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ESTIMATING GEOMAGNETICALLY INDUCED CURRENTS AT SUBAURORAL AND LOW LATITUDES TO ASSESS THEIR EFFECTS ON POWER SYSTEMS

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ABSTRACT

During large magnetic storm the geomagnetically induced current has a negative impact on ground conducting technology systems. The time derivative of the horizontal component of the geomagnetic field (dH/dt) is greater than 30nT/min for induced currents causing undesirable consequence in power grids. Multiple regression analyses were developed to predict the level of geomagnetic disturbance using time derivatives of the horizontal geomagnetic field, east and north components of the geoelectric field, auroral electrojet and disturbance storm times from 1994-2007 at low and subauroral latitudes. The statistical test RMSE (Root Mean Square Error) and MBE (Mean Bias Error) were employed to evaluate the accuracy of the geomagnetic disturbance. Different variables have been used to develop different types of models. Values of the correlation coefficient and the coefficient of determination were high, which indicates that the results are good. The equations produced the best correlations at subauroral and low latitudes, and the best correlation was obtained with low values of RMSE and MBE.

Keywords: Time derivatives of the geomagnetic field, geomagnetically induced current, latitudes.

INTRODUCTION

Grounds based technologies especially electric power, are susceptible to geomagnetic storms and geomagnetically induced current. This arises from the changes in the Earth's magnetic field, caused by high energy particle streams from the Sun. It creates voltage between grounding points in the grid, which in turn induces a small, irregular dc current to flow along electric power lines and into transformers. Both space-borne and ground-based technology can experience problems due to space weather (Pirjola *et al*., 2005).

Geomagnetically induced current (GIC) are directly related to the horizontal time derivatives of the geomagnetic field strength produced by the changing of electrical current in the ionosphere and magnetosphere. These changes in the geomagnetic field in turn produce an electrical current that flows around the Earth's surface. Disturbances in power grid systems are directly related to geomagnetic storms and are caused by voltages induced at ground level by variations in ionospheric and magnetosphere currents. The magnetosphere and ionospheric electric current induces changes in the magnetic field and varying voltage in the crust of the Earth and this in turn drives a direct current through transformers, called (GIC). These GIC can harm power equipment and even cause a collapse of the power system (Coles *et al*., 1992; Makinen, 1993; Viljanen, 1998, 2001; Kappenman, 2006). Observations also confirmed that geomagnetic field disturbances usually associated with equatorial region current intensification can be a source of large magnitude and long duration GIC in power grids in low and equatorial regions (Erinmez *et al*., 2002). Kappenman (2005) established the fact that GIC studied during an October 2003 storm that caused geomagnetic disturbance in low and equatorial areas were due to ring current intensification that served as a source for GIC in the mid latitude regions.

The fundamental principle of the flow of GIC in ground based technology is well understood using the Faraday law of induction. Electric fields drive current in ground technology networks. The geomagnetic variation and the geoelectric field observed at the Earth's surfaces which primarily depend on the magnetosphere and ionospheric current, determine the space weather conditions in the Earth's environment. Also, surface fields are affected by the current and charges induced in the Earth (Viljanen, 1997; Trichtchenko and Boteler, 2006). The 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 directly related to the rate of change of the geomagnetic field, which implies that many researchers have used time derivatives of the geomagnetic field as a measure of GIC strength. Boteler *et al*. (2000) concluded that geomagnetic disturbances are

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directly related to auroral electrojet and an assessment of the effects on the ground based technological systems requires that appropriate models of the electrojet are available. In the predicted levels of geomagnetically induced currents in power systems, it is significant that the electrojet model allows rapid calculations of the Earth-surface electric fields.

The geomagnetic disturbance that triggered the Hydro-Quebec collapse during the March 13, 1989, storm reached an intensity of 479nT/min. Power pools serving the entire north-eastern of Canada also came perilously close to a comparable calamity, with similar cascading system failures, during the same geomagnetic storm; its intensity ranged between 300 and 600nT/min. Malmo in Sweden experienced GIC problems leaving 50,000 customers with power blackouts on October 30, 2003, which lasted between 20 and 50 minutes. In South Africa, it was observed that the October and November 2003 geomagnetic disturbance damaged transformers (Campbell, 2003; Wik *et al.*, 2008; Kappenman, 2006; Poppe and Jordan, 2006). In Africa and South America the GIC effect was also observed at low and mid latitudes (Barkers and Skinner, 1980; Ogunade, 1986; Osella and Favetto 1999; Vodjannikov *et al.*, 2007). Koen and Gaunt (2002) carried out dH/dt measurement simultaneously with GIC records in the South African power grid. Comparison of GIC and dH/dt has shown that when dH/dt >30 nT/min, the induced current has an effect on the power grid.

Most of the ground technological systems located in higher latitude areas are prone to GIC effects. Pirjola (2004) reported that equatorial regions are affected by the equatorial electrojet current, and GIC investigation has been performed in Kenya, Nigeria and Argentina.

This paper presents the significance of GIC by measuring variation of the horizontal time derivatives of the geomagnetic field, at the threshold of dH/dt > 30nT/min at mid and low latitude. Multi regression analysis was also performed between the variables used.

METHODS

Data analysis

We used Dst and AE indices obtained from http://isgi.cetp.ipsl.fr and http://swdcwww.kugi.kyoto-u.ac.jp/index.html to define the substorms events from -90 up to -1800nT. The geomagnetic field parameters and telluric electric field (Ex and Ey) are obtained from the Canadian magnetic observatory for subauroral zones, and geomagnetic fields for low latitudes were obtained from INTERMAGNET. Table 1 gives the geographic and geomagnetic corrected coordinates (IGRF model http://www.iugg.org/IAGA/iaga_pages/pubs/igrf.htm) for the 6 observatories selected for this study which are: Ottawa, Victoria, St John, Addis Ababa, Bangui and M'bour. Ottawa, Victoria and St John are in the subauroral zone in the American longitude sector, M'bour is in tropical zone and Addis Ababa and Bangui are in the equatorial zone of the African longitude sector. The data used in this study covers the disturbed periods from 1994 -2007. We have taken a value as a threshold for the definition of total time of existence in the power grids of the selected geomagnetic observatories of the appreciable induced current, when dH/dt values are greater than 30nT/min, which appears to be significant in South Africa. Table 1 lists geographic and geomagnetic corrected coordinates.

A regression and correlation analyses were carried out between the time derivatives of the horizontal geomagnetic field (dH/dt), AE magnetic index related to auroral electrojets, Dst magnetic index related to the storm development, and North and East components of the geoelectric field (Ex and Ey). The regression values and correlation coefficients are reported in table 2 (a, b, c) and 2 (d, e, and f). The accuracy of the estimated values was tested by calculating the RMSE (Root Mean Square Error) and MBE (Mean Bias Error) for the variables.

$$RMSE = \left\{ \left[\sum \left(dH/dt_{pred} - dH/dt_{obs} \right)^2 \right] / n \right\}^{1/2} \quad (1)$$

$$MBE = \left[\sum \left(dH/dt_{pred} - dH/dt_{obs} \right) \right] / n \quad (2)$$

Table 1. Lists of geographic and geomagnetic corrected coordinates.

