2-2-6 Effects of Geomagnetically Induced Current on Power Grids

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There have been many reports that geomagnetically induced current (GIC) has affected the operation of electric power grids. Given Japan's location at lower geomagnetic latitude than its geographic latitude, the effects of GIC on electric power grids there are believed to be small, but have yet to be subjected to elaborate analysis. This paper describes the results of GIC measured in Hokkaido over a two-year period in collaboration with the National Institute of Information and Communications Technology (NICT), Hokkaido Electric Power Co., Inc., and the Solar-Terrestrial Environment Laboratory (STEL) of Nagoya University.

Keywords
Geomagnetically induced current (GIC), Geomagnetic storm, Power grid

1 Introduction

In an electric power grid, the neutral points of transformers in power plants and substations are normally grounded for safety. For that reason, any potential difference between neutral points due to variations in the geomagnetic field will induce current through those neutral points as shown in Fig.1. This current is called "geomagnetically induced current (GIC)"[1]-[3]. Whenever slowly changing current flows through a neutral point, the operating point of a transformer is known to shift from the optimum point, resulting in transformer loss in the form of overheating or a harmonic being produced, that may cause protective relay malfunction.

Many disorders in electric power equipment due to GIC have thus far been reported in North America, Scandinavia, and other parts of the world having higher geomagnetic latitudes

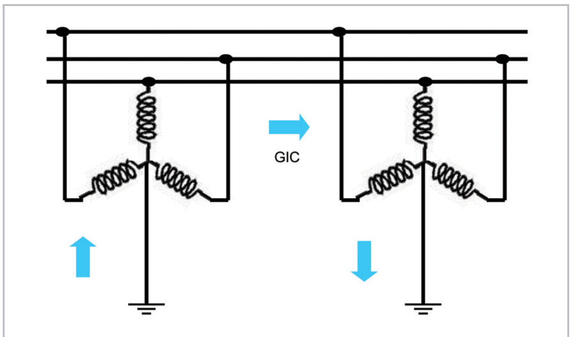

Fig.1 Geomagnetically induced current (GIC) flowing through an electric power grid due to variations in the geomagnetic field

Table 1 Major geomagnetic storms observed in and after 1957 at Memanbetsu Geomagnetic Observatory, JMA

No.	Start time (UT)	Duration (hours)	Amplitude of sudden commencement (nT)	Maximum variation of horizontal component (nT)
1	1982/07/13 1617	---	148	796
2	1989/03/13 0127	68.6	94	747
3	1958/07/08 0748	51.2	165	565
4	1959/07/15 0802	42.0	92	563
5	1958/02/11 0126	52.6	50	557
6	1967/05/25 1235	103.4	202	547
7	2000/07/15 1436	27.4	180	520
8	1972/08/05 1400	52.0	63	520
9	2003/10/29 0611	---	112	513
10	1960/11/12 1348	56.2	48	490

than geographic latitudes[1]-[3]. On March 13, 1989, GIC due to a major geomagnetic storm caused a wide-ranging blackout in the Canadian province of Quebec, thereby forcing approximately six million people to spend nine hours in darkness[2]-[4]. On October 30, 2003, a blackout in Malmo in southern Sweden due to GIC affected approximately 50,000 people.

In high-latitude regions where auroras can be seen, an intense current stemming from auroral activity is known to produce a large GIC in electric power grids[6]. A GIC due to an impulsive geomagnetic changes stemming from the arrival of interplanetary shock can affect an electric power grid. Kappenman reported on a major GIC measured in the USA that was due to an impulsive geomagnetic change stemming from the arrival of interplanetary shock on March 24, 1991[7]. Another report stated that a major GIC event could occur in the main phase of a geomagnetic storm even in low geomagnetic latitudes[8].

