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GLOBAL STUDY OF GEOMAGNETIC INDUCED CURRENT USING TIME DERIVATIVES OF GEOMAGNETIC FIELDS

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ABSTRACT

This report investigates variations in time derivatives of the geomagnetic field observed during great storms known to have caused disruption and to have had other adverse effects on power grids. The geomagnetic storms considered were those of 24th November 2004, 30th October 2003 and 28th October 2004, which occurred during the Autumnal event, and also 7th April 2000 and 31st March 2001 which occurred during the Spring events. Geomagnetic field variations are associated with geoelectric field variation at the surface of the Earth which is influenced by the conductivities of different structures of the Earth's interior. The induced electric field is proportional to the rate of change of the geomagnetic field, which explains why many researchers have used time derivatives of the geomagnetic field as a measure of GIC strength. Koen and Gaunt (2002) established that variation exceeding 30nT/min of the time derivatives of the geomagnetic field component appears to be significant, causing undesirable consequences in power grids.

Keywords: Time derivatives of geomagnetic fields, GIC (Geomagnetic induced current), higher latitudes.

INTRODUCTION

The Sun is the primary driver of space weather and most of the events have their origin in the corona. When intense surges of solar wind reach the Earth, many changes occur in the Earth's magnetosphere. On the dayside the solar wind dynamic pressure acts on the magnetosphere, forcing the magnetosphere current to become compressed closer to the surface of the Earth and the geomagnetic field to fluctuate. This is refers to as a geomagnetic storm. During geomagnetic storms the current in the higher latitudes changes as a result of the solar wind. These currents produce their own magnetic field and, combined with the Earth's magnetic field, are called geomagnetically induced currents (GICs). GICs are the ground end, space weather effect which are driven in technology systems such as electrical power transmission grids, oil and gas pipelines, phone cables and railway systems by the geoelectric field induced by geomagnetic storms at the Earth's surface.

It should also be noted that space weather-related spacecraft anomalies can occur even when there is no CME (coronal mass ejection) driven storm or high-speed stream. Energy transferred from the solar wind to the magnetosphere through the merging of the interplanetary and terrestrial magnetic field builds up in the magnetotail until it is explosively released in episodic events known as magnetospheric substorms. Substorms which occur during non-storm times as well as storm times inject energetic plasma into the inner magnetosphere and can cause an electrical charge to build up on spacecraft surfaces. The electrostatic discharge that occurs subsequently is one of the major causes of spacecraft anomalies.

GIC creates problems for all technological systems leading to economic losses and social disruption. Systems in the high magnetic latitudes, such as the northern United States, Canada, Scandinavia and Russia, are at particular risk because Earth's magnetic fields converge near the geographic poles. Oil and gas pipelines can be damaged by corrosion when buried in the ground. The voltage between a pipeline and the Earth strongly influence the electrochemical environment at the pipeline surface, which leads to corrosion occurrence (Trichtenko and Boteler, 2002; Boteler, 2000; Boteler *et al*., 1998; Gummow, 2002; Pirjola, 2002).

GIC is a function of many parameters including time derivatives of the horizontal geomagnetic field, the electric resistance of the Earth, and the geometry and resistance of the power grid. Recently, Poppe and Jordan (2006) established that GIC also occurs at mid and low latitudes even at Africa and South Africa (Baker and Skinner, 1980; Ogunade, 1986; Osella and Favetto, 2000). In South Africa, saturation of a transformer led to serious problems followed by the collapse of the whole system during the famous Halloween storm in October-November 2003. For large storms (or increasing dB/dt levels) both observations and simulations indicate that as the intensity of the disturbance increases, the relative levels of GIC and related power system impact will also increase proportionately. In these scenarios, the scale and

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speed of the problems that could occur on exposed power grids have the potential to impact power system operators in ways they have not previously experienced. Therefore, as storm environments reach higher intensity levels, it becomes more likely that these events will precipitate widespread blackouts in exposed power grid infrastructures.

GICs are driven by rapid variations in ionospheric current at high latitudes. Here the most intense GIC are experienced. These variations are thought to be related to the intensification of the electrojet during enhanced ionospheric convection conditions and to the development of the substorm current wedge during geomagnetic storms (Pulkkinen *et al*., 2003).

The objective of this paper is to study the effect of geomagnetic storm on power grids. The geomagnetic storm considered were those of 24th November 2004, 30th October 2003 and 28th October 2004, which occurred during the Autumn, and those of 7th April 2000 and 31st March 2001 which occurred during the spring. Data obtained from www.spaceweather.gc.ca/effect_e.php have been used to determine the rate of disturbance to magnetic storms occurring in different region; auroral region (Thule, 77.4^0), subauroral (Iqaluit, 63.7^0), mid (Boulder 40.1^0) and lower region (Tucson, 32.2^0).