Abbreviation	Name	Geographic Latitude (N)	Geographic Longitude (E)	Geomagnetic Latitude (N)	Geomagnetic Longitude (E)
AAE	Addis Ababa	9.0	38.8	5.28	111.79
BNG	Bangui	4.3	18.6	4.16	91.14
MBO	Mbour	14.4	343.0	20.13	57.44
OTT	Ottawa	45.4	284.5	55.63	355.38
STJ	St John	47.6	307.3	57.15	23.98
VIC	Victoria	48.5	236.6	54.12	297.6

Mid latitude

Table 2a. Shows equation, correlation coefficient, correlation of determination, MBE and RMSE.

Equations (Number)	Equations **(Ottawa)**	r	R^2	MBE	RMSE
4	dH/dt=-3.179- 0.197E_x+0.366E_y+0.00378AE-0.136Dst	0.959	0.920	1.416E-15	13.171
5	dH/dt=3.064- 0.0017Ex +0.256Ey+0.0012AE	0.953	0.908	-3.64E-15	12.963
6	dH/dt=4.233 +0.095Ex+0.263Ey	0.947	0.897	2.1E-5	13.759
7	AE=92.422+ 9.74Ex+0.567Ey	0.926	0.857	-5.507E-14	397.7
8	Dst=-51.639 -1.876Ex+0.777Ey	0.906	0.821	2.344E-13	45.278

Table 2b. Shows equation, correlation coefficient, correlation of determination, MBE and RMSE.

Equations (Number)	Equations **(Victoria)**	r	R^2	MBE	RMSE
9	dH/dt=6.479+0.335E_x+0.302E_y+0.0021AE-0.096Dst	0.966	0.933	1.200E-15	6.175
10	dH/dt=3.80+0.4027 Ex -0.1322Ey+0.00254AE	0.958	0.917	-2.387E-15	6.866
11	dH/dt=3.803 +0.4007Ex+0.129Ey	0.960	0.92	-2.609E-15	6.867
12	AE=-11.15+ 8.057Ex+13.15Ey	0.909	0.825	-7.240E-14	479.3
13	Dst=-27.59 +0.502Ex-2.089Ey	0.950	0.903	2.575E-14	33.35

Table2 c. Shows equation, correlation coefficient, correlation of determination, MBE and RMSE.

Equations (Number)	Equations **(St John)**	r	R^2	MBE	RMSE
14	dH/dt=-1.66+0.1286E_x+0.1109E_y+0.00092AE-0.0189Dst	0.989	0.977	-6.106E-16	4.194
15	dH/dt=-0.863+0.1386 Ex +0.1284Ey+0.0094AE	0.988	0.970	4.441E-16	4.26
16	dH/dt=0.95 +0.22Ex+0.208Ey	0.980	0.960	7.216E-16	5.44
17	AE=193.45+ 8.71Ex+8.54Ey	0.950	0.900	5.684E-14	360.94
18	Dst=-43.084-0.566Ex-0.966Ey	0.925	0.856	1.0658E-14	40.65

Low latitudes

Table 2d. Shows equation, correlation coefficient, correlation of determination, MBE and RMSE.

Equations (Number)	Equations **(Addis Ababa)**	r	R^2	MBE	RMSE
19	dH/dt= -1.42054 +0.0070AE -0.0286Dst	0.859	0.739	-2.498E-15	6.493
20	dH/dt= 0.489 +0.00934AE	0.853	0.727	11.703	6.633

RMSE and MBE are statistical instruments used to compare the models of geomagnetic distribution prediction. Low values of RMSE are desirable, but a few errors in the sum can produce a significant increase in the indicator. Low values of MBE are also desirable. It is also possible to have large RMSE values at the same time as a small MBE or vice versa.

Distribution of time derivatives of the horizontal magnetic field (dH/dt)

The large scale auroral ionospheric electric currents flow mainly in an east- west direction thus mostly affecting the X- Z components. Horizontal currents of small scales and amplitudes and field aligned currents also contribute to Y. The distribution of dH/dt provides a strong indication that the occurrence of large value time derivatives is strongly coupled with the occurrence of great magnetic storms.

Figure 1 illustrates the distributions of dH/dt for 4 intervals, in the 3 observatories Ottawa, Victoria and St John. It was observed that the power lines disruption which occurred when the geomagnetic rate of change exceeded 30nT/min posed a serious threat to high voltage power line circuits. Between 1994 and 2007, mid latitudes percentages of the horizontal component of time derivatives of the geomagnetic field (dH/dt) which were greater than 30nT/min were: 78.48 %(Ottawa); 64.56 %(Victoria); and 38.75 %(St John).

Table2 e. Shows equation, correlation coefficient, correlation of determination, MBE and RMSE.

Equations (Number)	Equations **(Bangui)**	r	R^2	MBE	RMSE
21	dH/dt= -2.051 -1.1E-06AE -0.0495Dst	0.952	0.907	3.60	1.641
22	dH/dt= 1.1306 +0.0031AE	0.791	0.626	-4.545	3.28

Table 2f. Shows equation, correlation coefficient, correlation of determination, MBE and RMSE.

Equations (Number)	Equations **(Mbour)**	r	R^2	MBE	RMSE
23	dH/dt= 0.6232 +0.004AE +0.0012Dst	0.917	0.841	8.327E-16	2.488
24	dH/dt= 1.072 +0.0050AE	0.912	0.832	5.274E-16	2.555

