Overview of Geomagnetic Storm Coupling to a Power Grid

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Abstract—**It is well known that a power grid can be vulnerable to collapse and damage from geomagnetic storm disturbances. However there is considerable uncertainty in how a power grid would respond to a future storm – including possibilities of shutdowns ranging from hours to months or years. This paper discusses the factors involved in the generation of the geomagnetically induced currents (GICs) that can, under severe circumstances, damage large transformers in a power grid.**

Keywords—Geomangtic storm, GMD, power grid vulnerability, SI, CHHSS, GIC, electric power infrastructure

I. INTRODUCTION

Geomagnetic storms can cause problems for the power grid [1,2]. We have limited data on the vulnerability of the power grid – very big storms occur very infrequently, while the grid continually evolves and so will be different when the next big storm hits. The classic large storm was the Carrington Event of 1859, but there have been some large, but smaller, more recent events that have caused grid collapses and damage. Unfortunately we do not have any real experience to judge how our present electric grids will respond if exposed by a large "perfect storm". We do not have a complete understanding of possible severe storms. But we also have not even fully characterized more recent lower level storms. Lack of a full understanding of geomagnetic storms and their possible effects on large high voltage power grids has hindered efforts to protect these grids against the possible impacts. In this paper we review the issues involved and present some examples of geomagnetic storm power grid responses.

II. POWER GRID CIRCUIT

The basic process is well known. Geomagnetic storms are perturbations in the geomagnetic field (as observed on the Earth's surface, for power line concerns) generated by solar charged particle ejections interacting with the Earth's geomagnetic field and ultimately creating currents flowing in the Earth's ionosphere, which further create time-varying magnetic fields at the Earth's surface. The horizontal components of these time-varying magnetic fields induce horizontal electric fields in the Earth. These E fields and currents depend on the ground conductivity down to great depths (as deep as 700 km), due to the low frequencies involved (sub Hertz). Some of the currents in the ground can take the parallel paths offered by power lines – flowing up through the transformer ground rods at one point, through the power line network, and then back down through ground rods at another point (this current is called GIC – geomagnetically induced currents).

The time variations are slow enough that the circuit response is quasi-DC with respect to 60 Hz and is calculated using only the resistances in the power grid. These are the spreading resistance of the fields in the ground around the ground rods, the winding resistances in the transformers, and the wire resistances of the power lines. The real complication is the power grid network with many interconnected lines, and many variations in transformers (delta, wye, autotransformers, etc.) and grounding, and the spreading out in a two dimensional line network over a large region with variations in ground conductivity and incident geomagnetic storm fields.

As a simplification for study of the variations from different geomagnetic storms, a single straight power line may be considered. A further helpful simplification applies if:

1. The line is long enough that the wire resistance dominates over the end resistances (grounds and windings).
2. The incident geomagnetic storm B (magnetic) field and ground conductivity are uniform over the length of the particular power line of interest.

If these conditions apply, then a GIC can be calculated, for the given storm and ground conductivity profile, that is dependent on the wire resistance (inversely proportional) and the geographical angle of the line to the electric field. The GIC is independent of line length. Assumptions of such conditions are convenient for studies of the geomagnetic storms themselves, independent of complex power grid layouts.

III. SOME IMPORTANT ISSUES

There are many factors involved in the analysis, and some have not been well characterized. There are several types of geomagnetic storms: three of which will be discussed below. For power line GIC response an important parameter is the B-dot (time variation of magnetic field, dB/dt). For a single parameter characterization, the peak B-dot value can be used. Assuming a ground conductivity profile, the resulting E field can be calculated, and it is characterized by its peak value. A peak GIC then can be found for an assumed line resistance; this would occur for a line aligned with the peak E field vector.

It is well known that there can be latitude variations in geomagnetic storms. Often geomagnetic storms are generally assumed to be of concern only for higher latitudes, and this is consistent with solar ejections of charged particles being diverted towards the poles. However this is not always true.

