NUMERICAL MODEL TEST OF GEOMAGNETIC INDUCED CURRENTS IN BRAZIL

Cleiton Barbosa[1], Katia Pinheiro[1], Gelvam A. Hartmann[2], Ricardo I. F. Trindade[2]

[1] Observatório Nacional – MCTI, Rua General José Cristino, 77, São Cristóvão, Rio de Janeiro, RJ, Brasil.

[2] Departamento de Geofísica, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo. Rua do Matão, 1226, 05508-090, São Paulo, SP, Brasil.

ABSTRACT

Rapid time variation of the geomagnetic field originated from magnetic solar activity may cause geomagnetic induced currents (GICs) at the Earth's surface. During magnetic storms, there are many reports of GICs hazards in transmission lines and transformers, mostly in high latitude regions. Despite of GICs occurrence in Brazil, the possible consequences and damage has not been evaluated in low latitude regions. In this work we apply a numerical model, using plane wave theory and a constant resistivity value, in order to reproduce the GICs measured directly in the Itumbiara – São Simão transmission line (18-19º S) during a magnetic storm from 7th until 10th November 2004. The simple numerical model presented here is a potential tool for calculating GICs in other low latitude regions.

Keywords: geomagnetically induced currents, numerical model, Vassouras geomagnetic observatory.

Resumo

As variações rápidas do campo geomagnético originadas da atividade solar podem causar correntes geomagneticamente induzidas (GICs) na superfície da Terra. Durante tempestades magnéticas, há muitos relatos de riscos de GICs em linhas de transmissão e transformadores, muitos deles em regiões de altas latitudes. Apesar da ocorrência de GICs no Brasil, as possíveis consequências e danos não foram avaliados em regiões de baixas latitudes. Neste trabalho, foi aplicado um modelo numérico (usando a teoria de ondas planas e um valor de resistividade constante) a fim de reproduzir GICs medidas diretamente na linha de transmissão Itumbiara – São Simão (18-19ºS) durante a tempestade magnética ocorrida entre 7 e 11 de Novembro de 2004. O modelo numérico apresentado neste trabalho pode ser utilizado como uma ferramenta para calcular GICs em outras regiões de baixas latitudes.

Palavras chave: correntes geomagneticamente induzidas, modelo numérico, observatório geomagnético de Vassouras.

Introduction

Geomagnetic Induced Currents (GICs) are result of solar magnetic activity, especially Coronal Mass Ejections (CMEs). The CMEs may cause magnetic storms at the Earth surface, which are rapid variations of the geomagnetic field, lasting usually hours. GICs may affect electric power transmission grids, oil and gas pipelines, telecommunication cables and railway equipment (Pirjola *et al*., 2000; Ptitsyna *et al*., 2008). For instance, the magnetic storm occurred in March 1989, caused a failure of the power system in Quebec. In this case, after nine hours there was still 17% of the load out of service. This event caused inconveniences and economic losses in Quebec during that time. This same storm caused a destruction of a transformer by overheating in New Jersey (USA) and, consequently, loss of several millions of dollars. Nowadays, we depend even more on technological networks that may be affected by GICs.

There is a tradition of GIC studies in high latitude locations where the magnetic field variation is large and hence, damages are well known. Research on risk analysis by GICs prediction in power systems and pipelines is fundamental to avoid damages. Intensive research on GICs has been developed especially in high latitude locations, such as Sweden (Wik *et al*., 2008) and Finland (Viljanen & Pirjola, 1994; Pirjola, 2009; Pirjola, 2010). Due to the lack of information about extreme events and the vast range of geological conditions, risk analysis of GICs in different regions is a challenge to the scientific community.

The well-known "Halloween magnetic storm" occurred in October 2003 and caused an uncommon auroral activity in lower latitude and affected networks in Europe, North America and South Africa (Pulkkinen *et al*., 2006). In low latitude regions, magnetic field variations are usually less severe and therefore GICs are smaller. However, the effects and risks of GICs in South America are poorly understood since there is not much work developed. In Brazil, there are two magnetic phenomena: the South Atlantic Magnetic Anomaly (SAMA) and Equatorial Electrojet (EE), which may be explored concerning the consequences for induced currents. Trivedi *et al*. (2007) presented results of GICs measured directly in the Itumbiara – São Simão transmission line (18-19ºS) during a magnetic storm from 7^{th} until 10^{th} November 2004. In this work, we aim to use the same magnetic storm as used by Trivedi *et al*. (2007) to test a numerical model of GIC, determined by direct measurements of geomagnetic field in Vassouras Observatory (VSS), Rio de Janeiro, Brazil.

