Assessment of Geomagnetically Induced Currents in Low Latitude Regions with respect to Severe Geomagnetic Storm over Solar Cycle 24

Zatul Iffah Abd Latiff\textsuperscript{1,2}, Mohamad Huzaimy Jusoh\textsuperscript{1} and Kharismi Burhanudin\textsuperscript{1}

\textsuperscript{1}Faculty of Electrical Engineering, Universiti Teknologi MARA, Shah Alam 40450, Malaysia
\textsuperscript{2}Faculty of Electrical Engineering, Universiti Teknologi MARA Johor, Masai 81750, Malaysia

Email : zatuliffah87@gmail.com

Abstract. Space Weather Perturbation – driven Geomagnetically Induced Currents (GIC) can cause the adverse impact to series of ground technological instruments. Power networks are the most affected technological facilities that experience malfunctions due to GIC phenomenon. High latitude regions experience more power network operation flaws due to this natural threat compared to mid latitude and low latitude regions. However different event of solar activities exhibit different space weather perturbations impacts regionally. Therefore, in this study, a thorough analysis of GIC activities during 6 severe geomagnetic storms in low latitude regions over solar cycle 24 based on Time Derivative of Horizontal Component of Geomagnetic Field (dH/dt) analysis are conducted. The results revealed that there is non-uniform latitudinal distribution of averaged dH/dt value in low latitude region and high GIC occurrences are observed during dayside. The correlation analysis between Solar Wind Parameters and GIC activities depicted that solar wind dynamic pressure (Psw) and Solar wind input energy (\(\varepsilon\)) act as Solar wind driver for the occurrences of GIC in low latitude region.

1. Introduction
The natural threat phenomenon called Geomagnetically Induced Currents (GIC) is the ground manifestation of Sun – Earth interaction. The example of solar activities is Coronal Mass Ejections (CME), Coronal Holes (CH) and Solar Flares. These explosive events from the sun yield the energetic plasma that will be carried by solar wind plasma which perturb to the earth magnetic field and cause high variations in geomagnetic field [1]. The fluctuations of earth magnetic field has led to the induction of the geoelectric field which responsible for driving the geomagnetically induced currents to the ground technological instrument such as power grid, gas pipelines, telecommunication cables and railway circuits [2]. The first eye-captured GIC event occurred at Hydro Quebec power system located in Canada where there is major power collapse in their power network due to the severe geomagnetic storm on 13\textsuperscript{th} March 1989. The chronology of the event is mentioned in [3]. Due to the major power collapse, the affected residents experienced blackout series for almost 9 hours [4]. The blackout series not only affected the residential area but the industrial area where the high capacity power is needed had also affected due to this event. The total of lost production and replacement of damaged equipment had embarked a new research effort to study the effect of geomagnetically induced currents to the technological system specifically on power systems.

Following from the 13\textsuperscript{th} March 1989 event, other countries also had started their research on the vulnerability of their national power grid system to the occurrence of GIC. A specific study including modelling of GIC had been performed by countries across high latitude, mid latitude and low latitude
region such as United Kingdom [5], United States [6], South Africa [7], Brazil [8], China [9], New Zealand [10] and any other countries.

However, a regional thorough analysis on certain region over specific solar cycle is not yet explored by other study. A study performed by [11] revealed the study on solar wind driver of GIC over Solar Cycle 23. However, this study only focuses on limited solar wind parameter which are solar wind electric field and epsilon parameter and in addition, the coverage of region was not specific. Therefore, in this study, a thorough investigation on the GIC activities in low latitude region over solar cycle 24 during severe geomagnetic storm is conducted. In this study, the GIC activities are indicated by the Time Derivative of Horizontal Component of Geomagnetic Field (dH/dt). The type of analysis covered on this research study is 1) The maximum value of dH/dt based on geomagnetic latitude variations; 2) The number of GIC activities with respect to the Local Time; and 3) The correlation analysis between solar wind parameters and GIC activities.

