EFFECTS OF RECENT GEOMAGNETIC STORMS ON POWER SYSTEMS

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Abstract. Significant geomagnetically induced currents (GIC) in power systems during the geomagnetic storms are the ground manifestations of the chain of events initiated by increased solar activity. Here we present the review of the largest geomagnetic storms, their solar sources and their associated GIC observed at the power grids. The geomagnetic activity was described by planetary Kp index and local hourly range index. Thus, we produce analogous GIC-indices, 3-hour and 1-hour, to compare them with geomagnetic indices. The results of comparison show relatively good correspondence of geomagnetic and GIC indices, better in case of local 1-hour indices. For more detailed investigations of GIC variations in time, however, the effects of ground conductivity need to be included. To show that, we compared GIC recordings with 1) rate-of-change of geomagnetic field as representation of the driving geo-electric field and 2) geo-electric field modeled by using 1-d approximation. It has been shown, that during sharp increases of the geomagnetic field, the effects of Earth conductivity are important to include in modeling; hence, modeled geo-electric field is better estimation of the GIC.

Introduction

Variations of the natural Earth magnetic field produced by disturbances propagated from the Sun, affect all the conducting networks at the surface of the Earth by inducing electric currents. Frequency of the geomagnetically induced currents (GIC) ranges from 10^4 Hz (12 hours period) to a few Hz. Hence, for power line networks, which operate at 50 or 60 Hz, these currents act as the direct currents (not varying in time). This defines the types of their effects on power grid components: immediate effects, such as saturation of transformers, generation of harmonics and waveform asymmetry; and cumulative effects, such as transformer heating. In the case of large magnetic storms it can lead to the dramatic scenario of a widespread power blackout such as occurred in March 1989 on the Hydro-Quebec power system, leaving their 6 million customers without power for 9 hours [1].

The largest events of the last solar cycle

The chain of events which leads to the generation of large GIC during the geomagnetic storms contains the following components: solar disturbances, their propagation through the interplanetary medium, excitation the magnetosphere, changes in the-ionosphere, excitation of Earth magnetic field and production of the GIC in the conducting networks.

The most significant recent effects on power systems were produced during a series of magnetic storms at the end of October 2003 (the so-called "Halloween" events). Fig. 1a is representing the image of the major solar source of the ground magnetic storms, a full halo coronal mass ejection (CME) which occurred on October 28.

The sequence of interplanetary and ground events which follow two full halo CMEs on October 28 and 29 is presenting in Fig. 1b. The top panel is showing changes in the vertical component of the interplanetary magnetic field (IMF) at the satellite (ACE), located at the orbit between Sun and Earth to monitor the propagation of solar disturbances. The second panel is showing the variations of the geomagnetic field at the Ottawa geomagnetic observatory and the two at the bottom are representing variations of GIC in the transformer neutral at two power grids in Canada.

The start of the events is marked by the increase in amplitude of the interplanetary magnetic field at 06:00 UT (Universal Time) on October 29. The active period ends at approximately 18:30 UT on October 31 as seen on GIC records.

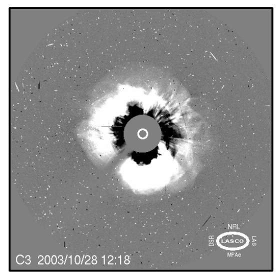

Fig. 1a Full halo CME on 28 October 2003.

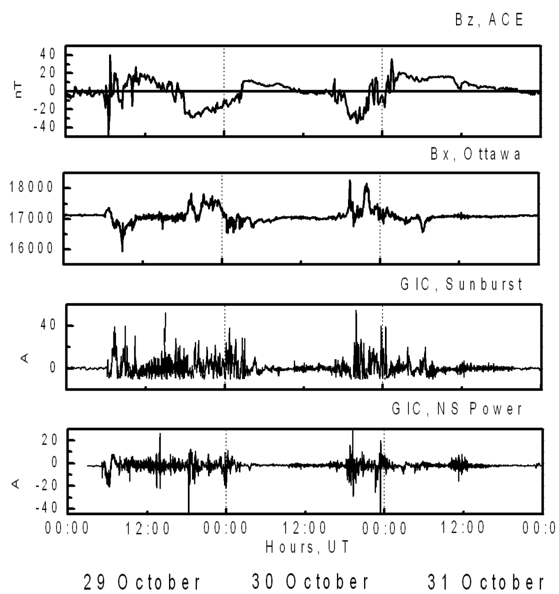

Fig. 1b. Time progression of October 29-31 event in interplanetary and geo-magnetic fields and GIC data.

