Global Geomagnetically Induced Currents during Quiet Geomagnetic Activity on 23 December 2014

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***Abstract*—In this study, the global GIC activity was investigated during the sudden impulse (SI) event associated with coronal mass ejection (CME) passage on 23 December 2014 in order to assess the GIC risks at different latitudes even without any strong geomagnetic activity. Firstly, the solar wind parameters, namely, solar wind speed (V_{sw}) and solar wind dynamic pressure (P_{dyn}), interplanetary magnetic field (IMF) B_z component, the auroral electrojet (AU and AL index) and SYM H index that represents the ring current are thoroughly studied for two days, during the SI event and after the event. Then, the temporal variation of SYM H was extracted to estimate the level of Earth's magnetospheric compression associated with the interplanetary shock. The global latitudinal temporal changes of magnetic field H-component during the SI event were statistically analyzed to observe its impact to the global GIC. The same method of analysis was then further examined in consideration of local time (LT) and the SI event period to identify the time corresponded to the strong impact of GIC activity. The results revealed an interesting finding where a comparable equatorial GIC activity with GIC activity in high latitude region occurred during the arrival of interplanetary shock due to the SI event. Besides, the result also gave the idea on important timing for large GIC prediction in particular area.**

Index Terms*—Geomagnetically induced currents (GICs); space weather; sudden impulse (SI) event; temporal variation of magnetic field *dB/dt

I. INTRODUCTION

GEOMAGNETIC INDUCED CURRENT (known as GIC afterward) is one of the space weather perturbation's effects that has the significant potential to be explored as fundamental knowledge for impact to the Earth surface technologies and buried equipment such as power electric, railways, pipelines, telecommunication cables and oil and gas technology. During space weather perturbation, the solar wind plasma interacts with the Earth magnetosphere thus spatially and temporally varying the initial magnetic field condition that will induce geoelectric fields in the ground based on Faraday's law; in turn drives ohmic currents along electrically conductive technological networks [1][2]. In large technological systems, these currents are called "GICs". GICs have a very low range of frequencies, typically mHz range compared to normal power transmission frequency of 50 to 60 Hz. With the characteristic of quasi-DC currents, GICs will cause bad implication in power network such as the transformer saturation, increase of harmonics in electricity, unexpected relay tripping, large reactive power consumption which finally lead to power failure as reported from Hydro-Quebec collapse on 13 March 1989 that blacking out the region for 9 hour [1][3][4] and also the blackout of the Finnish high voltage grid [4]. Historically, many researches on GIC have been conducted in high latitude regions because of the frequent occurrence of intense auroral activities in association with substorm onset of geomagnetic disturbance which identified as the dominant source of GICs in this region [3][5]-[8]. However, there is also high GICs activity detected at low-latitude power systems which are unconsidered to have the GICs impact and remote from the auroral zone.

Recently, many power grid failures have been reported in mid to low latitude, showing that the possibility of GIC problem there, too and this lead to direct GIC measurement in power systems at this region [4][5][9]. The previous researcher [10] conducted two years GIC measurement from 2007 in Japan power grid and they found that GIC activity in low latitudes observed in conjunction with various geomagnetic activities such as geomagnetic storms, substorm activities, and sudden commencement of geomagnetic fields associated with interplanetary shocks. The GIC measurement in mid and low latitudes also conducted in Brazil and China which revealed the GIC activity in November 2004 of the power grid in this region [11][12]. Unlike the GIC activity in high latitudes, in mid and low latitudes, GIC activities are considerably affected during sudden commencement (SC) events associated with interplanetary shock activity [4][5][9][10][12]-[15]. The SC event is categorized into two events which are storm sudden commencement (SSC) and sudden impulse (SI) event. The difference between these two events is that the interplanetary shock due to SSC leads to geomagnetic storm while during SI event, there is no geomagnetic storm afterward. The compression of Earth's magnetosphere due to interplanetary shocks yields to the enhancement of magnetopause current, ring current intensification, and equatorial electrojet, thus resulting in the important role of SC events to GIC activities in this region

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[5][8][9][15].