Numerical model

The calculation on GICs requires assumptions about its primary sources, on the ionosphere and magnetosphere, and about the Earth's conductivity structure. If one assumes that the primary field of a GIC is a vertically propagating plane wave, one can calculate the geoelectric field by the following equation (Viljanen & Pirjola, 1989):

$$E(t) = -\frac{1}{\sqrt{\pi \mu_0 \sigma}} \int_{-\infty}^{t} \frac{g(u)}{\sqrt{t-u}}\, du \quad E(t) = -\frac{1}{\sqrt{\pi \mu_0 \sigma}} \int_{-\infty}^{t} \frac{g(u)}{\sqrt{t-u}}\, du \qquad (01),$$

where $E(t)\,E(t)$ is the electric field, $\mu_0\,\mu_0$ is the vacuum permeability, $\sigma\ \sigma$ is the electrical conductivity of the Earth and $g(u)\,g(u)$ $g(u)$ is the first time derivative of the horizontal magnetic field (H). However, in order to test a numerical model for calculating GICs, one needs to discretize equation (01), which becomes (Liu *et al*., 2009):

$$E(T_N) = -\frac{2}{\sqrt{\pi \mu_0 \sigma \Delta}} \sum_{n=N-M+1}^{N} b_n\left(\sqrt{N-n+1} - \sqrt{N-n}\right)$$

$$E(T_N) = -\frac{2}{\sqrt{\pi \mu_0 \sigma \Delta}} \sum_{n=N-M+1}^{N} b_n\left(\sqrt{N-n+1} - \sqrt{N-n}\right) \qquad (02),$$

where $E(T_N)\,E(T_N)$ is the geoelectric field at time $T_N\,T_N$, $\Delta = T_N - T_{N-1}\ \Delta = T_N - T_{N-1}$, $b_n = B_n - B_{n-1}$ $b_n = B_n - B_{n-1}$ which is the first-order differential of a geomagnetic component (Viljanen & Pirjola, 1989) and M is the time of the past geomagnetic contributions are considered, in this work M = 20 minutes. In order to calculate $b_n\,b_n$ we used Vassouras observatory data between 7th until 10th November 2004. The north and east components of the magnetic field were calculated by:

$$B_x = H\cos D \quad B_x = H\cos D$$

$$(03),$$

$$B_y = H\sin D \quad B_y = H\sin D$$

and used as inputs of $b_n\,b_n$ in equation (02) to calculate the electrical components $E_x\,E_x$ and $E_y\,E_y$. The voltage source in the transmission line is equal to the integral of the geoelectric field along the line:

$$V_{AB} = \int_A^B E dl \, V_{AB} = \int_A^B E dl$$

(04).

Considering a transmission line between stations A and B, no variation in the electrical conductivity and the plane wave theory, and the Earth as an ellipsoid with smaller radius at the pole than at the equator (Horton, 2012) then the North-South distance is given by:

$$L_N = (111.133 - 0.56\cos(2\phi)).\Delta lat \; L_N = (111.133 - 0.56\cos(2\phi)).\Delta lat$$

(05),

where ϕ ϕ is the average between the two latitudes:

$$\phi = \frac{lat\ A + lat\ B}{2} \phi = \frac{lat\ A + lat\ B}{2}$$

(06),

and Δlat Δlat is the difference in latitude (degree). Similarly, the East-West distance is given by:

$$L_E = (111.5065 - 0.1872\cos(2\phi)).\cos \phi.\Delta lon \; L_E = (111.5065 - 0.1872\cos(2\phi)).\cos \phi.\Delta lon$$

(07).

Finally, the GIC in a power line transmission is calculated by:

$$GIC = \frac{V_{AB}}{R} GIC = \frac{V_{AB}}{R}$$

(08),

where R is the transmission line resistance, typically R = 0.1 ohm/km.

Results

An intense magnetic storm occurred between 7th and 10th November 2004, with a Dst (Disturbance Solar Storm) index below 300 nT. During the magnetic storm, two strong disturbances were observed in the horizontal component of the magnetic field (fig. 1). The first one started at around 11 a.m. on 7th November and the second disturbance occurred around 12 p.m. on 9th November. Two GICs, caused by this magnetic storm, were measured by Trivedi *et al*. (2007) by using a fluxgate magnetometer just below the transmission line called Itumbiara – São Simão (between 18ºS and 19ºS), Goiás, Brazil. Following Trivedi *et al*. (2007), the first disturbance induced a current peaked around 7 A and the second one induce a peak around 15 A.

