The Impact of Space Weather on the Electric Power Grid

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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

- Energetic Electrons → Damage to spacecraft electronics
- Solar Flare Protons → Radiation effects on avionics
- Ionospheric currents
- GPS Signal Scintillation
- HF Radio wave disturbance
- Geomagnetically induced currents in power systems
- Induced effects in submarine cables
- Magnetic interference in exploration surveys
- Telluric currents in pipelines
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.
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
Quebec Power System SVC tripped Lines tripped
Hydro blame

Consumers fear Hy POWER

Jumbo colored blocks are hot in toyland

Greenhouse effect

Companies tally the cost of blackout

Hydro will

Stocks plun

Maine won't reconsider Quebec power

Companies tally the cost of blackout

Jumbo colored blocks are hot in toyland

Greenhouse effect

Ottawa files part of a Chilean

The Gazette

ROLLING STONES

Hydro blame

Consumers fear Hy POWER

Jumbo colored blocks are hot in toyland

Greenhouse effect

Ottawa files part of a 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?

Conventional Transformer

- HV
- LV
- $N_H$
- $N_L$
- $i_H$
- $i_L$
- $r_g$

Autotransformer

- HV
- LV
- $N_S$
- $i_S$
- $i_C$
- $N_C$
- $r_g$
Real Power and Reactive Power

\[ W = V \cdot I_{\text{load}} \]
\[ \text{VAR} = V \cdot I_{\text{mag}} \]
Power Systems use 3-phase Alternating Currents

3-phase GIC
How magnetic disturbances affect power systems

- 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
Magnetic Storms
Substorms
Pulsations
Geomagnetic Induction in Power Systems

Auroral Electrojet
Geomagnetic Induction in a Power System

\[ \tilde{\delta}E = \frac{dF}{dt} = 0 \]
**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

- Crust 0-100 km thick
- Lithosphere (crust and uppermost solid mantle)
- Asthenosphere
- Mantle
- Inner core
- Core
- Liquid
- Solid
- Outer core
- 6,378 km
- 5,100 km
- 2,900 km

Rock Resistivities

- Resistivity (Ω·m)
- Conductivity (mS/m)
- Various geological layers and their resistivities and conductivities

To scale

Not to scale
Earth Models

Examples of 1-D Conductivity Models
Calculate Earth Response

Recurrence Relation

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

\[ r_n = \frac{1 - k_n \frac{Z_{n-1}}{i \omega \mu}}{1 + k_n \frac{Z_{n-1}}{i \omega \mu}} \quad k_n = \sqrt{i \omega \mu \sigma_n} \]

Last layer:
\[ Z_N = \frac{i \omega \mu}{k_N} \]

- \( \mu \) – permeability
- \( \omega \) – 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

\[ E(\omega) = Z(\omega)H(\omega) \]

Magnetic Field $\rightarrow$ FFT $\rightarrow$ Electric Field

- a) Amplitude (nT) vs. Frequency (Hz)
- b) Amplitude (mV/km) vs. Frequency (Hz)
- c) Amplitude (mV/km) vs. Frequency (Hz)
Electric Field Calculation (Plane Wave)

- $B_x$
- $B_y$
- $E_x$
- $E_y$

1000 nT
1000 mV/km
### Modelling Process: Basic Network

#### 3-phase

![Three-phase circuit diagram](image)

#### 1-phase

![Single-phase circuit diagram](image)
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

\[ r_{01}i_1 + r_1i_1 + r_{12}(i_1 - i_2) = e_1 \]
\[ r_{12}(i_2 - i_1) + r_2i_2 + r_{23}(i_2 - i_3) = e_2 \]
\[ r_{23}(i_3 - i_2) + r_3i_3 + r_{34}(i_3 - i_4) = e_3 \]
\[ r_{34}(i_4 - i_3) + r_4i_4 + r_{45}i_4 = e_4 \]
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

\[
\begin{bmatrix} Z \\ I \end{bmatrix} = \begin{bmatrix} E \end{bmatrix}
\]

Matrix inversion then gives the expression for the currents

\[
\begin{bmatrix} I \end{bmatrix} = \left( \begin{bmatrix} Z \end{bmatrix} \right)^{\prime} \begin{bmatrix} E \end{bmatrix}
\]
Effect of Line Length

Maximum GIC

\[ GIC_{\text{max}} = \frac{E_l}{r} \]

\[ GIC = \frac{U}{R_l + 2R_s} = \frac{E_l \cdot l}{r \cdot l + 2R_s} \]
Edge Effect

GIC flows from one edge of the network to the other

GIC flows past substations in the middle of the network
Impacts on Power System

Spikey waveform $\rightarrow$ harmonics

Harmonics cause misoperation of protective relays

Increased magnetising current $\rightarrow$ increased reactive power consumption

Lack of reactive power causes voltage collapse
Increased Reactive Power Requirements

Graph showing real power in megawatts and reactive power in Mvars over time.

Reactive Power Flows
NSP - USBR - 115 and 230 Kv Interconnection
Granite Falls, Minn.; 11 February, 1958
Transformer Overheating

GIC and TRANSFORMER TEMPERATURES

- GIC
- External Tank Temperature
- Top Oil Temperature

Temperature (Degrees C)

GIC (Amperes)

Time (Hour:Minute) 10 May, 1992

0 20 40 60 80 100 120 140 160 180 200

-30 -20 -10 0 10 20 30 40 50 60 70
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

“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 indicator 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
GIC for Northward Electric Field

Transmission Line GIC

Substation GIC

GIC (A/phase)
- 180–200
- 160–180
- 140–160
- 120–140
- 100–120
- 80–100
- 60–80
- 40–60
- 20–40
- 0–20

Electric Field
1 V/km
GIC for Eastward Electric Field

Transmission Line GIC

Substation GIC

Electric Field

1 V/km

GIC (A/phase)

- 180–200
- 160–180
- 140–160
- 120–140
- 100–120
- 80–100
- 60–80
- 40–60
- 20–40
- 0–20

Montreal

CHE

LG2

LG4

NEM

ALB

ABI

CHI

ARN

LVD

CHU

Electric Field

1 V/km

GIC (A/phase)

- 180–200
- 150–180
- 140–160
- 120–140
- 100–120
- 80–100
- 60–80
- 40–60
- 20–40
- 0–20

Montreal
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