Assessment of the Geomagnetically Induced Current (GIC) at Low Latitude Region based on MAGDAS Data

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Abstract The geomagnetically induced current (GICs) impact is no longer concentrated at high latitude region strictly. The objective of this study was to extend the GICs observation conducted at equatorial region using geomagnetic data extracted from magnetometer installed at Langkawi National Observatory (LNO), Malaysia for the long-term analysis involving the solar cycle 24. The observation is now continued with the GICs comparison between LKW stations with five low latitude station which is BCL, PTN, MND, DAW, and TWV obtained from the magnetic data acquisition system (MAGDAS). The assessment of the GICs behavior revealed the possibility of LKW station experiences GICs is high, based on the time derivative of the horizontal component (dH/dt) value. Extend from that, the GICs estimation was successful done by applying the plane wave method as a model to calculate the North-South and the East-West component, Ex and Ey respectively. The equation of the GICs was provided by excluding the topology constant parameters, which is a and b constant and the value of the underground conductivity for low latitude station. Subsequently, the comparison was limited in years of 2008 – 2014 due to insufficient geomagnetic data. Indeed, the GICs calculation is able to derive the GICs estimation and showed a good agreement with the corresponding value of the time derivative of the horizontal component. However, the accurate current value (A) is able to gain by conducting a direct measurement of the high voltage power transmission system.

1. Introduction
The space weather perturbation is believed to affect the ground-based technology system in term of theoretical and experimental approached. The space weather perturbation mentioned above is the geomagnetically induced current (GIC). These GIC flow into the transformer architecture of the bulk power system through the winding where the current in the winding might be increased. More current
formed in the winding, more magnetic flux might be generated and the core might be received a partial saturation on the part of the transformer. The partial saturation is believed to damage the working principle of the transformer [1]. The AC waveform might be misinterpreted, the protective relays might be desperation and drives to trip out the power transmission line. More so, affected by that, the stability problem, the voltage drop, also the power blackout moment is possible to occur. Rapidly mentioned the famous event in 1989 which is the Hydro - Quebec power transmission blackout and the society suffered for nine hours without electricity [2]. The stimulation of the bulk power system enhances the consideration of awareness to identify to what extent the GIC can be impactful to the power transmission system [3]. The rate of the change of the total magnetic field (dB/dt) normally used to identify the GIC level at high latitude region [4]. The magnitude of dB/dt (nT/min) exceeding 30 nT was indicated the occurrence of the GIC. The high latitude regions are the one that achieves a high possibility that affected by the GIC event due to the auroral electrojet current as a driving mechanism. Previously, the dB/dt value during Hydro – Quebec power transmission is approximately 479 nT/min. Some of GIC cases, there was produced not only occurring due to the substorm, but the sudden impulse (SI) and the storm sudden commencement (SSC) also encourage the GIC to occur [5 and 6]. The authors [7] bring some information about the dB/dt value are not depending on the substorm as a single caused, but the SI event and the SSC had prepared the evidence that the value of dB/dt can still be high enough to penetrate in the power transmission system. This has been discussed by a great number of authors in literature, they proposed a model on how the ionospheric current penetrates in the lithosphere by applying the concept of Lorentz force. It has been reported that substations situated at the ends and at the corners of long transmission lines are prone to maximum GIC magnitudes [8, 9, and 10]. These are the substations which are only connected to one substation on one end and a transmission line on the other end. However, a number of the study was done in a region close to the auroral zone and may not necessarily agree with regions far from the auroral zone. An investigation was done on the Namibian network and reported that south northerly lines appeared to be more susceptible to GICs than the east-westerly lines [11]. This finding was also reported by [8] for the Japanese network. The method had been used previously is by determining the time derivative of the horizontal component as conducted by [12, 13, 2 and 14] to determine the GIC phenomena. Meanwhile, other studies are done by calculation approached [15, 16, and 17]. In addition, the on-site measurement that needs an equipment that must be conducted under the transmission line that operated with high voltage also had been used by [18, and 19]. However, the space weather perturbation that drives GIC during the descending, peak, and ascending phases of the solar cycle is still questionable due to the different mode of solar activity. Therefore, this study aims to observe and estimate the value of GIC by implementing the plane wave method as well as to investigate the dominant parameter of the space weather physic that contributes more to the higher time derivative of the horizontal component (dH/dt) at each low latitude station.

