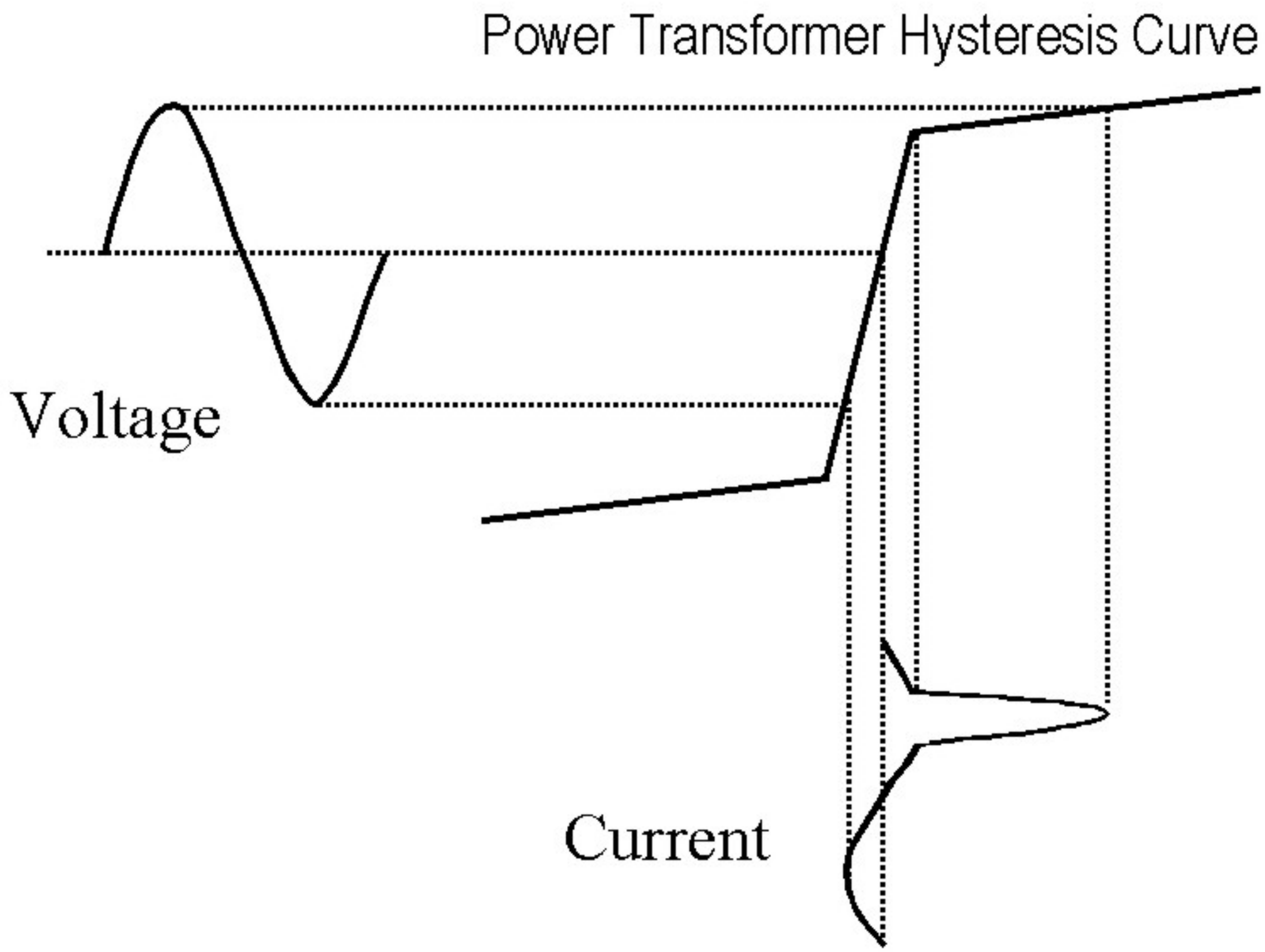


Edge Effect



GIC flows from one edge of the network to the other

GIC flows past substations in the middle of the network



Power Transformer Hysteresis Curve
Voltage
Current

Impacts on Power System