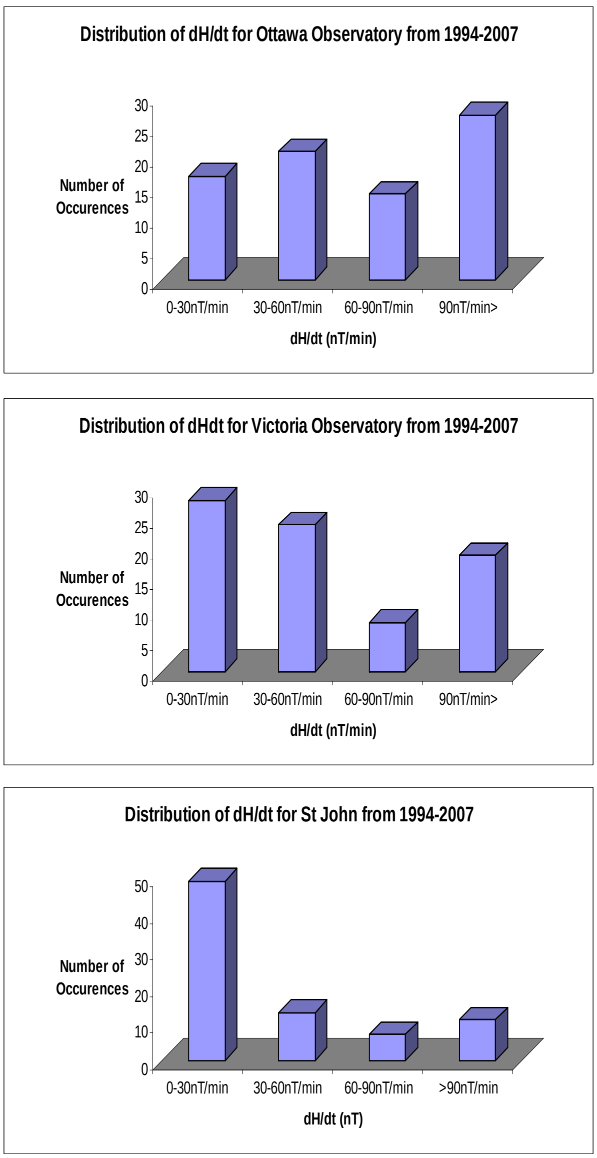


Fig. 1. Distributions of dH/dt at mid latitude of Ottawa, Victoria, and St John geomagnetic field Observatories.

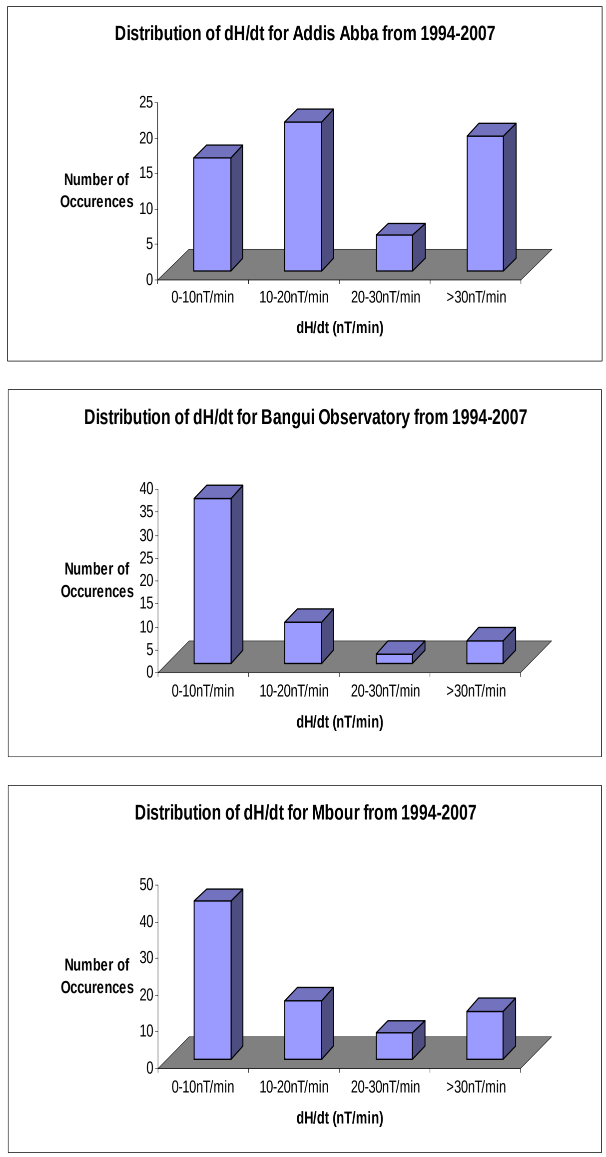
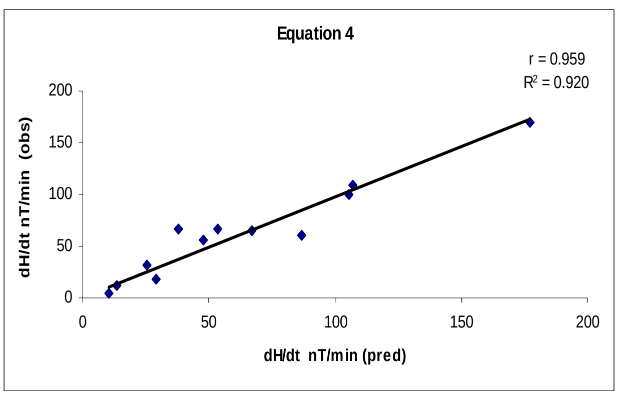


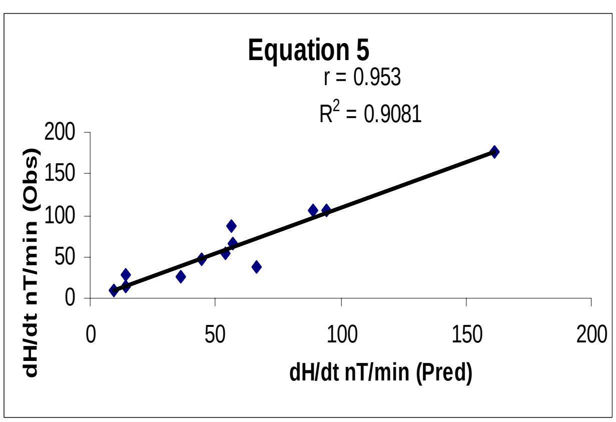
Fig. 2. Distributions of dH/dt at mid latitude of Bangui, Mbour and Addis Ababa geomagnetic field observatories.

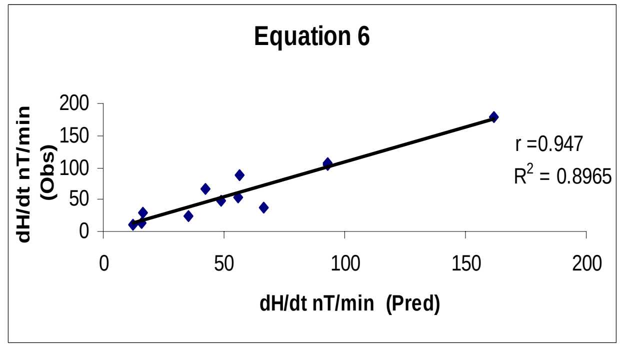
Figure 2 is similar to Figure 1, for the observatories of the low latitudes in the African longitude sector and illustrates the data recorded at Bangui, M'bour and Addis Ababa. From figure 2, the geomagnetic disturbances are not significant in value at Bangui and M'bour; they more significant at low latitude in Addis Ababa. Between 1994 and 2007, low latitudes percentages of the horizontal component of time derivatives of the geomagnetic field (dH/dt) which were greater than 30nT/min were: 9.6 %(Bangui); 24.2 %(M'bour); and 45.2 %(Addis Ababa). Figures 3-8, further illustrate the comparison between observed and predicted values of the correlation coefficient.

