From fluctuating magnetic fields and electrojets to electric fields on the earth

Risto Pirjola$^{1,2}$

$^1$Finnish Meteorological Institute, Helsinki, Finland
$^2$Natural Resources Canada, Ottawa, Ontario, Canada

Swiss Re, Zürich & Rüschlikon, Switzerland

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Geomagnetically Induced Currents (GIC) in technological networks

inductive coupling between magnetospheric-ionospheric currents and the “Earth+network” system through the non-conducting atmosphere

Magnetospheric-Ionospheric Currents
Principle of GIC in technological conductor networks

*Solar Activity => Space Weather Event
  => Geomagnetic Disturbance

*Time Variation of Geomagnetic Field => Geoelectric Field
  (*Faraday’s Law of Induction*)

*Geoelectric Field => Currents in Conductors
  (*Ohm’s Law*)
**Geoelectromagnetic induction**

- Primary contribution from space currents $\implies (B_{\text{prim}}, E_{\text{prim}})$
- Secondary contribution from currents and charges induced in the conducting Earth $\implies (B_{\text{sec}}, E_{\text{sec}})$

$\implies$

**Geomagnetic (variation) field at the Earth’s surface:**
$$B = B_{\text{prim}} + B_{\text{sec}}$$

**Geoelectric field at the Earth’s surface:**
$$E = E_{\text{prim}} + E_{\text{sec}}$$

- *For GIC, the horizontal component of $E$ is important.*
- *For $E$, it is very important to consider both $E_{\text{prim}}$ and $E_{\text{sec}}$.*
- *For $B$, it is sometimes (or often) sufficient to consider $B_{\text{prim}}$ only.*
Faraday’s Law of Induction

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]

- In geoelectric and GIC modelling, the geoelectric (\( \mathbf{E} \)) and geomagnetic (\( \mathbf{B} \)) fields are considered at the Earth’s surface.
- Only the horizontal component of \( \mathbf{E} \) is important for GIC.
- \( \mathbf{B} \) includes the contributions from all space currents (+ from the corresponding induced currents in the Earth).
- Thus, regarding geoelectric and GIC modelling using measured \( \mathbf{B} \) data, it is irrelevant (though interesting) to (try to) distinguish between the different types of space currents that contribute to \( \mathbf{B} \) or even more importantly to \( \partial \mathbf{B}/\partial t \).
- But the next slide summarises some general features related to different space currents.
dB/dt is created by:

- Regular daily variation of ionospheric currents due to conductivity changes caused by variations of solar UV radiation (amplitudes 10 … 100 nT, small dB/dt)
- Eastward Auroral Electrojet in the afternoon and evening (amplitudes 100 … 1000 nT, moderate dB/dt)
- Westward Auroral Electrojet during auroral substorms in the evening and night (amplitudes 100 … a few 1000 nT, significant dB/dt especially in the beginning of the substorm)
- Pulsations: more or less regular ULF waves caused by processes in the magnetosphere and ionosphere (amplitudes 10 … a few 100 nT, possibly significant dB/dt especially in the morning)
- Sudden Impulse (SI) (or Sudden Storm Commencement (SSC)): solar wind impact on the magnetosphere at any time (amplitudes usually 10 … 100 nT or in extreme cases a few 100 nT, possibly significant dB/dt)
- Ring Current at the equator (flowing westwards, height ≈ 25000 km), small effect at mid-to-high latitudes
- Equatorial Electrojet, insignificant effect at mid-to-high latitudes, smaller amplitudes than those of the Auroral Electrojet
March 24, 1991

Raumā 400 kV transformer (60 s values)

Nurmijärvi (10 s values)

SSC  WEJ  pulsations  auroral substorm  WEJ
“smooth” electrojet

\[ \text{\textbf{B}} \]

\[ \text{\textbf{B}} \]

rapid changes of the current both in time and space

\[ \text{\textbf{dB}}/\text{dt} \]
Calculation of GIC in a Technological Network Includes Two Parts

1.) “Geophysical Part”
   • determination of the horizontal geoelectric field at the Earth’s surface
     -input = ground conductivity + geomagnetic data (or ionospheric-magnetospheric current data)

2.) “Engineering Part”
   • determination of GIC
     -dc calculation (due to low frequencies compared to 50/60 Hz)
     -input = network topology and resistances + geoelectric data
Geophysical Part

Geoelectric field:

- Primary contribution from space currents
- Secondary contribution from currents and charges induced in the Earth

\[ E = E_{\text{prim}} + E_{\text{sec}} \]
Calculation Techniques of \( E \)

- Computation Directly from Maxwell’s Equations and Boundary Conditions
- Plane Wave Method ---\( \rightarrow \) Local Plane Wave Method
- Complex Image Method
- Series Expansion Method

Note that calculation of \( E \) is always an approximation since the Earth’s conductivity and the magnetospheric-ionospheric currents affecting the geoelectric field are never known exactly, and even if they were known they would be so complicated that an exact calculation would be impossible.
General situation

Magnetospheric-Ionospheric Current System at height $h$ (and higher)
EURISCIC

European Earth Conductivity Model
Plane Wave Method

(**The geoelectric field is calculated from geomagnetic data.**)

The primary field is assumed to be a plane wave propagating vertically downwards, and the Earth is assumed to have a layered conductivity structure. The fields oscillate with an angular frequency $\omega$.