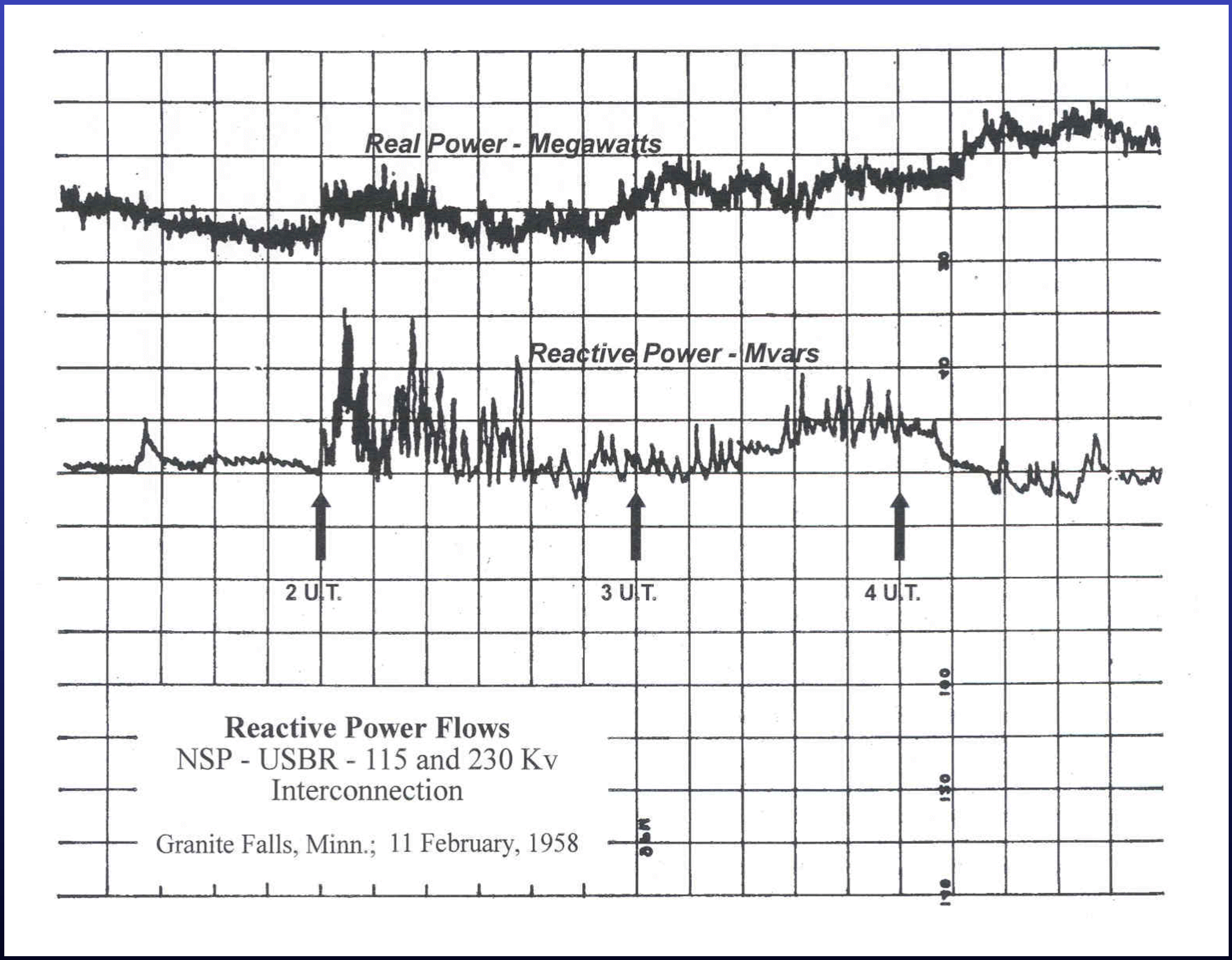
Spikey waveform → harmonics

Harmonics cause misoperation of protective relays

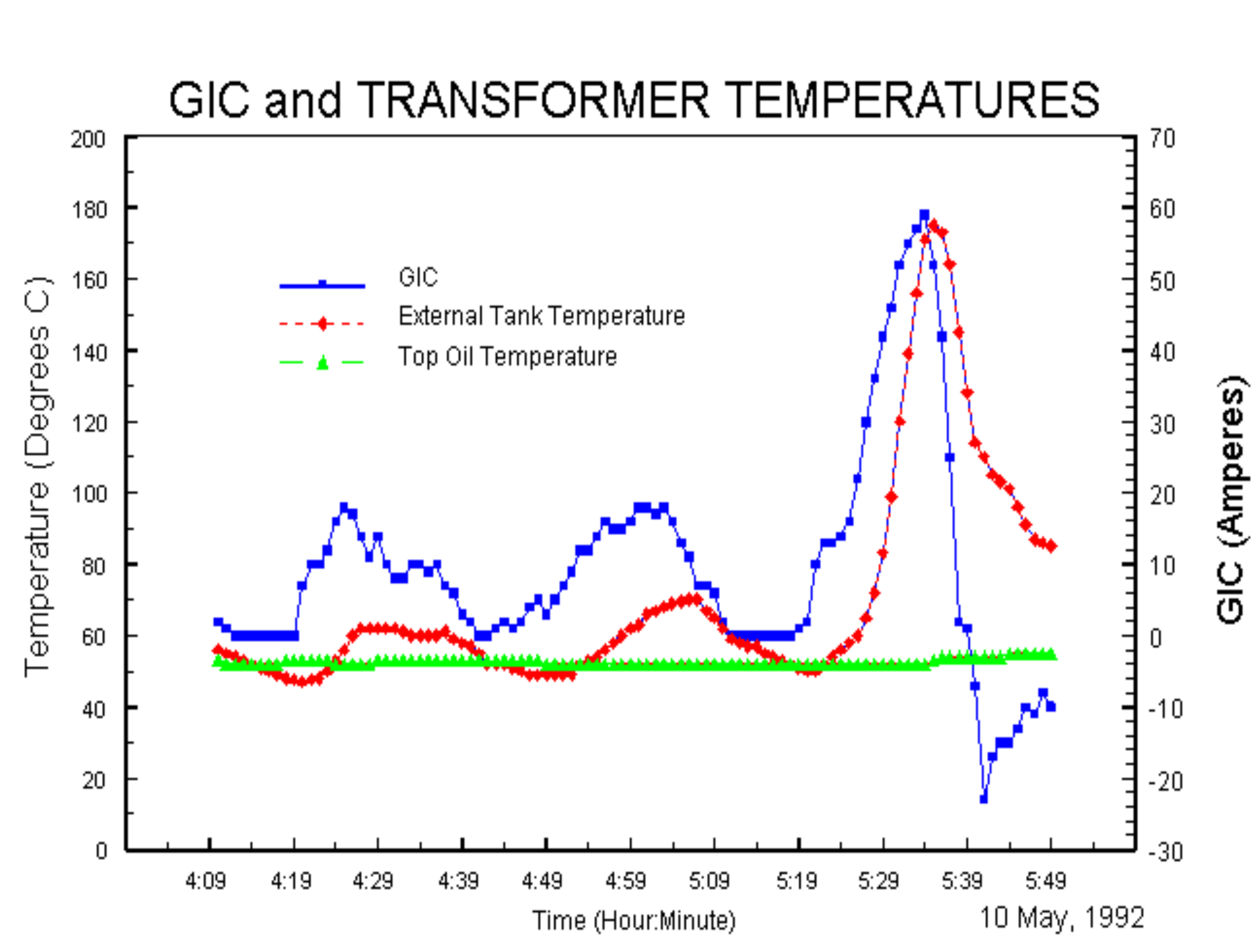
Increased magnetising current → increased reactive power consumption