The Itumbiara – São Simão transmission line was used to calculate the induced geoelectric field and compare with results of Trivedi *et al*. (2007). We considered the layered model of homogeneous resistivity calculated by Bologna *et al*. (2001) and used the shallower conductivity value (1500 ohm.m) as reference for our model. Figure 2 show the electric field (Ex and Ey) calculated using this model. Using equation (08), we calculate the GIC in this transmission line and the results are shown in Figure 3. The first GIC signature occurred at approximately 6 p.m. on the 7th November and peaked at around 7 A. The second signature happened around 11 p.m. on the 9th November and presented a peak around 13 A.

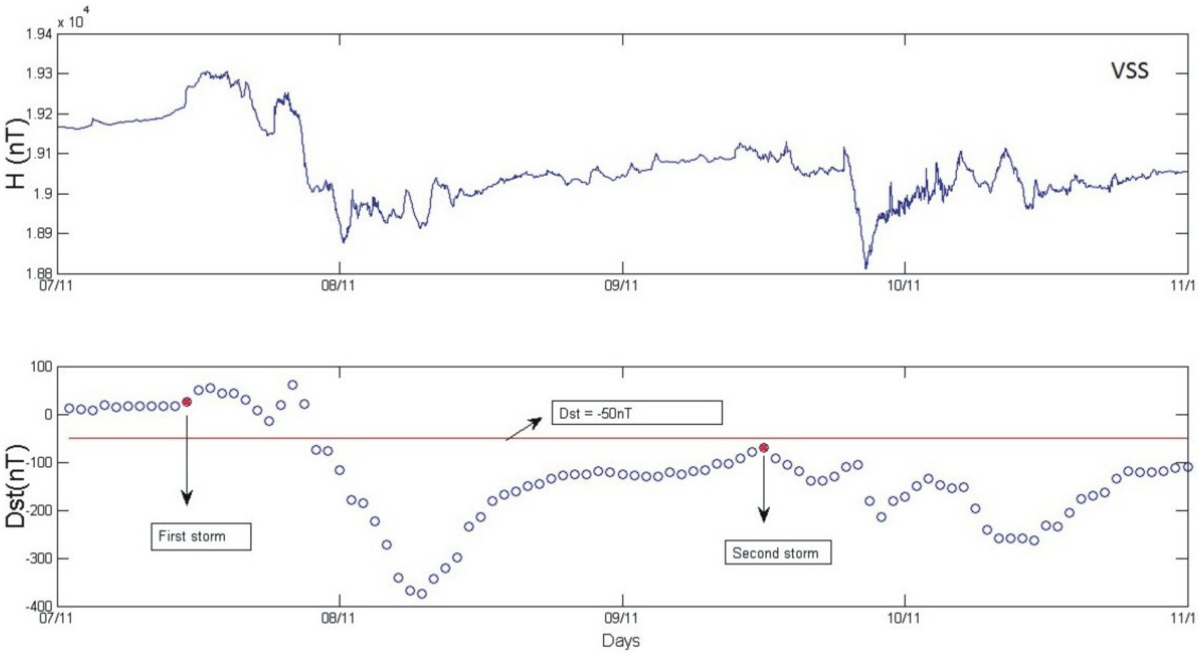

Figure 1. Horizontal magnetic field at the Vassouras (VSS) geomagnetic observatory between 7th and 11th November 2004. Dst index for the same time interval. Note that Dst index for this magnetic storm was -50 nT and the minimum observed value of Dst was -374 nT.