Effects of these "Halloween" storms on power grids were recorded all around the globe. The most significant were seen in Europe, such as a power blackout for one hour in Malmo, Sweden [2]. In North American power systems effects were seen as very large GIC (>100A), high (up to 10%) total harmonic distortion and unstable voltage for TV transmitters

Large GIC and geomagnetic variations coincide in time, as has been demonstrated by the above example of the storm. To simplify the description of the strength of geomagnetic variations, different types of geomagnetic indices have been designed and used for more than 70 years. These are derived from geomagnetic data recorded at the observatories around the globe. The most widely known is the 3-hour Kp index of geomagnetic activity, which ranges from 0 for very quiet conditions up to 9 for major geomagnetic storms.

Table 1. The largest magnetic storms in 1998-2005

Date	CME type	IMF min, nT	Kp	GIC max,A
02-04 May **98**	Halo	-32	9-	70
23-25 Sep **98**	N/A	-23	8+	N/A
21-22 Oct **99**	NE	-30	8	50
04-07Apr **00**	W	-27	9-	80
14-16 Jul **00**	Halo	-44	9	80
16-17 Sep **00**	Halo	-23	8+	N/A
30 M-1Apr **01**	Halo	-41	9	80
10-12 Apr **01**	Halo	-23	8	30
03-06 Nov **01**	Halo	-70	9-	60
22-24 Nov **01**	Halo	-25	8	90
20-23 May **02**	Halo	-43	8+	20
27-30 May **03**	Halo	-33	8+	60
28-31 Oct **03**	Halo	-48	9	>100
18-20 Nov **03**	Halo	-53	9-	60
20-27 Jul **04**	Halo	-21	9-	50
03-10 Nov **04**	Halo	-50	9-	>100
13-15 May **05**	Halo	-43	8+	80
22-24 Aug **05**	Halo	-55	9-	100

The largest geomagnetic storms evaluated by Kp index, their solar sources, associated IMF changes and maximum values of GIC recorded in one of sites on North American power grid are presented in Table 1 in chronological order. As can be seen from this table, the majority of CME which produced significant geomagnetic storms (Kp>8) are halo-type CMA, which means Earth-directed disturbance propagation. They produce significant (<-20nT) negative exertion of vertical component of IMF, normally varying between -5 and +5 nT. The response of power system to these storms shows significant GIC at the recording site, but not always directly proportional to the size of geomagnetic disturbance expressed in Kp. More detailed comparisons of geomagnetic and GIC variations are described in the following paragraph.

GIC and geomagnetic indices

The simplest way to estimate GIC values would be to derive some statistical relations between GIC and geomagnetic indices. To follow this idea instead of non-linear Kp index expressed in rather non-mathematical values like "8+"or "9-", we use linear 3-hour ap index, derived from Kp and available at the same World Data Centres for geomagnetism, such as, for example, http://web.dmi.dk/fsweb/projects/wdcc1/master.html .

A more specific index of geomagnetic activity, designed to describe local variations at each observatory is the hourly range index produced for Canadian geomagnetic observatories at Geomagnetic Laboratory, Ottawa (http://gsc.nrcan.gc.ca/geomag/index.php).

The strength of the GIC can also be characterised by producing some GIC-indices. The first attempt to create such indices has been described in [3], which used the maximum GIC in a 3-hour period (GIC_3) and the maximum GIC in 1 hour period (GIC_1).

