Research of geomagnetically induced currents as ground effects of space weather

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Abstract

"Space Weather" refers to electromagnetic and particle conditions in the Earth's space environment that may disturb and damage ground-based and space-borne technological systems. At the Earth's surface, space weather manifests itself as "Geomagnetically Induced Currents" (GIC) in technological conductor networks, such as electric power transmission grids, oil and gas pipelines, telecommunication cables and railway equipment. GIC are a potential source of problems to the systems. In power networks, GIC can cause saturation of transformers with different harmful consequences. In pipelines, GIC may create problems associated with corrosion and its control. GIC are a particular high-latitude phenomenon but networks at lower latitudes may also experience large and harmful GIC sometimes. In this paper, we mostly concentrate on GIC in power networks. GIC effects are summarised. We also discuss studies of GIC, which can include both theoretical modelling and measurements.

Introduction

"Space Weather", whose origin is in the activity of the Sun, relates to electromagnetic and particle conditions in the near-Earth space (e.g., Lanzerotti et al., 1999; Bothmer and Daglis, 2007). Space weather can disturb the operation of technological systems both in the space and on the ground and even cause permanent damage. Possible space weather effects on humans also have to be taken into account especially in connection with manned space flights. The high dependence of modern societies on reliable technology increases the significance of space weather risks (e.g., Pirjola et al., 2005).

The plasma physical processes related to solar-terrestrial interactions and involved in space weather are very complicated and not yet fully known, so continuous research efforts are needed. Charged particles emitted by the Sun and carried by the solar wind to the Earth interact with the geomagnetic field forming the magnetosphere with a sharp boundary in the day side and a long tail in the night side. The magnetosphere is coupled to the ionosphere. An explosion on the Sun leading to a burst in the solar wind results in increased radiation and in intense and rapidly-varying electric currents in the magnetosphere-ionosphere system. Solar activity follows the eleven-year sunspot cycle giving the same statistical variation to space weather phenomena. However, it is important to note that large space weather storms are also possible during sunspot minima.

"Geomagnetically Induced currents" (GIC) flowing in technological networks at the Earth's surface, such as electric power transmission grids, oil and gas pipelines, telecommunication cables and railway equipment, constitute the ground end of space weather. GIC are driven by the geoelectric field induced by a time variation of the geomagnetic field during a space weather storm. Thus, the physical principle of GIC can simply be described by Faraday's and Ohm's laws.

Effects of GIC

GIC effects were already observed in the first telegraph equipment in the mid-1800's, i.e. very much earlier than the term "Space Weather" was introduced, (e.g., Boteler et al., 1998; Lanzerotti et al., 1999; and references therein). In the past several GIC problems have occurred in telecommunication systems (see Boteler et al., 1998; and references therein). However, today's optical fibre cables are not directly affected by space weather but GIC may flow in metallic wires used for powering repeaters. Trans-oceanic submarine communication cables are a special category regarding GIC since the distances imply large end-to-end voltages (Lanzerotti et al., 1995). So far, research on GIC impacts on railways has not been done much. A documented event occurred in Sweden in July 1982 when railway traffic lights turned unexpectedly red (Wallerius, 1982; Wik et al., 2009). Recent investigations also report disturbances due to GIC on Russian railways (Belov et al., 2007; Ptitsyna et al., 2008).

Anyway, today, oil and gas pipelines and power networks seem to be the most significant regarding GIC. Unprotected buried pipelines are prone to serious corrosion of the steel, which is an electrochemical process occurring at points where a current flows from the pipe to the soil. Roughly speaking, a dc current of 1 A causes a loss of about 10 kg of steel in a year. A detailed description about the chemistry etc associated with corrosion is provided by Gummow (2002). To minimise currents from the pipe to the soil, pipelines are covered by an insulating coating. Cathodic protection (CP) systems are applied as well. They keep the pipeline in a negative voltage of typically around 850 mV with respect to the soil, and so current flows in the hazardous direction are opposed. Too large a negative voltage is not acceptable since it would also create harmful chemical reactions. Pipe-to-soil voltages associated with the flow of GIC in a pipeline network may easily be larger than the CP voltage, thus invalidating the protection. Furthermore, control surveys of pipe-to-soil voltages during geomagnetic disturbances may be completely unreliable.