By performing the time derivative of the ground magnetic field variation (*dB/dt*), it specifies the geoelectric fields which can be used as GIC indicator. The study on *dB/dt* component to identify GIC level at locations of interest, has widely established by several researchers [2][3][5][7][9][14]-[18] and the sharp increase of *dB/dt* component is also observed during SC event showing that it was not particularly occurred during substorms. The increased value of time derivative of the magnetic field (*dB/dt*) are also caused by sudden commencement at the beginning of the geomagnetic storm, pulsation of the magnetic field during the recovery phase and magnetic disturbance during the main phase of the geomagnetic storm [7]. Recently, the equatorial GIC activities during geomagnetic sudden commencement due to interplanetary shock events and during extreme geomagnetic storms [19][20] are investigated. Previous researchers [3] has focused their study on equatorial GIC during sudden impulse (SI) events from 2001 to 2013 associated with interplanetary shock events and the study demonstrated that equatorial electrojet amplifies the magnetic field signature of sudden commencement (SC) events resulting in higher GIC risk in this region compared to low latitude regions. Other studies also revealed that SC events might cause a higher risk of power network damage at magnetic equator [19][20] compared to low latitude due to equatorial intensification. A significant impact of sudden impulse event in the equatorial region has been revealed by authors [21] where a higher variation of local ground magnetic field H-component in low latitude than in high latitude was observed associated during SI event on of 23 December 2014. However, a much more detailed investigation on global GIC assessment was not thoroughly examined to study the latitudinal impact of this SI event. Therefore, in this study, we continue the study on the impact of this SI event on 23 December 2014 to the associated GICs. The particular focus of this research was to investigate the global GIC level with the presence and absence of compression of Earth's magnetosphere due to the interplanetary shock. With the high-resolution ground magnetometer around the world, it allows a detail investigation on the impact of SI event to GIC activity.

II. Global Magnetometer Observation

Ground-based magnetometer station data are primarily used in this analysis. Several magnetometer networks installed around the world by numerous group, and this study the magnetometer data is obtained from SuperMag data repository (http://supermag.jhuapl.edu/). Data are collected from magnetometer stations arrays distributed globally and represented in a single coordinate system with unit vectors pointing in the direction of local magnetic north (B_n), local magnetic east (B_e), and in the vertical (B_n). Magnetometer data are available in a 1 min resolution and in this study, H-component of magnetic field, [3] is used, $H = \sqrt{{B_n}^2 + {B_e}^2}$.

A. Solar wind and IMF data

Measurements of the solar wind and interplanetary magnetic field (IMF) parameters, including the solar wind velocity and orientation of IMF are made by Advanced Composition Explorer (ACE) satellite. ACE measurements are obtained from OMNI database that available online (http://nssdc.gsfc.nasa.gov/omniweb/). ACE satellite, which is located at LI point to 17 R_E of the Earth, provides the measurement values for the solar wind and IMF near the outer boundary of Earth's magnetosphere.

B. Ground magnetic indices

In order to study the geomagnetic activity, different magnetic indices are analyzed. AU and AL indices are used to understand the influence of SI event impact to auroral electrojets. These indices are derived from magnetometer stations located in the auroral zone in the northern hemisphere. AU index is an indicator of the eastward auroral electrojet which flows on dayside and AL index represents the westward auroral electrojet which flows on nightside. Besides that, these indices are a good indicator to measure substorm activity in the auroral zone. Symmetric disturbance field in H (or known as SYM-H afterward) describes the variation of the ring current in the magnetosphere and tail current. The SYM-H index is made by averaging the horizontal magnetic field measured by several low-latitude and mid-latitude magnetometers in order to avoid the contamination of auroral and equatorial electrojets. Increase pattern of SYM-H shows the compression phase of geomagnetic storm and it also shows the eastward magnetopause current. Westward ring current and main phase of the geomagnetic storm are represented by the decreasing pattern of SYM-H. These indices (AU, AL, and SYM-H) are obtained from World Data Center for Geomagnetism that operated by Kyoto University, Japan (http://wdc.kugi.kyoto-u.ac.jp/). Table. I is the geomagnetic activity classification based on SYM-H index and IMF Bz parameter [22].