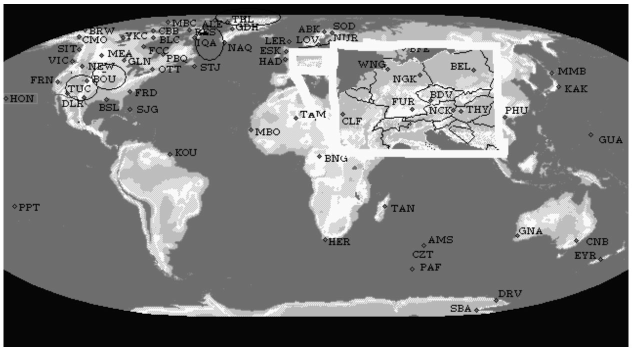


Fig. 1. Geographic location of the observatories.

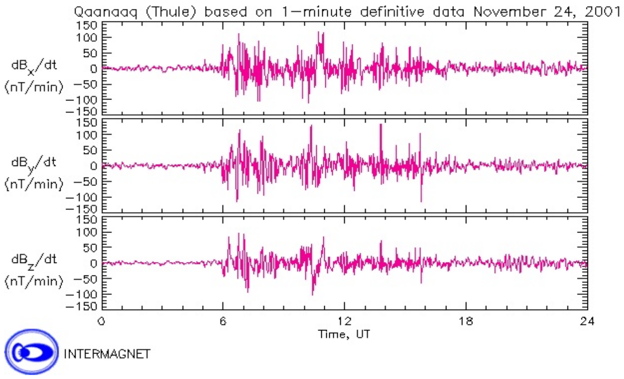
OBSERVATIONS

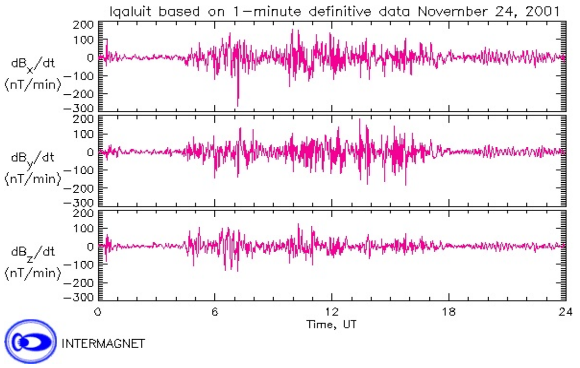
24th November 2001

The event of November 24th 2001 was a severe magnetic storm which was characterized by a pronounced SSC (sudden storm commencement) that started at 5: 50UT in the auroral region. The disturbance lasted for about 10 hours with enhancement in the auroral electrojet index 3242nT exceeding 3000nT with a maximum value of rate of change of disturbance of dBx/dt 150nT/min, dBy/dt 150nT/min and dBz/dt 100nT/min at higher latitudes (geographic latitude Thule 77.5^o).

In the subauroral region large enhancements of the geomagnetic field were observed at 6:00UT with large geomagnetic variation (dBx/dt 350nT/min, dBy/dt 2000nT/min and dBz/dt 200nT/min) measured at Iqaluit (63.7^o). The time of occurrence of the substorm at mid latitude (Boulder 40.1^o) coincided with the onset in the subauroral region and its amplitude was not big enough for it to be considered active storm in the mid latitude region (dBx/dt 60nT/min, dBy/dt 30nT/min and dBz/dt 15nT/min). It is also clear that the rate of change of disturbance from the auroral latitude reached the lower latitude at Tucson, 32.2^o (dBx/dt 60nT/min, dBy/dt 20nT/min and dBz/dt 4nT/min). The large geomagnetic variation with a significant geoelectric field and high GIC magnitude took place during the geomagnetic storm in the auroral region.

Leonard *et al*. (2000) suggested that the electric currents in the ionosphere are the major factor in geomagnetic disturbance in the auroral region and also that the geoelectric field and other parameters are essential in computing GIC in a power system. It is also known that GIC are a proxy for the rate of change of the geomagnetic field (Trivedi *et al*., 2007). Less geomagnetic field variation is associated with low GIC value and geoelectric fields, which implies that GIC values were less active at Tucson (geographic latitude 32.2^o) and also that minimum values of time derivatives of the geomagnetic field were not big enough to drive the transformers at the power stations into saturation (see Fig. 2).