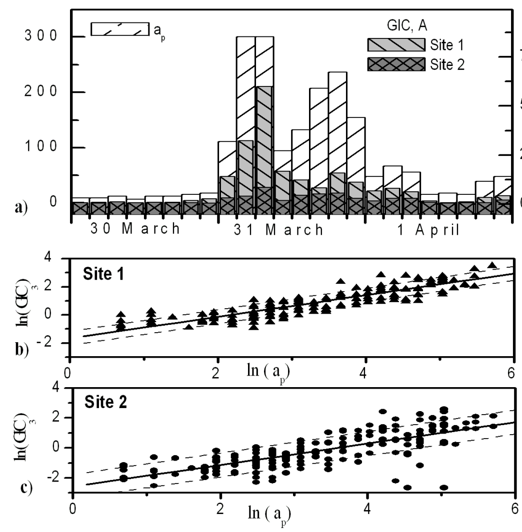

Fig. 2. Comparisons of GIC_3 and a_p indices for geomagnetic storm 30 March-1 April 2001.
a) Time variations;
b) Site 1: scatter plot, linear fit and SD
c) Site 2: scatter plot, linear fit and SD

An example of comparisons made for a_p index and 3-hour GIC indices (GIC_3) produced from measurements at two different power grids (USA, site 1 and Canada, site 2) for geomagnetically active days of 30 March-1 April 2001 is presented in Figure 2. Periods with large a_p and GIC indices are roughly coincided (Fig. 2a). Linear correlations between logarithms of GIC_3 and a_p for 10 magnetic storms are shown in Figs. 2b, c. The general linear trend is easily recognisable, with more scatter beyond the two standard deviations (dashed lines) for Site 2. This is because Site 2 is located more to the North than Site 1, while global geomagnetic a_p index is derived from the set of mid-latitude observatories.

The most variable geomagnetic conditions, however, are at so-called "auroral" latitudes, where the large part of Canada is located. At these latitudes the geomagnetic field is naturally more closely coupled with the disturbances in the interplanetary media and shows more local variability. The hourly range geomagnetic index has been developed to better describe this variability. Hourly GIC-index correlates well (up to 93%) with the hourly range geomagnetic index [3]. Because the GIC flow in the direction of the power line, the comparison should be done with geomagnetic index obtained from the component of the magnetic field, perpendicular to the direction of the power line (electric field, driving GIC, is perpendicular to the magnetic field). More detailed analysis has been done in [3].

Figure 3 is illustrating the variability of the hourly range magnetic index and GIC_1 index for the same event as Figure 1. The GIC measuring Site 1 is located closer to the geomagnetic observatory in Ottawa (OTT), while Site 2 is closer to the magnetic observatory in Glenlea (GLN). The general direction of Site 1 power grid is such that approximation by hourly range Bx (North component) is better, while for the second site By (East component) is better. Note the logarithmic scale for GIC and magnetic indices is used here.

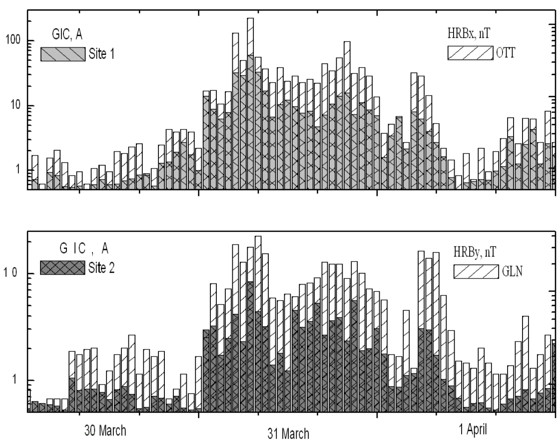

Fig. 4 Comparisons of hourly range magnetic and GIC_1 indices for magnetic storm 30 March-1 April 2001. Site 1 and HRBx at OTT (top); Site 2 and HRBy at GLN (bottom).

The relations between GIC_1 and hourly magnetic indices for 10 magnetic storms are shown in Fig. 4. Results for Site 2 (bottom panel) are more scattered due to the greater variability of the geomagnetic variations in the auroral zone.