Japan has lower geomagnetic latitudes than its geographic latitudes, and therefore failures of electric power grids caused by GICs have yet to be reported there. However, geomagnetic storms are natural phenomena and no one can completely deny the possibility of an unprecedentedly huge geomagnetic storm. Table 1 lists the major geomagnetic storms observed during the past five decades at the Memanbetsu Geomagnetic Observatory of the Japan Meteorological Agency (JMA), and shows that several major geomagnetic storms occurred in the past. To obtain basic data and conduct elaborate analysis, we measured GICs due to variations in the geomagnetic field flowing through the electric power grid in Hokkaido for about two years[9]. This paper reports the results of the measurement.

2 Measurement of GIC and data used for analysis

GICs were measured for about two years from December 2005 to December 2007 at the Memanbetsu substation in cooperation with Hokkaido Electric Power Co. The GIC data were compared with geomagnetic field variations recorded at the Memanbetsu Geomagnetic Observatory. The Memanbetsu Geomagnetic Observatory is located near the east end of the trunk line for a 187-kV power transmission line running about 95 km in length, and connecting Memanbetsu and Tokachi. GICs were measured with a clamp-on ammeter equipped with a hole device capable of measuring DC current and installed on the neutral line of the transformer (187/66 kV). The data sampling rate was set to 1 millisecond in considering the detection sensitivity of digital-type protective relays and analysis of high harmonics components. Analysis was conducted by using the one-second values of GIC obtained in the measurements and the one-second values of the three components of geomagnetic fields taken at the Memanbetsu Geomagnetic Observatory.

3 GIC and geomagnetic activity

Table 2 lists the geomagnetic storms that occurred from December 2005 to December 2007 reported by JMA's Memanbetsu Geomagnetic Observatory, and the maximum values of GIC associated with those storms. This period corresponds to the minimum phase of the solar cycle. Table 2 also shows that no major geomagnetic storms occurred during this

Table 2 *Geomagnetic storms from December 2005 to December 2007 reported by Memanbetsu Geomagnetic Observatory, JMA and maximum values of GIC associated with those geomagnetic storms*

Start time (UT)	End time (UT)	Type	Maximum variation of horizontal component (nT)	Maximum value of measured GIC (A)
2006/04/04 07.6	2006/04/06 16:00	SG	132	1.29
2006/04/08 22.3	2006/04/10 18:00	SG	106	0.95
2006/04/14 01.6	2006/04/16 17:00	SG	157	1.58
2006/07/27 13:53	2006/07/28 17:00	SSC	130	1.06
2006/08/07 00:35	2006/08/07 21:00	SSC	97	1.29
2006/08/19 10.5	2006/08/20 19:00	SG	103	1.52
2006/11/09 13.0	2006/11/11 21:00	SG	122	2.23
2006/11/30 02.4	2006/11/30 22:00	SG	108	1.75
2006/12/05 22.2	2006/12/07 18:00	SG	101	0.78
2006/12/14 1414	2006/12/16 00:00	SSC	239	3.85
2007/07/10 18.1	2007/07/11 10.7	SG	100	0.98
2007/07/20 0616	2007/07/20 13.5	SSC	86	0.66
2007/11/20 0908	2007/11/21 17:00	SSC	105	1.13
2007/12/17 0252	2007/12/17 24:00	SSC	103	0.77