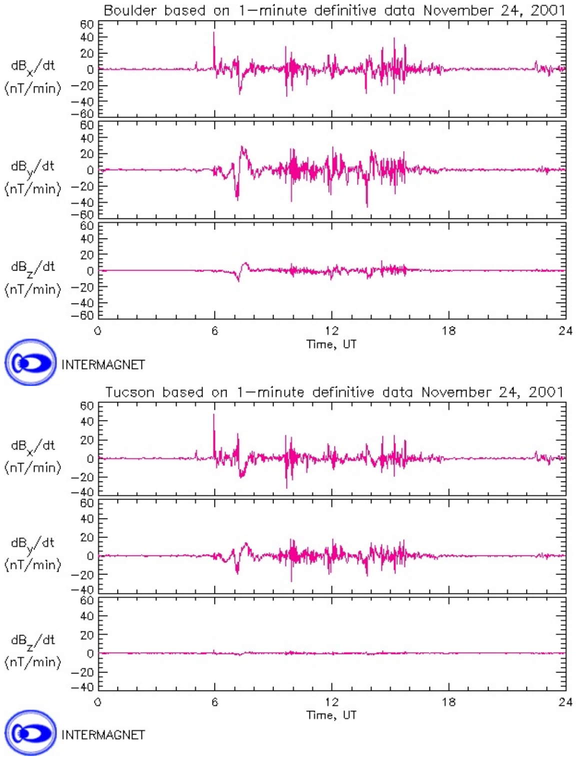


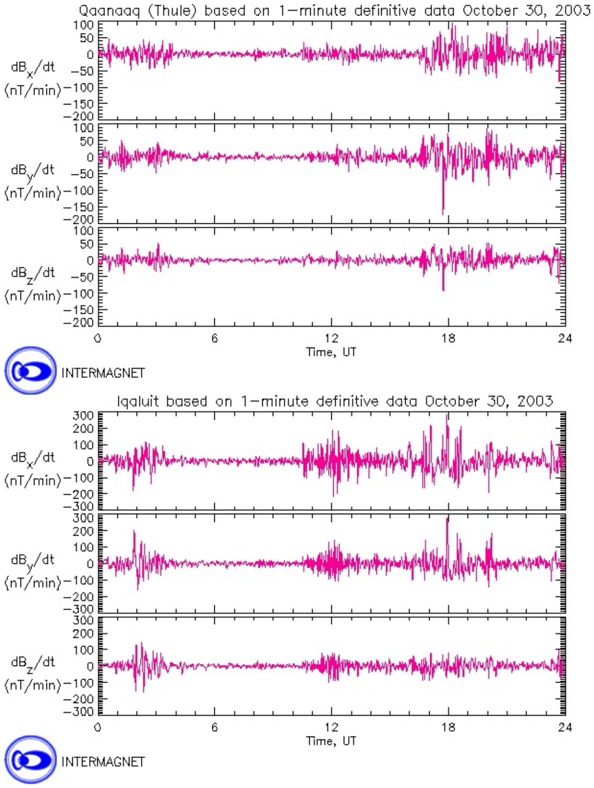
Fig. 2. Variation of the time derivatives on 24th November 2001 (a) auroral region at Qaanaaq. (b) subauroral region at Iqaluit. (c) mid latitude at Boulder (d) lower region at Tucson.

30th October 2003

The 30th October 2003 storm, known as the Halloween storm, attracted wide attention from scientists and industrial communities. On 30th October the IMF (Interplanetary Magnetic Field) reached the Earth with a southward orientation due to the magnetic reconnection between the IMF and Earth's magnetic field. As a result of this, the magnetic field was able to connect to the IMF directly so that energetic particles in the solar wind were free to enter the Earth's magnetosphere along the magnetic lines. The energetic particles entered the Earth's magnetosphere, causing the largest geomagnetic storm of 2003, as measured by the low latitude Dst index, and were also associated with ionospheric intensification.

The time derivatives signatures represent a characteristic scenario in the evolution of the geomagnetic field from a quiet period to a highly fluctuating one, and extended to the next day. In Figure 3, the first time derivatives signatures was seen in the early morning and another signature was observed at 16:20UT at the auroral region which was associated with increasing energy input from solar wind and dynamic reconfiguration in the magnetotail, as suggested by Pulkkinen *et al.* (2003). Enhancement of time derivatives of geomagnetic disturbance was also observed in the subauroral region (Iqaluit 63.7^0) in the early morning (1:50UT), with dBx/dt 120nT/min, dBy/dt 220nT/min and dBz/dt 150nT/min and at 11:00UT with dBx/dt 200nT/min, dBy/dt 300nT/min and dBz/dt 100nT/min. Another signature was also noticed between the hours of 1700UT and 1800UT with dBx/dt 300nT/min, dBy/dt 300nT/min and dBz/dt 50nT/min. In the mid latitudes, during the 30th October storm the rate of disturbance was noticed pre-midnight, with dBx/dt 40nT/min, dBy/dt 70nT/min and dBz/dt 50nT/min. Strong driving magnetospheric activity can cause auroral oval to expand towards the mid latitudes. In view of this, variations in ionospheric current can also cause large GICs at latitude where GIC is not typically experienced (Pulkkinen *et al.*, 2000). In low latitude regions the effects of this substorm were noticed in the north and east components of the rate of change of geomagnetic disturbance dBx/dt 50nT/min, dBy/dt 30nT/min and dBz/dt 9nT/min.