2. Technique and Procedure

2.1. Plane Wave Method

The plane wave method was successfully employed in this analysis. The details of the plane wave method fully described in the previous studies and the [20] are prepared as references. The primary source of GIC is geoelectric field caused by the ambient magnetic field changes on the Earth’s surface. The input of geoelectric calculation consists of knowledge about the Earth’s conductivity and about the magnetospheric-ionospheric currents or about the geomagnetic variations at the Earth’s surface. The existing model such as simple plane wave model can be applied to calculate the geoelectric field of north-south, $E_x$, and east-west, $E_y$ component:
\[ E_{x,y}(t) = \frac{1}{\sqrt{\pi \mu_0 \sigma}} \int_{-\alpha}^{t} \frac{g_{y,x}(t')}{\sqrt{t - t'}} dt' \]  

(1)

From the plane wave model, the geoelectric field value can be performed from the inverse Fourier transformation to the time domain and derivative of the magnetic component where \( g_{x,y}(t') = dB_{y,x}/dt' \). \( \mu_0 \) is the vacuum permeability and \( \sigma \) is the Earth's conductivity. Derivatives of the ambient magnetic field in the north-south, \( B_x \), and east-west, \( B_y \), is a good indicator for GIC activity and it can be considered as a major component of the geoelectric field.

On the other hand, the characterization of GIC will also be implemented using the rate of change of geomagnetic field data (\( dH/dt \)) from the available equatorial stations. The \( dH/dt \) measurement simultaneously with GIC records can provide the threshold level of derivative value that causing undesirable consequence in power grids. Thus, the significance of GIC can be characterized by measuring the variation of horizontal time derivatives of the geomagnetic field, at the identified threshold value.

Table 1: MAGDAS station used for this analysis.

| MAGDAS Station       | Longitude and latitude |
|----------------------|------------------------|
|                      | GG Lat. | GG Lon. | GM Lat. | GM Lon. |
| BCL, Bac Lieu Vietnam| 9.32    | 105.71  | -0.36   | 178.36  |
| LKW, Langkawi Malaysia| 6.30   | 99.78   | -3.30   | 172.44  |
| PTN, Pontianak Indonesia| -0.07 | 109.31  | -9.75   | 181.96  |
| MND, Manado, Indonesia| 1.44   | 124.84  | -7.80   | 197.63  |
| DAW, Darwin, Australia| 12.41  | 130.92  | -21.91  | 202.81  |
| TWV, Townsville, Australia| -19.63| 146.86  | -28.73  | 220.30  |

The plane wave method required the \( a \) and \( b \) constant where it’s referring to the resistance and voltage threshold value based on the topology of power transmission system of each station that definitely different. The underground conductivity also used in order to obtain the East-West and South-North electric field. In order to get the underground conductivity that should be set to be uniform value, the spherical harmonic analysis method has been implemented. The process flow and the description of the method were clearly explained in [21]. The equation of the underground conductivity is provided below.

\[ \sigma_n = \frac{5.4 \times 10^4}{m(\pi p)^2} \]  

(2)

3. Result and Discussion

Becoming a relevant question, what is the driven mechanism to enhance the \( dH/dt \) value at low latitude region in southern hemisphere whereas the northern hemisphere normally experiences a direct physical effect from the Sun activities. Basically, the Sun-Earth coupling system was produced an electric current around the Earth. The electric current generated the magnetic variation that can be measured from magnetometer installed at the Earth surface which is the ground level. Usually, the electric current can be measured experimentally but due to the lack of appropriate equipment, the variation of the magnetic field normally being used to estimate the electric current in the magnetosphere and ionosphere layer as well. The electric current formed at upper part might flow into the Earth atmosphere and induced into the underground level. A superfluity current that induced is harmful to the ground-based technologies system. This phenomenon so-called geomagnetically
induced current. Based on [22], the GICs level is possible to high during the geomagnetic storm and the GICs level was enhanced by several factors of the magnetospheric source. The source of magnetospheric current including the magnetopause current; closely related with the sudden impulse (SI) event by observing the increase of solar wind dynamic pressure (SW Pdyn), the instability plasma in the magnetospheric current contribute to the magnetic pulsation also increased the GICs level. Second, the variation of ionospheric Sq current system by applying the dynamo process in such a way caused the high level of GICs for the moment.