Lack of reactive power causes voltage collapse

Increased Reactive Power Requirements

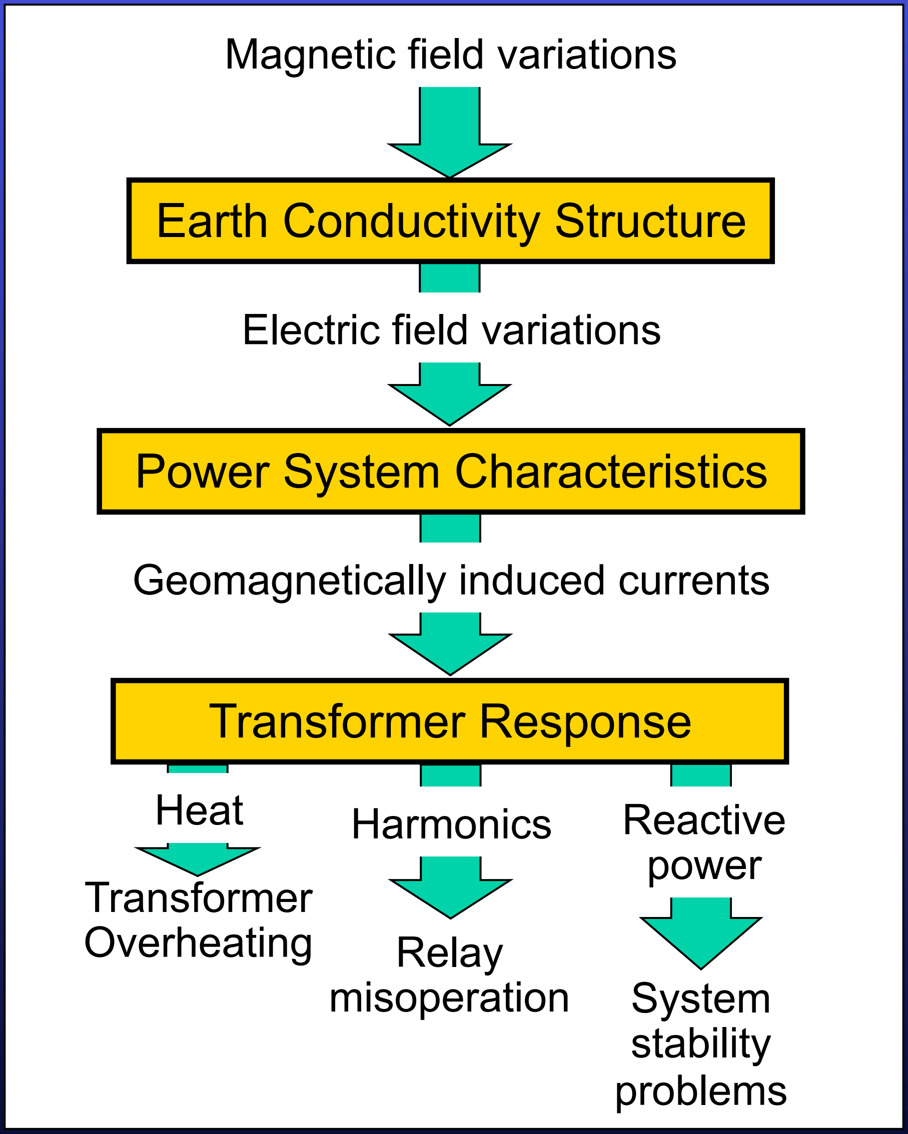


Transformer Overheating



Recap:

- Magnetic variations have different frequency content
- Induction process is frequency dependent
- Power grids modelled as resistive networks
- Transformer inductance limits higher frequencies (T=L/R)