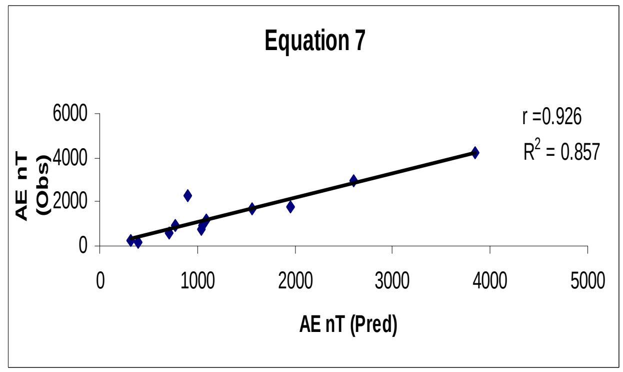
Figure 3 illustrates the comparison between observed and predicted values of the correlation coefficient at Ottawa. For equations (4/ Table 2a), a correlation coefficient of 0.959 exists between time derivatives of the horizontal geomagnetic field, north and east components of the geoelectric field, auroral electrojet and disturbance storm time. The coefficient of determination of 0.920 which implies 92.0% of time derivatives of the horizontal geomagnetic field can be accounted for using the auroral electrojet index, disturbance storm time, and north and east components of the geoelectric field.

Ottawa









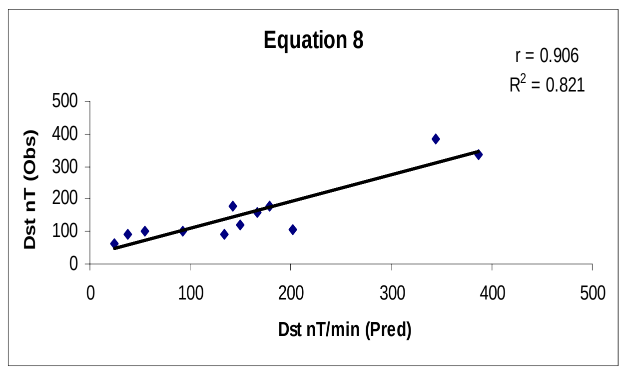
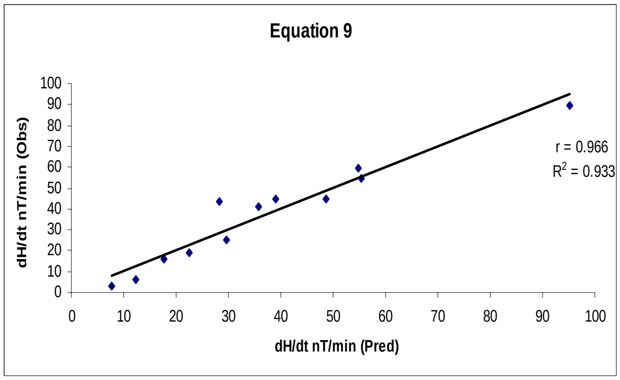
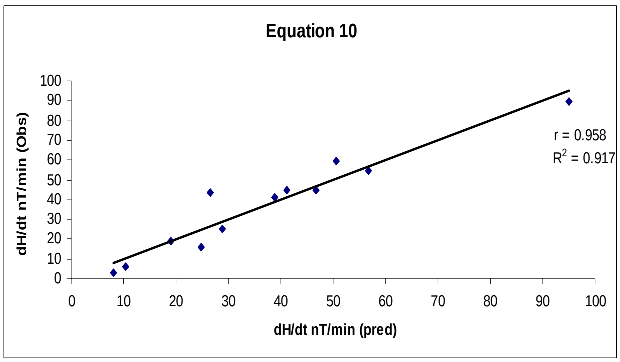


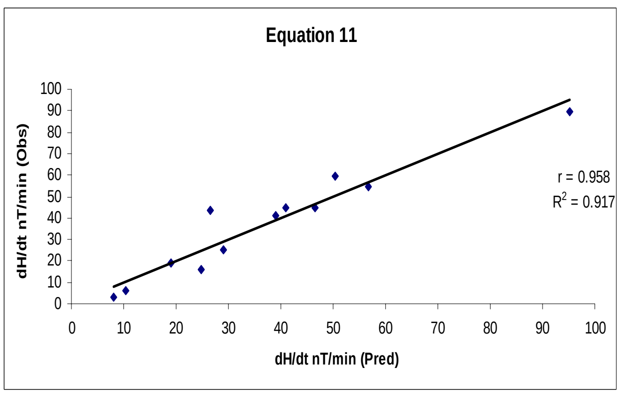
Fig. 3. Comparison between observed and predicted values of the correlation coefficient at Ottawa.

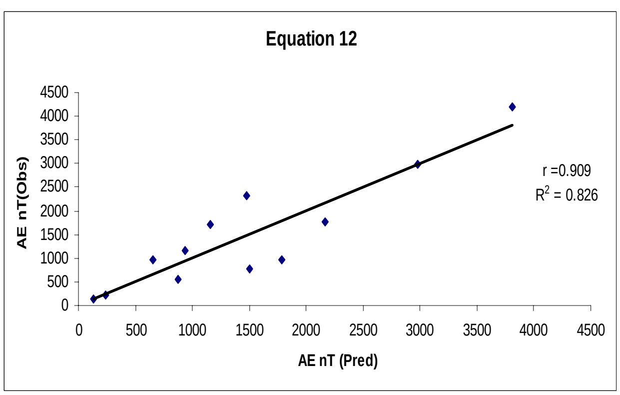
Figure 4 is devoted to the comparison between observed and predicted values of the correlation coefficient at Victoria. Equation (9/ Table 2b) shows the correlation coefficient of 0.966 that exists between time derivatives of the horizontal geomagnetic field, north and east components of the geoelectric field, the auroral electrojet and disturbance storm time. The coefficient of determination of 0.933 which implies 93.3% of time derivatives of the horizontal geomagnetic field can be accounted for using the auroral electrojet index, disturbance storm time, and north and east components of the geoelectric field.

