High-Voltage Power Grid Disturbances During Geomagnetic Storms

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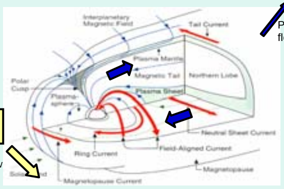
Introduction. In addition to provide fascinating auroral displays, the large and violent magnetic substorms may endanger power grids and cause problems for a variety of other important technical systems. Such substorms generally result from the build-up of excessive stresses in the magnetospheric tail region caused by imbalance between the transpolar antisunward convection of plasma and embedded magnetic fields and the sunward convection (return flow) at auroral latitudes. The stresses are subsequently released through substorm processes, which may, among other, cause rapidly varying ionospheric currents in the million-ampere range that in turn endanger power grids through the related "Geomagnetically Induced Current" (GIC) effects.

View of the Earth's Magnetosphere in the Solar Wind



Solar wind dynamic pressure controls Magnetosphere shape and Magnetopause currents

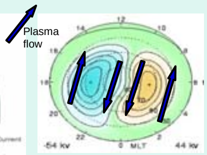
$P_{SW} = D_{SW} V_{SW}^2$

Solar wind electric field controls internal currents and plasma convection

E_{SW}

$E_{SW} = -\mathbf{V}_{SW} \times \mathbf{B}_{SW}$

Polar Cap Convection example



IMF B_Z = - 8 nT, V_{SW} = 450 km/s, E_M=3.6 mV/m (Weimer)

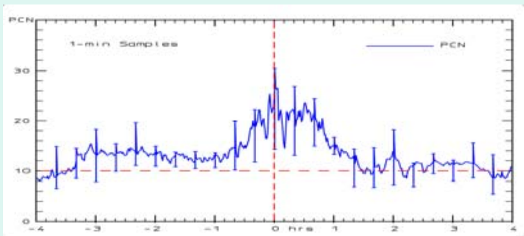
Convection cycle. In a simplified model the interplanetary magnetic field, when southward, interacts strongly with the northward geomagnetic field at the frontal magnetopause (above illustration). The dawn-dusk oriented interplanetary electric field extended over the magnetosphere drives the convection cycle of plasma and embedded geomagnetic fields. Over the polar caps the motion is tailward while in the near-equatorial regions the plasma motion is sunward. The ionospheric projection of the magnetospheric convection cycle is the tailward motion of ionospheric plasma and embedded magnetic fields from the dayside across the polar cap to the nightside and the corresponding sunward return flow along the morning and evening sides of the auroral oval. The ionospheric plasma flows cause oppositely directed Hall currents in the lower ionosphere.

Stress build-up. The tail region is getting increasingly stressed of accumulated magnetic fields and plasma when the tailward convection is strong and exceeds the sunward return flow. Then a sudden substorm with strong sunward convection and strong ionospheric electrojet currents may result in order to release stresses and restore balance. These auroral electrojet currents in the ionosphere (at heights ~100 km) are responsible for the large *Geomagnetically Induced Currents* (GIC) known to cause disturbances on power line circuits particularly during substorms.

Substorms. The occurrences of substorms can be monitored through magnetic recordings from auroral latitudes. These recordings are summarized in the global Auroral Electrojet (AE) index. The AE index is formed as the difference between the upper (AU) and lower (AL) envelope of the horizontal component of auroral magnetic recordings and represents the sum of the contributions from the eastward and westward auroral electrojets. Both electrojets represent sunward ionospheric plasma convection. During substorms particularly strong and variable electrojets are formed in the midnight sector.

Monitoring and warnings. The transpolar convection can be monitored through the associated geomagnetic effects as expressed by the *Polar Cap* (PC) index derived from magnetic recordings from central polar cap stations: Thule in the northern polar cap, Vostok in the southern. The PC index can be considered an index for the power input from the solar wind to the magnetosphere. Thus, an unusually high value of the PC index is a warning of immediate risk for the onset of strong substorm activity.

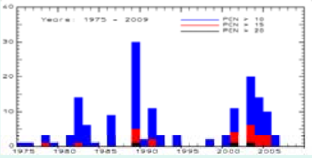
GIC events in the past. The present poster reports the analysis of past major events like the 13-14 July 1982, 8-9 February 1986, 13-14 March 1989, and 30-31 October 2003 power outage events in order to qualify on-line PC data for the potential forecast of large substorms that may endanger power grids. The average PCN index values during 4 hours preceding the occurrences of these reported power line disruptions is shown in the figure. Standard deviation ranges are marked be "error bars".