TABLE I
GEOMAGNETIC ACTIVITY CLASSIFICATION BASED ON SYM-H INDEX AND IMF BZ COMPONENT [22]

	SYM-H (nT)	IMF, Bz (nT)
Intense	-100	-10
Moderate	-50	-5
Small (typical substorm)	-30	-3

III. Result and Discussion

A. Geomagnetic activity summary on 23 December 2014

During interplanetary shock event on 23 December 2014, a CME was hurled away from the sun active region 2241 causing a sudden increase of solar wind speed of around 180km/sec which first detected by ACE spacecraft at 1036UT. This event caused unusual phenomena where the interplanetary magnetic field, IMF component Bz pointed northward for long period. In this part, a brief overview of SI event on 23 December 2014 is explained. In Fig. 1, from top to bottom, presents solar wind speed V_{sw} (km/s), solar wind dynamic pressure P_{dyn} (nPa), interplanetary magnetic field IMF B_z, ground magnetic indices SYM-H including its temporal variation and finally the AU and AL index. The analysis of those parameters is made in two days of 23 – 24 December 2014 to observe any geomagnetic disturbance after interplanetary shock event. The interplanetary shock on 23 December 2014 happened at 1115UT and there is an abrupt pattern of the ground magnetic field at auroral region (AU and AL index) and low latitude region (SYM-H index), that coincides with the initial increase of solar wind speed, solar wind dynamic pressure and northward pointing of IMF B_z. During the CME passage, the IMF B_z polarity was pointing northward for a period of 8 hours until 2000UT before it turned to southward. The impact of this sudden passage causes a compression of the Earth's magnetosphere based on the increase pattern of SYM-H index and the maximum change in SYM-H index of 30 nT/min observed during the SI event. When the IMF B_z started to decrease and turned southward, the decreasing pattern of SYM-H index happened. However, the variation of SYM-H started to increase when the IMF B_z keep on oscillating around 2200 – 0000LT and remained at the initial state. The impact of the shock arrival was also noticed in the auroral region regarding the sharp increase and decrease of AU and AL index respectively as indicated as number 1. Other assigned number at AU and AL index (2 – 4) illustrates the level of substorm activities that have occurred in this region. High variations of AU and AL index happened 10h (2100UT), 28h (1400UT) and 31h (2000UT) respectively after the arrival of SI event. The second variation of AU and AL index is well-coincided with westward ring current/decrease pattern of SYM-H but for other two substorm activities (3 – 4), the substorm activities triggered by some trapped plasma instability in the magnetosphere. During the second to fourth substorm, the AL magnitudes were higher than AU magnitude which represents the higher variation of westward auroral electrojet in nightside compared to dayside. This pattern was caused by the penetration of explosive release of stored magnetotail energy into the near-Earth nightside auroral region and thus increase the westward electrojet, AL index [23]. During magnetic reconnection, some energetic particles will penetrate into the Earth's magnetospheric but some of them will be trapped in the magnetotail depending on the IMF B_z polarity and in this SI event, no strong geomagnetic activity or substorm has occurred due to the polarity of IMF Bz that keeps modulating during the southward. Hence, less magnetic reconnection happened to the Earth's magnetosphere with the lowest SYM-H was not even -100nT.

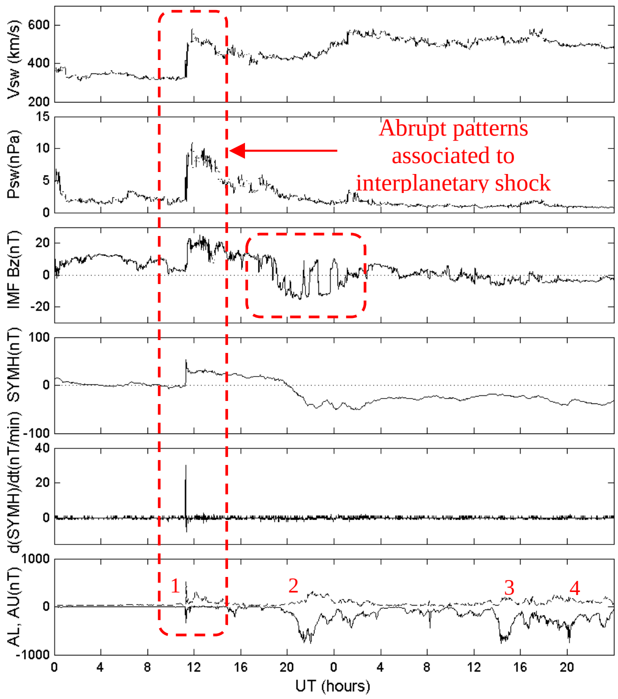

Fig. 1. Geomagnetic activity summary for 23 December 2014 sudden impulse (SI) event on 1115UT, including the next day of SI event. From the top figure, solar wind speed, the solar wind dynamic pressure, the interplanetary magnetic field (IMF) Bz component, SYM-H index and the temporal variations in the SYM-H index, and finally the AU and AL. The first dashed box represents the moment of SI event and the second dashed box indicates the southward but oscillating IMF B_z component. The red numbering at AU and AL index shows 4 different auroral activities.

