Assessment of Geomagnetically Induced Currents (GICs) in Johor Malaysia During the Severe Geomagnetic Storm of 11th May 2024

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Assessment of Geomagnetically Induced Currents (GICs) in Johor, Malaysia During the Severe Geomagnetic Storm of 10^{th} to 11^{th} May 2024

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Abstract: *This study examines the susceptibility of Malaysia's power grid to geomagnetically induced currents (GICs) during the severe geomagnetic storm of 10^{th} -11^{th} May 2024, the most intense geomagnetic storm since 2003. GICs pose significant threats to power grid integrity, especially during severe geomagnetic storms, yet low-latitude regions like Malaysia have received limited attention. Utilizing data from geomagnetic observatories in Johor, we analyzed key solar wind parameters and geomagnetic indices. Our methodology involved calculating the rate of change of the horizontal magnetic field (dH/dt) and conducting a power spectral density (PSD) analysis. The results indicated significant dH/dt variations exceeding the 30 nT/min threshold, suggesting high GICs potential. PSD analysis identified dominant frequencies between 0.01 to 0.1 Hz, with increased power during local daytime hours. These findings underscore the critical need for continuous monitoring and real-time analysis to mitigate GICs impacts, providing valuable insights into space weather effects on low-latitude regions.*

Keywords: Geomagnetically Induced Currents (GICs); Geomagnetic Storm; Space Weather; Low-latitude region; dH/dt

1. INTRODUCTION

Geomagnetically induced currents (GICs) are a major threat to the integrity of the power grid and its ground infrastructure mainly during geomagnetic storms. These currents are due to fluctuations of the earth's magnetic field affecting the electrical equipment such as transformers and substations. Past works have primarily investigated these phenomenon at high latitude regions since these regions are likely more affected by the geomagnetic storms because of their closeness to the magnetic poles [1]. Nevertheless, there is a growing recognition of the potential impacts of GICs in low-latitude regions, including Malaysia.

The geomagnetic storm that commenced from 10th to 11th May 2024 will also be marked in history as the strongest geomagnetic storm since the Halloween Solar Storms of 2003. This particular event was marked with an X5.8 solar flare that contributed to the heightened geomagnetic activity and indicated the importance of further research work on the effects of the GIC in various regions.

Numerous research investigations have emphasized on the vulnerability of power grids in high-latitude locations to GICs. A study conducted by [2] examined the impacts of geomagnetic storms specifically in Europe. Another study, performed by [3] simulated the consequences of an extremely severe space weather event on the global power grid. A study performed by [4] examined the effects of GICs on the power network in New Zealand, offering important insight on the challenges encountered in regions located at mid-latitudes.

The impact of GICs on power systems can be both profound and multifaceted. GICs have the potential to cause overheating and harm to transformers, resulting in a decrease in lifespan or even instantaneous failure [5]. In addition, they have the ability to cause voltage fluctuations and consume reactive power, which can lead to power outages and substantial financial losses. GICs have the potential to cause extensive power outages, as demonstrated by the widespread blackouts that occurred in Quebec, Canada during the severe geomagnetic storm in March 1989 [6]. Given the critical role of a reliable power supply in modern societies, it is one of the utmost importance to comprehend and mitigate the effects of GICs.

However, there is still a lack of research in understanding the effects of GICs in low-latitude locations such as Malaysia. A preliminary study on GICs in Malaysia was conducted by [7] which highlighted the need for more detailed investigations. Therefore, this study aimed to close this disparity by evaluating the geomagnetic events and their capacity to generate GICs in Malaysia during the intense geomagnetic storm occurring from 10th May to 11th May 2024.

The main objective of this paper is to evaluate the geomagnetic activities and their impact on the power grid in Malaysia during the severe geomagnetic storm of 10^{th} – 11^{th} May 2024. The study provides (1) a detailed summary of geomagnetic activity parameters such as solar wind speed, dynamic pressure, and the interplanetary magnetic field Bz component, (2) an analysis of the time derivative of the horizontal component of the geomagnetic field (dH/dt) at the MAGDAS geomagnetic observatory in Johor, Malaysia, highlighting significant variations and their potential to induce GICs, and (3) a power spectral density analysis to understand the frequency characteristics of geomagnetic variations.