In addition there are line-coupling coherence length issues: the variation of storm magnetic fields with distance (which may vary differently in latitude than in longitude). The GICs are computed by integrating the E fields along a long length of line, and the fields must peak simultaneously along the whole length to maximize the GIC (and the E field direction must also remain aligned with the power line along its full run).

In the presentation we will emphasize an important but often unappreciated issue: the B field perturbation is not overwhelming in the north-south direction. If instead this was true, then the E field and the GIC would mostly only be of concern for east-west lines. For a sample of geomagnetic storms we have found that there is significant rotation to the fields with time; the field directions vary with time, so that a line can observe significant GIC no matter which direction it runs

IV. GROUND CONDUCTIVITY PROFILE

The E field and resulting GIC are influenced by the ground conductivity profile under each power line. The detailed method used for these computations has been published [3]. The E field is driven by dB/dt (higher frequencies emphasized), but the skin depth decreases with frequency. The net affect is complex, but an approximate generalization is that E varies inversely as the square root of conductivity for uniform profiles; variations add complexity. Fig. 1 shows the ground profile used in sample results presented later in this paper; Fig. 2 shows the resulting ground impedance in the frequency domain; this is a relatively low impedance ground model. This produces electric fields that are high, but not worst case.

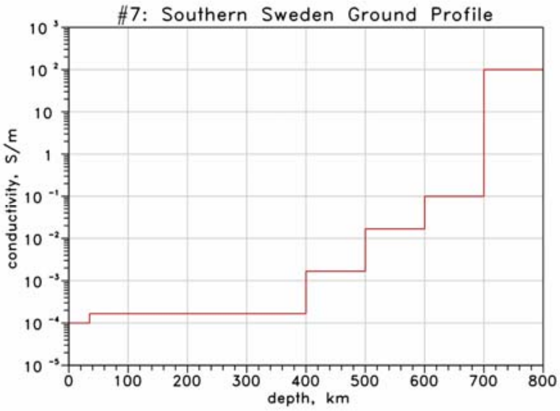

Fig. 1. Ground conductivity profile used for sample results.

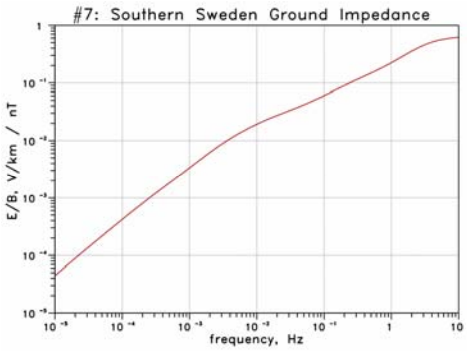

Fig. 2. Surface ground impedance for a sample ground profile.

Such ground modeling assumes a 1D variation (into the ground, and no variations are assumed in the transverse directions). There can be variations from 3D variations, and there is an "edge effect" enhancement near a coastline, but these are not important for generic studies.

V. STORM CHARACTERISTICS

We have not found a comprehensive database of geomagnetic storm results, and so a limited set of data was found to prepare a CIGRE technical brochure [4]. Three types of storms were evaluated, each using a similar method. Relevant magnetometer data, as available in usable form, was downloaded from the Internet, for selected storms. First the B field perturbations were characterized. Note that the steady-state part of the B field is not of interest to compute E and GIC (dB/dt is the driver), and we subtracted out the background B field values just before each storm began. The measured perturbations consist of two components of the horizontal field, normally the B field oriented toward the north and the east. It is important to note that the perturbation is incompletely characterized if only the total magnitude of the horizontal B field is used, as will be seen below, when we show "rotation" plots.

We then use the B field data to calculate sample E and GIC results. These all use the same ground profile given above, and the same power line wire resistance (15 milliohms/kilometer for one of the phase wires). This gives maximum peak GIC for a line optimally aligned: parallel to the E. Rotation plots of E show that its direction changes through all 360^o with time, so the line cannot see the optimal coupling for all time. We could go through all fixed variations of the line to find the peak GIC (which would just be the same as using the peak E field), however transformers can be adversely affected by the length of time the GIC flows, so we also looked at time-integrated current for all possible wire directions – this is used as a more realistic indication of possible transformer damage, and accounts for the fact that the field direction changes with time.