Victoria









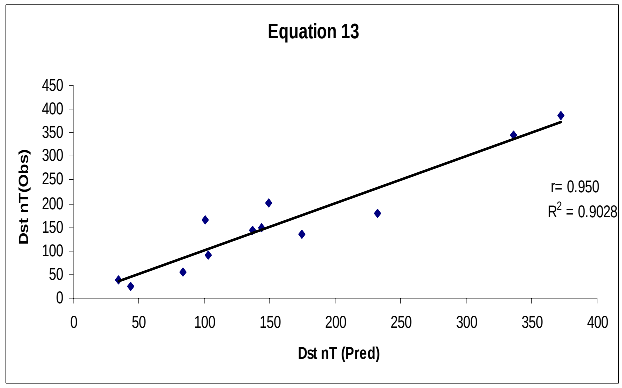
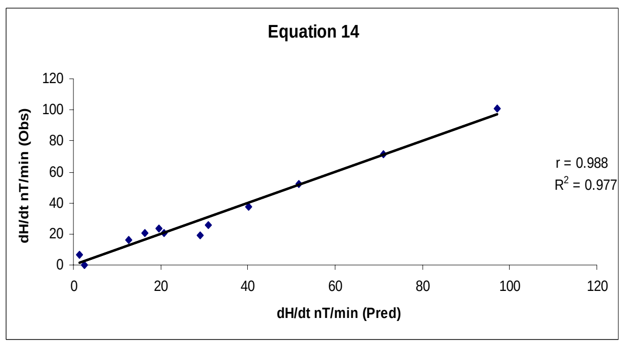
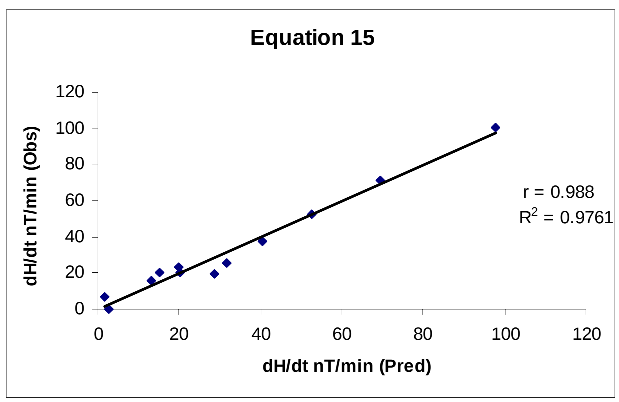


Fig. 4. Comparison between observed and predicted values of the correlation coefficient at Victoria.

Figure 5 shows the comparison between observed and predicted values of the correlation coefficient at St John. Equation (14/ Table 2c) shows a correlation coefficient of 0.988 that exists between time derivatives of the horizontal geomagnetic field, north and east components of the geoelectric field, auroral electrojet and disturbance storm time. The coefficient of determination of 0.977 which implies 97.7% of time derivatives of the horizontal geomagnetic field can be accounted for by using the auroral electrojet index, disturbance storm time, and the north and east components of the geoelectric field.





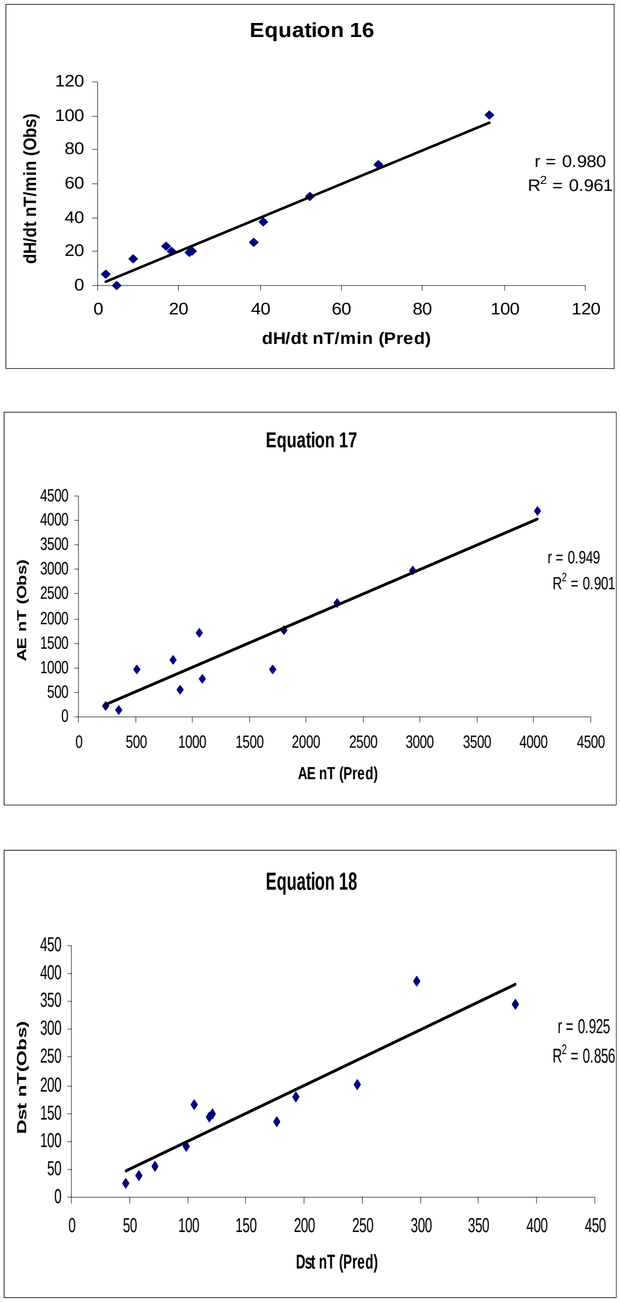


Fig. 5. Comparison between observed and predicted values of the correlation coefficient at St John.

Figure 6 illustrates the comparison between observed and predicted values of the correlation coefficient at Addis Ababa. From equation (19/ Table 2d) a correlation coefficient of 0.859 exists between time derivatives of the horizontal geomagnetic field, the auroral electrojet and disturbance storm time. The coefficient of determination of 0.739 implies 73.9 % of time derivatives of the horizontal magnetic field can be accounted for by using the auroral electrojet and disturbance storm time.