B. *Global magnetic field fluctuations*

This section carries out the latitudinal analysis on *dB/dt* during the SI event on 23 December 2014 at 1115UT. Fig. 2 shows an example of latitudinal *dB/dt* analysis in African sector starting from high latitude station in New Aalesund (MLAT: 76.57°) and in Abisko (MLAT: 65.74°), mid-latitude stations in Kiev (MLAT: 46.56°) and in Iznik (MLAT: 34.7°) and equatorial station in Addis Ababa (MLAT:-0.06°). The SI event (SI time ~ 1413LT) caused significant *dB/dt* levels at all latitudes with the highest *dB/dt* amplitude of 69 nT/min observed in magnetic equator station and the *dB/dt* amplitude tend to 0 nT/min during a normal condition of geomagnetic activity. The *dB/dt* pattern in all station well corresponds with the temporal change in SYM-H index in Fig. 1 except for the ABK station where maximum *dB/dt* level noticed around 2100UT. This increased level in ABK station corresponds to the second phase of auroral electrojet in Fig. 1. This result indicates that the magnetic field variation in this latitude is more influenced by the auroral activity since ABK station is located in the auroral region than other stations outside of this area.

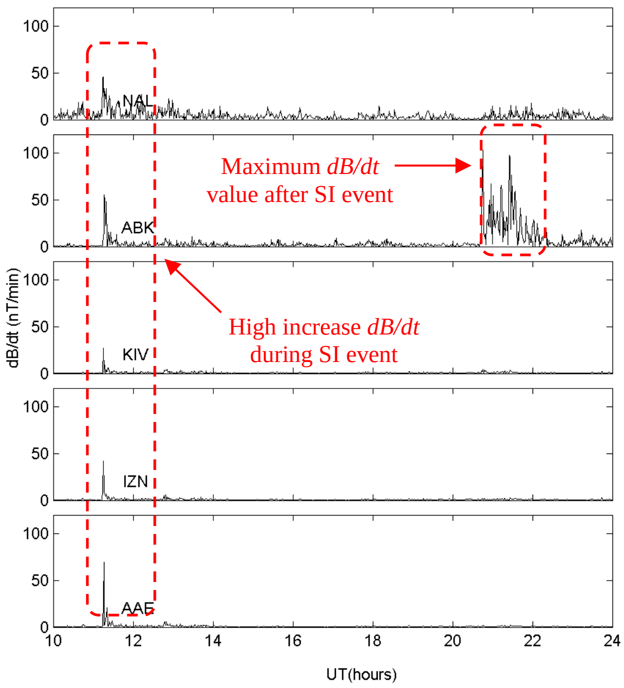

Fig. 2. An example of *dB/dt* analysis in African sector as function of geomagnetic latitude using 1-min magnetometer data during SI event on 23 December 2014 at 1115UT. From top figure to bottom represents *dB/dt* in NAL and ABK (high latitude station), KIV and IZN (mid-latitude station) and AAE (equatorial station). The first dashed box indicates the *dB/dt* amplitude at the moment of SI event and the second dashed box shows the maximum *dB/dt* amplitude (if present).