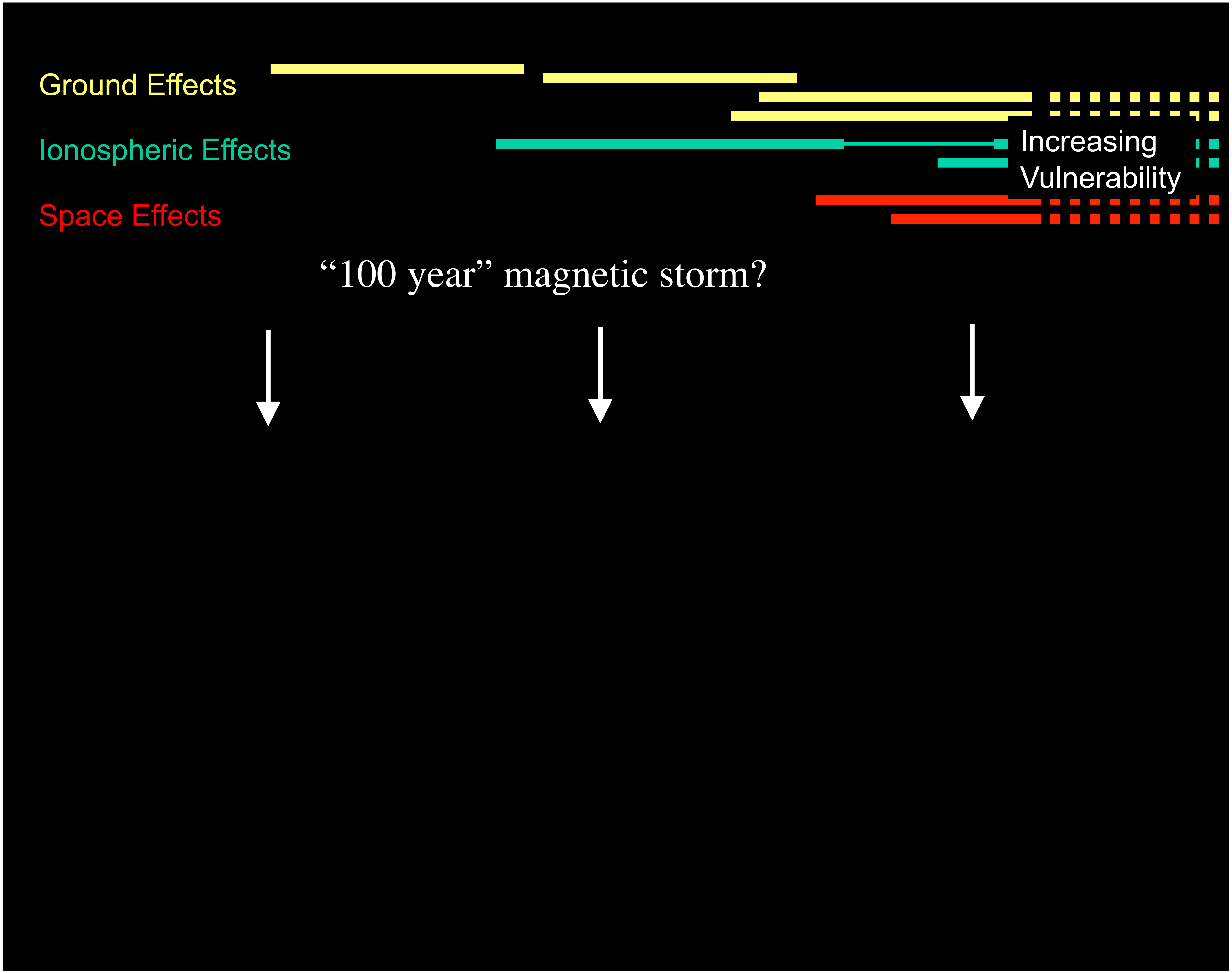
Main phase: too slow

Substorms & Pulsations: just right

SSC: too fast

Part 3. What New Knowledge is Needed

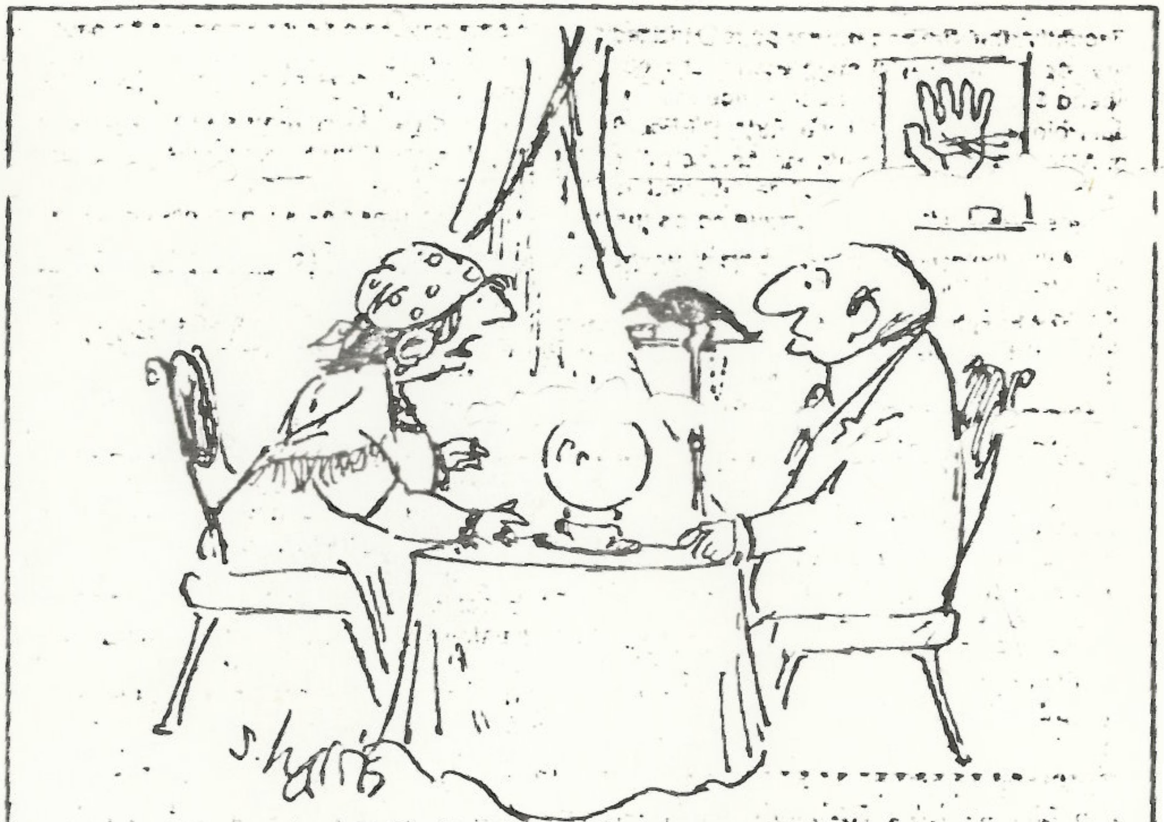
- Defining the "100-year" disturbance
- Theoretical upper limit on disturbances
- Improved Predictions


