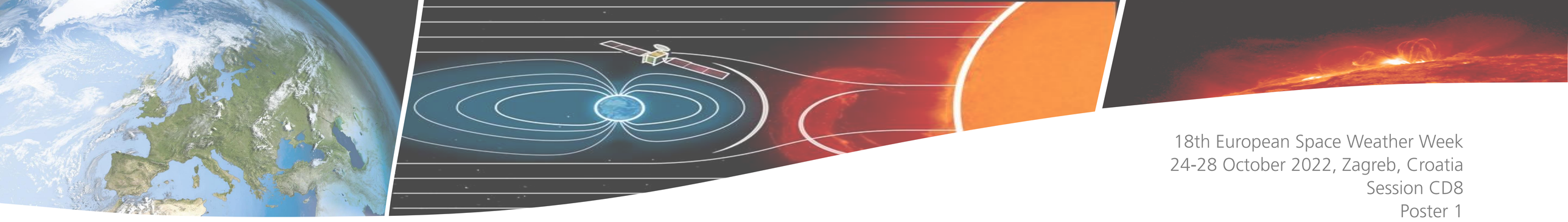

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Poster 1

Geomagnetically induced currents in the German power grid

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Introduction

Space weather driven geomagnetically induced currents (GICs) occur under conditions of intense geomagnetic disturbance (GMD), which is particularly strong in the vicinity of the high-latitude ionospheric electrojets during magnetospheric substorms. By now, it is well established that even mid-latitude regions are at risk of GICs disrupting ground conducting systems in response to the storm-time expansion of the auroral electrojets. Nevertheless, GIC research in Germany is still in its infancy. Here, we present our current progress toward a comprehensive assessment of GICs in the German high-voltage power grid.

Our analyses comprise both the geophysical (boxes 1-3) as well as the engineering (boxes 4-5) sides of the problem. We illustrate the workflow starting with the recorded GMD (box 1) via the induced electric field (box 3) to the actual GIC (box 5) for the geomagnetic storm in September 2017. The GIC is modeled as a direct current (DC) in the neutral point of a grounded three-phase Wye-Wye transformer at a selected substation of the high-voltage (HV) transmission grid in the northwestern part of Germany.

1. Magnetic field

The first step is concerned with the acquisition and spatial interpolation of the GMD observations.

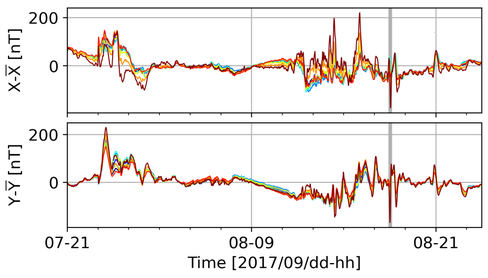


Fig. 1a: Data
27h time series of horizontal (X: north, Y: east) geomagnetic disturbance (1min means) from 9 INTERMAGNET observatories (4 in Germany, see map below).

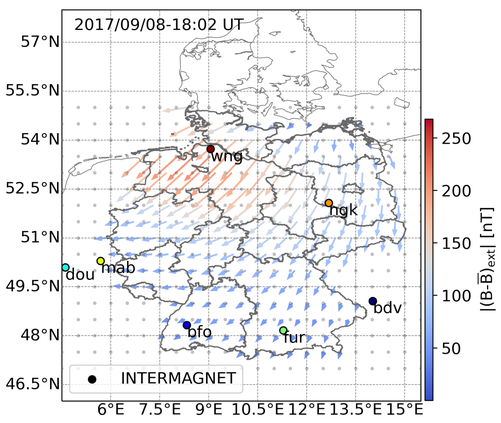


Fig. 1b: Interpolation
Snapshot of the horizontal GMD field interpolated based on the SECS method[1]:

- Horizontal GMD ($\boldsymbol{B}_\perp$) caused by divergence-free (DF) part of 2D ionospheric equivalent current at 110 km altitude
- DF Spherical Elementary Current Systems (SECS) represent local DF equivalent current on sphere
- Invert $\boldsymbol{B}_\perp = \underline{T}\boldsymbol{S}^{DF}$ for scaling factors $\boldsymbol{S}^{DF}$ ($\underline{T}$ is known from geometry)

The map also depicts 7 out of 9 observatories. CLF (France) and WIC (Austria) are not shown.

2. Surface impedance

The second step is concerned with the calculation of surface impedances from the EURHOM[2] conductivity model (1D).