2. Methodology
This research consists of the observations of GIC activities indicated by the time derivative of Horizontal Component of Geomagnetic Field (dH/dt) during the severe geomagnetic storms over solar cycle 24. The analysis included the latitudinal analysis of maximum value of dH/dt at low latitude region, the pattern of GIC activities with respect to the local time and the behavioural relationship between solar wind parameter and GIC occurrences at low latitude region. The list of selected Geomagnetic Storms is presented in Table 1. The whole analysis of this study is simplified in Figure 1.

| No | Event             | Storm Onset | Minimum SYM-H index (nT) |
|----|-------------------|-------------|--------------------------|
| 1  | 26th September 2011 | 1750 UT     | -116                     |
| 2  | 24th October 2011  | 1831 UT     | -135                     |
| 3  | 14th July 2012    | 1810 UT     | -123                     |
| 4  | 17th March 2013   | 0600 UT     | -132                     |
| 5  | 17th March 2015   | 0445 UT     | -234                     |
| 6  | 22nd June 2015    | 1833 UT     | -208                     |

2.1. Space Weather Parameter
The geomagnetic storms are selected based on the severity of the geomagnetic storm events which are indicated by the SYM-H index. SYM-H index constitute the global magnetic field’s variation. SYM-H index is derived from ground magnetic observatories which are located at mid latitude and low latitude region to eliminate the effect of auroral and equatorial electrojet currents. In this study, the selected geomagnetic storm events is limited to the category of super geomagnetic storm based on the geomagnetic activity classification [12] as tabulated in Table 2.

The study of relationship between GIC activities indicated by dH/dt and solar wind parameter requires the information of the space weather data. The data is extracted from The Space Physics Data Facility (SPDF) based at NASA’s Goddard Space Flight Center. In this study, the space weather parameters are focused on Solar Wind Input Energy (ε), Solar Wind Dynamic Pressure (Psw) and Interplanetary Magnetic Field (IMF) Bz Component. The correlation between these parameters with the GIC activities were quantified and justified in the next section.
2.2. Horizontal Component of Geomagnetic Field

The geomagnetic field data is recorded by fluxgate magnetometer which is installed on the ground. This magnetometer is functioned to measure the variation of earth’s magnetic field consists of three components; Horizontal Component (H), Declination Component (D) and Vertical Component (Z) as depicted in Figure 2. Every single component of geomagnetic field carries significant data on the earth’s magnetic field variation. In the study of Geomagnetically Induced Currents, Horizontal Component is utilized as an indicator for GIC activities [12]. Time Derivative of Horizontal Component of Geomagnetic Field (dH/dt) were calculated in 1-minute interval to indicate the existence of any GIC activities at specific ground observatories. In this analysis, the ground stations are selected based on the minimum requirement of the GIC occurrences based on study performed by [13]. According to this study, the existence of GIC activities can be stipulated by the minimum requirement of the dH/dt value \( \geq 30 \text{ nT/min} \).

![Overall Flowchart of the study](image)

**Figure 1.** Overall Flowchart of the study

![Three Dimensional Vector of Geomagnetic Field Components](image)

**Figure 2.** Three Dimensional Vector of Geomagnetic Field Components
Table 2. Classification Of Geomagnetic Storm based on SYM-H Index

| No. | Geomagnetic Storm        | SYM-H index (nT)          |
|-----|--------------------------|---------------------------|
| 1   | Super                    | -100 > SYM-H ≥ -250       |
| 2   | Intense                  | -50 > SYM-H ≥ -100        |
| 3   | Moderate                 | -30 > SYM-H ≥ -50         |
| 4   | Small (substorm)         | SYM-H ≥ -50               |

3. Results and Discussion

3.1. Analysis of the averaged value of Time Derivative of Horizontal Geomagnetic Field in function of Geomagnetic Latitude (MLAT)

Through the accumulation of all GIC activities from several stations in low latitude region during 6 severe geomagnetic storms over solar cycle 24, the averaged value of $dH/dt$ based on latitudinal variation is computed and the results are presented in Error! Reference source not found. The list of geomagnetic observatories selected for this analysis is tabulated in Table 3. From the figure, the maximum averaged value of $dH/dt$ is 70 nT/min recorded at Sonmiani (19.36 MLAT) while the lowest averaged value of $dH/dt$ is 34.8 nT recorded at Los Cerillos (-19.71 MLAT). This figure revealed that from latitude variation of 15° to 30° and -15° to -30°, non-uniform distribution of GIC activities can be observed. There is no increasing or decreasing pattern can be perceived over latitudinal variation in low latitude region compared to the analysis that had been performed by [12] in equatorial region. Previous study performed by [12] shows that the averaged maximum $dH/dt$ value tends to increase when the equatorial stations approach the dip equator and it tends to decrease when they are few degrees away from the dip equator.

