SCIENTIST'S THOUGHTS ABOUT THE FORECASTING PROBLEM OF GEOMAGNETICALLY INDUCED CURRENTS

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ABSTRACT

Geomagnetically induced currents (GICs) flowing in technological systems on the ground are a manifestation of ground effects of space weather. Rapid variations of ionospheric currents are the main cause of GICs. Despite numerous studies, there is not yet any good quantitative understanding about detailed structures of ionospheric currents producing large GICs. A key issue related to possible GIC forecasting is a correct prediction of rapid changes of ionospheric currents systems. An additional difficulty arises from the fact that relevant length scales vary from global to very local ones.

Key words: geomagnetic induction; geomagnetically induced currents; GIC; rapid geomagnetic variations.

1. STATUS OF MODELLING GEOMAGNETICALLY INDUCED CURRENTS

Geomagnetically induced currents (GICs) in ground-based technological conductor systems provide an excellent possibility for testing space weather models, since the full understanding of the phenomenon requires that the whole physical interaction chain from the Sun down to the Earth's surface is considered.

As a specifically defined electromagnetic problem, GICs can be determined if the spatiotemporal behaviour of ionospheric currents is known and models of the Earth's conductivity are available. Then it is in principle possible to solve the geoelectric field, which drives GICs. If the electric field is known it is a relatively straightforward DC problem to compute GICs in a given conductor system, may it be discretely (power networks, e.g. Lehtinen and Pirjola (1985)) or continuously grounded (buried pipelines, e.g. Pulkkinen et al. (2002a)). Thus, the challenge is to calculate the electric field reasonably accurately and fast.

It is an empirical fact, and can be argued by the Maxwell equations, that GIC in a given conductor is closely related to the time derivative of the magnetic field measured at a nearby location. This provides a pragmatic tool for deriving statistical predictions of the occurrence of GICs using measured geomagnetic field. Simplified models of the ground conductivity allow for the use of the plane wave model to calculate the geoelectric field (Pulkkinen et al., 2000). It is also possible to derive a direct relation between magnetic variations and GIC (Viljanen, 1998). These approaches do not require any deeper understanding of near-space phenomena beyond GIC.

Concerning experimental investigations, recent extensive measurement campaigns have provided direct information of GICs and associated voltages in pipelines (Boteler and Trichtchenko (2000), Pulkkinen et al. (2002b)).

A recent achievement presently under further applications combines a method to derive equivalent ionospheric currents from ground magnetic field recordings (Amm and Viljanen, 1999) to a fast computation technique of the surface fields which allows for the use of multilayered conductivity models (Pirjola and Viljanen, 1998). The result is a handy tool, which could be efficiently used for nowcasting purposes too. In an earlier study, it was already possible to apply advanced ionospheric models to investigate some prototype events (Viljanen et al., 1999).

Forecasting GICs early enough before a large geomagnetic event is still more difficult. One reason is that only extreme cases seem to be significant from the industrial viewpoint, and such events have not been investigated very much. A gradual degradation of a transformer or a pipeline due to GIC may also be possible.

One of the few (if not only) operative GIC forecasting systems is provided by Kappenman et al. (2000). It starts from solar wind observations by the ACE satellite and utilises statistical models to deduce large-scale ionospheric currents. The geoelectric field is then determined, GICs are calculated in a given power network, and finally GIC effects on the system are evaluated. So in principle this is quite an ideal system, since it can provide advance warnings at least 30 minutes before solar wind disturbances hit the magnetosphere. This procedure may yield a reasonable hint of forecoming higher geomagnetic activity. However, as discussed below, it is hardly possible yet to derive reliable predictions of the accurate location and time of large GICs.

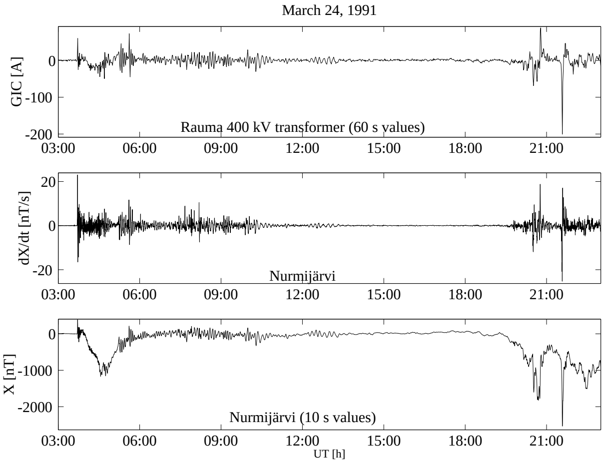

Figure 1. Top panel: Geomagnetically induced current at the Rauma 400 kV transformer in southwestern Finland on March 24, 1991. Centre panel: Time derivative of the northward magnetic field at the Nurmijärvi Geophysical Observatory in southern Finland. Lowest panel: Variation of the northward magnetic field at Nurmijärvi.

2. TEMPORAL AND SPATIAL SCALES OF GEOMAGNETICALLY INDUCED CURRENTS

It is known that spatial scales of large GIC events vary from very local to global ones (Viljanen et al., 1999). Examples of the former are rapid auroral activations, whose spatial extents can be only about 100 km (e.g. Kauristie et al. (2000)). In turn, sudden impulses due to solar wind pressure pulses are clearly global events. A common feature, and a necessary requirement for significant GICs, is a large time derivative of the ground magnetic field (up to a few 10 nT/s). The duration of geomagnetic storms can be some days, but continuous sequences with rapid magnetic field variations last typically a few minutes only.