The magnetic field measurements are very important in determining the intensity, location and orientation of the auroral electrojet which are the major causes of the geomagnetic disturbance. The enhancement of the auroral electrojet index on 30th October was 3375nT with a Dst index of -383nT. Leonard *et al.* (2000) emphasised that variations in the time derivatives of the magnetic field are due to changing intensity and movement of the electrojet. When the magnetic field increases, the resulting electric fields are found to be anti-parallel to the electrojet, while it is parallel to the electrojet, the magnetic field is found to be decreasing.



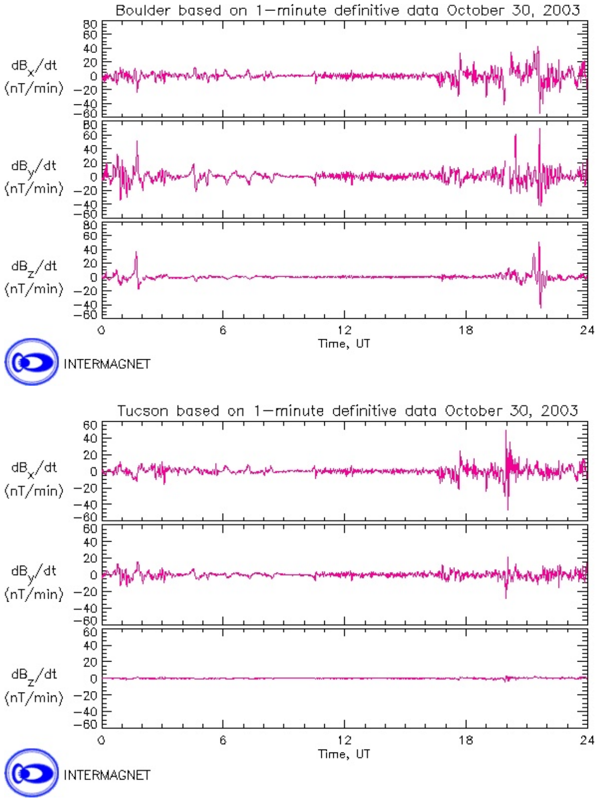


Fig. 3. Variation of the time derivatives on 30th October 2003 (a) auroral region at Qaanaaq. (b) subauroral region at Iqaluit. (c) mid latitude at Boulder (d) lower region at Tucson.

28th October 2004

We observed that dBx/dt is larger in comparison with dBy/dt and dBz/dt. The burst in time derivatives occurred at practically the same time 3:30UT (see Figure 4) in different region. The Subauroral region substorm was observed at 3:30UT in the early morning sector with high values of rate of change of disturbance of dBx/dt 130 nT/min, dBy/dt 100nT/min and dBz/dt 100nT/min. At mid latitude it was noticed that the time derivatives responded to the disturbance signature which occurred in the early morning with low value time derivatives of the geomagnetic field. The time derivatives of the north and east components at low latitude responded to the disturbance with low values of time derivatives of the geomagnetic field but the southward component of the time derivatives of the geomagnetic field did not respond to the disturbance. From our analysis we discovered that variation of the geomagnetic field during large magnetic storm induces electric current in high voltage transmission lines. GIC are a problem to higher latitudes, like the auroral and subauroral, also during large geomagnetic storms GIC can appear at all latitudes.