This phenomenon occurred as the equatorial region is under the influence of equatorial electrojet that cause an amplification on averaged $dH/dt$ value at stations located in dip equator region. Therefore, in the absence of equatorial electrojet in low latitude region, no unique pattern of averaged $dH/dt$ value can be observed. However, another factor that can affect the value of averaged $dH/dt$ in low latitude region is the variation of Local Time (LT) where the results are discussed in next analysis.

3.2. Analysis of GIC Occurrences with respect to Local Time (LT)

The relationship between the number of maximum $dH/dt$ with respect to local time (LT) in low latitude region is depicted in Error! Reference source not found.. As presented in figure, there is an increasing pattern in the number of maximum $dH/dt$ on the dayside from 1100 LT to 1500 LT. The highest number of GIC activities is recorded at 1500 LT with 10 cases while the lowest number of GIC activities are observed at 1600 UT, 1700 UT and 2200 UT with no GIC activities are recorded. This finding is consistent with the study performed by [12] and [14]. The analysis of GIC activities in equatorial region performed by previous studies revealed that the same pattern of number of maximum $dH/dt$ is observed on the dayside. This phenomenon is attributed to the high electron density which is known to be maximum close to noon time as the E-region drift velocities are maximum due to rising of the sun at E-layer height.

Table 3. List of Ground Magnetic Observatories in Low Latitude Region with its Geomagnetic Latitude (MLAT)

| No | Code | Name           | Country      | MLAT (°) |
|----|------|----------------|--------------|----------|
| 1  | BGY  | Bar Gyora      | Israel       | 24.99    |
| 2  | CER  | Los Cerrillos  | United States| -19.71   |
| 3  | CTA  | Charters Towers| Australia    | -28.92   |
3.3. The Correlation Analysis between Solar Wind Parameter and Time Derivative of Horizontal Component of Geomagnetic Field in Low Latitude Region

One of the severe geomagnetic storm occurred in solar cycle 24 was geomagnetic storm which is occurred on 22nd – 23rd June 2015 where one of the active solar region (AR12371) generated several Coronal Mass Ejections associated with M-class flares [15]. The perturbations of Coronal Mass Ejections to the earth’s magnetosphere had resulted a moderate to severe G4 geomagnetic storm on 22nd
to 23rd June 2015. This correlation analysis is focused on this event in order to identify the most prominent solar wind parameter towards the occurrences of Geomagnetically Induced Currents. The chosen solar wind parameters are solar wind input energy (ε), solar wind dynamic pressure (Psw) and Interplanetary Magnetic Field, Bz component. Figure 5 shows the geomagnetic activity summary for 22nd to 23rd June 2015 involving the response of solar wind speed (Vsw), Solar Wind Dynamic Pressure (Psw), Interplanetary Magnetic Field (IMF) Bz component, Solar Wind Input energy (ε), SYM-H index and Time Derivative of Horizontal Component of Geomagnetic Field (dH/dt) based on geomagnetic reading recorded at Jaipur (JAI) station. Based on the Figure 5, a sudden increase can be observed on solar wind speed, solar wind dynamic pressure, solar wind input energy, and SYM-H index indicating the arrival of interplanetary shock as highlighted in red-dashed box. Along with the sudden increase in solar wind parameters, it has resulted the increment of dH/dt value up to 70.6 nT/min on 22nd June 2015 at 1834 UT. At 1834 UT, a sudden increase of solar wind speed from 439 km/s to 551 km/s followed by the second increment up to 639.1 km/s can be noticed. An increment of solar wind speed also associated with an increment of solar wind dynamic pressure from 22.31 nPa to 51.08 nPa, an increment of solar wind input energy from 2.96 × 10^{19} \text{erg/min} to 15.49 × 10^{19} \text{erg/min} and an increment of SYM-H index around 108 nT. Interplanetary shock wave also can be related to magnetospheric compression during the perturbation of the solar wind plasma to the earth magnetic field. Interplanetary shock wave can be characterized by the sudden increase in the solar wind plasma as presented in Figure 5.