The low frequencies, typically in the mHz range, associated with geoelectromagnetic phenomena make GIC have a (quasi-)dc character compared to the 50/60 Hz ac currents in power networks. This means that the presence of GIC potentially leads to half-cycle saturation of transformers (e.g., Molinski, 2002; Kappenman, 2007). The result is a nonlinear operation of transformers with large and asymmetric exciting currents causing increased harmonic contents, unnecessary relay trippings, excessive reactive power demands, voltage fluctuations, and even a collapse of the whole power network. Transformers may also be overheated with permanent damage. The most famous GIC event so far occurred in the Hydro-Québec 735 kV network in Canada resulting in a province-wide blackout for several hours during a large geomagnetic storm in March 1989 (e.g., Bolduc, 2002; and references therein). A transformer was permanently damaged in New Jersey, USA, during the same storm, and it had to be replaced (Kappenman and Albertson, 1990). The increasing sizes of high-voltage power grids, the complex interconnections and the extensive transport of energy make GIC issues more and more important. Brooks (2009) presents dramatic views about the catastrophes that GIC might possibly cause in power networks now and in the future. This paper is particularly focussed on GIC in power systems.

The plasma physical coupling between the solar wind and the Earth's magnetic field implies that geomagnetic disturbances and storms are the largest in auroral regions located at high latitudes. This naturally means that GIC are a special problem in the same areas. However, during major geomagnetic storms, the auroral oval can extend substantially towards lower latitudes. Furthermore, GIC magnitudes also depend on the network topology, configuration and resistances, and they vary much from site to site in a system. Particularly prone to large GIC are ends and corners of a network. Moreover, it should be noted that sensitivities of systems to GIC also vary from one network to another, which means that a certain GIC value that is not problematic in one system can be serious in another. These facts mean that mid- and low-latitude systems may be affected by GIC as well (see Kappenman, 2003). Therefore research efforts on GIC for example in Brazil, China and South Africa are well justified (Kappenman, 2005; Gaunt and Coetzee, 2007; Trivedi et al., 2007; Liu et al., 2008).

Studies of GIC

GIC can be investigated by theoretical model calculations or by measurements, and the former should always be verified and adjusted by using recorded GIC data. Theoretical modelling of GIC is usually performed in two separate parts:
1) Determination of the horizontal geoelectric field at the Earth's surface.
2) Computation of GIC in the system produced by the geoelectric field.
The first part, called the geophysical part, is independent of the technological system considered. It requires knowledge or assumptions about the Earth's conductivity structure and about the ionospheric-magnetospheric currents or about the geomagnetic variations at the Earth's surface. Viljanen et al. (2004) have demonstrated that a local plane wave technique combined with the method of spherical elementary current systems (SECS) seems to be appropriate for the geophysical part in practice. The input of the method consists of geomagnetic data, which are interpolated by SECS to a grid that is suitable regarding the network where GIC should be calculated. Assuming the Earth's conductivity structure lets us determine the surface impedance, which enables the computation of the geoelectric field from the magnetic data at the grid points. Usually the assumed Earth conductivity model has some shortcomings, which can be compensated by comparing calculated and measured (if available) GIC values later.

The second part, called the engineering part, can in principle be performed exactly by utilising Ohm's and Kirchhoff's laws if all connections and resistances of the system are known. For a discretely-earthed network, such as a power system, matrix formulas are available (Lehtinen and Pirjola, 1985), and for a buried pipeline, which is continuously-earthed by leakage through the (non-perfect) coating, the distributed-source transmission line theory (DSTL) is applicable (Pulkkinen et al., 2001). The network data are provided by the power and pipeline companies. To our experience, those data are never complete and some approximations are necessary. As concerns power systems, all line connections and disconnections should be known precisely whereas exact resistance values are less critical (Pirjola, 2009).

In power networks, GIC are usually recorded in the earthing leads of transformer neutrals. It can be simply performed by using a small shunt resistor in the lead or a coil around the lead. Measuring GIC at the neutral is reasonable because the ac currents in the three phases sum to zero, so that in the normal situation there is no current in the lead. It should also be noted that GIC flowing between the network and the Earth is the most important in practice because it is responsible for the possible saturation of transformers. However, regarding scientific use, data of GIC flowing in transmission lines are as valuable as GIC recordings to (from) the Earth. A technique in which a magnetometer lies below the transmission line and another reference magnetometer is located further away has been successfully used for measuring GIC in power transmission lines at least in Brazil and in Finland (Trivedi et al., 2007; Viljanen et al., 2009). The same method is also used to record GIC in the Finnish natural gas pipeline since 1998.