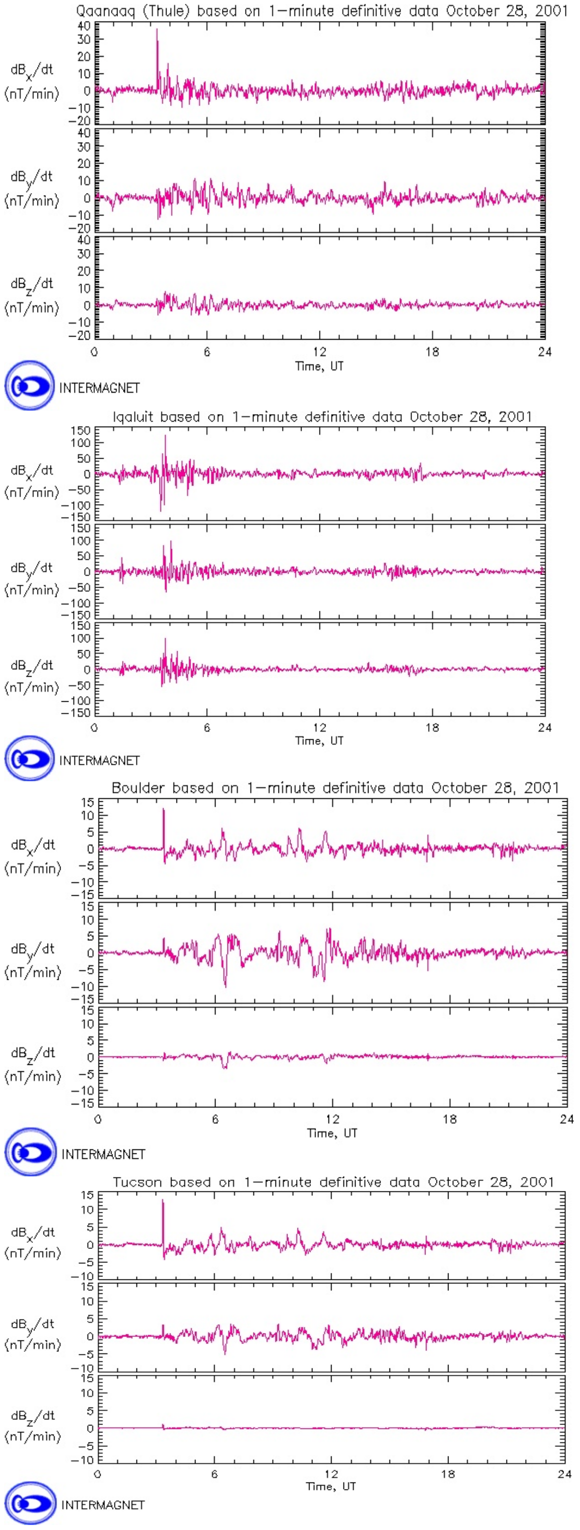


Fig. 4. Variation of the time derivatives on 28th October 2001 (a) auroral region at Qaanaaq. (b) subauroral region at Iqaluit. (c) mid latitude at Boulder (d) lower region at Tucson.

7th April 2000

From Figure 5, the magnetospheric shock associated with sudden impulse or storm sudden commencement was noticed pre-midnight on 6th April 2000 and main phase events occurred on the 7th April 2000, during a strong geomagnetic storm triggered by a complex interplanetary structure passing near the Earth. The first, second and third signatures of disturbance were observed at 00:00UT, 7:00UT and 17:00UT. In the auroral region the first signature values were dBx/dt 20nT/min dBy/dt 25nT/min and dBz/dt 17nT/min at 0:00UT. The second signature was noticed at the hour of 7:00UT with values of dBx/dt 30nT/min, dBy/dt 10nT/min and dBz/dt 10nT/min and the third signature was noticed at 17:00UT. Also in the subauroral region the geomagnetic field signature was observed at 00:00UT with dBx/dt 60nT/min, dBy/dt 20nT/min and dBz/dt 21nT/min, another was noticed at 7:00UT with values of dBx/dt 50nT/min, dBy/dt 42nT/min and dBz/dt 30nT/min while the third signature with the highest rate of disturbance occured at 17:00UT