During a single storm, there can be several totally different ionospheric current systems responsible for GICs. One of the most extreme events occurred on March 24, 1991, and it is an illustrative example (Fig. 1). The storm started with an expectionally strong SSC (Araki et al., 1997) followed by an intense westward electrojet and pulsations with large amplitudes during the local morning. Before and around the local midnight, there were several substorm activations, one of which caused the largest GIC (201 A) ever observed in Finland.

An example of a very localised intense GIC event on February 18, 1999, is given in Fig. 2. Four successive snapshots of the time derivative of the horizontal magnetic field vector ($d\mathbf{H}/dt$) are shown. The reason for prefering the time derivative instead of the conventional ground equivalent current (rotated $\mathbf{H}$ field) is that $d\mathbf{H}/dt$ provides a quantitative indicator of GIC activity (Viljanen et al., 2001). The vectors are rotated 90 degrees anticlockwise to mimic the geoelectric field. Very large values occur only at two timesteps (18:09:40 and 18:09:50 UT) before and after which the time derivative is clearly smaller (although still significant). Extreme values are observed only at four nearby sites (about 200 km from each other), so the ionospheric current system causing the large $d\mathbf{H}/dt$ values was evidently very localised. It is suggested that this event was associated with an auroral horn (Kauristie et al., 2000).

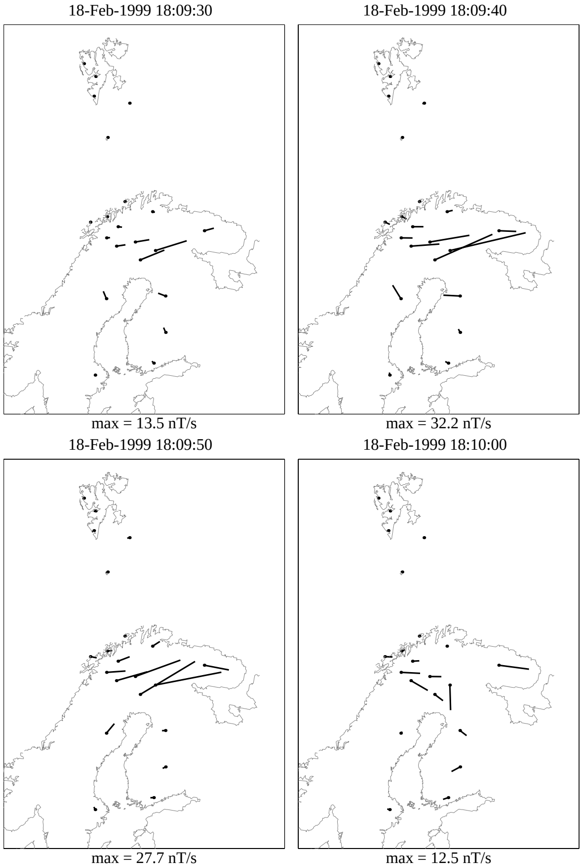

Figure 2. Sequence of $d\mathbf{H}/dt$ vectors recorded by the IMAGE magnetometer network on February 18, 1999. To mimic the geoelectric field, vectors are rotated 90 degrees anticlockwise.

Inspection of GIC events in the Finnish natural gas pipeline in 1999-2001 indicate that a high geomagnetic activity is a necessary condition for large GIC values. For example, 19 of the 20 most active days defined by the maximum of GIC are classified at least in the category of major storms (A_k index at the nearby Nurmijärvi observatory larger than 50).

It is obvious that extreme GIC events generally require as a ”background” high global geomagnetic activity. However, the present physical knowledge is evidently insufficient to predict the exact locations of activations relevant to GIC (i.e. the sites where large $d\mathbf{H}/dt$ can be expected). The February 18, 1999, event described above is a good example of this difficulty.

3. NEAR-FUTURE GOALS

It is even not exactly known which kinds of ionospheric currents can cause large GICs. Consequently, an immediate task is to derive a quantitative classification. Unless such a research is done, forecasting may remain useless in practice with too many false alarms.

It follows that a physics-based model to forecast GICs is very demanding. Today's aim should be to predict the ground magnetic variation field, from which it is possible to calculate GICs. The required temporal accuracy is one minute or less and the field should be known in a grid with a cell size of 100 km x 100 km or smaller. We emphasize that for GIC purposes the time derivative of the magnetic field should be known accurately, as well as the region where the event occurs.

Physical models are scientifically preferable, but it may take more than one solar cycle before any really operational tools are available. Alternative approaches, which may become useful more quickly, are neural networks and (non-)linear techniques (e.g. Valdivia et al. (1999)). One idea mixing different approaches could be to forecast the occurrence of specific types of events which are known to cause large GICs.

GICs can cause harmful effects on various man-made systems (Boteler et al., 1998), so GIC studies are often justified by the potential space weather risk. However, there are only few very serious failures (for example, the March 1989 power system blackout in Canada), so the danger of ground effects should not be exaggerated. On the other hand, large GIC events are often interesting from other space physical aspects. GIC is also an interesting phenomenon for a scientist and consequently worth studying as such.

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