2. METHODOLOGY

Data for this study were obtained from geomagnetic observatories in Johor, Malaysia maintained by the MAGDAS network. The analysis was conducted in three parts:

2.1 Geomagnetic Activity Summary

The geomagnetic activity summary involved the collection and analysis of key solar wind parameters and geomagnetic indices over the period surrounding the storm. The OMNI dataset provided measurements of solar wind speed, solar wind dynamic pressure, and the IMF Bz component. These parameters provide valuable information about the solar wind conditions that cause geomagnetic storms. In addition, the SYM-H index and the resulting dSYM-H index were employed to summarize and characterize the overall geomagnetic activity. These indices accurately represent the strength and changing pattern of the geomagnetic storm throughout time. The parameters were obtained via the OMNIWEB service, accessible at http://omniweb.gsfc.nasa.gov.

2.2 Analysis of dH/dt

dH/dt component was computed at MAGDAS Johor observatory during a four-day periods that was centered on the geomagnetic storm. The objective of this analysis was to identify substantial variations that could potentially induce GICs. The dH/dt values were calculated using geomagnetic field data with a resolution of one minute. The investigation primarily aimed to discover the maximum dH/dt and how these values were distributed over time at the geomagnetic observatory.

According to [8], a dH/dt value exceeding 30 nT/min indicates a high potential for inducing GICs in power systems. This threshold level provides a benchmark for assessing the risk of GICs during geomagnetic storms. In this study, the computed dH/dt values were compared against this threshold level to evaluate the potential GIC risk at the geomagnetic observatory.

The MAGDAS (Magnetic Data Acquisition System) network, operated by the International Research Center for Space and Planetary Environmental Science (i-SPES) at Kyushu University, Japan, provides high-resolution geomagnetic field data from a global array of observatories. This network is instrumental in monitoring space weather and understanding its impacts on Earth's magnetosphere. The data from the MAGDAS network are critical for assessing geomagnetic disturbances and their potential impacts on technological systems.

The MAGDAS magnetometer employs a fluxgate magnetometer to measure the three components of the geomagnetic field, which are the Horizontal component (H), the Declination component (D), and the Vertical component (Z), as shown in Fig. 1. The H component represents the horizontal intensity of the geomagnetic field, D represents the declination or the angle between the magnetic north and true north, and Z represents the vertical component of the geomagnetic field. These components are essential for understanding the full vector nature of geomagnetic variations. In this study, the focus was primarily on the horizontal component (H), dH/dt is directly related to the induction of GICs in power systems.

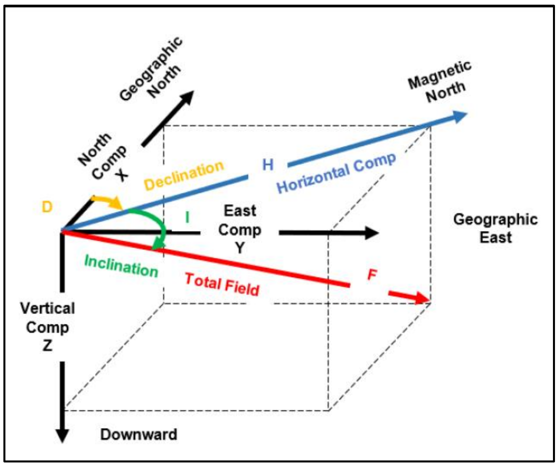

Fig. 1 Three-Dimensional Vector of Magnetic Field Components.