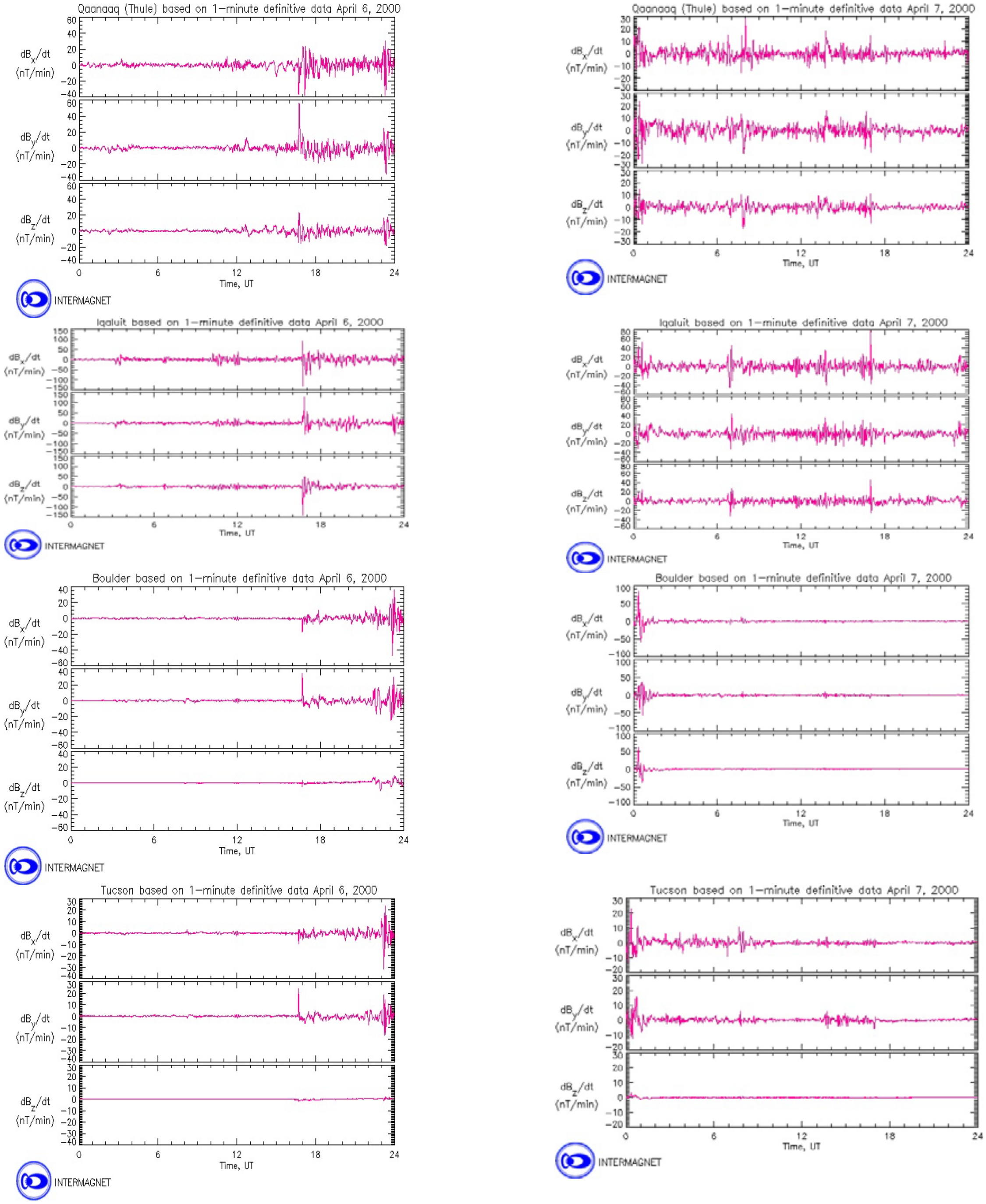


Fig. 5. Variation of the time derivatives between 6th and 7th April 2000 (a) auroral region at Qaanaaq. (b) subauroral region at Iqaluit. (c) mid latitude at Boulder (d) lower region at Tucson.

with dBx/dt 80nT/min, dBy/dt 20nT/min and dBz/dt 45nT/min.

When an increased dB/dt occurs at this location, the increases may be due to enhancement in the spectral content of the disturbance. An interesting result was also observed at mid latitude with a high value of disturbance in the early morning after 00:00UT with dBx/dt 100nT/min, dBy/dt 40nT/min and dBz/dt 60nT/min. At low latitude, the disturbances also occurred in the early morning after 00:00UT with dBx/dt 25nT/min, dBy/dt 16nT/min and dBz/dt 3nT/min.

31st March 2001

In the early hours of 31st March 2001, a sudden burst in the geomagnetic field occurred after 00:00UT (dB/dt 90nT/min dBy/dt 80nT/min and dBz/dt 90nT/min) in the auroral region under the enhanced westward electrojet; the rate of change of disturbance lasted for several hours (see Fig. 6). In the subauroral region, we noticed a high value of the rate of disturbance, dB/dt 300nT/min, dBy/dt 200nT/min and dBz/dt 200nT/min at 1:00UT. At mid latitude, the rate of disturbance at 6:20UT was dBx/dt 80nT/min, dBy/dt 190nT/min and dBz/dt 30nT/min. At low latitude, the rate of change of disturbance noticed in the early morning at 1:00UT was dBx/dt 70nT/min, dBy/dt 15nT/min and dBz/dt 6nT/min**.** Kappenman (2003) established that the risk of GIC is plausible. It may become apparent on power grids at very low latitude locations that are typically not concerned about or seldom in the proximity of large electrojet intensification.

The sudden burst of disturbance can extend to mid and low latitudes while large electrojet disturbances are generally confined to high latitudes. At low latitudes large GIC flow in power grids due to SSC. For example Fukumitsu is a substation in Japan (geographic latitude ~34^0, geomagnetic latitude ~ 26^0) where a peak GIC of 40A was observed during a moderate storm event on 6th November 2001. It was also reported that New Zealand experienced failure in a large power transformer due to an SSC event (Small, 2003).

6th November 2001

Another chain was observed on 6th November, 2001 at Qeqertarsuaq (GDH 69.2^0, 306.5) in the auroral region with dBx/dt 190nT/min, Narsarsuaq (NAQ 61.2^0 , 314.6) in the subauroral region with dBx/dt 200nT/min, St John (STJ 47.6^0, 307.3) at mid latitude with dBx/dt 120nT/min and Korou (KOU 5.2^0, 307.3) in the low latitude region with dBx/dt 40nT/min**.** Geomagnetic storms can cause serious problems for the operation of power systems, disrupting the functioning of transformers. Obviously, the amplitude of the time derivatives of the geomagnetic field, on this occasion, was big enough to drive the transformer into saturation. One can infer from the result that GIC do

