Effects of CME-induced Geomagnetic Storm on Geomagnetic Induced Current at High and Middle Latitudes

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Abstract. Geomagnetic storm has been one of greatest events in space weather studies. Apart from the formation of aurora, geomagnetic induced current (GIC) is also induced during the storm when the storm intensity gets severe. Coronal mass ejection (CME) is a massive eruption created by the Sun and is believed to be the driver of geomagnetic storm. This paper is aimed to examine the effects of CME-induced geomagnetic storm on geomagnetic induced current (GIC) at high and middle latitudes by studying four levels of storm: minor (Kp 5), moderate (Kp 6), strong (Kp 7) and severe (Kp 8). We applied qualitative analysis through descriptive approach to describe the relationship between the storm intensity and GIC activity. Since the exact value of GIC were inaccessible, we adopted horizontal component time derivative magnetic field (dH/dt) as the indicator for GIC activity. At the end of the study, we found that the GIC highly depends on the storm intensity, by which higher levels of storm triggers more actively induced current. Besides, high latitude ionosphere was showing strong reactions to the storm arrival compared to middle latitude ionosphere as the magnitudes of dH/dt recorded by Barrow station at high latitude fluctuated within wider and higher range.

1. Introduction
Coronal Mass Ejection (CME) is an enormous and vigorous explosion of magnetic fields and mass particles coming out from corona. During these powerful eruptions, large number of solar materials are blown out into the interplanetary space in just a few hours, involving $10^{20} - 10^{25}$ J of energy release, travelling at a speed of 400–500 km/s, but can reach up to 2000 km/s [1]. The first ‘modern’ CME was detected on December 14, 1971, by the white light coronagraph on board NASA’s solar observatory [2]. As Earth’s magnetosphere encounters the first contact with solar wind plasma, its magnetic field changes with time due to strong shock wave from the CMEs and this disturbance is called solar storm. These storms lead most of space weather processes which may disrupt navigation and communication, long-distance ground transmissions of electric power, oil, and gas [3]. CMEs are believed to be the main driving source of solar storms due to its strong shock wave hitting the Earth. The energy contained by the solar wind is shifted to the magnetospheric current system and is released into the ionosphere [4].

Geomagnetic induced current (GIC) has a strong relationship with geomagnetically induced electric field (GIE) as the GIC travels through electric circuits connecting the power transmission lines with the ground [5]. The Carrington event is marked as the most disastrous event of magnetic storm in history that happened on 1st and 2nd September 1859 [6] that was caused by a strong X class flare on 1st September 1859 and the storm initiated a day after. The studies on GIC have been the centre of interest since a catastrophic power transmission grid failure in Quebec that was caused by an extreme
geomagnetic disturbance in March 1989 [7]. The formation of GIC follows the Faraday’s law whereby the change in magnetic field causes an induced electric field as explained by Equation (1):

$$\nabla \times \vec{E} = -\frac{d\vec{B}}{dt}$$

whereby \(\vec{E}\) is induced electric field and \(\vec{B}\) is magnetic field.

When the plasma from CMEs approaching the Earth, the magnetized plasma that is in contact with Earth’s magnetic field prompts a geoelectric field at the surface and underground [8]. The geoelectric field or in this study we say as GIC gives rise to the destruction of power systems that is brought by the compression of magnetosphere [9]. The estimation of GIC values can be done based on the horizontal component of time derivative magnetic field [10]. According to Faraday’s law, the change in magnetic field, specifically in horizontal component (dH/dt) is directly correlated to GIC. As the law represents the pattern of the GIC, the important parameter that should be focused is the dB/dt which is the representativeness of GIC [11]. The power grids would be immensely influenced if the values of dH/dt were greater than 30 nT/min [12]. A sudden impulse (SI) event that manifested prominent fluctuations in magnetic field found that equatorial countries could possibly experience geomagnetic disturbance if dH/dt values go beyond 30 nT/min [13]. Our aim was to analyze the GIC patterns for each storm level (Kp 4, 5, 6, 7 and 8) at high and middle latitudes, and to distinguish the intensity of GIC activity for each latitude. Considering we lack exact GIC values and this study focuses on the overall pattern of the GIC, we adopted dH/dt values to visualize the GIC activity as literature provided good correlations between them.