The rate of change of H with respect to t, denoted as dH/dt, was determined by subtracting the value at each time point from the subsequent value and dividing by the sampling interval, as outlined in equation (1). In this equation, H represents the recorded geomagnetic field data, and h represents the length of the sampling interval [9]. According to the prior study conducted by Falayi and Beloff, a dB/dt value beyond 30 nT/min serves as an indication of the presence of GICs [8]. This study is aimed to thoroughly examine the possibility for GIC in Malaysia during the severe geomagnetic storm that occurred from 10th May to 11th May 2024. This was achieved by analyzing the temporal distribution of maximum dH/dt value and comparing them with a predetermined threshold level. The results of this investigation are essential for understanding the susceptibility of the Malaysian power grid to geomagnetic disturbances and for developing suitable measures to reduce their impact.

$$\frac{dH}{dt} = \frac{H(t+h) - H(t)}{h} \quad (1)$$

2.3 Power Spectral Density Analysis

Analyzed were the frequency characteristics of geomagnetic changes by computing the power spectral density (PSD) of dH/dt. The Power Spectral Density (PSD) analysis is a useful tool for determining the main frequencies present during a geomagnetic storm. These frequencies are important for evaluating the effects GICs. The PSD computation was performed using the Welch method, which offers a reliable characterization of the frequency components. A study was conducted for MAGDAS Johor observatory, enabling an assessment of the frequency characteristics across this location.

3. RESULTS & DISCUSSIONS

3.1 Geomagnetic Activity Summary

The geomagnetic activity summary for the period from 10th May 2024 to 13th May 2024, depicted in Fig. presents a comprehensive analysis of the variables that characterize the geomagnetic storm. This geomagnetic storm is the most severe event since the Halloween Solar Storms of 2003, which was triggered by an X5.8 solar flare.

The solar wind speed (Vsw) had a significant increase beginning on 10th May at 1706 UT, reaching a peak of roughly 1025.9 km/s on 12 May at 0112 UT, and then steadily declining in the following days. The rise in solar wind speed is a crucial element in stimulating enhanced geomagnetic activity, since it accelerates the rate of energy transmission from the solar wind to the Earth's magnetosphere [10], [11]. The solar wind dynamic pressure (Pdyn) exhibited significant variations, starting on 10 May at 1716 UT, with maximum values reaching over 70 nPa between 10th May at 1716 UT and 11th May at 0936 UT. These high dynamic pressure values indicate a stronger impact of the solar wind on the Earth's magnetosphere, causing the high magnetospheric compression which can significantly enhance geomagnetic disturbances. The Interplanetary Magnetic Field Bz component (IMF Bz) displayed significant southward excursions starting from 10 May at 1600 UT, with minimum values reaching approximately -47.85 nT around 11 May at 0600 UT. Prolonged periods of southward IMF Bz facilitate magnetic reconnection at the dayside magnetopause, which is a key mechanism for transferring solar wind energy into the Earth's magnetosphere, thus intensifying geomagnetic activity.

