MODELLING ELECTROJET CURRENTS CAUSING POWER LINE DISTURBANCES DURING LARGE GEOMAGNETIC STORMS

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ABSTRACT.
Variable currents in space induce secondary voltages and related currents (geomagnetically induced currents, GIC) at ground level. The GIC's may have adverse effects on extended conducting structures at ground like high-voltage power grids, oil and gas pipe lines, and signal lines. Such effects are particularly strong in auroral and subauroral regions like Northern Europe and Canada. This report investigates the time variations of the horizontal geomagnetic field observed during great storms known to have caused disrupts and other adverse effects on power grids. These results are compared to conditions during recent magnetic storms that, in Northern Europe, have been less severe. Modelling of the electrojet currents responsible for the GIC events is discussed and examples presented.

1. INTRODUCTION

Disturbances on power grid systems related to geomagnetic storms are caused by voltages induced at ground level by variable currents in the upper ionised atmosphere, the ionosphere, mainly at altitudes of 100-150 km. The induced potential differences drive currents along the power transmission lines, through the windings of connected power transformers, and to the Earth through the grounded null as sketched in Fig. 1.

These geomagnetically induced currents (GIC), which typically vary at periods ranging from seconds to minutes, act as DC bias and may cause transformer unbalance and overload. If not guarded by protective circuits the transformer can be permanently damaged and eventually face burn-out during events of strong GIC's.

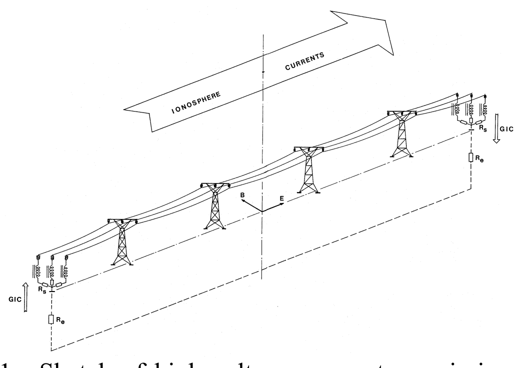

Fig.1. Sketch of high-voltage power transmission line and the associated transformer and grounding circuits.

Furthermore, some types of protective circuit for transmission lines and for phase-correcting capacitor banks react on indications of over-voltage, unbalanced null-currents or other consequences of GIC events. Their action may also disrupt the power circuits.

GIC's are directly related to the time derivative of the magnetic field strength [4, 5]. Due to the extended and strongly variable auroral electrojet currents, GIC's in power grids are most intense for circuits with long high-voltage power transmission lines located in the auroral and subauroral regions. The array of geomagnetic observatories in these regions has now grown to an extent where a detailed modelling of the ionospheric electrojet currents from ground magnetic observations seems possible. Such modelling shall help to disclose the geophysical conditions responsible for large values of the time derivative of the magnetic fields and thus the high GIC currents.

Various techniques have been developed to model the time-varying ionospheric currents responsible for observed magnetic variations at ground level. Reference [1] uses the upward continuation technique based on the expansion of a magnetic potential function into series of orthogonal functions like spherical harmonics. Each of these functions is a solution of the Laplace equation $\Delta\Phi = 0$ that is valid in current-free regions. For regional mapping the spherical cap harmonic functions like used, for instance, in [3] are more adequate.

In a different approach used, for instance, in [2] the electric and magnetic response at ground level to various models of the variable ionospheric current system is calculated. This method uses a complex image method to derive the contributions from the secondary currents induced in the conducting layers of the Earth. Based on the results the responsible current system can be inferred from the appearance and strength of the magnetic disturbances in actual recordings.

In both cases the modelling is restricted to simplified representations of the real current systems in space and coarse models of the conductivity distribution in the Earth. Here we have first used magnetometer recordings from an array of observatories to derive the large-scale equivalent ionospheric current pattern disregarding the induced currents in the ground. In the next step we have derived the latitudinal profile of the ionospheric currents now taking induced ground currents into account.

Based on recordings from a subauroral observatory (Lovö) located at the middle of exposed high-voltage power transmission lines we have investigated the amplitude distribution for samples of the time derivative of the horizontal geomagnetic field component. The distributions of time derivatives found during the great storms known to have caused power line cuts are compared with the corresponding distributions observed during the recent large geomagnetic storms. Further, the occurrence distribution of samples of large values of the geomagnetic rate-of-change has been derived for a time interval spanning a complete 11-year solar cycle.

2. SELECTED GEOMAGNETIC STORMS

Observed geomagnetic variations and related high-voltage power-line disturbances have been examined for selected major geomagnetic storm events. For these selected events Fig. 2 displays the recordings of the geomagnetic horizontal component from Lovö (59.35N, 17.83E, inv.lat.=56.4^{o}) in Mid-Sweden. There is a panel for each of the selected storm events: 13-14 July 1982 (post solar max.), 8-9 February 1986 (solar min), and 13-14 March 1989 (solar max event).