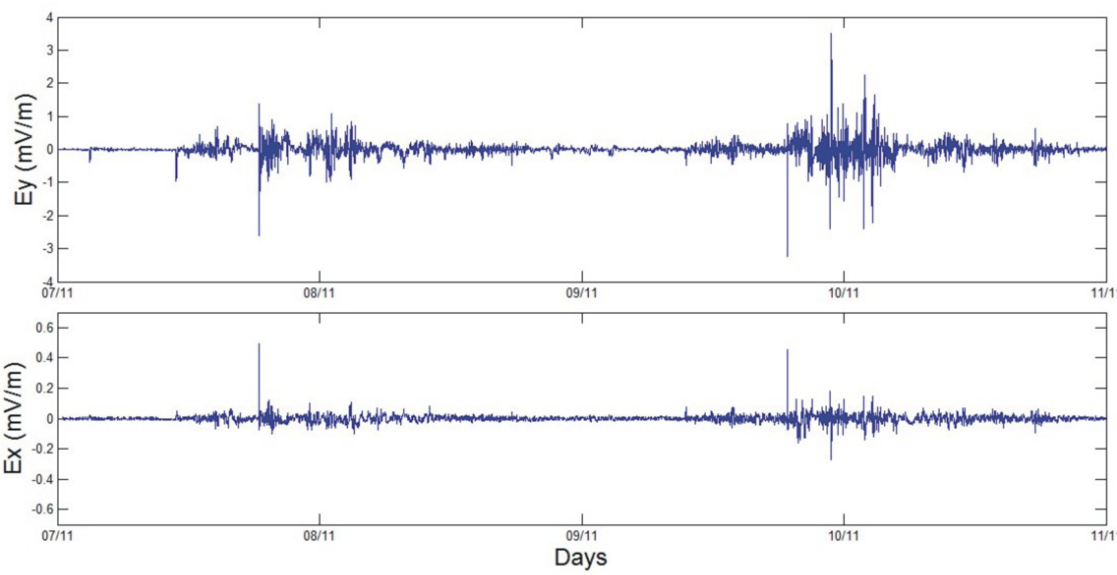

Figure 2. Eastward (Ey) and northward (Ex) components of the electrical field computed from the geomagnetic data determined during 7th and 11th November 2004.

Discussion and conclusions

We built a simple numerical model based on plane wave theory in order to calculate GICs in a low latitude region, considering a constant value of resistivity. These simplifications showed to be reasonable since this numerical model was able to reproduce the general patterns of GICs, compared to the direct measurements performed by Trivedi *et al*. (2007). Therefore, the numerical model developed in this study is a potential tool for calculating GICs in other low latitude regions.

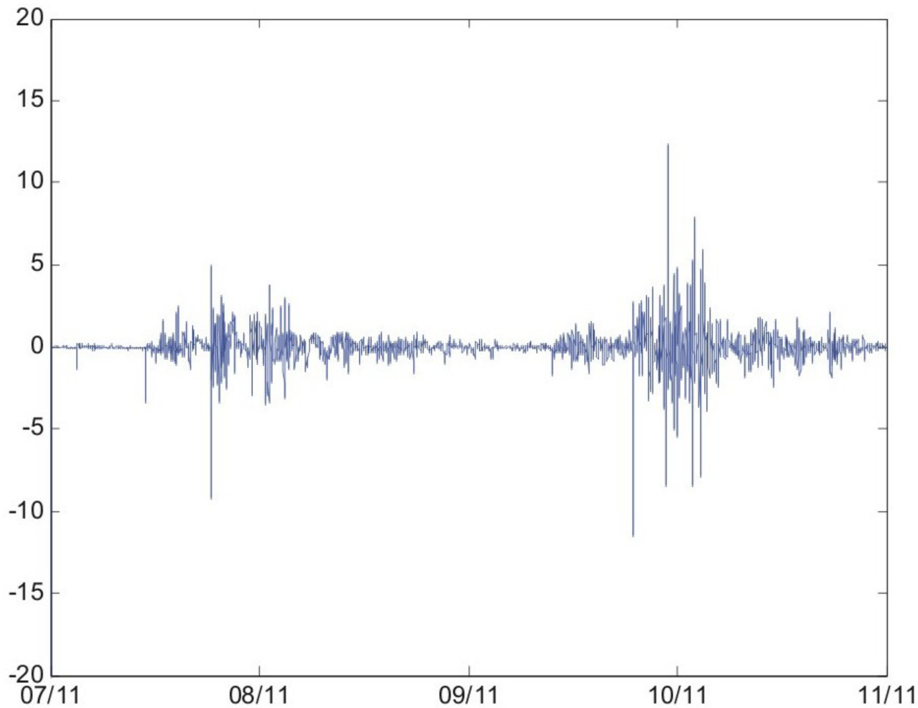

Figure 3. GIC computed from the numerical model. Note that the maximum values are very similar to that obtained from the direct measurements made by Trivedi *et al*. (2007).

We are currently passing through a solar maximum period, where magnetic storms occur more frequently. Thus, continuous measurement of the magnetic field, monitoring of the currents induced in transmission lines and improvements on the numerical modelling of GICs are fundamental for risk analysis of GICs in low latitude regions.

The results also demonstrated that even low latitude regions, as Brazil, might be vulnerable to GICs caused by strong magnetic storms. The possibility of transmission lines and transformers hazard may not be excluded in the Brazilian range of latitudes. Since GICs present a time delay in relation to the beginning of a magnetic storm, it is possible to create an alert system to avoid hazards.

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