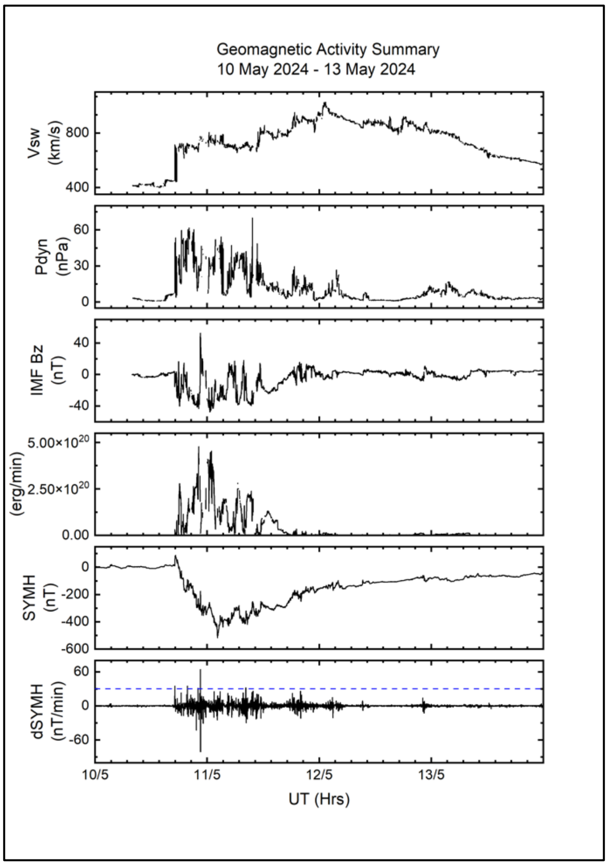

Fig. 2 Geomagnetic Activity Summary for severe Geomagnetic storm occurred during 10th May 2024 till 13th May 2024

Solar wind input energy surged suddenly starting around 10th May, coincided with the sudden increase of Solar wind speed with the maximum value of solar wind input energy amounted 5×10^{24} erg/min on 11th May 2024. This measure of energy influx quantifies the total energy delivered by the solar wind to the Earth's magnetosphere, and these high values correspond to the periods of heightened geomagnetic activity observed during the storm as observed in SYM-H index. The SYM-H index, a measure of the strength of the ring current and overall geomagnetic activity, experienced a sharp decline starting from 10 May at 1913 UT, reaching a minimum value of approximately -518 nT on 11th May at 0214 UT. This substantial drop in SYM-H indicates the occurrence of a severe geomagnetic disturbance, consistent with the characteristics of a major geomagnetic storm. Based on the computed Solar wind input energy, the range of heightened value of energy is around 10th May 2024 till end of 12th May 2024 coincided with complete phase of geomagnetic storm shown by the SYM-H index. As can be observed from the figure, the highest value of Solar wind input energy is associated with the minimum value of SYM-H index suggesting the most disturbed period. The dSYM-H index, representing the rate of change of the SYM-H index, showed rapid variations, particularly between 10 May at 1706 UT and 10 May at 2234 UT, with peaks approaching 64 nT/min. These immediate fluctuations indicate occasions of high geomagnetic activity, which are crucial for the generation of GICs.

In summary, a thorough analysis of these space weather parameters indicates notable variations and highlights periods of increased geomagnetic activity during the geomagnetic storm. These results highlight the possibility of GICs, especially during the sudden fluctuations in geomagnetic conditions observed on 10 and 11 May 2024. This overview offers crucial insights into the characteristics and effects of the geomagnetic storm on geomagnetic activities.

3.2 Analysis of dH/dt

The analysis of dH/dt was performed for the geomagnetic observatories in Johor. The results as shown in Fig. 3 indicate significant variations in dH/dt around the geomagnetic storm period, with peak values providing insights into the potential for GICs.

In Johor station, the dH/dt values showed notable fluctuations starting from 10th May at 1800 UT, with a peak value of approximately 63.4 nT/min occurring around 11th May at 0427 UT. These values exceeded the threshold of 30 nT/min identified by [8] as indicative of

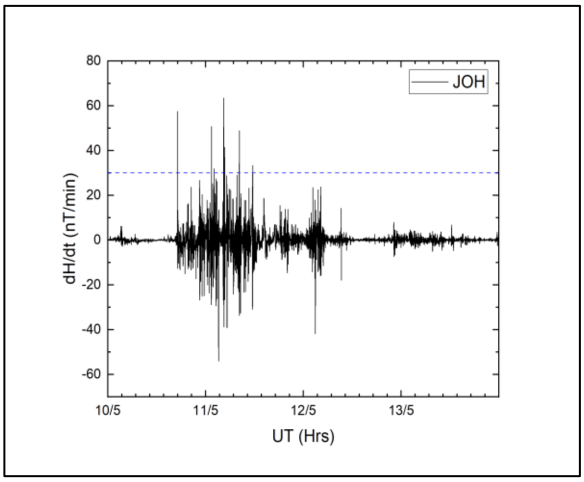

Fig. 3 The Maximum dH/dt in geomagnetic observatories in Johor, Malaysia

Johor observatory correspond well with the periods of high solar wind speed, dynamic pressure and solar wind input energy, as well as the significant southward excursions of the IMF Bz component. The correlation between these parameters suggests that the enhanced solar wind conditions directly influenced the geomagnetic activity observed in Johor station.