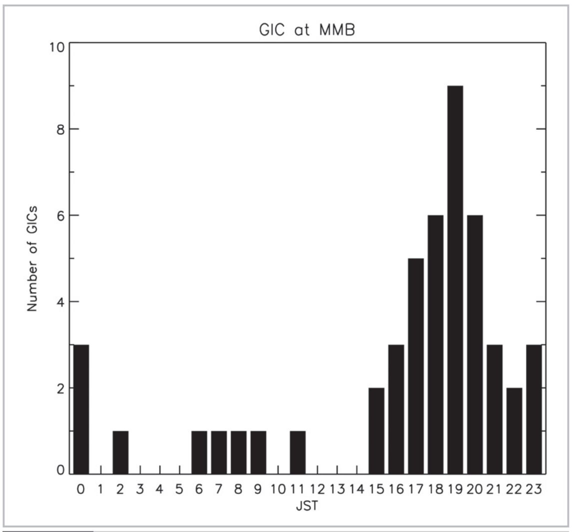

Fig.2 Local time dependence of occurrence of GIC

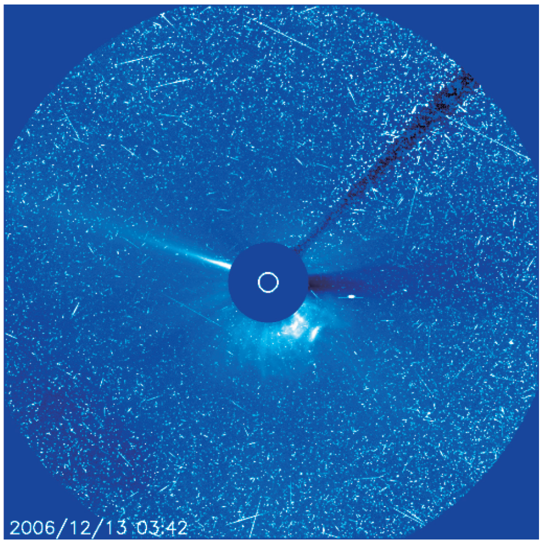

Fig.3 CME that caused the geomagnetic storm on December 14, 2006, as observed by SOHO/LASCO (ESA & NASA)

period. However, in response to bay-like changes of the geomagnetic horizontal component (bay disturbances) stemming from auroral activity, GIC of approximately 1 ampere has often been measured. Moreover, several observations have been made of GICs stemming from impulsive changes in the geomagnetic field in response to the arrival of interplanetary shocks and GICs stemming from geomagnetic pulsations.

Figure 2 shows the distribution of the times of day when GICs exceeding 1 ampere were measured from December 2005 to December 2007. From Fig. 2, we see that GIC events are often observed to occur around 19:00 JST (at nighttime). Auroral activity tends to be more active from midnight to dawn, though GIC does not reflect that trend.

4 Examples of GIC observed in response to geomagnetic activity

4.1 Example of GIC in response to a geomagnetic storm

The largest of all GICs observed from December 2005 to December 2008 was measured in response to a large variation in the geomagnetic field during a geomagnetic storm on December 14, 2006. A current of about 3 amperes was observed at that time. This geomagnetic storm resulted from a full-halo CME (coronal mass ejection) stemming from the X3/4B flare generated in activity region 10930 at 2:40 UT on December 13. Observations made by Japan's Hinode satellite revealed that this flare was a white light flare[10]. Figure 3 shows the CME that caused the geomagnetic storm observed by SOHO/LASCO (ESA & NASA). The solar energetic particles stemming from this flare caused ground-based neutron monitors to observe a rise in flux. Along with the arrival of an interplanetary shock and the full-halo CME, a geomagnetic storm of the sudden commencement type occurred at 14:14 UT on the 14th. Large variations in the geomagnetic field from the initial to main phase of this geomagnetic storm resulted in the greatest GIC observed in all measurements taken until that time. Figure 4 shows an example of GIC stemming from the geomagnetic storm. From this figure, GIC proves to have a good correlation with variations in the geomagnetic field (regarding the By component and Bz component).