Ground Effects
Ionospheric Effects
Space Effects
Increasing
Vulnerability
“100 year” magnetic storm?

Is there an upper limit on size of disturbances?

- Size of solar flare
- Size of CME
- Speed of CME (not necessarily a good indictor of storm size, eg 1972)
- Size of disturbance (relevant variation, not Dst)
- Expansion of auroral zone
- Size of substorm (energy store or release)

Need to Improve Predictions

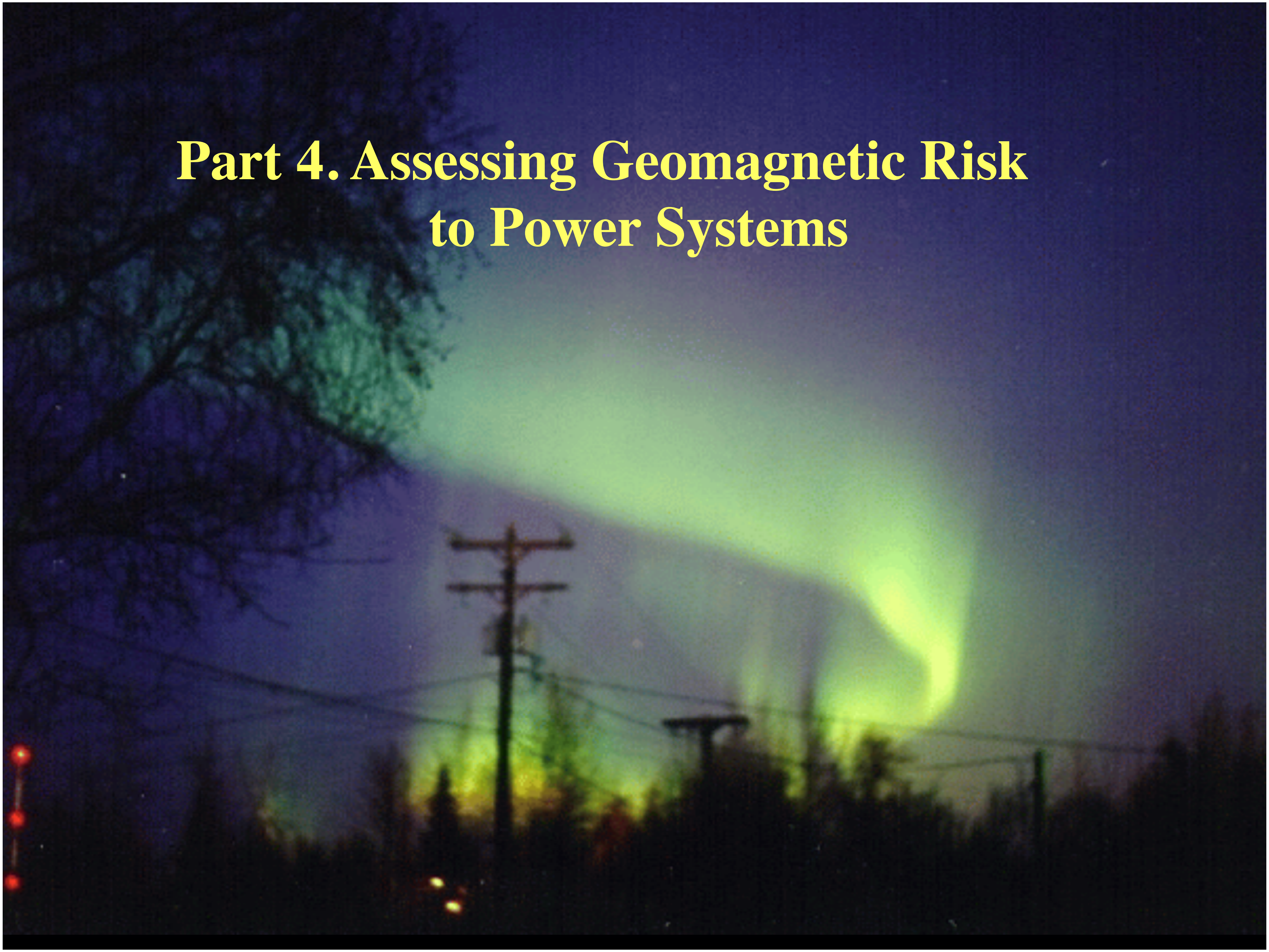


"How do you want it—the crystal ball mumbo-jumbo, or statistical probability?"