A. Auroral Electrojet

Our limited data set used four Scandinavian sites and 12 events from 1989 to 2004. The auroral electrojet signal tends to be stronger for higher latitudes, but we could not determine the latitude dependence from our limited data. Fig. 3 shows the B field magnitudes for the four locations, and we see that the signals are similar. The farthest separate was 1013 km, and this provides some indication that there might be sufficient correlation to have good coherence and integrated E over a long line length, but the dataset was too limited to make a strong conclusion. Fig. 4 shows the E field magnitudes, which show sharp spikes associated with B field variations.

These are vector magnitude waveform plots. Figs. 5 and 6 show rotation plots, plotting the two vector components against each other. For the B field we see that the north-south variation is more than the east-west width; and for E it is correspondingly the east-west width that is somewhat larger, but there is not a huge difference for the other directions. This also applies to the other two types of storms studied, and a major conclusion was that it would be an error to assume that only east-west lines will observe significant GICs. A related conclusion is that the magnitude of the total B field is not sufficient for computing the full E field for line coupling.

As a summary for the auroral electrojet case, the maximum peaks found for the limited set of cases were:

ΔB: 2013.0 nT
dB/dt: 1260.0 nT/min
E: 9.410 V/km
GIC: 627.33 A (per phase)

(The E and GIC are high cases, but not worst case.)

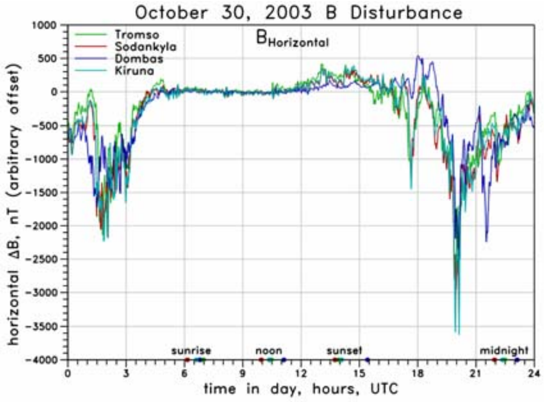

Fig. 3. Sample electrojet B signals.

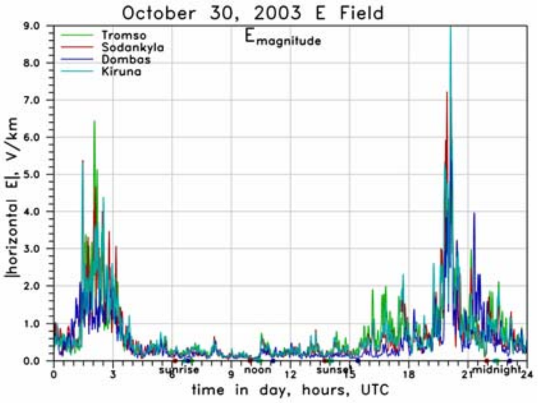

Fig. 4. E fields from electrojet B field samples of Fig. 3.

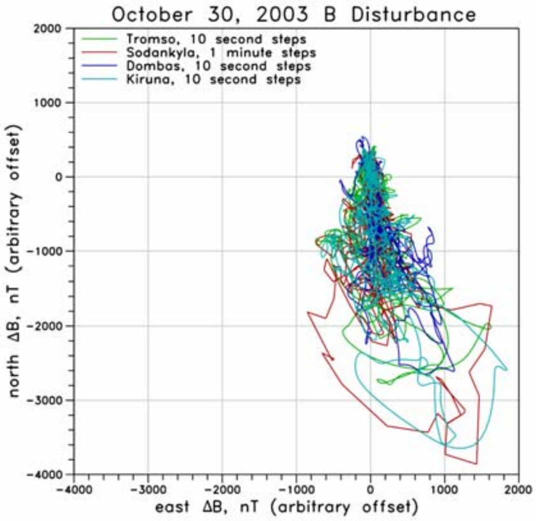

Fig. 5. Rotation plot of sample electrojet B fields.