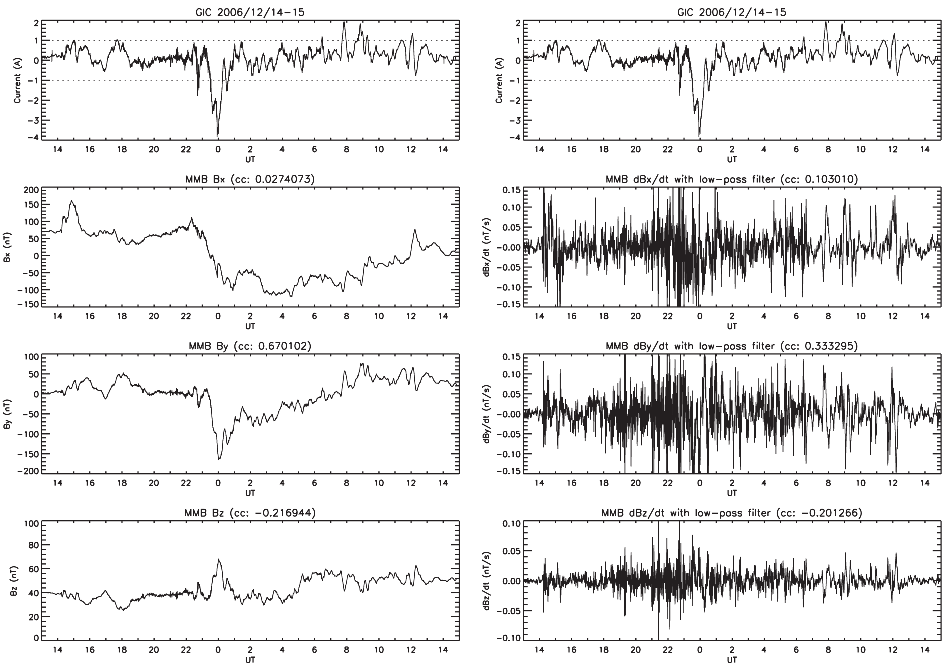

Fig.4 An example of GIC stemming from a geomagnetic storm

4.2 Example of GIC stemming from an impulsive change in the geomagnetic field associated with an interplanetary shock

GIC may be generated by impulsive changes in the geomagnetic field stemming from the arrival of interplanetary shocks known as a sudden storm commencement (SSC) or a sudden impulse (SI)[6]. Figure 5 shows an example of GIC induced by SI. The figure shows that the GIC measured has a good correlation with variations in the geomagnetic field (regarding the By component and Bz component). This SI was caused by the arrival of an interplanetary shock accompanied by a partial halo CME that occurred on July 6, 2006. A LDE (long duration event) flare of M2.5/2F that occurred in active region 10898 in connection with this CME was also observed. Solar energetic particles with energy levels exceeding 10 MeV and associated with this event have been observed by the GOES satellite.

4.3 Example of GIC stemming from auroral activity

In high-latitude regions, strong currents stemming from auroral activity are known to cause GIC[8][11].

Auroral activity generates bay disturbance at middle latitudes[12]. This kind of geomagnetic variation is called a “positive bay.” GICs measured in Hokkaido revealed that GIC is often generated in association with positive bays. Figure 6 shows an example of GIC stemming from a positive bay.

4.4 Example of GIC stemming from geomagnetic pulsations

Periodic geomagnetic changes with a period of 0.2 second to approximately 100 seconds are called geomagnetic pulsations[13]. These geomagnetic pulsations may result in GIC being observed. Figure 7 shows an example of GIC stemming from geomagnetic pulsations. Reports on the GIC measurement of the Scandinavian pipeline mentioned GIC due to geomagnetic pulsations with periods of 1 to 600 seconds[14][15]. The GIC observed from