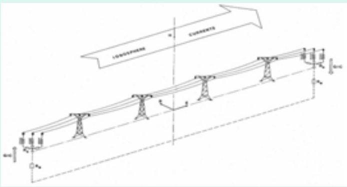


Alert intervals. The data for the 4 events considered (bottom diagrams) indicate that GIC-related disruptions occur when the Polar Cap (PC) index takes values above ~10 (denoted "red alert" in diagrams) for some time, often 1-2 hours preceding the line disrupts.

In order to provide an indication of the occurrence frequency of such cases the figure below displays the yearly number of hours where the PCN index values consistently exceed 10 (blue), 15 (red) and 20 (black) units, respectively. The display spans the interval from 1975 to 2006, i.e. three solar cycles. The trend follows (largely) the sunspot activity. Three of the four cases occurred close to peaks of solar activity in the 11-years sunspot cycles. However, the events on 8-9 February 1986 took place during a solar minimum epoch.

It is seen below that even in years of sunspot maxima the number of hours with consistently large PC index values (alert periods) is fairly small.





Sketch of power transmission line and the associated transformer and grounding circuits.

Physics of GIC events. In a crude approximation the GIC's can be derived from the ionospheric current systems by using a plane wave approximation. This model assumes that the ionospheric currents are uniformly extended in the horizontal plane such that all variations are either in the current direction or purely temporal (see sketch). In that case the electromagnetic disturbances associated with the currents can be expressed in the form of a plane wave extending downward from the source currents. In the simplest two-layer case the environment is described by assuming vacuum above ground and uniform material below ground level.

GIC numerical example. For an order-of-magnitude numerical example consider a high-voltage transmission line of length D≈500 km (e.g., from northern to southern Sweden) like sketched in the above figure. Let the line over its full length be exposed to magnetic variations with a rate-of-change of $dB/dt \approx 20$ nT/s due to magnetic variations at $\omega \approx 0.1\ s^{-1}$ (~1-min period). With ground conductivity ranging from 10^{-1} (wet soil) to $10^{-5}\ \Omega^{-1}m^{-1}$ (bed rock) the skin depths according to (4) range from 10 to 1000 km. Assuming an average skin depth of 100 km, Faradays induction law applied to the above loop with area $A = D \cdot \delta/\sqrt{2}$ then gives a total induced voltage of:

$$V \approx A \cdot dB/dt \approx 500[km] \cdot 100/\sqrt{2}[km] \cdot 20[nT/s] \approx 700\text{Volts}$$

For a typical high-voltage line the sum of line resistances and earthing resistances is around 5 Ω, hence the resulting current amounts to:

$$GIC \approx 140\ \text{Ampères}$$

This corresponds well to values in the grounding circuit of power grid transformers measured during strong geomagnetic storms

The above example was based on extremely simple ionospheric current, ground compound and power grid configurations. Ionospheric currents are 3-dimensional quantities having complex temporal and spatial variations. Ground composition is usually very complicated. Power grids, in reality, are constructed as 2-dimensional networks with earthing connections at many grid points. However, it is possible (but complicated) to model GIC effects in real power systems with adequate accuracy.

Preferred location of adverse GIC events. In all events reported here the power-line systems disturbed by GIC effects were located in the middle or southern part of Sweden at geomagnetic invariant latitudes around 56-60º, i.e. in the sub-auroral zone. There are two factors of importance for this localization:

1. The time variations of geomagnetic disturbances are often faster in this region than in auroral and polar regions. During the great geomagnetic storms the amplitude of disturbances at sub-auroral latitudes are similar to those normally found at higher latitudes. Hence the time derivatives may exceed values which could be considered typical of disturbances observed at auroral and polar latitudes.