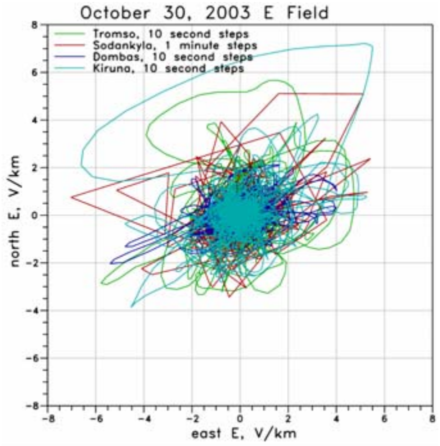

Fig. 6. Rotation plots of E fields from sample electrojet B fields.

B. Coronal Hole

For the Coronal Hole High Speed Stream (CHHSS) type of storm, we had a limited data: two sites for February to May 1994. The results seem similar to the auroral electrojet signals, although one difference was that the signals repeated night after night for many months, as shown in the B plot of Fig. 7.

Maximum peaks were:

ΔB: 756.0 nT
dB/dt: 613.6 nT/min
E: 4.372 V/km
GIC: 291.6 A (per phase)

These are about half the electrojet maxima, although this case used a very limited database; but its repetition every night could exacerbate conditions for transformer heating. Fig. 8 shows that there might be less correlation over distance than for the electrojet, and this might lessen the adverse effects for this type of storm.

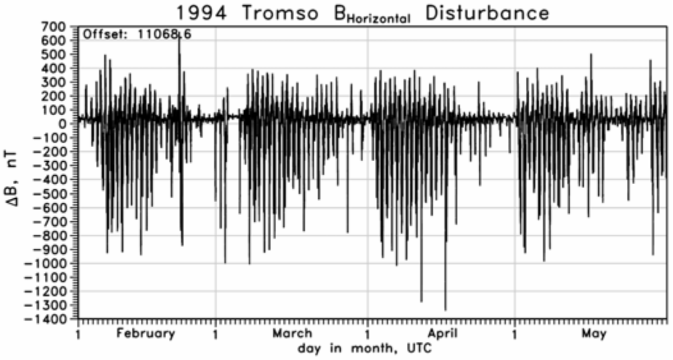

Fig. 7. Coronal hole B disturbance magnitude for four months.

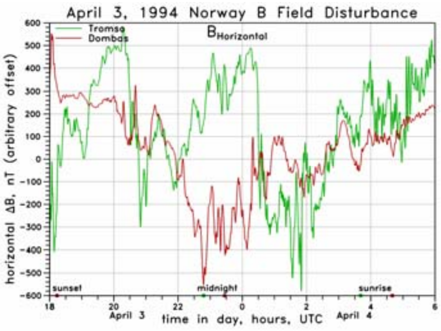

Fig. 8. Coronal hole B disturbances for two sites for one night.

C. Sudden Impulse

The sudden impulse (SI) storm is seen as a fast disturbance in the B field, which can be followed by other, longer terms such as the electrojet.

More data were used in this evaluation: 22 events from 1999 to 2005 at 28 locations. Maximum peaks were:

ΔB:	201.39	nT
dB/dt:	525.19	nT/min
E:	1.791	V/km
GIC:	119.5	A (per phase)

The peak B value is not as high as for the other two storm types, but as suggested by the "sudden" name, it is fast, and so the E and GIC are significant. Another major find was that SI does not (with some exceptions) have a latitude (or longitude) variation; it is approximately the same everywhere. (It might have an enhancement near the equator under certain circumstances.)

Fig. 9 shows sample SI B fields; note that in general the waveforms are similar in start time, waveshape, and amplitude, and these are for locations throughout the world. Fig. 10 shows a sample E rotation plot, and again the E field signal is far from being oriented exclusively east-west.