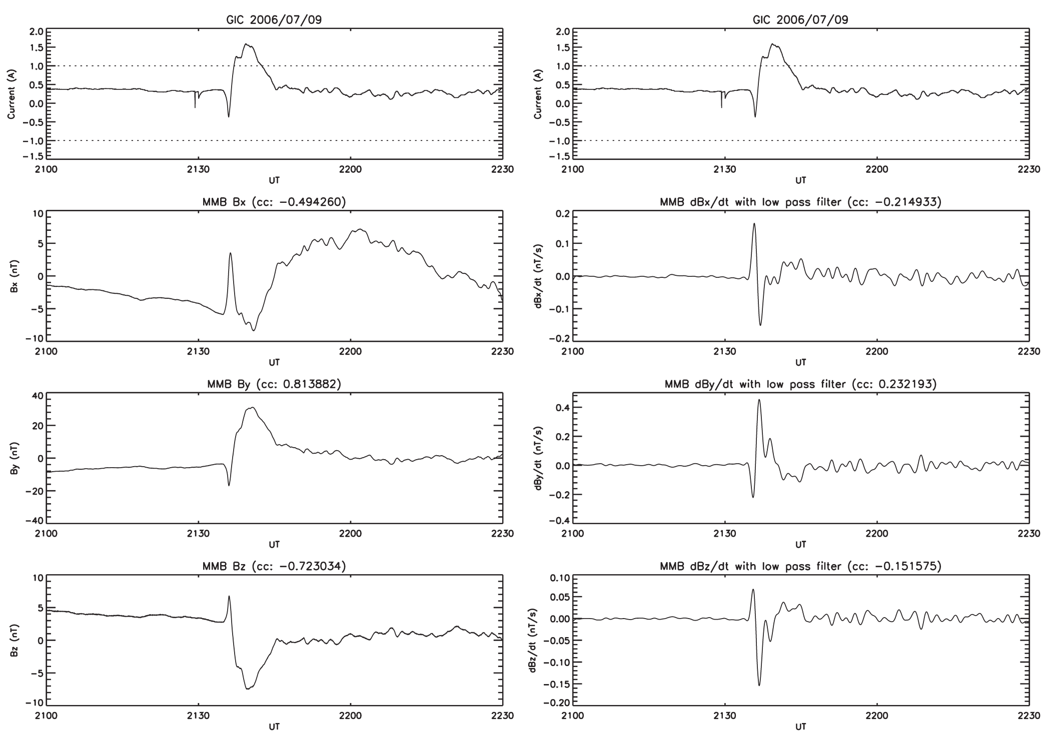

Fig.5 An example of GIC stemming from an impulsive change in the geomagnetic filed due to an interplanetary shock