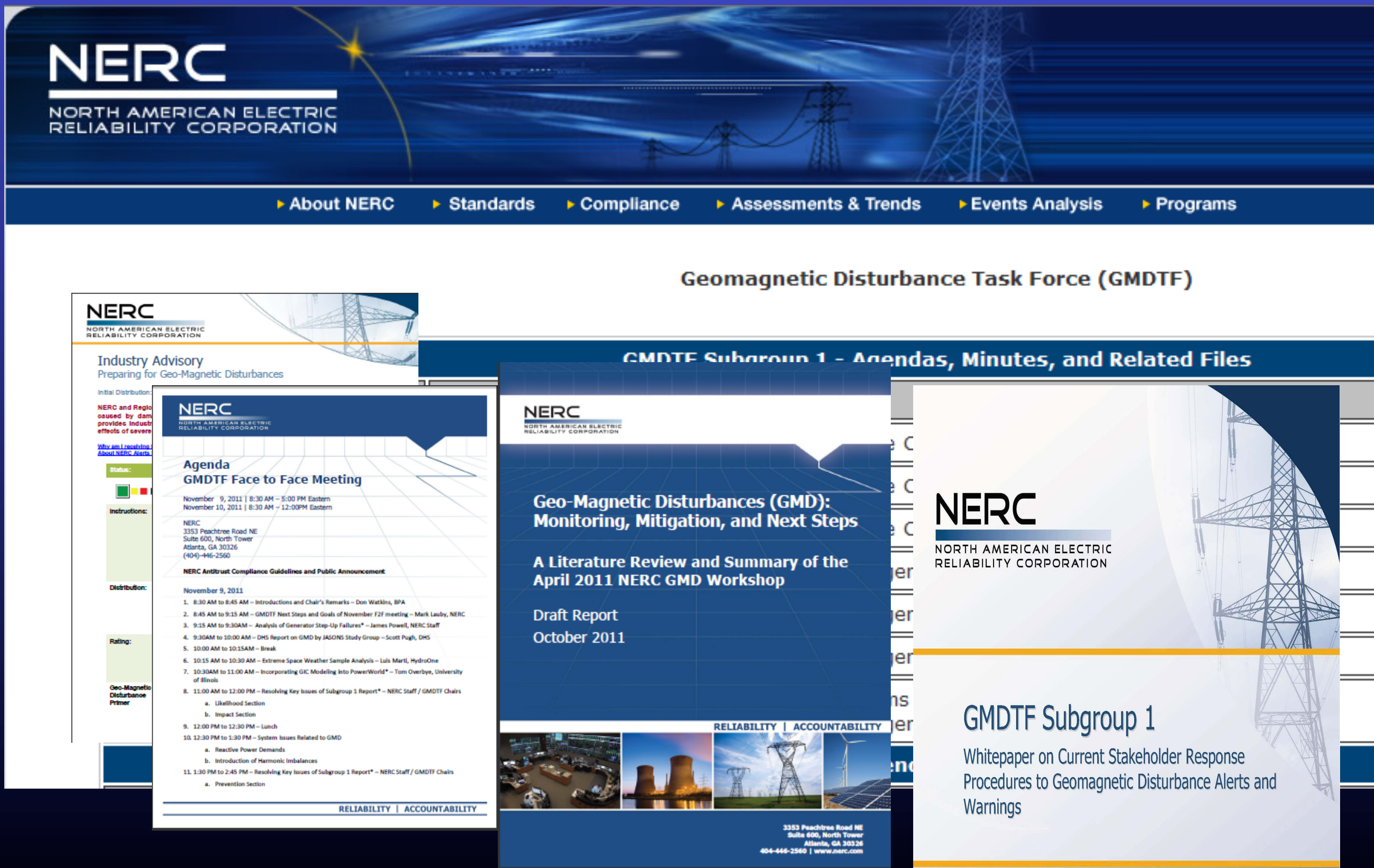
Need to Improve Predictions

- CME Speed
- CME Magnetic Field
- Size of substorm
- Expansion of auroral oval

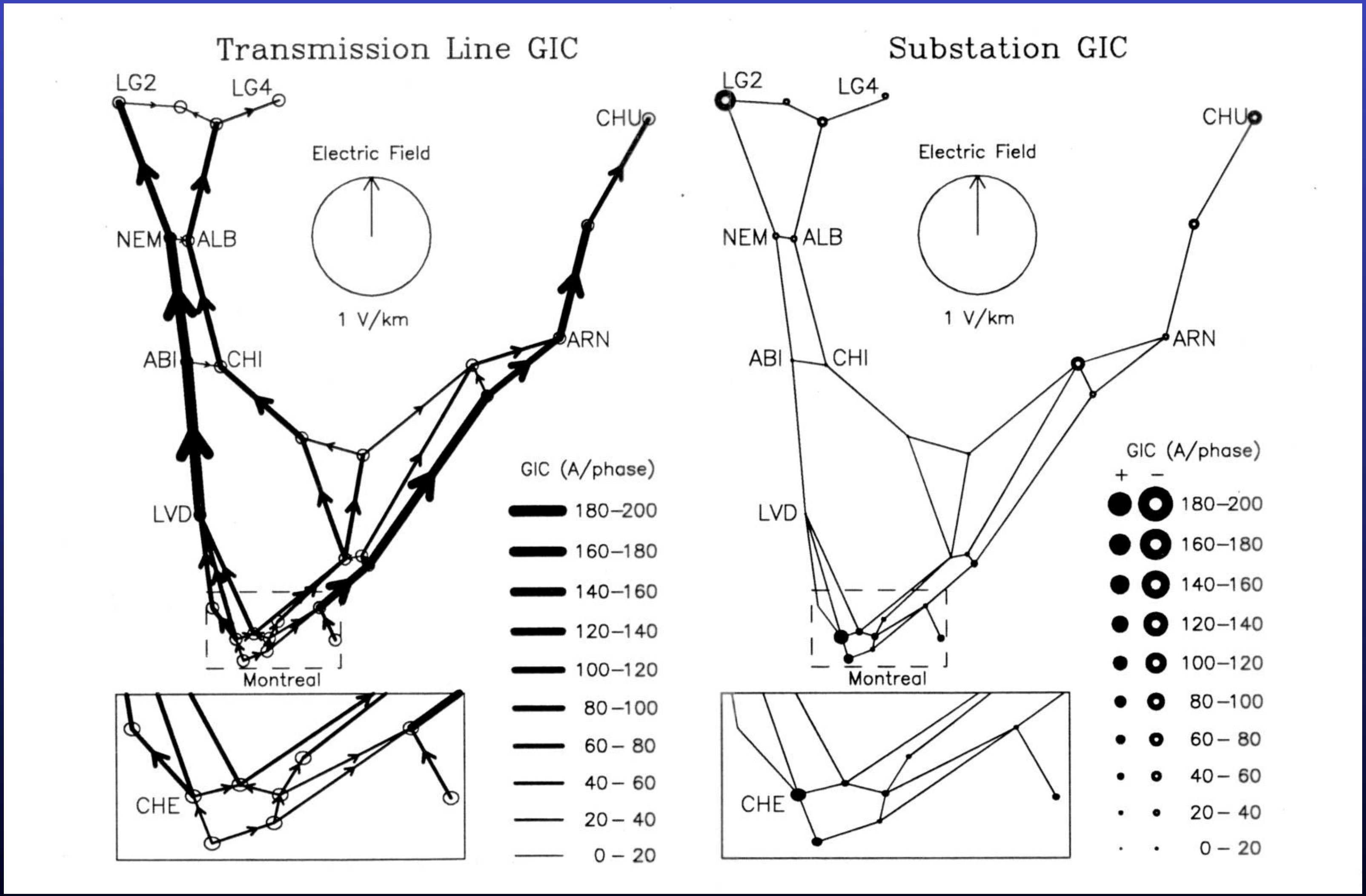
Part 4. Assessing Geomagnetic Risk to Power Systems