Another interesting result is shown in Fig. 11. For this plot the peak B values were normalized by the average peak for each event (to account for the fact that each solar ejection has its own strength). The horizontal axis is set to plot the peaks for each site according to how close the site was to having the sun directly overhead (an angle from vertical to the sun position, expressed in 15° increments, or solar hours, but this is not solar time; the higher the latitude for the site, the higher the lowest value that the angle can be). Although some cases did seem to show some slight effects from being on the day or night side of the Earth, we do not see an obvious relationship with sun location, except for the red and black solid lines. These are near the equator and may indicate a correlation with equatorial electrojets; but we have insufficient data to conclude this.

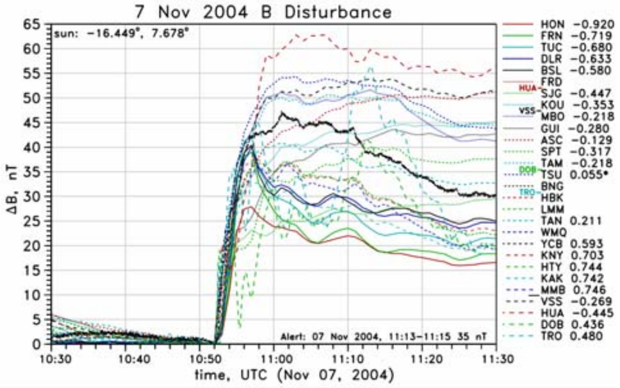

Fig. 9. SI B disturbance magnitudes for November 7, 2004.

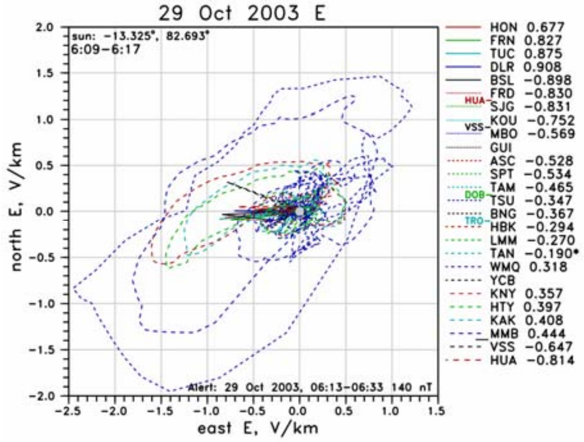

Fig. 10. SI E rotation plot for October 29, 2003.

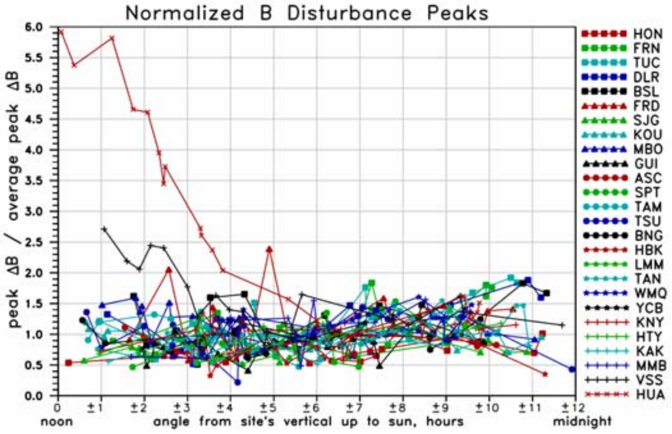

Fig. 11. Normalised SI B disturbance magnitude peaks vs sun position.

VI. SUMMARY

The primary purpose of the talk will be to introduce geomagnetic storm concerns for power grid, but we will also emphasize several points, some of which may not be widely appreciated:

1. B total magnitude does not completely represent the disturbance.
2. There is considerable "rotation" in the fields.
3. It is incorrect to think only east-west lines are at risk.
4. There are several types of disturbances.
5. Even with our limited data set we found high disturbance levels.
6. Even low latitudes can have significant disturbances (SI).
7. For electrojets and coronal holes more data would be needed to determine latitude variations and coherence over typical line lengths.

Examples will be presented for all these important points.

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