Figure 5. Geomagnetic Activity Summary for 22nd June 2015 until 23rd June 2015. From top figure, the Solar Wind Speed, the Solar Wind Dynamic Pressure, the Interplanetary Magnetic Field (IMF) Bz Component, SYMH-Index and finally the Time Derivative of Horizontal Component of Geomagnetic Field (dH/dt) at Jaipur (21.02 MLAT). The Red Dashed Box Represents the arrival of interplanetary shock wave.

From the graphical observations, it can be observed that the sudden increase of solar wind plasma is positively correlated with the rise of the dH/dt value. However, the correlation analysis needs to be performed in order to quantify the correlation between them. This correlation analysis is performed between dH/dt value recorded in JAI (21.02 MLAT), SFS (27.11 MLAT) and KNY (24.49 MLAT)
station from 21st June – 23rd June 2015 and solar wind parameters as mentioned before. From the correlation analysis computation as presented in Figure 6, there is high positive correlation between the recorded dH/dt value at JAI, SFS and KNY stations with the solar wind input energy (ε) with the correlation coefficient of 0.6737, 0.7056 and 0.6747 respectively. The correlation analysis between solar wind dynamic pressure and recorded dH/dt value also shows high positive correlation with the correlation coefficient of 0.7155, 0.6865 and 0.6829 respectively. This result has suggested that the dH/dt value in low latitude regions had high positive dependency on the energy dissipation from the solar wind. The amount of energy transferred from the solar wind was estimated using ε parameter with the high dependency on the magnitude of southward IMF Bz. The enormous energy loading has contributed to most of GIC activities. Enhanced solar wind dynamic pressure has led to the increase of the magnetopause current where it becomes one of the primary source of the geomagnetic field disturbance [16]. This high positive correlation between solar wind dynamic pressure and dH/dt value is consistent with the finding made by [17]. The correlation analysis between IMF Bz component and dH/dt has revealed that there is low negative correlation thus suggested the low dependency between dH/dt value and southward-pointed IMF Bz component. The summary of each correlation coefficients is tabulated in Table 4.

Figure 6. The Hourly Correlation between Solar Wind Parameters (Solar Wind Input Energy (ε), Solar Wind Dynamic Pressure (Psw) and IMF Bz Component) and dH/dt of JAI, SFS and KNY station on 21st – 23rd June 2015.
Table 4. Correlation Coefficient (r) from Correlation Analysis between Solar Wind Parameters and Averaged dH/dt of JAI, SFS and KNy stations

| Solar Wind Parameters          | Averaged dH/dt (r) |
|-------------------------------|--------------------|
|                               | JAI    | SFS    | KNy    |
| Solar Wind Input Energy (ɛ)   | 0.6737 | 0.7056 | 0.6747 |
| Solar Wind Dynamic Pressure (Psw) | 0.7155 | 0.6865 | 0.6829 |
| IMF Bz Component              | -0.2516| -0.2909| -0.2312|

4. Conclusions
A thorough analysis of GIC activities in low latitude region during 6 severe geomagnetic storms in solar cycle 24 had been characterized in this study. The study included the analysis of the maximum dh/dt with variation of Geomagnetic Latitude (MLAT) and analysis of the number of GIC activities with respect to the Local Time (LT). The results revealed that there is no specific pattern on the maximum value of dh/dt as the increasing and decreasing value of dh/dt occurred at random geomagnetic latitude while the increasing pattern of number of GIC occurrences can be observed during 1100 LT to 1500 LT attributed to high electron density closed to noon time. The correlation analysis depicted that there is high positive correlation between the averaged of dh/dt, solar wind dynamic pressure and solar wind input energy. Thus, it can be concluded that these 2 parameters are the important driver of the occurrences of GIC in low latitude region. However, the phenomenon of GIC is not solely attribute to the space weather perturbations knowns as the external factors but they are also can be influenced by internal factors such as conductivity, geoelectric field and skin depth. These two combinations can contribute to accurate modelling of the effect of GIC towards the power network.

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