Several analyses on temporal variation in the magnetic field, *dB/dt*, as function of geomagnetic latitude with respect to local time and SI period event are done. Temporal variation of ground magnetic H-component data from 137 magnetometer stations in different latitude is analyzed. Fig. 3 shows the global *dB/dt* analysis in function of geomagnetic latitude during the moment of SI event at 1115UT. The points at this figure illustrate the level of GIC activity of each station. This result shows the latitudinal distribution of *dB/dt* during SI event, with substantially larger values at latitudes higher than 50° MLAT, which is consistent with the previous finding [3][19]. The most striking observation to emerge from this result is that high *dB/dt* value also observed in equatorial region (MLAT ~0°) and this value is comparable to those stations in high latitude region. In general, the pattern of this *dB/dt* latitudinal distribution can be classified into four categories: (1) increasing *dB/dt* value in equatorial region, ±15°, (2) low *dB/dt* at low-to-mid latitude, (3) increasing *dB/dt* in mid-to-auroral region 50° - 80° and (4) decreasing *dB/dt* in polar region. During the SI event, the equatorial magnetopause current increases as well as solar wind dynamic pressure that imposed by shock passage. However, the compressional wavefront is not solely happened within the equatorial but also occurred in high latitude due to the inhomogeneity of magnetospheric plasma. Therefore, this magnetospheric compression concurrently produces current in the polar ionosphere which is known as field-aligned currents (FACs). This FAC flows into the polar ionosphere and extends to the auroral electrojet [24]. This supports the increasing pattern of *dB/dt* in the equatorial and auroral region of the result in Fig. 3. The similar analysis was extended with respect to local time to understand in detail the physical mechanism that influences the GIC level of the different area.

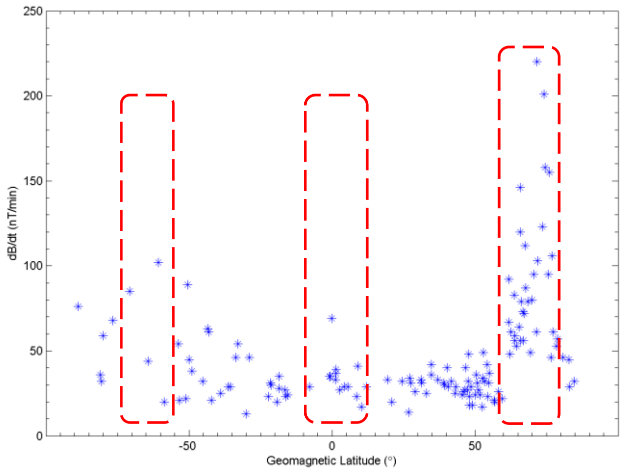

Fig. 3. Analysis of *dB/dt* as a function of geomagnetic latitude using 1-min magnetometer data during the arrival of SI event. The dashed box at the left and right sides illustrate the increasing *dB/dt* in high latitude of southern and northern hemisphere respectively. The middle dashed box indicates the increasing *dB/dt* in equatorial.

Fig. 4 is similar to the Fig. 3 but the maximum value of *dB/dt* associated with the SI event is plotted in different latitudes. The colored points represent the local time during the maximum GIC level. The difference of this figure with Fig. 3 is noticeable in high latitude *dB/dt* where the greater value of *dB/dt* recorded and most of maximum *dB/dt* value in this region occurred during the dusk and dawn time. It is mainly due to the dusk-to-dawn current imposed by FACs. This current will propagate to the equator and carry electric field in ionosphere but the amplitude will decrease along the propagation process towards the equator. That is why the decreasing *dB/dt* amplitude was noticed in this region. Again, the increasing pattern of maximum *dB/dt* in equatorial was observed and the highest maximum equatorial *dB/dt* value which was observed during SI event happened in noon sector around 1415LT is 69 nT/min. This value is higher than low latitude and is comparable to high latitude region. It is produced by the enhancement of the ionospheric current during the propagation from the auroral region with the aid of enhancement of Cowling conductivity [24][25]. This result also highlighted that besides the equatorial magnetopause current due to high dynamic pressure, greater equatorial *dB/dt* value also corresponds to the dayside equatorial enhancement [2]. The cause of equatorial enhancement in dayside has been widely investigated [24]-[26] and it also supports that the higher conductive of the equatorial ionosphere is enhanced by Cowling effect.

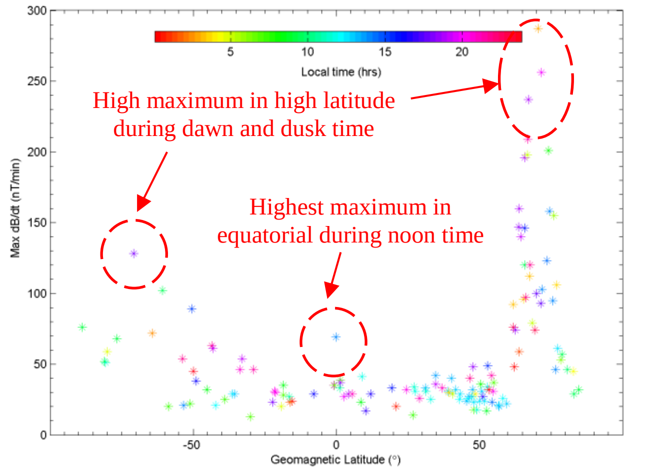

Fig. 4. Analysis of maximum *dB/dt* as a function of geomagnetic latitude using 1-min magnetometer data during SI event with the different colors indicating the local time. Three red-dashed circles represent high maximum *dB/dt* in high latitude (during dawn and dusk) and equatorial (during noon).