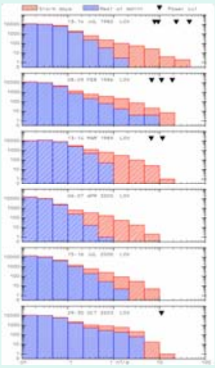
2. The geological properties of the underground are also of importance. The disturbed power grid stations are typically situated in the low-land areas at the southern border of the granite bed-rock that constitutes the underground of the middle and northern part of Sweden. Many of the lines connect from (a.o., hydroelectric) power plants in the northern part of Sweden to the southern regions across large distances of poorly conducting underground. Hence the geomagnetically induced voltages may become particularly large.

Time variations. The most significant parameter in control of GIC events is the magnetic field rate-of-change (dB/dt) value.

The right diagrams display histograms of dB/dt values for Lovø in Mid-Sweden through the stormy months reported here. The colums indicate along the vertical axis the monthly number of occurrences of dB/dt (1-min samples) within specific limits defined along the horizontal axis. The solid red hatching displays occurrences on two storm days. The light blue hatching denotes occurrences on the other days of the month.

The black triangles indicate dB/dt values at power line disruptions. They are clearly positioned at the upper end of the distributions for the 1982, 1986, 1989, and 2003 cases. During the two strong magnetic storms in 2000 the dB/dt values did not reach the level required for power line tripping.

The maximum dB/dt values (1-min samples) reached at Lovø during the storms are given in the table below.



Above: Monthly histograms of Lovø magnetic field time derivative (dB/dt).

Below: Table of max. dB and dB/dt for Lovø during some selected magstorms.

Storm period	Max dB	Max dB/dt	Power cuts
13-14 July 1982	5353 nT	44.8 nT/s	14 reports
8-9 February 1986	2115 nT	19.0 nT/s	5 reports
13-14 March 1989	2828 nT	11.6 nT/s	9 reports
6-7 April 2000	1324 nT	7.2 nT/s	no reports
15-16 July 2000	1248 nT	6.6 nT/s	no reports
29-30 October 2003	2423 nT	11.1 nT/s	Malmö outage

Discussions. The adverse GIC events that affect power grids are clearly associated with fast and deep geomagnetic variations. However, the reported events (all events reported here) are mainly related to tripping of protection circuits and not to equipment (HV transformer) damage in contrast to the Quebeck (1989) transformer burn-out.

It is worth noting that the GIC currents by themselves could not possibly overheat transformers. They could shift the operating base magnetism of the core such that the core may enter saturation in one or the other half-wave phase of the operating AC current if the transformer is operated close to its limits. Thus, it is the operating currents that may heat the transformers beyond safe limits.

Trippings of protective circuits during GIC events are probably unavoidable. However, overheating of transformers, which is the most alarming GIC effect, could be avoided either by operating them within safe limits of max. load or by replacing the DC-ground connection by capacitive or resistive coupling.

Predictions of the strength and time variations of magnetic substorms have not yet reached a mature level for practical applications. General warning of magnetic storm conditions following solar outbursts (CMEs) are provided by satellite data.

The possibly best indication of imminent substorm activity is provided by using on-line PC indices to provide monitoring of polar cap convection building stresses in the magnetotail that could be released in strong substorms. All events reported here are preceeded by PCN index values at or exceeding 10 through one or more hours before the stroke.

The PC indices – particularly the northern PCN indices – could be made available on-line since the magnetic data used for their derivation are available on-line in near real time.

Conclusions.

-Tripping of protection circuits during GIC events are probably unavoidable. The management of power grids should minimize consequences and provide quick restoration. The regions of highest risk are just equatorward of the usual auroral zones.