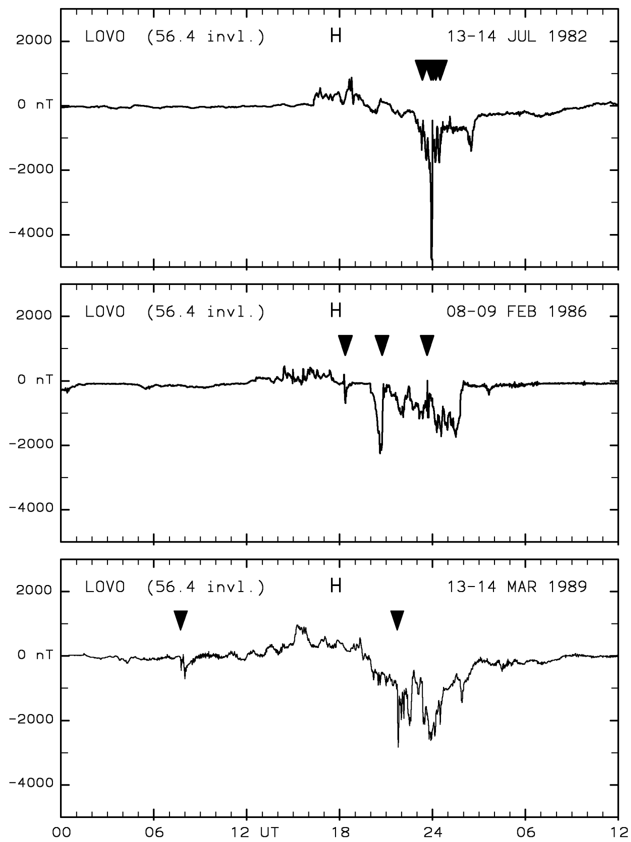

Fig. 2. Magnetic recordings from Lovö and power grid disturbances in Sweden during geomagnetic storms.

In these panels the arrow-heads indicate the times of power grid disturbances in the region. Most disturbances occurred at the southern "consumer end" of the high-voltage power transmission lines from hydro-electric power plants in northern Sweden. It is evident from Fig. 2 that power line disturbances occur at times when the geomagnetic field displays sharp changes. It is also noticeable, that the total magnetic deflection does not always appear to play a major role.

For the three storm cases we have examined the amplitude distribution for observed samples of the rate-of-change of the geomagnetic field at Lovö Observatory. The results are shown in Fig. 3. Both axes use logaritmic scales. The horizontal axis depicts the rate of change, dH/dt, based on 1-min samples of the horizontal components. The recorded changes in the northward and the eastward components have been vectorially added. The vertical axis depicts the number of cases occurring through the selected intervals. The lightly hatched columns indicate the distribution of dH/dt samples through the entire month in question less the two disturbed days.

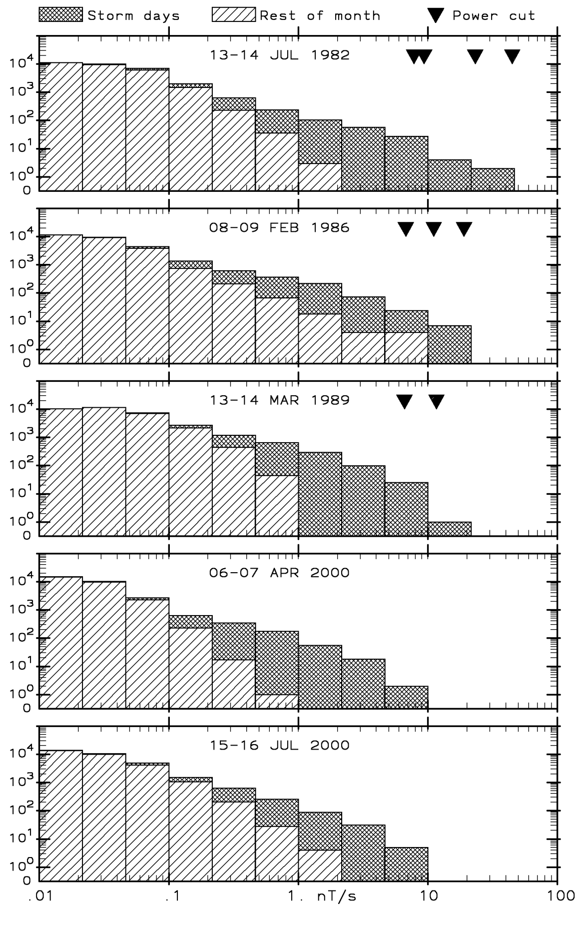

Fig. 3. Distribution of samples of geomagnetic rate of change, dH/dt, for Lovö Observatory in Mid-Sweden (inv.lat=56.4^{o}) and occurrences of power line disrupts.