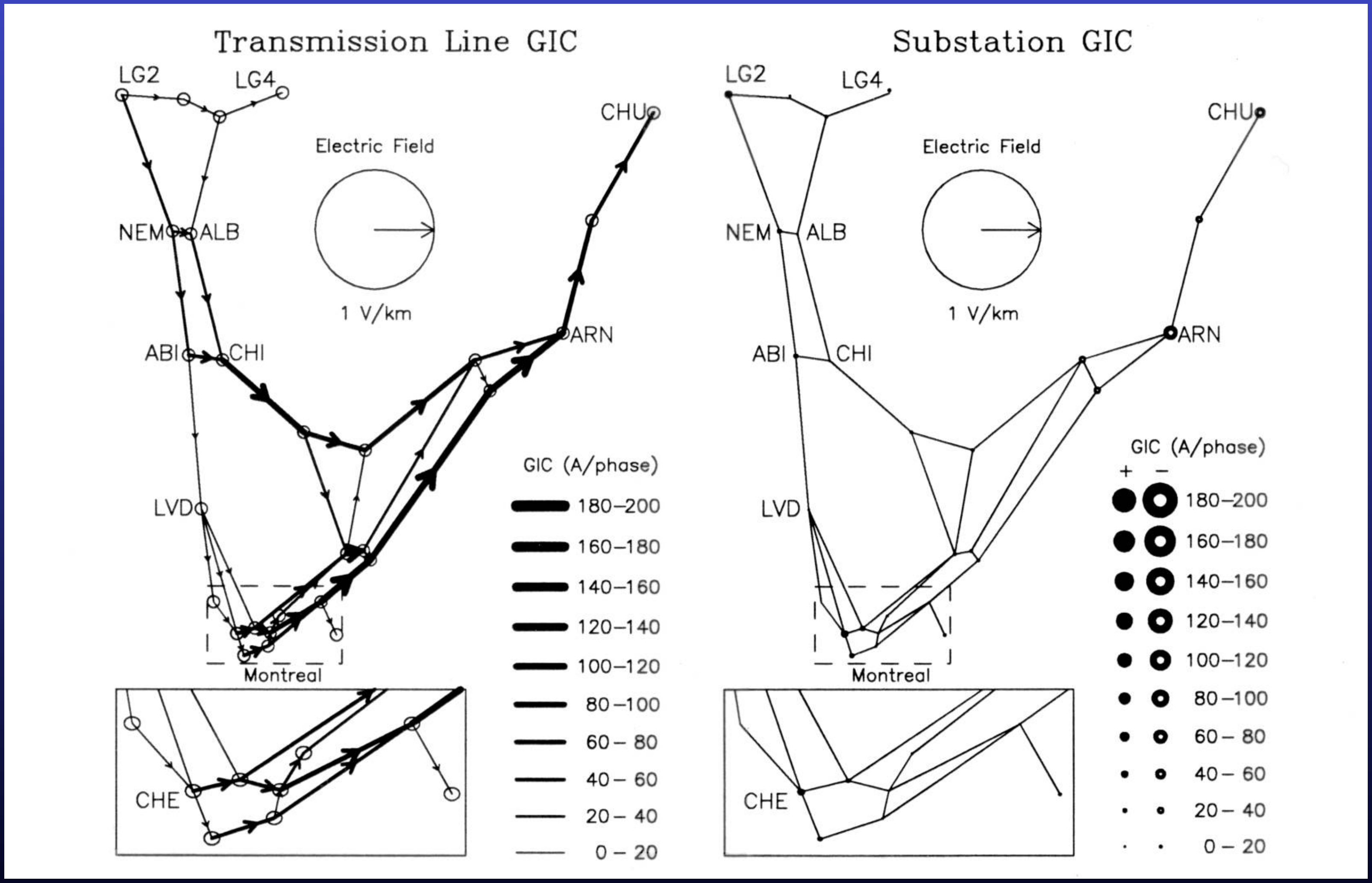
Geomagnetic Disturbance Task Force



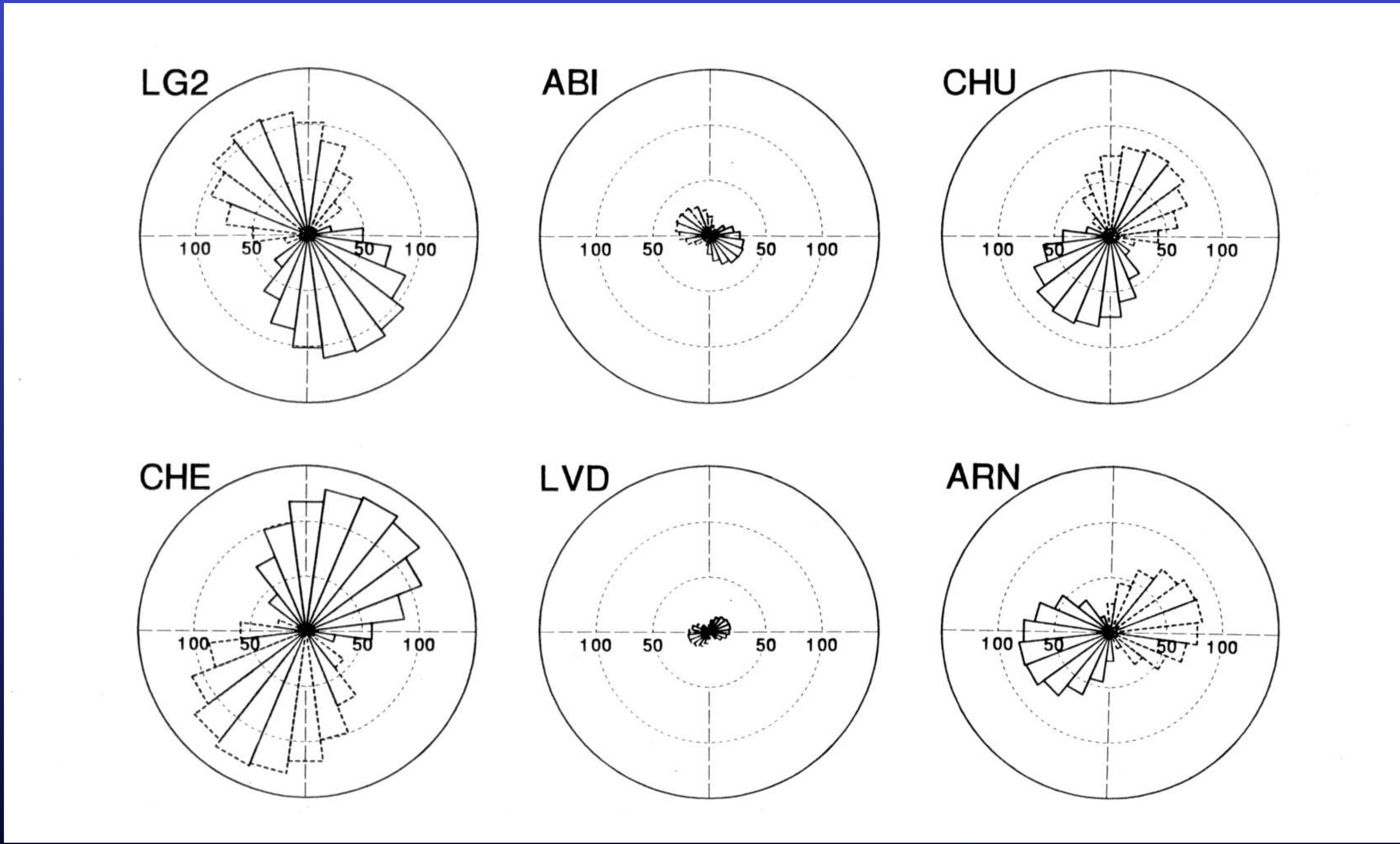
GIC for Northward Electric Field



GIC for Eastward Electric Field



Directional Sensitivity



Conclusions

- Space weather is a natural hazard of the technological age
- Increasing vulnerability in many systems
- Hazard assessment to determine extent of the problem
- Understanding space weather effects assists design of engineering solutions
- Space weather forecasts needed to implement special operating procedures


Thank you