Analysis conducted at Johor MAGDAS geomagnetic observatories indicates that the geomagnetic storm resulted in significant and extensive fluctuations in dH/dt. These fluctuations surpassed the 30 nT/min threshold in several events. The results indicate a significant possibility of GICs occurring in the Malaysian power grid during this geomagnetic storm. This highlights the need for ongoing monitoring and the adoption of measures to reduce the impact on ground technological infrastructure.

To get to know the distribution of the event when dH/dt exceeded 30 nT/min, the SYM-H index graph can be used to observe the distribution. From the SYM-H index, the phases of geomagnetic storm can be determined. Geomagnetic storm can be divided into 3 phases which are initial phase, main phase and recovery phase. Fig. 4 shows the SYM-H index during the geomagnetic storm occurred from 10th May – 13th May 2024. As shown in the figure, the graph is divided into 3 shaded regions where each region indicating the initial, main and recovery phase of geomagnetic storm represented by blue, maroon and green shaded area respectively. In this graph also, there is computation of the event of dH/dt that exceeded 30 nT/min. In total, there are 10 cases of dH/dt events that exceeded 30 nT/min occurred in Johor station. Based on the figure it can be observed that there are only 1 event that fall into initial phase, 7 events occurred during main phase and 2 events take place during recovery phase of geomagnetic storm.

The indication of initial phase of the geomagnetic storm can be observed when there is sudden increase of SYM-H index followed by the continuous decrement of the SYM-H index up to certain level. The level of decrement is the one that indicates the severity of the geomagnetic storms. The event that occurred during the initial phase of geomagnetic storms is aligned with the study done by [12] where most of the GICs event in low-latitude region occurred during the initial phase of the geomagnetic storms. As for the most of dH/dt events it took place during the main phase of the geomagnetic storm. It can be observed that the events are associated with the increase of SYM-H index during the main phase of geomagnetic storms. Similar condition goes to the dH/dt events that took place during the recovery phase of the geomagnetic storms. The sudden increase of SYM-H index is indicated the magnetospheric compression that is also can be observed from the level of Solar Wind Dynamic Pressure. The summary of dH/dt events that exceeded 30 nT/min is tabulated in Table 1. Based on the table, it can be observed that the highest dH/dt occurred during 11th May 2024 at 0427 LT with dH/dt amounted to 63.4 nT. At the local time, the highest dH/dt event was occurred at 1227 LT where it is associated with the influence of Electrical Electrojet Current (EEJ). As mentioned by study done by [13], where there is increasing trend of dH/dt level from morning to noon where the peak value is observed at noon. After that, there is decreasing trend of the dH/dt level from noon to evening/night. This event occurred during the main phase of the geomagnetic storm. It is followed by the dH/dt event that took place on 10th May 2024 at 1506 UT with dH/dt amounted to 57.44 nT. This event occurred during the initial phase of geomagnetic storms.

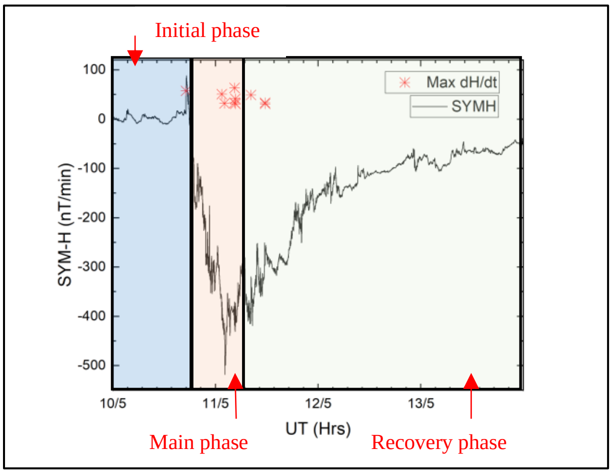

Fig. 2 The Maximum dH/dt across SYM-H index during geomagnetic storm on 11th May to 13th May 2024