The cross-hatched heavily shaded fractions in Fig. 3. on top of the columns display the distribution of dH/dt samples through the two disturbed days for each storm interval. The arrow-head symbols in the upper part of each frame indicate the power grid disrupts. They are placed corresponding to the largest observed dH/dt value within ±5 min of the reported times of the corresponding power transmission line cuts.

It is readily seen, that the largest values of dH/dt are confined to the two-day storm intervals where also the reported power-line disrupts occurred. It may also be noted that the power cuts appeared only when the geomagnetic rate-of-change exceeds approximately 10 nT/s. For comparison, the corresponding statistical analysis was made for the more recent geomagnetic storms occurring on 6-7 April 2000 and 15-16 July 2000. It is apparent that neither of these recent events produced variations as steep as those observed during the three previous storms from the past solar cycle.

3. SOLAR CYCLE VARIATIONS

The distribution of dH/dt samples in Fig.3 provides a strong indication that the occurrences of large values of the time derivative are strongly coupled to the occurrences of great magnetic storms. Such storms are known to occur preferably, but not exclusively, during maxima in the solar activity cycle. In order to observe solar cycle variations in the occurrence frequency of large time derivatives in the magnetic field we have analyzed 11 years of data from Lovö Observatory. Fig.4 displays the result.

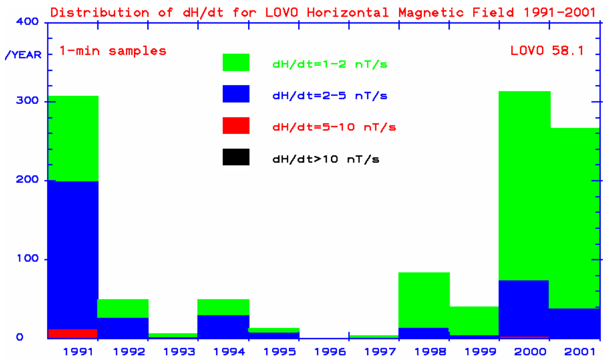

Fig.4. Distribution over a solar cycle of 1-min samples of time derivatives of the horizontal magnetic component measured during 1991-2001at Lovö.

It is clear from Fig. 4 that there is a very strong solar cycle modulation in the number of samples with large values of dH/dt. It should be noted, that while the total number of samples above 1 nT/s is approximately the same at the past and the present maxima, then the number of samples of very large dH/dt is significantly different. The number of samples above 2 nT/s is several times greater in 1991 than in 2000. These high dH/dt samples represent the most serious threath for high-voltage power line circuits.

4. MODELING OF ELECTROJET CURRENTS

Basis for the calculations of electrojet currents are magnetometer observations from the existing array of stations in Europe, including Svalbard to the north, supplemented by stations at Iceland, Greenland, and Canada. The magnetic perturbations deduced from the array of stations are combined by bivariate interpolation to form regular patterns of horizontal disturbance vectors over the entire Canada-Greenland-Europe sector. These vectors are then rotated 90 deg CW to form patterns for the equivalent overhead currents. At this initial step, the induced currents in the ground are neglected. An example of the resulting patterns calculated for the 15 July 2000 storm is shown in Fig. 5.

These patterns are now assumed to provide the directions of the current elements responsible for the magnetic perturbations. A north-south chain of stations is formed by using data from observatories in Thule and Nord in Greenland, Svalbard, Scandinavia and selected stations in Mid-Europe which, approximately, are located on the same magnetic meridian. The ionospheric currents are divided in differential current strips. Each strip has the direction given by the general patterns and is given initial current strength corresponding to the interpolated values found at the first step. The resulting magnetic perturbations in both the horizontal and the vertical components are then calculated for this current distribution. The calculations use pseudo-spherical geometry and include the effects from the secondary induced currents in the ground.

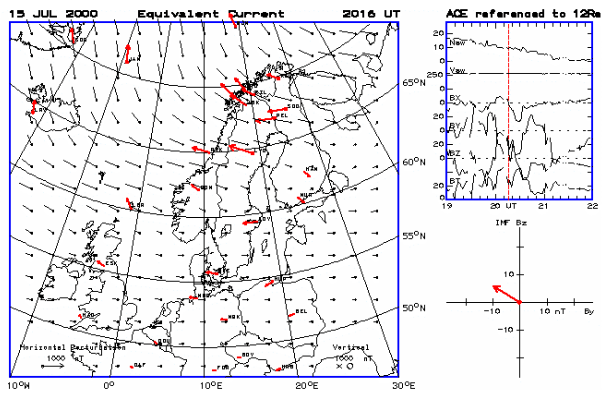

Fig. 5 Equivalent current distribution over Northern Europe at 20:16 UT on 15 July 2000. The red arrows represent observed magnetic perturbations at the array of stations while the black line segments represent interpolated values. The two small diagrams present data from the ACE satellite. The solar wind velocity and density, are strongly disturbed by solar proton radiation.