To our knowledge, the largest reported GIC value (almost 300 A in April 2000) measured in a power network comes from Sweden (Wik et al., 2008). During the history, there are several examples of GIC disturbances in Sweden. The worst and most recent case is the power blackout in the city of Malmö in southern Sweden during a geomagnetic storm in October 2003 (Pulkkinen et al., 2005; Wik et al., 2009). The high-latitude location, together with a high ground resistivity (which tends to enhance geoelectric fields), provides an explanation for GIC experiences in Sweden. Finland located at the same latitudes and having a similar geology has not suffered from GIC problems. However, extensive research on GIC in the Finnish high-voltage power network, as well as in the Finnish natural gas pipeline, has been carried out for about thirty years. Basically the power systems in Sweden and Finland are similar: 400 kV and 220 kV grids effectively earthed are used for power transmission, the ground resistivities are high (2300 Ωm is assumed for Finland), the sizes of the grids are roughly of the same order of magnitude, etc. In Finland, however, mostly five-legged core-type full-wound three-phase transformers are used while the Swedish high-voltage network includes many autotransformers, the oldest of which are made of single-phase units. In addition, the protective relays seem to be more sensitive to GIC-produced harmonics in Sweden than in Finland, thus producing unwanted relay trippings in the former.

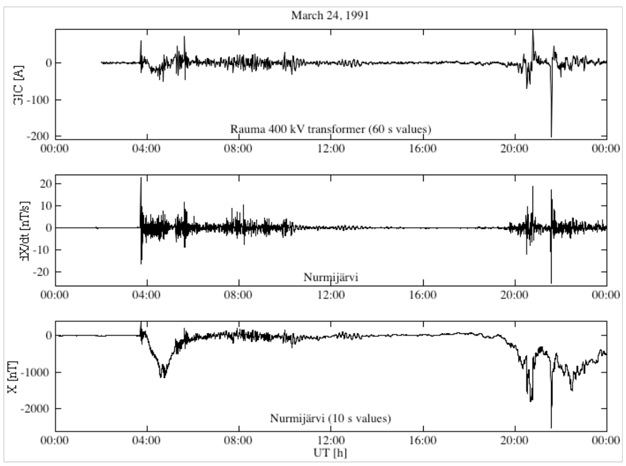

Figure 1: Top panel: GIC in the earthing lead of the Rauma 400 kV transformer neutral in southwestern Finland on March, 24 1991. Bottom panel: north component (X) of the geomagnetic field at the Nurmijärvi Geophysical Observatory in southern Finland. Middle panel: the time derivative of X shown in the bottom panel (Pirjola et al., 2005).

The largest GIC measured in the Finnish power network is 201 A, i.e. 67 A per phase, (as a one-min mean value) in the earthing lead of the 400 kV transformer neutral at the Rauma substation in southwestern Finland on March 24, 1991. The top panel of Fig. 1 depicts the GIC recording at Rauma for the whole day. The bottom and middle panels show the simultaneous north geomagnetic component and its time derivative observed at the Nurmijärvi Observatory in southern Finland. The distance between Rauma and Nurmijärvi is roughly 200 km. The GIC curve clearly has more similarities with the time derivative than with the magnetic field. However, in general, the relation of the geoelectric field (and thus also GIC) with the magnetic field and with its time derivative is not self-evident, and the relation seems to vary from one location to another. Trichtchenko and Boteler (2007) present an example from Canada in which GIC resembles the geomagnetic variation and another example, also from Canada, in which a correspondence between GIC and the magnetic time derivative exists. Watari et al. (2009) demonstrate that in recordings at a site in the Japanese power network GIC show a high correlation with the geomagnetic field rather than with the time derivative.

As indicated above, the Finnish power network has practically never experienced GIC problems. To confirm the immunity to GIC, field tests have also been performed by injecting dc currents into transformer neutrals and by monitoring and measuring the consequences (Lahtinen and Elovaara, 2002). The general conclusion is that the probability of GIC events that could damage transformers or cause serious problems in Finland is small. It should also be noted that the neutral point reactors installed in many Finnish 400 kV transformers tend to decrease GIC (Pirjola, 2005).

Conclusions

GIC constitute the ground end of the complicated space weather chain originating from solar activity. The history of GIC dates back to the first telegraph equipment more than 150 years ago. Regarding GIC issues today, electric power transmission networks are the most significant. In them, dc-like GIC may saturate transformers with different harmful consequences including even a wide blackout and permanent transformer damage. Thus research of GIC is not only scientifically interesting but it also has important practical applications. Although the GIC problem is the largest at high-latitudes, where geomagnetic storms are the most intense and frequent, GIC can seriously impact mid- and low-latitude networks as well. Therefore GIC studies are motivated all over the world.

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