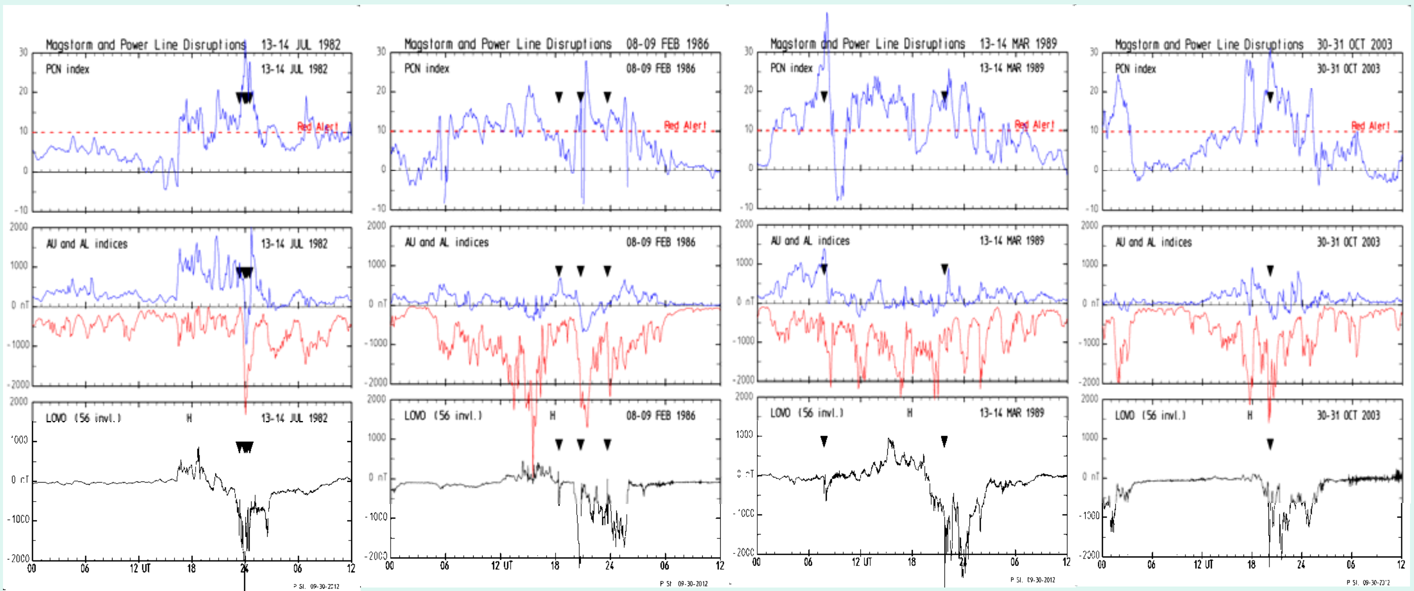
-Overheating of transformers is avoidable. At times of possible strong substorm activity and in the risk zone transformers with ground connections should be operated within conservative safe limits.

-An on-line polar cap PC index should not be considered a replacement of other early warning systems based, for instance, on monitoring solar wind conditions from interplanetary spacecrafts like the ACE satellite. But rather as a supplement with two important features, namely:

-The Polar Cap real-time monitoring of the convection provides a realistic measure of the terrestrial effects of solar wind enhancements and may help to avoid false alerts.

-The real-time PC index should be considered a back-up system to be used in case the satellite(s) are disabled by technical problems or possibly harmed by the intense high-energy radiation, which at times accompany the strong solar eruptions.

References:
Stauning, Peter: Power grid disturbances and polar cap index during geomagnetic storms. *J. Space Weather Space Clim.*, **3** A22. Published online: 2013-06-25 at: **http://dx.doi.org/10.1051/swsc/2013044**
Stauning, P. (2013), The Polar Cap index: A critical review of methods and a new approach, J. Geophys. Res., Space Physics, 118, 5021–5038, doi:10.1002/jgra.50462. Available (free) at: **http://onlinelibrary.wiley.com/doi/10.1002/jgra.50462/pdf**



Data. Data from strong magnetic storms. Top: Polar Cap (PCN) Index. Middle: Auroral Electrojet Indices AU (blue), AL(red). Bottom: Recordings of the geomagnetic North (H) component from Lovø, Mid-Sweden (56.7 Inv.lat.).

Power line disruptions: The triangular symbols in the above diagrams mark the occurrences of high-voltage power line disturbances reported by the Swedish agency "Vattenfallet". The disturbances resulting from geomagnetically induced currents caused disruption of a number of high-voltage lines due to:

1. Tripping of line protecting circuits.
2. Tripping of capacitor protective circuits.
3. Tripping of transformer protective circuits.

The power grid was managed to avoid general power outage in all but the October 2003 event where a.o. Malmø was subjected to 1 hr power outage. None of the events caused permanent equipment (e.g. transformer) damage.

Geomagnetic signature: Note, that there is a clear "spike" in the geomagnetic recordings from Lovø in Mid-Sweden through all cases of power line disruption. This signature provides a nice indication of the physics resulting in the GIC disturbance event, but no forecast since the spikes occurred at the time of the power line cuts.