Table 1. Summary of dH/dt at MAGDAS JOH station during Severe Geomagnetic Storm 10th May 2024 – 13th May 2024

No	Dates	UT (Hrs)	LT (Hrs)	Max. dH/dt (nT/min)
1	10 May 2024	1706	0106	57.44
2	11 May 2024	0129	0929	50.68
3	11 May 2024	0206	1006	31.85
4	11 May 2024	0427	1227	63.40
5	11 May 2024	0428	1228	33.23
6	11 May 2024	0440	1240	41.39
7	11 May 2024	0441	1241	31.17
8	11 May 2024	0818	1618	48.83
9	11 May 2024	1135	1935	33.26
10	11 May 2024	1136	19.36	31.16

By examining the temporal distribution of dH/dt peaks and comparing them with established thresholds, this study provides a comprehensive assessment of the potential for GICs in Malaysia during the severe geomagnetic storm on 10 May – 11 May 2024. The results underline the necessity for improved monitoring and immediate analysis of data to reduce the effects of geomagnetic disturbances on the electrical grid.

3.3 Power Spectral Density Analysis

An analysis of the power spectral density (PSD) was conducted to examine the frequency characteristics of geomagnetic changes, specifically focusing on dH/dt. Fig. 5 displays the spectrogram of PSD for the MAGDAS Johor station. The spectrogram of the dH/dt for the Johor station, spanning from 10th May 2024 to 13th May 2024, offers important details about the frequency properties of geomagnetic fluctuations during

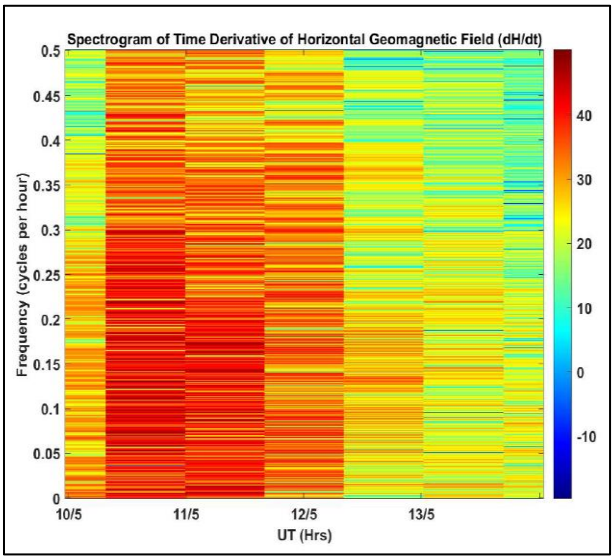

Fig. 3 Spectrogram of Time Derivative of Horizontal Geomagnetic Field (dH/dt) at LKW Geomagnetic Observatory

the intense geomagnetic storm. The spectrogram indicates that the dominant frequencies fall between 0.01 and 0.1 cycles per hour, with the highest power concentrations recorded at 0.05 cycles per hour. The alignment of this frequency range with the natural resonant frequencies of power transmission lines makes it extremely effective for generating GICs.

Temporal study reveals that the most intense power levels occurred during the most intense phase of the geomagnetic storm on 11th May, with substantial dH/dt levels persisting until 12th May 2024. The aforementioned period aligns with increased solar wind speed, solar wind input energy, solar wind dynamic pressure, and a southward IMF Bz component, as outlined in the summary of geomagnetic activity. In addition, the spectrogram displays diurnal variations in power level, with greater level recorded during the hours of daylight in the local region. The occurrence of this phenomenon can be explained by the heightened ionospheric conductivity caused by solar radiation, which strengthens the interaction between the solar wind and the Earth's magnetosphere.