Addis Ababa

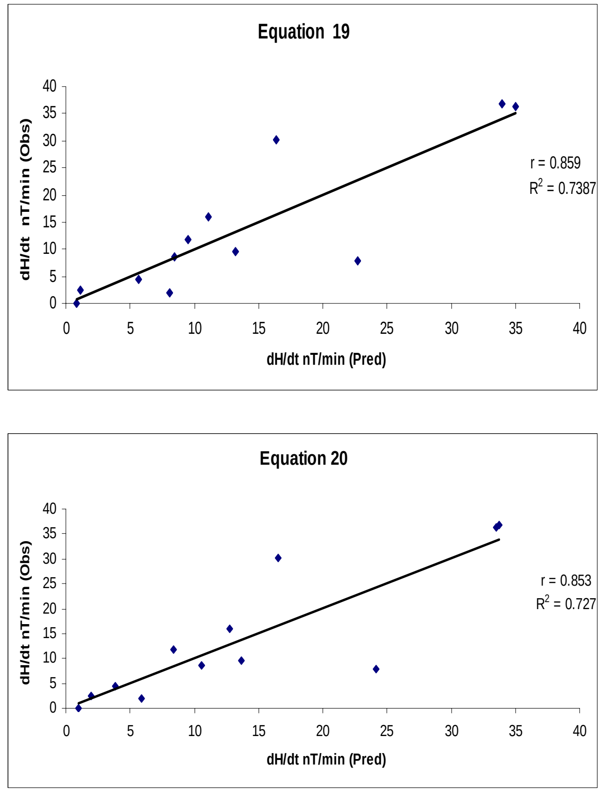
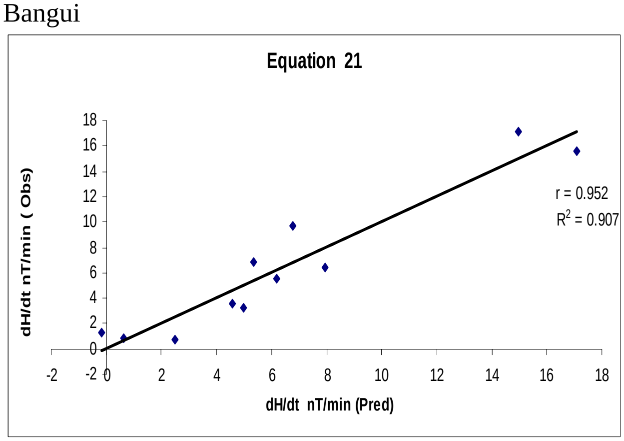


Fig. 6. Comparison between observed and predicted values of the correlation coefficient at Addis Ababa.

Figure 7 shows the comparison between observed and predicted values of the correlation coefficient at Bangui. Equation (21/ Table 2e) shows a correlation coefficient of 0.952 that exists between time derivatives of the horizontal geomagnetic field, the auroral electrojet and disturbance storm time. The coefficient of determination of 0.907 implies 90.7% of time derivatives of the horizontal magnetic field can be accounted for by the using auroral electrojet and disturbance storm time.

Bangui



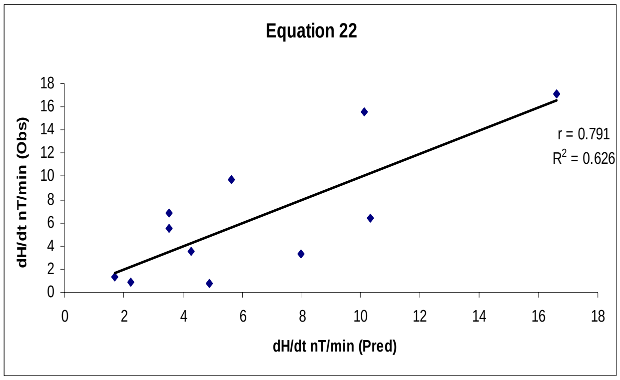
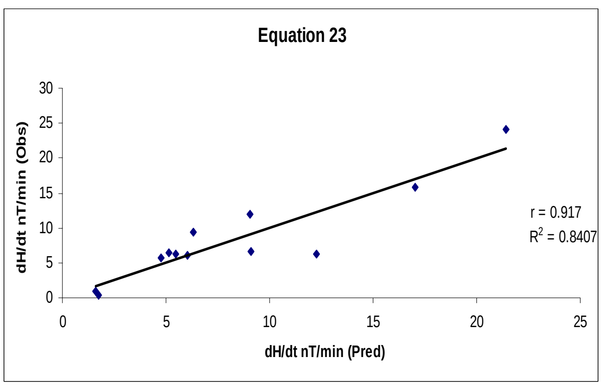


Fig. 7. Comparison between observed and predicted values of the correlation coefficient at Bangui.

Figure 8 is devoted to the comparison between observed and predicted values of the correlation coefficient at Mbour. Equation (23/ Table 2f) shows a correlation coefficient of 0.917 that exists between time derivatives of the horizontal geomagnetic field, auroral electrojet and disturbance storm time. The coefficient of determination of 0.841 implies 84.1% of time derivatives of the horizontal magnetic field can be accounted for by using the auroral electrojet and disturbance storm time.

M'bour



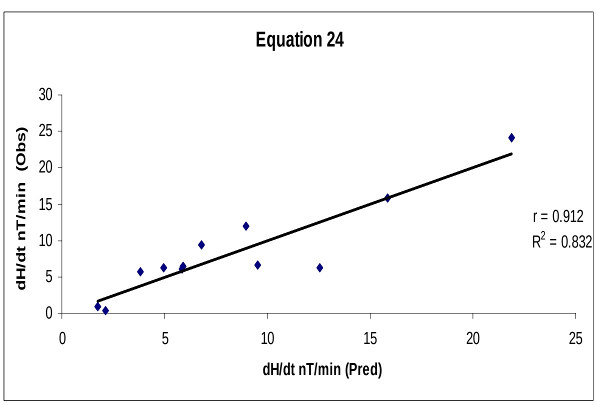


Fig. 8. Comparison between observed and predicted values of the correlation coefficient at Mbour.

The statistical tests, RMSE and MBE were used to evaluate the accuracy of the predicted time derivatives of the geomagnetic fields. They provide the long and short term performances of an equation. The smaller the values, the better the equation.

RESULTS AND DISCUSSION

During geomagnetic activity periods, the amplitude of auroral electrojets flowing along the auroral oval increases and the auroral oval can extend toward and usually reach subauroral zones. Sometimes during very strong magnetic storms the auroral oval extends toward middle and equatorial latitudes, occasionally becoming visible from tropical latitudes. Many physical processes are involved in auroral zones: the precipitation of particles which increase the electric conductivities in the E region, the field aligned currents which close magnetospheric electric currents and the dawn dusk potential drop imposed by the solar wind flowing around the magnetosphere. All these processes contribute to an increase in the electric currents flowing in the ionosphere (Kikuchi *et al*., 1996; Abduet *et al*., 1998; Kobea *et al*., 1998).

As the geomagnetic storm is intense the edge of the auroral boundary moves to a lower geographical latitude. Geomagnetic activity, even when there is not a big storm, affects the whole Earth from auroral to low latitudes. Kobea *et al*. (2000), shows the latitudinal profile of a magnetic disturbance observed on May 27, 1993 (Fig. 4 of the paper). The amplitude of this disturbance is ~ 150-200nT at auroral latitudes ~ 80-100nT (half) at subauroral latitudes and still ~30nT at equatorial latitudes. Kappenman (1996, 2005) reported that the power grids are seriously affected by geomagnetic storms at high latitude due to large impulsive geomagnetic disturbance driven by auroral intensification, but there are signs that space weather poses significant risks to ground technology at low latitude (Addis Ababa) and subauroral latitudes (Ottawa and Victoria); it is reported in our investigation that when the rate of change of geomagnetic disturbance exceeded 30nT/min it posed a threat to power grids. Vanhamaki *et al*. (2005) established that changes in ionospheric current will give rise to induction current in the conducting ground which can significantly contribute to magnetic and electric fields. It has been reported that auroral electrojet, substorm onsets, geomagnetic pulsation and sudden impulses are responsible for large GIC (Boteler, 2001; Lam *et al*., 2002; Kappenman, 2003; Pulkkinen *et al*., 2003, 2005; Viljanen *et al*., 2006). Recently, Watari *et al*. (2009) confirmed that GIC associated with substorms were detected in Japan over a 2 year GIC measurement period, during the solar minimum although intense GIC do occur mostly during geomagnetic storms.