=>$

The relation between perpendicular horizontal components $E_y = E_y(\omega)$ and $B_x = B_x(\omega)$ of the geoelectric and geomagnetic fields at the Earth’s surface is

$$E_y = -\frac{Z}{\mu_0} B_x$$

$\mu_0 = \text{vacuum permeability}$

$Z = Z(\omega) = \text{surface impedance determined by the Earth’s conductivity structure}$
Practical calculation of the geoelectric field $E(t)$ ($t = \text{time}$) from measured geomagnetic data $B(t)$

1) Fourier transform $B(t)$ to obtain $B(\omega)$

2) Multiply $B(\omega)$ by $-Z(\omega)/\mu_0$ to obtain $E(\omega)$

3) Inverse Fourier transform $E(\omega)$ to obtain $E(t)$
Plane Wave Method

For a uniform Earth with a conductivity $\sigma$:

$$Z(\omega) = \sqrt{\frac{i\omega\mu_0}{\sigma}}$$

This enables an analytic transformation from the frequency domain ($\omega$) to the time ($t$) domain:

$$E_y(t) = -\frac{1}{\sqrt{\pi\mu_0\sigma}} \int_0^\infty \frac{g(t-u)}{\sqrt{u}} du$$

$$g(t) = \frac{dB_x(t)}{dt}$$

Note:
1. An increase of the Earth’s conductivity decreases the electric field.
2. $E_y(t)$ depends on past values of $dB_x(t)/dt.$ (\Longrightarrow causality).
Plane Wave Method is an idealisation because:

1. The primary field is never uniform in a large area, such as a power network.
2. The Earth’s conductivity structure is never layered in a large area, such as a power network.

***However, in practical GIC computations, a large area may be divided into blocks, and the Plane Wave Method can be used separately in each block. 

=> “Local Plane Wave Method” = “Piecewise Layered-Earth Model”

***In practice, the measured geomagnetic data should be interpolated on a grid suitable for the network in which GIC are considered, e.g. using the “Spherical Elementary Current Systems (SECS)” method.
Example: *Change of Level of the Geomagnetic Field*

**Uniform Earth: 1000 Ωm**

Magnetic North Component (RED) & Magnetic North Derivative (BROWN) & Electric West Component (BLUE)
- Largest geoelectric field value in the previous figure:
  \[ \sim 300 \text{ mV/km} = 0.3 \text{ V/km} \]

- Geoelectric field values during geomagnetic storms typically in the order of 1…10 V/km.

- In the literature, values of 10…20 V/km can be found.

- Even values as large as 45…55 V/km are mentioned in the literature.
  
  \[ \Rightarrow \text{Consider with caution!} \]
Statistics of geoelectric field values and the effect of the ground conductivity

Different curves represent different IMAGE stations.

Visual extrapolation to 100-year amplitudes (well-justified if physics of the process remains the same)
Effect of geomagnetic latitude on E and dB/dt

50 deg. of geomag. latitude

Approx. order of magnitude drop in max. amplitudes

Max. values over March 1989 storm

Max. values over October 2003 storm
Calculation of GIC in theory

Ionospheric-Magnetospheric Currents

Ground Conductivity

- Exactly by Maxwell’s Equations & Boundary Conditions
- Approximately by the Complex/Image Method

OR

Geoelectric Field

- Ohm’s & Kirchhoff’s Laws, Thévenin’s Theorem

GIC
**Calculation of GIC in practice**

Ground Magnetic Field Data

- Linear interpolation

OR

- Determination of ionospheric equivalent currents by the SECS method and calculation of the magnetic field by the Biot-Savart law

Interpolated Ground Magnetic Field

Ground Conductivity

- Local Plane Wave Technique

Geoelectric Field

- Ohm’s & Kirchhoff’s Laws, Thévenin’s Theorem

GIC
Engineering Part (for a power grid)

Geovoltage $U_{mn}$ affecting the transmission line $L$ between substations $m$ and $n$ is the line integral of the geoelectric field $\mathbf{E}$ along $L$:

$$U_{mn} = \int_{m}^{n} \mathbf{E} \cdot d\mathbf{l}$$

**In general, $\mathbf{E}$ is rotational.** Thus, no “(geo)potential” or “Earth surface potential” or “potential difference” exists, and the line integral of $\mathbf{E}$ depends on the integration path $L$. **The voltage sources $U_{mn}$ creating GIC should be understood to be located in the transmission lines.**

$$\mathbf{E} = -\nabla \Phi - \frac{\partial \mathbf{A}}{\partial t}$$

Both the first (scalar potential) term and the second (vector potential) term are important contributions to $\mathbf{E}$. 
CONCLUDING REMARKS

- Geomagnetically induced currents (GIC) in electric power transmission grids (and in other conductor networks) are the ground manifestation of space weather.
- GIC are driven by the geoelectric field induced by geomagnetic variations following Faraday’s law of induction.
- The geoelectric field has a primary contribution from space currents and a secondary contribution from currents and charges in the Earth.
- In practice, the geoelectric field is most conveniently calculated from geomagnetic data using the “Local Plane Wave Method”.
- Future research should concentrate on modelling two- and three-dimensional Earth conductivity structures, especially the “coast effect” near ocean-land boundaries.
- Research should also be focussed on the largest geoelectric fields occurring during “space weather superstorms”.
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