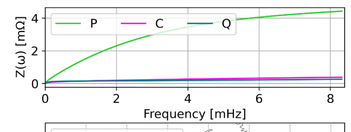


Fig. 2a: Model impedances
Surface impedance for 3 substations of the HV transmission system located in different „cells" of the EURHOM model (see map below).

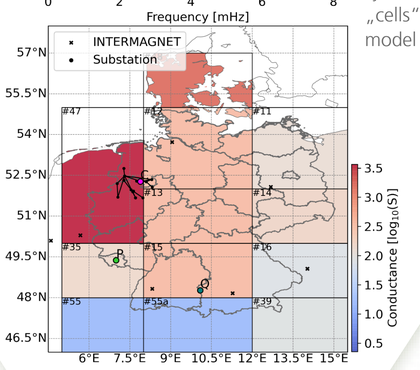


Fig. 2b: Model conductance
Conductance of upper 80km in 12 cells covering Germany according to EURHOM and grid section with station C.

3. Induced electric field

The third step is concerned with the modeling of the induced electric field from the outputs of steps 1 & 2.

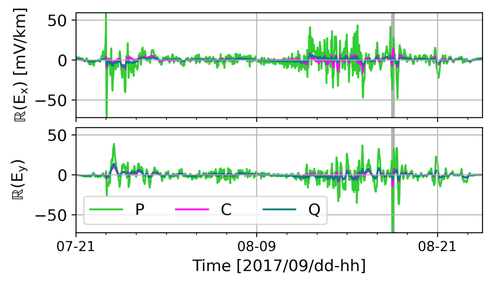


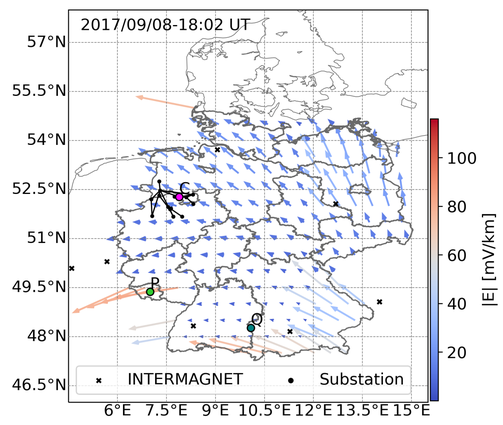
Fig. 3a: E-field
Real part of modeled E-field for 3 substations shown in Fig. 2b in the same format as Fig. 1a. Largest values are reached at substation P in the state of Saarland.

Fig. 3b: Induced E-field map
Snapshot of the horizontal E-field modeled based on the Plane-Wave method[3]:

- Assumes plane electromagnetic wave propagating downward into a layered Earth
- Frequency-dependent (ω) plane-wave equations describe relation between horizontal electric and magnetic fields:

$$E_x(\omega) = \frac{Z(\omega)}{\mu_0} B_y(\omega) \quad (1)$$

$$E_y(\omega) = \frac{-Z(\omega)}{\mu_0} B_x(\omega) \quad (2)$$



Geophysics

Engineering

4. Power grid

The engineering side largely consists of producing an adequate model of the power grid section in question. We initially chose the section shown in Fig. 4 and 5 as GICs were modeled *and measured* at substation C before[4] which facilitates validation. Our model is built from the following sources:

- Station locations: TSO Amprion GmbH & OpenStreetMap
- Connections and line voltages: Amprion's static network model version 2020[5]
- Winding & grounding resistances from literature[6]

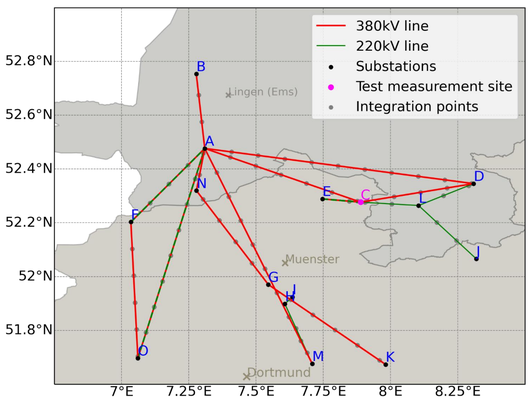


Fig. 4: Power grid section operated by Amprion
Zoom on grid section shown in Fig. 2b comprising of 15 substations (letter codes) and connected transmission lines north of Dortmund.