Tables 2 (a-f) contain summaries of various linear regression analyses. It is clear that the correlation coefficient r, correlation of determination R^2, MBE (nT/min), and RMSE (nT/min) vary from one variable to another. Generally, correlation coefficients (0.990 - 0.779) are high for all the variables. This implies relationships between the time derivatives of the horizontal geomagnetic field (dH/dt), auroral electrojet (AE) index, disturbance storm time (Dst), and north and east components of the geoelectric field (Ex and Ey). This is further demonstrated by high values of the coefficient of determination R^2 (0.980 - 0.607) across the variables. There is a significant relationship between ionospheric response and ground based parameters.

Comparing the output, we can see that all regressions give good results. For better analysis we considered high values of the correlation coefficient and coefficient of determination and a low value of RMSE. The following equations produced the best subauroral correlations: Eq. 4 (Table 2a, Ottawa), Eq. 9, (Table 2b, Victoria) and Eq. 14 (Table 2c, St John). At low latitude: Eq. 19 (Table 2d, Addis Ababa), Eq. 21 (Table 2e, Bangui), and Eq. 23 (Table 2f, M'bour) were considered the best correlations with low values of RMSE and MBE.

Our result has demonstrated that temporal variation of time derivatives of the horizontal geomagnetic field shows high correlation with the geoelectric field and ionospheric response (AE and Dst indices) at different stations in mid and low altitudes. The variation in correlation coefficient may be a result of geographical orientation of the power grids and also Earth conductivities.

Pulkkinen *et al*. (2006) suggested that GIC magnitudes also depend on grid topology, configuration and resistances and vary greatly from site to site in a network. Pulkkinen *et al*. (2001) reported that GIC flow in the pipeline responds differently for the east-west and north-south geoelectric fields in association with temporal changes of the magnetic field. Also Pirjola (2000) recommended that power grids should be aligned as close to north-south as possible rather than east–west direction. This is because of the auroral electrojet which is significant in connection with magnetic disturbance inducing GIC in an east-west direction. Our analysis has shown that geomagnetic storm effects were not so strong at St John (subauroral), M'bour and Bangui (low latitude), and the effect on consumers was small during weak and mild geomagnetic disturbance.

CONCLUSION

Kataoka and Pulkkienen (2008) reported that the horizontal geomagnetic field (dH/dt) is an excellent indicator of GIC and the relationship between the GIC and dH/dt is always the same in a very large dynamic range of about three orders of magnitude. This study examined the possibility of geomagnetic induced current (GIC) using time derivatives of the horizontal geomagnetic field (dH/dt) at the threshold of 30nT/min at mid and low latitude. When the rate of change of geomagnetic disturbance exceeded 30nT/min it posed a serious threat for power grids. Strong relationships between time derivatives of the horizontal magnetic field (dH/dt), auroral electrojet (AE) index, disturbance storm time (Dst), and the geoelectric field (Ex and Ey) led to the conclusion that auroral activity influences GIC down to low latitudes.

An interesting phenomenon was also detected in the Addis Ababa region, which showed much higher GIC activity when compared to other typical low latitude regions (Bangui and M'bour). This may be due to current moving at equator called equatorial electrojet. Ionospheric current systems exist which can occasionally affect equatorial electrojet. This current is generated at high latitudes in the vicinity of the auroral zones as a result of motions in the magnetosphere (Onwumechilli and Ogbuechi, 1967). During magnetically disturbed conditions this current system may undergo considerable enhancement and may extend to equatorial latitudes. Akasofu and Chapman (1963) showed that polar geomagnetic storms can greatly enhance the equatorial electrojet current and Rastogi (1977) suggested that when there is fluctuation in the magnetic field during SSC at low latitude station are due to the imposition of electric field over the equatorial ionosphere leading to equatorial electrojet. Kappenman (2003) showed that during the global burst (the sudden beginning of a magnetic storm), the intensity of the geomagnetic field can be a reason of significant GIC at all geomagnetic latitudes, including the equatorial region.

The results obtained in this paper are applicable to the estimation of geomagnetically induced currents GIC using time derivatives of the horizontal geomagnetic field in connection with research of space weather effects.

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REFERENCES

Abdu, MA., Sastri, JH., Liihr, H., Tachihara, H., Kitamura, T., Trivedi, NB. and Sobral, JHA 1998. DP 2 electric field fluctuations in the dusk-time dip equatorial ionosphere, Geophys. Res. Left. 25:1511-1514.

Akasofu, S. I and Chapman, S. 1963. The lower limit of latitude (US sector) of northern quiet auroral arcs, and its relation to Dst (H), J. Atmos. Terr. Phys. 25**:**9-12.

Barker, RH. and Skinner, NJ. 1980. Flow of electric current of telluric origin in a long metallic pipeline and their effect in relation to corrosion control, Mater. Performance. 19(2):25-28.

Boteler, DH., Pirjola, R. and Trichtchenko, L. 2000. On calculating the electric and magnetic fields produced in technological systems at the Earth's surface by a wide electrojet. Journal of Atmospheric and Solar terrestrial Physics. 62:1311-1315.

Boteler, DH. 2001. Space weather effects on power systems. In: Space Weather, Geophys. Monogr. (vol. 125). Eds. Song, P., Singer, H. and Siscoe, G. pp. 347--352, AGU, Washington, DC, USA.

Campbell, WH. 2000. Introduction to geomagnetic fields. Cambridge University Press, (2nd ed). 235-236.

Coles, RL., Thompson, K. and Jansen van Beek, G. 1992. A comparison between the rate of change of the geomagnetic field and geomagnetically induced currents in a power transmission system, Proc. EPRI Conf. Geomagnetically Induced Currents, Burlingame, Ca., 8–10 Nov. 1989, EPRI TR-100450. 15:1-8.

Erinmez, I.A., Majithia, S., Rogers, C., Yasuhiro, T., Ogawa, S., Swahn, H. and Kappenman, JG. 2002. Application of Modeling Techniques to Assess Geomagnetically Induced Current Risks on the NGC Transmission System, CIGRE Paper 39-304.