2. Data acquisition

This study was carried out based on geomagnetic events in 2017 which comprises four level of intensities: Kp 5, Kp 6, Kp 7 and Kp 8. All parameters were obtained and downloaded from free-access databases which are verified by NASA and other space agencies. The 1-min resolution solar wind velocity and IMF Bz parameters measured by ACE/WIND satellites are supplied on OMNIWeb NASA database, despite the presence of some data gaps. Besides, AE index and SYM-H parameters are also considered in this study which can be acquired from the same database. The auroral electrojet (AE) index is a quantitative measurement used to measure the magnetic activity at auroral zone as ionospheric currents circulating in the auroral oval region [14]. Meanwhile, longitudinal symmetric disturbance for horizontal component (SYM-H) is another important geomagnetic index used to measure the intensity of geomagnetic storm. The inclination in SYM-H is due to southward component of IMF Bz which drops below zero value [15]. According to [14], SYM-H must be equal or lower than -50 nT (SYM-H ≤ 50) in order to identify an event as a storm [4].

Through a descriptive approach, we investigated the relationship between geomagnetic storm strength and GIC activity at high and middle latitudes by applying qualitative analysis. Values of dH/dt were calculated by substituting values of time derivative magnetic field (dB/dt) in north (X) and east (Y) components obtained from Intermagnet.org into Equation (2).

$$\frac{dH}{dt} = \sqrt{\left(\frac{dB_x}{dt}\right)^2 + \left(\frac{dB_y}{dt}\right)^2}$$

where, \(H\) is horizontal component magnetic field, \(B_x\) is north component magnetic field and \(B_y\) is east component magnetic field.

A particular station at all locations was used to study the time derivative magnetic field (dH/dt) of high and middle latitudes during the storm. By measuring dH/dt, we can see how the magnetic field fluctuates at the respective location due to the disturbance. For this study, high latitude is represented by Barrow station and middle latitude is represented by Nurmijarvi station.
3. Results and Discussion

3.1. Minor storm (23\textsuperscript{rd} April 2017)

A minor storm was reported on 23\textsuperscript{rd} April 2017 which commenced at 0600 UT and came to an end at 1800 UT. By referring to geomagnetic and solar wind graphs in Figure 1, all values recorded during minor storm were greater than previous event which explain the higher intensity of the current storm.

![Figure 1](image-url)

With reference to Bz graph in the first panel, strong and active fluctuations can be observed at the beginning of the day as the graph showed multiple rise and fall phases until it reached the peak point of -7.51 nT at 1259 UT. Besides, the solar wind speed also went through the same phase in the range of 600 km/s to 810 km/s. AE index also recorded significant amplifications with its peak of 1641 nT at 0850 UT as ionospheric currents acquired strength from the contact with Bz. In the intervening period when AE index hit the peak, SYM-H was seen to drop to -46 nT following the third lowest peak of Bz throughout the day. As displayed in the dH/dt graph in Figure 2, the GIC once again was immensely triggered at high latitude while middle latitude detected very weak presence of GIC. There are sudden increases can be observed at 0700 UT onwards with its peak of 405.95 nT/s. The presence of the GIC activity occurred concurrently with the outstanding signals from SYM-H and AE index. However, at middle latitude, dH/dt were recorded at much lower values with similar fluctuations pattern as high latitude data and the peak that Nurmijarvi station obtained was only at 27.88 nT.

3.2. Moderate storm (16\textsuperscript{th} July 2017)

One level higher than the previous event is the moderate storm which was triggered on 16\textsuperscript{th} July 2017 as a consequence from a CME that emerged at 0545 UT. Figure 2 shows dH/dt graph representing the GIC activity, solar wind and geomagnetic data. Based on a rough inspection, the storm was initiated at 0600 UT as all geomagnetic and solar wind data showed sudden fluctuations at the same time when dH/dt graph displayed indications of the presence of GIC activity.

A moderate CME that was believed to be the main cause of this event can be detected from the solar wind data whereby its speed was promptly increased exactly at 0600 UT from 318.5 km/s to 419.1 km/s. Right after the emergence of the CME, all parameters (Bz, AE-index and SYM-H) began to show signals of the disturbance due to the CME. As displayed in Figure 3, Bz slowly dropped to its maximum negative value of -15.49 UT at approximately 4 hours after the launch of CME. This maximum phase of Bz was coinciding with the maximum phase of AE-index as the value has gone beyond 1500 nT. The The moment when the CME was set off at 0600 UT, the dH/dt graph immediately manifested the signs of GIC activity as the magnitudes started to fluctuate until the end of
the day. As equivalent to previous storm events, high latitude still gained a stronger disturbance with 225.91 nT/s of its peak and middle latitude’s peak at only 47.01 nT/s.