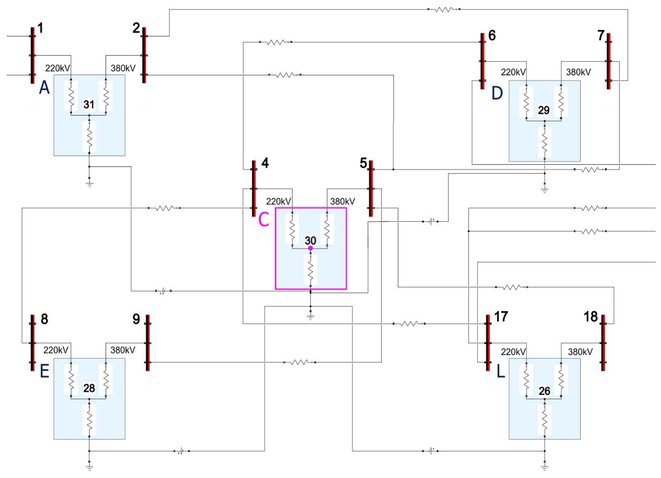


Fig. 5: Circuit diagram for substation C
Diagram showing the 4 substations connected to substation C. All stations host grounded three-phase transformers which are connected through their numbered buses. The induced E-field gives rise to DC voltages induced in the lines which are considered as equivalent current sources at the buses. The GIC is finally calculated at bus 30 (magenta dot, see box 6).

5. GIC calculation

In the final step the GIC flowing through the transformer neutral (bus 30) at substation C is estimated as follows:

- Calculate DC voltages induced in the lines from the E-field and the line lengths (L): $V_{ind} = E_x L_x + E_y L_y$ (assuming uniform field over the length of the line)
- Convert induced voltages (V_{ind}) into Norton equivalent current sources (I_{inj}) injected at the buses
- Calculate nodal DC voltages based on Nodal Admittance Matrix method[7]:

$$V = G^{-1} I_{inj} \quad (3)$$

G is a MxM matrix of conductances with $M = N + S$, N: #buses and S: #stations with grounded Wye-Wye transformers.

- Calculate transformer effective GIC:

$$I_{GIC,t} = C_t V \quad (4)$$

Matrix C_t holds the conductances relevant to transformer #t.

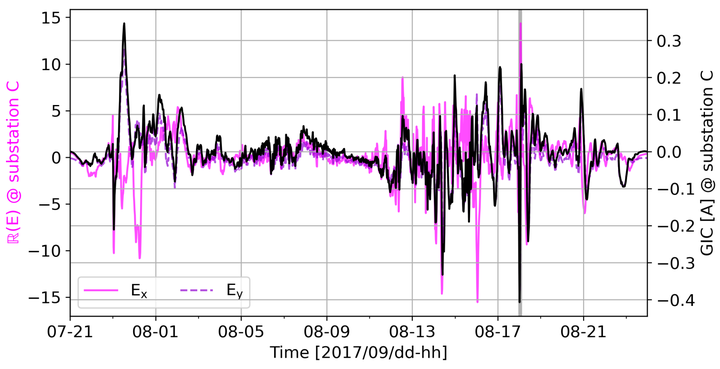


Fig. 6: GIC at station C
Repetition of induced electric field at substation C (magenta, left Y-axis) from Fig. 3a overlain with calculated $I_{GIC,t}$ in the transformer neutral of substation C (black, right Y-axis).

Conclusions & Outlook

Conclusions

- We applied a newly-established workflow for modeling GICs in Germany to a substorm period in 2017 (Fig. 1a) and a grid section in the northwest („test site", Fig. 4) where surface impedance is relatively low (Fig. 2a, magenta).
- The modeled E-field at the test site reaches ~0.02V/km (Fig. 6, magenta) leading to GICs up to ~0.4A (Fig. 6, black).
- Larger E-fields of ~0.1V/km in more resistive regions (Fig. 2b, 3b) suggest that the calculated GIC presents a *lower boundary* of expected GICs for the 2017 storm event.

Outlook

- Use a more realistic 3-D conductivity model or, preferably, magnetotelluric survey data
- Obtain missing grid characteristics from transmission system operators
- Extend modeling to more geomagnetic disturbance events and the whole of Germany
- Verify modeled GICs with DC measurements in transformer neutrals (in cooperation with Amprion GmbH)
- Establish routine GIC monitoring system (in cooperation with BSS Hochspannungstechnik GmbH)

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