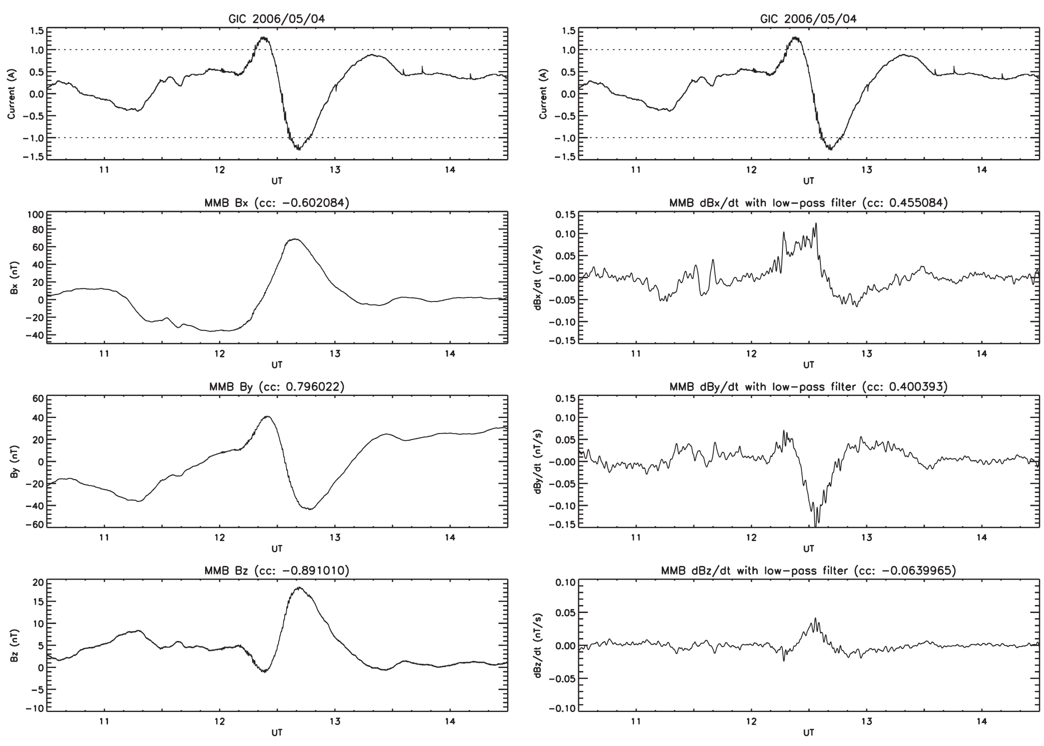

Fig.6 An example of GIC stemming from auroral activity

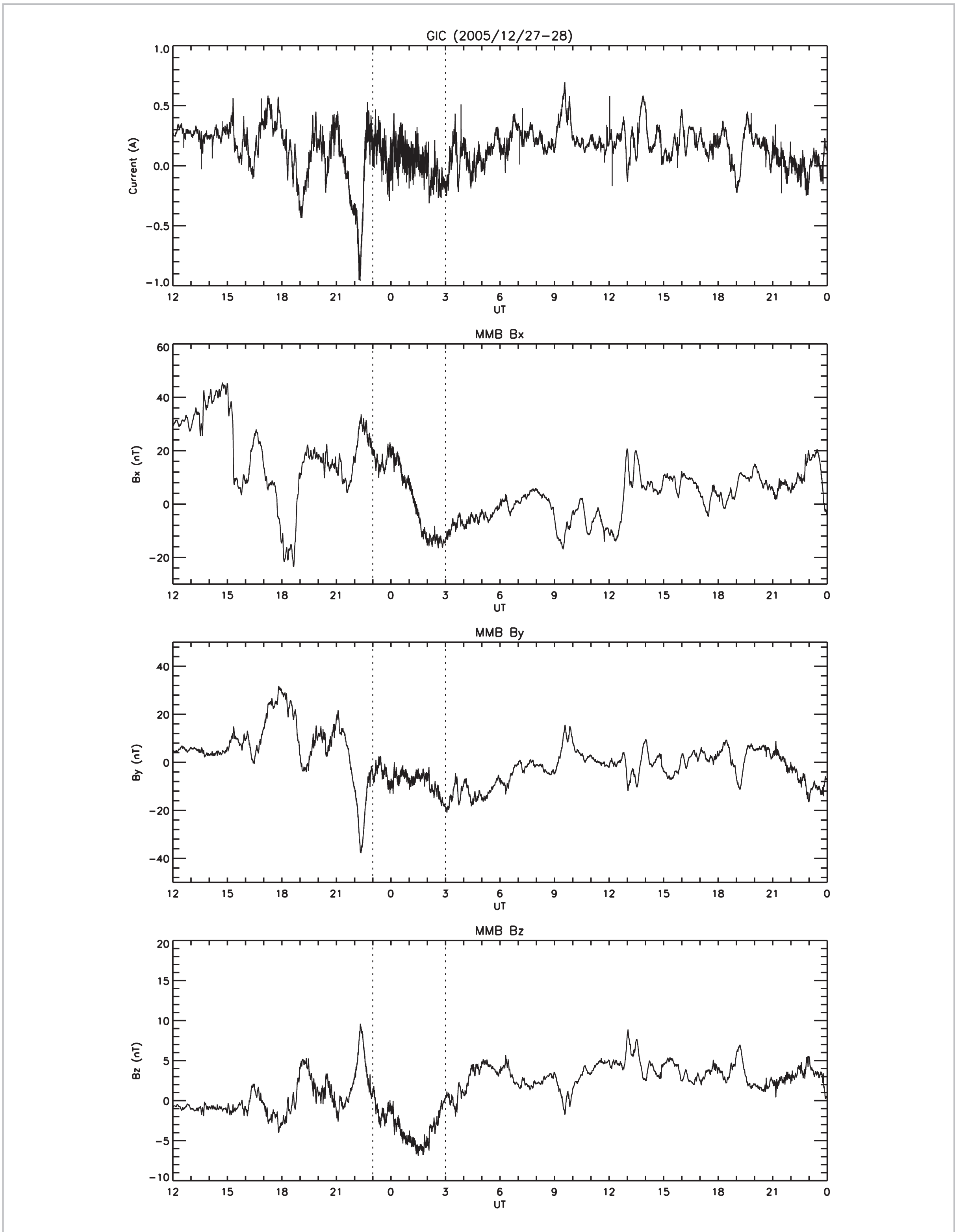

Fig.7 *An example of GIC due to geomagnetic pulsations*

23:00 to 3:00 UT in Fig. 7 corresponds to geomagnetic pulsations related to fast solar wind from coronal holes. Given the small amplitude of GIC due to geomagnetic pulsations, such GIC presumably has little influence on power grids. However, a frequent flow of GIC due to geomagnetic pulsations may cause erosion of pipelines in high-latitude regions.