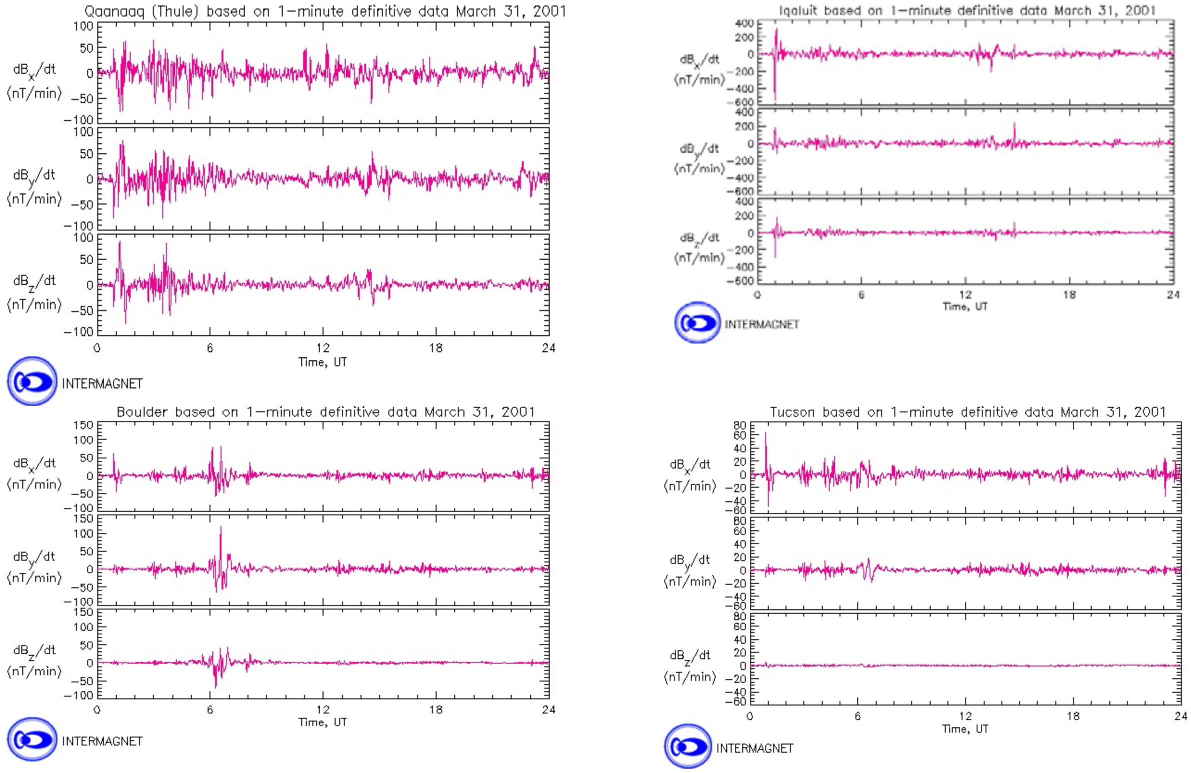


Fig. 6. Variation of the time derivatives at 31 March 2001 (a) auroral region at Qaanaaq. (b) subauroral region at Iqaluit. (c) mid latitude at Boulder (d) lower region at Tucson.

appear at low and mid latitudes. Meanwhile, even low latitudes confirm the presence of SSC events and large GIC flow (see Fig. 7).

DISCUSSION

The effects of space weather on power grids are caused by fluctuation of the Earth's magnetic field caused by high energy particles that stream out from the Sun, creating voltages between grounding points in the grid, which induce currents that flow along electric power lines and into transformers. The greater the power line, the greater the current flow will be for a given change in magnetic field (Kappenman *et al*., 1997).

Normally these GICs are small enough that the electric power system can adjust to them, but when space weather occurs GICs can grow larger, damage transformers and disrupt the power supply to consumers. Very large GICs damage the transformer beyond repair leading to large scale electrical blackout. The time derivatives of the geomagnetic field are caused by geomagnetic field variation, by a sudden pulse noticed at the beginning of the geomagnetic disturbance, pulsation of the magnetic field at recovery phase and casual disturbance of the magnetic field during geomagnetic disturbance.

During the disturbance the GIC causes the saturation of transformers, which leads to failure in power transmission grids. The low and mid latitudes are far from the magnetic poles; therefore one may propose that they do not experience such serious geomagnetic disturbance as high latitudes (auroral and subauroral regions). However, this report demonstrates (see Fig. 4) that even mid and low latitudes are considerably affected by electromagnetic disturbances. The magnitude of time derivatives of the geomagnetic field determines the geoelectric field which drives the GICs. Variation exceeding 30nT/min of the X or Y component appears to be significant causing undesirable consequences in power grids (Koen and Gaunt, 2002; Vodjanikov *et al*., 2007). Also large scale auroral ionospheric electric currents flow mostly following the east-west direction thus mostly affecting X-Z components. Horizontal currents of small scale and amplitude and field aligned currents also contribute to the Y component (Viljanen, 1997). Trichtchenko and Boteler (2006) have also confirmed that dBx/dt components represent the driving electric field and characterize GIC.