![Kp 6 storm](image)

**Figure 2.** The graph of dH/dt (top), southward IMF (Bz), solar wind speed, AE index and SYM-H

### 3.3 Strong storm (28th May 2017)

![Kp 7 storm](image)

**Figure 3.** The graph of dH/dt (top), southward IMF (Bz), solar wind speed, AE index and SYM-H

On 28th May 2017, the Earth experienced a strong storm with Kp-index of 7 which can be specifically witnessed at high and middle latitude locations. The CME was travelling at a maximum speed of 629 km/s and it reached into the Earth’s atmosphere, inducing the geomagnetic storm. As shown in Figure 3, solar wind speed at the beginning of the day was noticeably active within 0000 UT until 0800 UT, which happened at the same time when southward IMF (Bz) was at its maximum phase with a peak of -21.50 nT. An AE-index recorded vigorous fluctuations when solar wind speed and Bz were at their maximum phases. As solar wind particles making their way into the Earth’s magnetic field, the AE-index began to rise until it reached its maximum magnitude at 1960 nT. In the case of SYM-H, it started at -10 nT at 0000 UT and the signal rapidly dropped to lower negative values in the next
minute. Over the phase of decrement, the maximum value of SYM-H achieved was -142 nT at 0713 UT and nearly all values were seen to be below -50 nT which demonstrated the condition of strong storm throughout the day. In observing the GIC activity, dH/dt graph gave strong fluctuations at both latitudes in the morning until 1200 UT. For this event, Nurmijarvi station at middle latitude showed quite intense readings which is represented in blue line graph in figure below and the highest point was 60 nT/s. Nevertheless, high latitude still obtained much greater signals with recorded peak of 129.18 nT/s and this peak appeared within the active phase of AE-index.

3.4. Severe storm (8th September 2017)
Severe storm (Kp 8) is the most intense level of geomagnetic storm. During the Kp 8 storm on 8th September 2017, a powerful CME made contact with Earth's atmosphere on 7th September. The event began with a south-directed IMF, and its maximum negative value reached -30.41 nT at 0022 UT. In addition, solar wind speed was seen to undergo major variations in the morning as it went over 700 km/s for several hours. The maximum negative value of Bz took place at the same when AE-index hit its peak of 2337 nT at 0017 UT and simultaneously, SYM-H exhibited a sharp drop to the lowest point of the day which is -146 nT. Within the period, SYM-H had a sudden declination as the reading fell to -115 nT while AE-index was actively evolved. For this level of storm, the GIC was much more significant at both latitudes as dH/dt graphs display quite many peaks representing the GIC activity. High latitude was seemingly more influenced by the storm with recorded highest dH/dt of 368.27 nT/s, which appears to be the second highest value among all storm events. Meanwhile, Nurmijarvi station at middle latitude obtained 202.59 nT/s as its peak that showed up a couple of hours after Barrow read its peak. As the storm commenced and solar wind speed increased, the southward component of IMF, Bz began to drop to negative values while SYM-H started to decline up to -50 nT which indicated the arrival of the storm. The higher the intensity, the higher the negative values of the SYM-H. At the same time with the down phase of SYM-H, the AE-index also showed multiple inclinations towards higher positive values which implied the intense auroral activities experienced by high and middle latitudes. Therefore, these correlations can be understood as the drop in Bz was due to the increment in solar wind speed.

According to all graphs of dH/dt presented in Figure 1 until Figure 4, the GIC activity at high latitude has gone beyond 100 nT/s during all levels of storm. The most intense GIC activity was during Kp 5 storm with the maximum dH/dt hit 405.95 nT/s, followed by the second highest during Kp 8 storm with maximum dH/dt of 368.27 km/s. The magnitudes of dH/dt at middle latitude were much lower
compared to high latitude data. Besides, they did not exceed 100 nT/s except for Kp 8 storm that recorded significantly high GIC activity as its peak attained to 202.59 nT/s. For each storm event, the GIC arise phase and duration are not identical as the GIC occurs during the first contact with the southward IMF and the ionospheric disturbance.

4. Conclusion
In all cases, we found a linear relationship between GIC activity and storm intensity. As the storm intensified, the GIC appeared to be greatly provoked. When the geomagnetic parameters deteriorate to higher negative values, the electric currents circulating in the ionosphere intensify as the AE-index climbs and the SYM-H values increase, implying that the storm has intensified. As storm intensity has increased, dH/dt values have risen, indicating a rise in GIC activity and increased storm intensity. It was caused by ionospheric disturbances that altered the magnitudes of magnetic field and, therefore, induced an electric field on the ground and beneath it.

5. References
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