A precise estimation of the dominant frequencies and their temporal properties is essential for evaluating the probability of GICs. A previous study conducted by [14] demonstrated that low-frequency geomagnetic fluctuations are particularly efficient for generating GICs in power systems. The power levels measured at the MAGDAS Johor station indicate an elevated probability of GICs during the analyzed period, especially on 11th May when the geomagnetic storm was at the highest intensity.

In addition, the spectrogram's diurnal variations correspond with the findings of [15], which indicate that the conductivity of the ionosphere during the day has an important effect on the intensity of geomagnetic variations and the subsequent occurrence of GICs. The elevated power level observed at the MAGDAS Johor station during daylight hours underline the importance for ongoing monitoring and immediate analysis to reduce the GICs, as the power system is particularly susceptible during this period.

In general, the PSD analysis improves the results obtained from the dH/dt and geomagnetic activity summaries by providing a viewpoint based on frequency-domain study of the geomagnetic disturbances. The significant power levels detected in the frequency range of 0.01 to 0.1 Hz throughout the storm period highlight the possibility of GICs, especially when there are sudden fluctuations in the geomagnetic field, as indicated by elevated levels of dH/dt.

The findings of this study provide a complete analysis of the effects of the severe geomagnetic storm that occurred on 10th May – 11th May 2024, on Malaysia's geomagnetic environment. The study also highlights the potential of this geomagnetic storm to generate GICs. The summary of geomagnetic activity highlights significant fluctuations in significant variables such as solar wind speed, solar wind dynamic pressure, and the IMF Bz component. These variables, combining together, caused the geomagnetic storm. The SYM-H and dSYM-H indices provided additional evidence of the storm's intensity, demonstrating significant variations that indicate an immense geomagnetic disturbance.

The analysis of dH/dt revealed important insights into the possibility of GICs occurring in Johor, Malaysia. The measured dH/dt values that beyond the threshold of 30 nT/min, indicating a high probability of GICs. In addition, the maximum dH/dt values, corresponded closely with periods of high geomagnetic activity. This activity was caused by specific conditions in the solar wind, including enhanced solar wind speed, increased dynamic pressure, increased solar wind input energy and southwest deviations of the IMF Bz component.

In addition to these findings, the PSD revealed prominent frequencies between 0.01 and 0.1 Hz, which are crucial for evaluating the potential for GICs. The spectrogram displayed significant intensity at these frequencies, especially during the geomagnetic storm's most intense period on 11 May, corresponding to the observed high dH/dt values. Furthermore, the PSD analysis revealed significant daily variations in geomagnetic activity, with elevated power levels observed during daylight hours. This is likely attributed to increased ionospheric conductivity affected by solar radiation.

4. CONCLUSIONS

This study assesses geomagnetic activity and its capacity to generate GICs in Malaysia during the geomagnetic storm of 10th to 11th May 2024, utilizing data from MAGDAS Johor geomagnetic observatories. Significant and sudden changes in solar wind speed, dynamic pressure, Solar wind input energy and the IMF Bz component led to the severe geomagnetic storm, confirmed by patterns displayed by SYM-H and dSYM-H indices. Numerous dH/dt occurrences surpassed 30 nT/min, mainly during the geomagnetic storm's main phase, indicating high GICs potential. Based on PSD analysis, the identified prominent frequencies which is 0.01 to 0.1 Hz are crucial for GICs evaluation, with significant daily geomagnetic activity variations, especially during daylight hours.

These findings highlight the need for continuous monitoring and immediate analysis to safeguard the electrical grid. Future studies should examine space weather variables' effects on geomagnetic activity and GICs, considering not only solar wind conditions and geomagnetic field fluctuations but also need to take into consideration the ground parameters such as ground conductivity and geoelectric fields. Additionally, future studies should map regional conductivity and explore geoelectric field orientations during geomagnetic storms to enhance Malaysia's power system resilience against space weather phenomena.

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