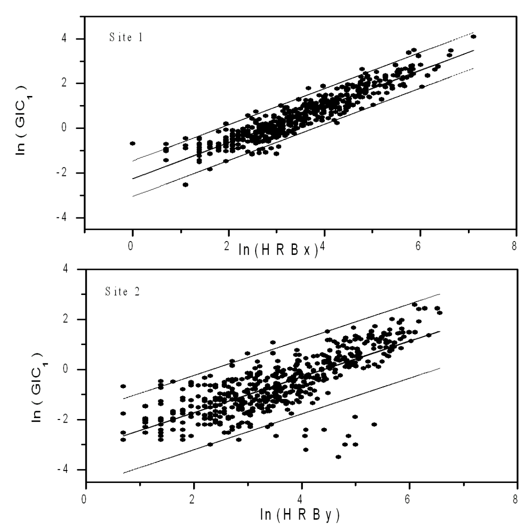

Fig. 5. Relation between GIC_1 and hourly range magnetic indices for Site 1 (top) and Site 2 (bottom). Lines are linear fit and standard deviation

The evaluations of the GIC indices based on the geomagnetic indices demonstrated here and in more details in [3] are useful but cannot provide all the details of the GIC variations during the magnetic storm.

GIC and ground structure

It is well known, that fluctuations of GIC follow the variations of the driving electric field. The first very simple approach is to estimate the electric field is to calculate the time derivative of the geomagnetic field variations. More sophisticated models of the geoelectric field involve knowledge of ground deep conductivity structure of the area [4]. Among them the simplest is the plane wave model, which we use to construct the geoelectric field in all following examples. I.e. it has been assumed that the source of the electromagnetic variations is a downward propagating plane wave and geomagnetic field is uniform over the network and the earth conductivity varies only with the depth. We also assumed that the network consists of ohmic resistances (GIC are DC currents), hence, the power system response is independent of the frequency.

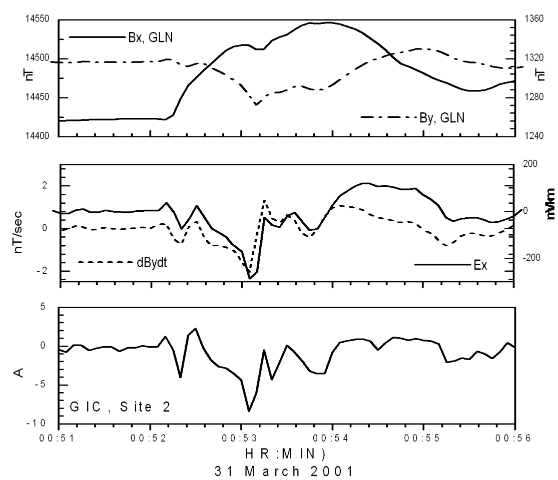

Figure 3. Geomagnetic field (top), time derivative and geoelectric field (middle) and GIC (bottom) at Site2.

Calculations of the driving electric field can be done by multiplying the geomagnetic field with the surface response, derived from the conductivity model of the earth in the area of the network.

Because the power system response to GIC is independent of frequency, the variations of GIC recorded in the transformer neutral have to follow variations of the driving electric field. This geoelectric field can be evaluated by using only time derivative of magnetic variations or by simple model which takes into account earth conductivity model. To illustrate the applicability of dB/dt approach and plane wave model approach we made the modelling calculation for the magnetic storm on March 30-April 1 2001 and plot the first 5 minute of the storm, when the sharp variations of the magnetic field occurred (storm sudden commencement, SSC). As can be seen from Fig. 5, which presents geo-electromagnetic field and GIC variations at Site 2, the GIC variations (bottom panel) follow dB/dt variations and modelled geoelectric field variations (middle panel) quite good.