Kataoka, R. and Pulkkinen, A. 2008. Geomagnetically induced currents during intense storms driven by coronal mass ejections and corotating interacting regions. Journal of geophysical research. 113, A03S12, doi:10.1029/2007JA012487.

Kappenman, JG. 1996. Geomagnetic Storms and Their Impact on Power Systems, IEEE Power Engineering Review.

Kappenman, J.G. 2005. An overview of the impulsive geomagnetic field disturbance and power grid impacts associated with violent Sun -Earth connection events of 29-31 October 2003 and a comparative evaluation with other contemporary storms, Space Weather. 3. S08C01,doi.1029/2004SW000128.

Kappenman, JG. 2006. Great geomagnetic storms and extreme impulsive geomagnetic field disturbance events – An analysis of observational evidence including the great storm of May 1921. Advances in Space Research. 38:188-199.

Kappenman, JG. 2003. Storm sudden commencement events and associated geomagnetically induced current risks to ground-based systems at low-latitude and mid-latitude locations, Space weather 1, 3, 1016, doi: 10.1029/2003SW000009.

Kikuchi, T., Lfihr, H., Kitamura, T., Saka, O. and Schlegel, K. 1996. Direct penetration of the polar electric field to the equator during a DP2 event as detected by the auroral and equatorial magnetometer chains and the EISCAT radar, J. Geophys. Rest. 101(17):161-173.

Kobea, AT., Mazaudier, CA., Do, JM., Luhr, H., Houngninou, E., Vassal, J., Blanc, E. and Curto, JJ. 1998. Equatorial electrojet as part of the global circuit: A case study from the IEEY, Ann. Geophys. 16:698-710.

Kobea, A., Richmond, A., Emery, BA., Peymirat, C., Lürh, H., Moretto, T., Hairston, M. and Amory-Mazaudier, C. 2000. Electrodynamic coupling of high and low latitudes observations on May, 27, 1993, Journal of Geophys. Res. 105, A 10:22979-22989.

Koen, J. and Gaunt, CT. 2002. Geomagnetically Induced currents at mid latitudes, Abs. The 27th General Assembly of URSI, 17-24 August, Netherlands, Maastricht. 177.

Lam, HL., Boteler, DH. and Trichtchenko, L. 2002. Case studies of space weather events from their launching on the Sun to their impacts on power systems on the Earth, Ann. Geophys. 20:1073-1079.

Makinen, T. 1993. Geomagnetically induced currents in the Finnish power transmission system, Finn. Meteorol. Inst. Geophys. Publ. 32, 101.

Onwumechilli, A. and Ogbuechi, A. 1967. Daily variation and secular variation of the geomagnetic field. Journal atmospheric and terrestrial physics. 29:149.

Ogunade, S. 1986. Induced electromagnetic field in oil pipelines under electrojet current sources, Phys. Earth Planet. 43:307-315.

Osella, A. and Favetto, A. 1999. Numerical simulation of current induced by geomagnetic storms on buried pipelines. An application to the Tierra del Fuego, Argentina, Gas Transmission Route, IEET. Geosci.Remote. 37:614.

Pirjola, R., Kauristie, K., Lappalainen, H. and Pulkkinen, A. 2005. Space weather risk. AGU Space Weather. 3,S02A02, doi:10.1029/2004SW000112.

Pirjola, R. 2004. Effects of space weather on high-latitude ground systems. Advances in Space Research. 36:2231-2240.

Pirjola, R. 2000. Geomagnetically induced current during magnetic storms. IEE Transactions on Plasma Science. 28:1867-1872.

Poppe, B.B. and Jordan, KP. 2006. Sentinels of the Sun: Forecasting space weather. Johnson, Boulder, Colo. pp196.

Pulkkinen, A., Viljanen, A., Pajunpaa, K. and Pirjola, R. 2001. Recordings and occurrence of geomagnetically induced currents in the Finnish natural gas pipeline network, J. Appl. Geophys. 48:219-231.

Pulkkinen, A., Thomson, A., Clarke, E. and McKay, A. 2003. April 2000 storm: ionospheric drivers of large geomagnetically induced currents, Ann. Geophys. 21:709-717.

Pulkkinen, A., Lindahl, S., Viljanen, A. and Pirjola, R. 2005. Geomagnetic storm of 29–31 October 2003: Geomagnetically induced currents and their relation to problems in the Swedish high-voltage power transmission system, Space Weather. 3, S08C03, doi:10.1029/

2004SW000123.

Pulkkinen, A., Viljanen, A. and Pirjola, R. 2006. Estimation of geomagnetically induced current levels from different input data. Space Weather. 4, doi:10.1029/2006SW000229.

Rastogi, RG. 1977. Geomagnetic storms and electric fields in the equatorial ionosphere. Nature. 268:422-424.

Trichtchenko, L. and Boteler, DH. 2006. Response of power systems to the temporal characteristic of geomagnetic storms. IEE, CCECE/CCGEI, Ottawa.

Viljanen, A. 1998. Relation of Geomagnetically Induced Currents and Local Geomagnetic Variations, IEEE Trans. Power Delivery. 13:1285-1290.

Vanhamäki, H., Viljanen, A. and Amm, O. 2005. Induction effects on ionospheric electric and magnetic fields, Ann. Geophys. 23, 1735.

Viljanen, A. 1997. The relation between geomagnetic variation and their time derivatives and implication for estimation of induction risks. Journal of geophysical research letter. 24: 631- 634.

Viljanen, A., Nevanlinna, H., Pajunpaa, K. and Pulkkinen, A. 2001. Time derivative of the horizontal geomagnetic field as an activity indicator. Annales Geophysicae. 19:1107–1118.

Viljanen, A., Taskanen, E.I and Pulkkinen, A. 2006. Relation between substorm characteristics and rapid temporal variations of the ground magnetic field, Ann. Geophys., 24:725-733.

Vodjanikov, VV., Gordienko, GI., Nechaev, SA., Sokolova, OI., Homutov, SJ. and

Yakovets, AF. 2007. Study of geomagnetically induced current from time derivatives of the

Earth’s magnetic field. PUBLS. INST. GEOPHYS. POL. ACAD. SC. C-99 (398).

Watari, S., Kunitake, M., Kitamura, K., Hori, T ., Kikuchi, T., Shiokawa, K., Nishitani, N., Kataoka, R ., Kamide, Y., Aso, T., Watanabe, Y. and Tsuneta, Y. 2009. Measurements of geomagnetically induced current in a power grid in Hokkaido, Japan. Space Weather. 7, S03002, doi:10.1029/2008SW000417.

Wik, M., Viljanen, A., Pirjola, R., Pulkkinen, A., Wintoft, P. and Lundstedt, H. 2008. Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden. Journal of Space weather. 6, doi:10.1029/2007SW000343.

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