GIC causes a great deal of damage to power systems at high latitudes due to their proximity to the dynamic auroral electrojet. Ionospheric response is a good measure of magnetic field that can be used to monitor the strength of geomagnetic disturbance associated with auroral activity. The ionospheric wind dynamo may be considered as one of the major factors that contribute to the generation of ionospheric electric current during geomagnetic disturbance. The magnetospheric electric

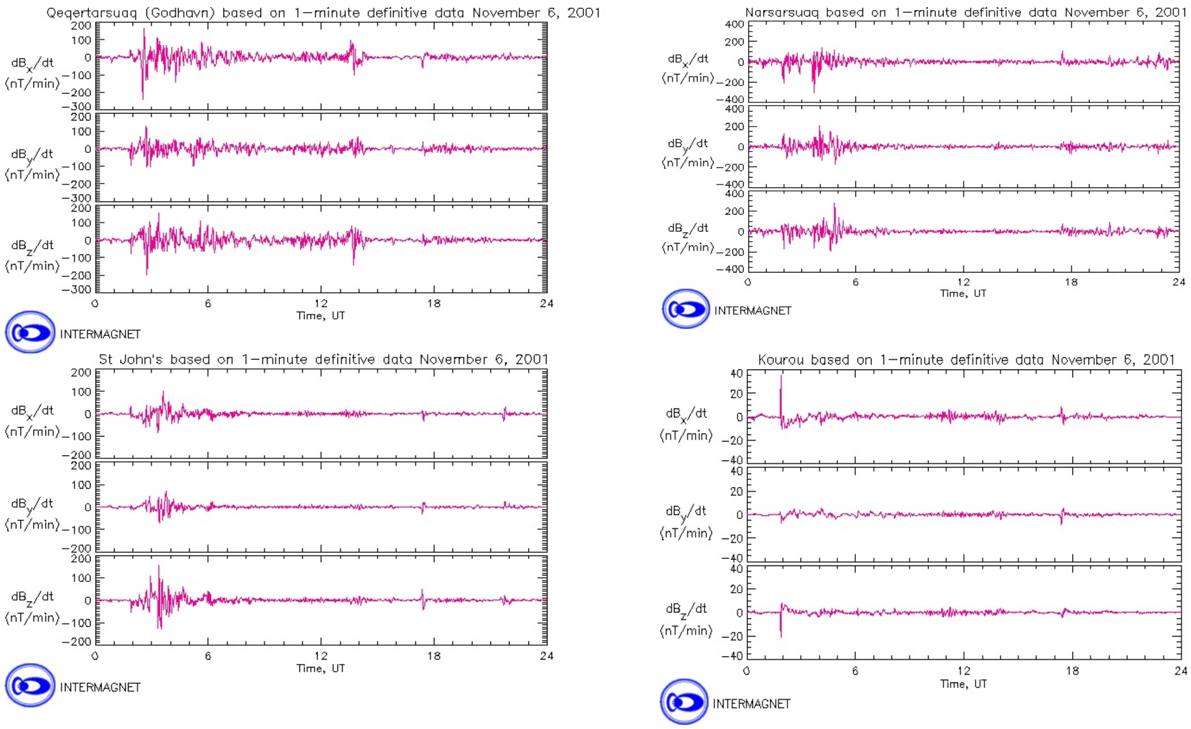


Fig. 7. Variation of the time derivatives on 6th November, 2001(a) auroral region at Qeqertarsuaq. (b) subauroral region at Narsarsuaq. (c) mid latitude at St John's (d) lower region at Kourou.

field penetrates into the low latitude ionosphere which can be another source for the electric field.

During space weather effects, the magnetospheric electric field disturbs the auroral ionosphere forming an auroral electrojet and the high latitude electric field penetrates into the equator. The electric field of the field aligned current can penetrate through the mid latitude ionosphere to the equator and may serve as a coupling agent between the auroral and equatorial ionosphere. Geomagnetic disturbance is significant at mid which poses a serious threat for high voltage power line circuits, when the rate of disturbance exceeds 30nT/min (see Figures 2, 3, 5, 6, and 7).

CONCLUSION

Space weather information and forecasts are beneficial to those who maintain electric power transmission lines, which are vulnerable to space weather effects. These arise from rapid changes in the Earth's magnetic field, caused by highly energetic particles from CMEs (Coronal Mass Ejections), creating voltage between grounding points in the grid, which in turn induce a small, irregular dc current that flows along electric power lines into the transformer. The highest rates of disturbance occur in auroral and subauroral regions. The mid and low latitudes are far from the magnetic poles and they do not experience the same severity of geomagnetic storm. From our analysis, it was clearly shown that geomagnetic disturbance can also occur at mid and low altitudes with values exceeding 30nT/min of the X or Y component; these appear to be significant, leading to failure in power transmission grids. Space weather parameters and the GIC measured by magnetometers under power grids have to be monitored. GIC values for regions both close to the auroral zones and at mid and low latitudes, should be calculated whenever major or minor changes occur and should be recorded and used to improved current knowledge

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