5 Discussion

According to the Faraday's law of induction, GIC is proportional to the time derivative of variations in the geomagnetic field. However, the results of GIC measured in Hokkaido show a good correlation with variations in the geomagnetic field (regarding the By component and Bz component), as can be seen in Figs. 4, 5, 6 and 7. Lanzerotti et al[16]. reported that GIC measured in a submarine cable showed a similar trend. Trichenko and Boteler[17] also pointed out that GIC and variations in the geomagnetic field have a good correlation due to the structure of underground conductivity. Pulkkinen[18] stated that an underground model with high conductivity in a shallow region can explain this characteristic. This suggests the importance of knowing the structure of underground conductivity in order to predict GIC. Owada[19] calculated underground conductivity by the magneto-telluric method using data from the Memanbetsu Geomagnetic Observatory of JMA, and reported the conductivity at depths of 8 to 20 km as 3×10^{-17} to 1×10^{-2} S/m, that at depths of 20 to 90 km as 1×10^{-3} to 2×10^{-4} S/m, and that at depths of 90 to 170 km as 3×10^{-3} to 2×10^{-3} S/m.

Figure 8 plots maximum variations in the horizontal component (ΔH) at the time of the geomagnetic storms listed in Table 2 and the maximum values of corresponding GIC. The correlation coefficient between the two shows good correlation with 0.91. Equation 1 is the result of fitting the data indicated in Fig. 8 by using the least square method.

$$\text{Maximum value of GIC (A)} = 0.0158 \times \Delta H(\text{nT}) - 0.558 \qquad (1)$$

ΔH at the time of the geomagnetic storm on July 13, 1982, as observed at the Memanbetsu Geomagnetic Observatory (in and after 1957 in Table 1) is 796 nT. A maximum value of GIC of approximately 12 amperes is predicted by entering that value into Equation 1 for the geomagnetic storm on July 13, 1982.

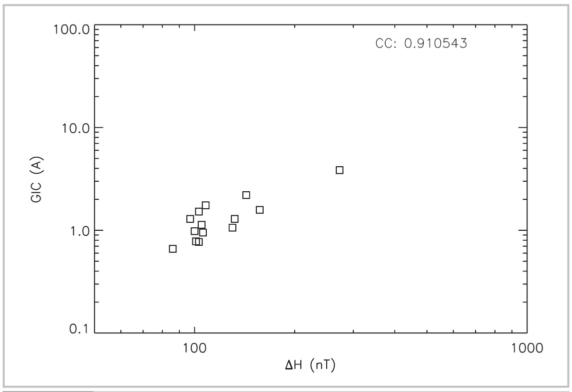

Fig.8 A plot of maximum variations in the horizontal component (ΔH) at the time of the geomagnetic storms listed in Table 2 and maximum values of corresponding GIC

6 Conclusion

GIC studies have been conducted in high geomagnetic latitude regions. In low geomagnetic latitude regions, long-term GIC data of the electric power grid was successfully obtained this time in Japan in cooperation with Hokkaido Electric Power Co. Our GIC measurement shows observed GIC almost in proportion to variations in the geomagnetic field. This is presumably due to the high conductivity of a shallow part underground in the region where the GIC measurement was conducted. The results we have obtained will be helpful in predicting GIC when a major geomagnetic storm occurs.

Acknowledgements

We wish to thank the Kakioka Geomagnetic Observatory of the Japan Meteorological Agency for having provided one-second geomagnetic observation data and a list of geomagnetic storms observed at the Memanbetsu Geomagnetic Observatory.

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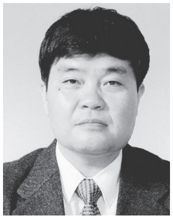

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