The error square sum is formed over the differences between the measured H and Z components and the values calculated for the positions of the stations in the chain.

$$ERSQ = \sum\{(H_{obs}-H_{calc})^2 + (Z_{obs}-Z_{calc})^2\}$$

(sum over all stations)

Through repeated iteration of the current distribution the error square sum (ERSQ) is gradually minimised. An example of the calculated latitude profile of the time varying current intensities is presented in Fig. 6. for the time interval from 1900 to 2300 UT on 15 July 2000.

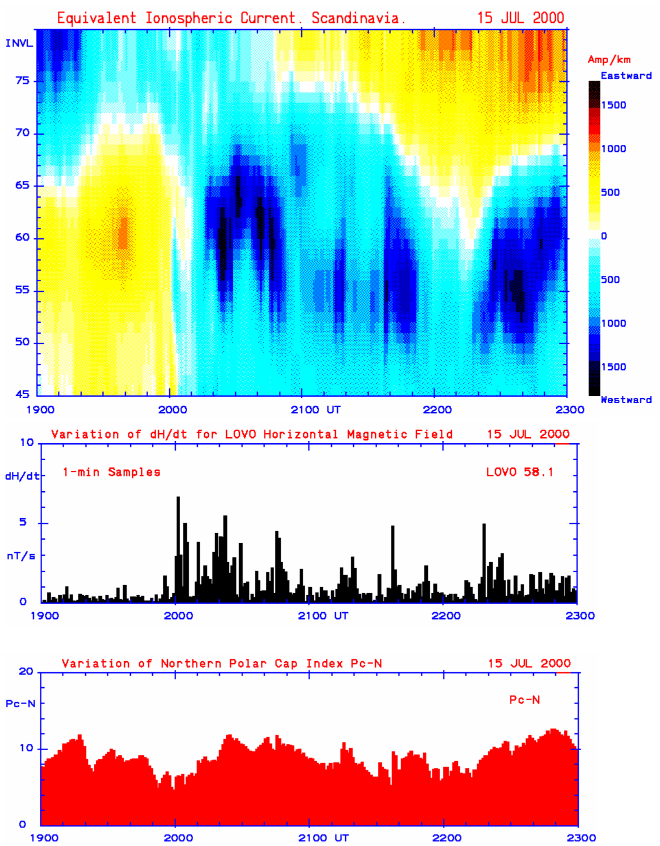

Fig. 6. Top panel: Latitude profile of equivalent ionospheric current intensities. Middle: Time derivative of geomagnetic horizontal component at Lovö. Bottom: Values of Northern Polar Cap (Pc-N) index. All panels present data through 1900-2300 UT on 15 July 2000.

It is clear from the top and middle panels of Fig.6. that the high values of the time derivative dH/dt for Lovö are associated with dramatic movements or intensifications of the equivalent overhead current pattern. The large dH/dt samples (5-7 nT/s) just after 2000 UT are associated with an electrojet reversal. They are close to the level which previously have given high-voltage power line cuts (cf. Fig. 3).

The Pc-N patterns with high values at or exceeding 10 indicate polar convection rates at a very high level. The polar convection carries plasma and magnetic fields from the dayside to the tail region building a highly stressed magnetospheric configuration which is then relieved by series of substorms. These substorms, in turn, produce the strong enhancements and the equatorward displacements of the westward electrojet (the blue intensifications) which also, at times, give large dH/dt samples at Lovö.

5. CONCLUSIONS.

- The high-voltage power line disrupts associated with geomagnetic storms occurred only when the 1-min average rate of change in the horizontal component of the magnetic field exceed around 10 nT/s measured at a central location for the transmission circuits (Lovö).
- Such large values of the time derivative of the field occurred only during the largest geomagnetic storms, among other during the 14-15 July 1982, 8-9 February 1986, and 13-14 March 1989 storms. During the present solar cycle 1-min values of dH/dt>10 nT/s were never observed at Lovö.
- The electrojet modelling may provide mapping of the sources of the GIC disturbances which could be useful for the design of transmission circuits and - if available in real-time - very useful for power grid operators.
- The PC index, which is available in near real-time, provides a fair indication of the magnetospheric build-up of stresses. A high Pc level gives warning of imminent substorm occurrence, not the precise time.

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