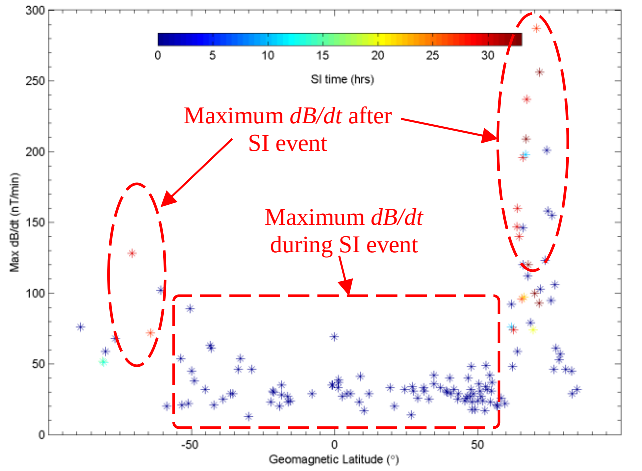

Fig. 5. Analysis of maximum *dB/dt* as a function of geomagnetic latitude using 1-min magnetometer d ata with the different colors indicating the hours after the SI event time. Two red-dashed ovals highlight the occurrence time of maximum *dB/dt* after SI event and the red-dashed box is the maximum *dB/dt* during SI event.

The detailed analysis on latitudinal maximum *dB/dt* value with respect to the SI period is exhibited in Fig. 5. The colored points represent the time (hour) after the SI time. As shown in that figure, maximum *dB/dt* at mid-latitude and equatorial stations took place at the moment of SI swap the Earth. The most striking finding to emerge from this figure is that the maximum *dB/dt* in high latitude stations or in the auroral region happened several hours after the moment of SI event which is most likely corresponded to the phases of AU and AL index as explained in previous part. This finding also highlights that the maximum value of *dB/dt* in mid-latitude to equatorial stations occurs during the moment of sudden impulse (SI) event where the dominant current during this period is magnetospheric current induced by the sudden magnetospheric compression [2]. While for high latitude stations, the maximum *dB/dt* value is well-corresponded to the significant auroral activity based on AU and AL indices (as indicated in Fig. 1) [3][5][7][10][17][19] where the highest *dB/dt* occurred during night, dawn and dusk time. The result is in agreement with the penetration of stored magnetotail energy into the near-Earth nightside auroral region and the dawn-to-dusk current as previously discussed. In overall, these results (Fig. 2 – 5) show the high GIC level in high latitude region and in magnetic equator caused by the auroral current as well as the equatorial enhancement during the moment of SI present. Hence, showing that this region is highly susceptible to GIC risk even though with the absence of strong geomagnetic activity as usually reported by previous studies [1][17].

IV. Summary and Conclusion

This study was devoted to assessing the global GICs activity caused by a significant SI event on 23 December 2014. In order to examine the level of GIC, the temporal variation of magnetic field H component was performed. During the arrival of SI event, high level of GIC occurred in the equatorial region. The equatorial GIC activity was comparable to high latitude region, thus showing that the conductive technological infrastructure equatorial region is very susceptible as those in high latitude region due to space weather activity. At middle and low latitude, the GIC level was decreased compared to those at high latitude and equatorial. For regions in the auroral zone, the GICs activity level was well-coincided with auroral electrojet. This means that GIC activity in this region was also depending on the auroral activity. In overall, the present study revealed that the occurrence of high GICs activity is not limited during the strong geomagnetic storm, but the *consideration* of the quiet geomagnetic period should not have been overlooked especially for the regions situated in the magnetic equator. Furthermore, for the country where the system infrastructures were not designed to cope with the space weather effect, this finding has illustrated some crucial implication.

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