Quite different result has been obtained for Site 1 and presented in Fig. 6. Here the GIC variations (bottom panel) seems to follow more closely Bx-variations (top panel), rather than dB/dt variations (middle panel, dotted line). When compare with the modelling geoelectric field (middle panel, solid line), the similarity of GIC and geoelectric field is evident. The explanation of these features is quite simple. In the case of Site 2, ground conductivity structure is acting like a high pass filter, thus higher frequencies are dominant in the variations of the geoelectric field, which made them look like variations of dB/dt. At the location of the Site 1 the ground conductivity structure is different and acts more like a low pass filter, giving more power to the lower frequencies, thus the geoelectric field better follow slow variations of the magnetic field rather than dB/dt.

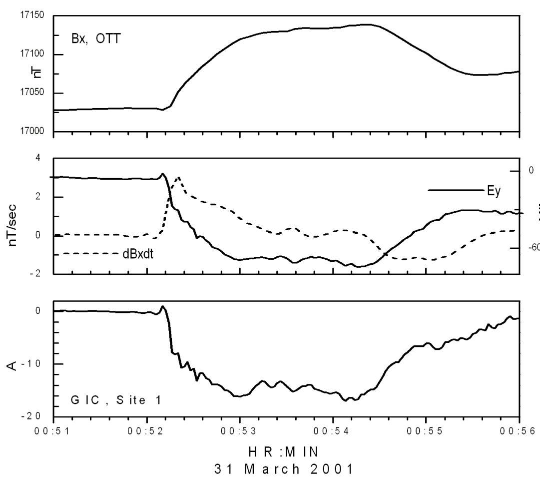

Fig. 6. Geomagnetic field (top), time derivative and geoelectric field (middle) and GIC (bottom) at Site1

As has been shown by the simple example of the sharp increase of geomagnetic field (SSC), the geology can play significant role in GIC estimations. In some cases GIC variation follows the time derivative of the magnetic field, while at location with different geology it might follow the magnetic field variation. The best result for the detailed GIC studies and modelling gives the proper geoelectric field modelling which includes conductivity structure of the Earth.

Discussion and Conclusions

Large geomagnetic fluctuations, such as geomagnetic storms, induce large electric currents in earthed conductors. These electric currents have frequency content, which is defined by the frequency content of the geomagnetic variations and structure of the conductive earth. While for forecasting purposes it is reasonable to use indices and avoid complexity of the detailed fluctuations, the physical picture of the geomagnetic induction is frequency dependent.

Forecasts of the global Kp-index are produced by the US NOAA Space Environment Centre in Boulder (http://www.sec.noaa.gov/index.html) and of the hourly indices by Canada Regional Warning Centre in Ottawa http://www.spaceweather.gc.ca/forecasting_e.shtml.

In the Figure 7 we present the empirical fit lines which have been derived from data used to plot Fig.4, i.e. from recordings made for 10 geomagnetic storms, together with data (dots), which were not included in the dataset used to derive the linear fit. These GIC data were recorded during the next few geomagnetic storms. As can be seen, these new data points located mostly between two standard deviations lines (dashed). This might present the way to forecast GIC-indices, if empirical linear fit is known, i.e., if the measurements of GIC were made for this site in the past, provided configuration of the power grid did not change much.

When these conditions cannot be applied, the numerical modelling of the GIC became of primary importance.

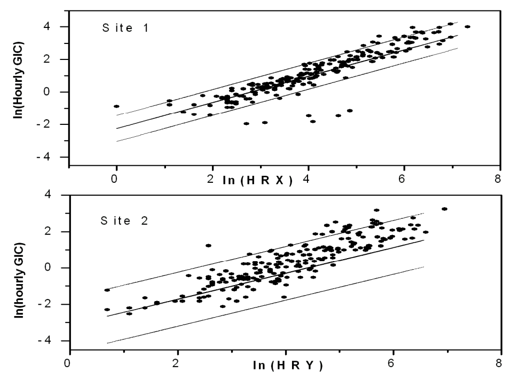

Fig. 7. Verification of the linear fit predictions of the GIC indices from previously known relationships (lines) by adding new data points from recent events (dots)

The modelling calculations of GIC can provide a useful guide for mitigation action. For power systems, real-time modelling is used to provide system operators with an overview of conditions throughout the network. GIC observations can complement the modelling but are too expensive to make at every ground point and are difficult to make on power lines.

References

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