Before the analysis of the GICs behavior, a brief overview of the significant event is presented in Table 2. The nine GICs event was initiated or driven by the solar activities and it was classified under storm commencement which is sudden impulse (SI) when there is no further disturbance or sudden storm commencement (SSC) due to the subsequence of the magnetic storm. From the listed nine significant GICs event experiences at LKW station, the comparing step between LKW and other low latitude station to investigate the higher dH/dt managed to cover only a period of time which is from 2008 – 2014 due to insufficient geomagnetic data can be obtained at low latitude station. The analysis carried out in this studies have been placed in accordingly in a few sub-section to ensure the flow of work is manageable as well as the contribution was clearly defined. The sub-section is pointed below.

3.1 Characteristics of Sudden Commencements (SC)

A brief discussion on the characteristic of the sudden commencement that highlighted before continued at this session. The disturbance originated from the Sun was created the geomagnetic storm that carries a huge plasma moving downward to the Earth. The energetic plasma carried by the geomagnetic storm with the high-speed solar wind leads a coronal mass ejection (CME) or coronal holes (CH). The CH event was formed by the process namely co-rotating interaction regions (CIR). The driven mechanism of the geomagnetic storm is CME event during the active year, while the CH able to drive geomagnetic storm during inactive years. The impactful CME or CH event leads to high solar wind dynamic pressure. The high pressure of the solar wind pushing the magnetosphere and increased the magnetopause current. This moment can be observed by the signature of the horizontal geomagnetic variation that increased sharply so-called SSC or SI event depending on the further signature after the main phase of the SI or SSC. Normally, the SIs or SSCs is closely related to the high time derivative of the magnetic component dB/dt (nT/min) due to the energetic compression to the magnetosphere layer. Author [2] point out the condition classified as SI if there is no further disturbance while the classification of SSC is depending on the consequence of the magnetic disturbances. Based on Table 2, a single SI event was observed on 23rd November 2014 while the rest was classified as SSC event. The observation of H-component is due to the variation of the magnetic field. The magnetic field can be measured by using the ground-based magnetometer installed at the Earth surface to estimate the physical performance of the Sun-Earth system. Normally, the SI and SSC event always associated with the enhancement of the magnetopause current.
Table 2: The nine (9) significant date with the maximum dH/dt recorded in Universal Time (UT) and Local Time (LT). The classification of the geomagnetic disturbance also added. The dash (-) represent two meaning, the data is not available or there is no GICs event on the date at that stations.

| Date      | UT (Hr) | LT (Hr) | dH/dt (nT/min) | SC Class |
|-----------|---------|---------|----------------|----------|
| 27-Mar 08 | 06:18   | 14:18   | -33.66         |          |
| 24-Jan 12 | 15:07   | 23:07   | 34.83          |          |
| 15-Jul 12 | 01:52   | 09:52   | 30.3           |          |
| 17-Mar 13 | 06:00   | 14:00   | 41.2           |          |
| 2-Oct 13  | 01:58   | 09:58   | 88.28          |          |
| 8-Feb 14  | 07:15   | 15:15   | 30.8           |          |
| 16-Feb 14 | 04:50   | 12:50   | 35.11          |          |
| 12-Sep 14 | 15:54   | 23:54   | 31.46          |          |
| 23-Dec 14 | 11:25   | 19:25   | 40.44          |          |

Other than the enhancement of the magnetopause current, the geomagnetic activity associated with the severe disturbance leads to the significant effect such as Aurora at high latitude region normally. Nevertheless, low latitude region also experiences a significant effect from the geomagnetic disturbance for the sometimes. Based on the period conducted in this studies, the SSC event is frequently occurred compared to SI event. Previously, the researchers revealed the primary cause of the SSC event is the magnetospheric shock that initiated by the extreme solar activities. The intense disturbance from the Sun able to affect the until low latitude region, not to mention high latitude region. According to [x], the output on the studies revealed the low latitude region is more affected due to the SSC event and that the reason only a single SI event can be observed in Table 2. The source of the SSC event comes from several factors such as coronal mass ejection (CME), coronal holes (CH), high-speed solar wind, (HSSW). Due to this factors, the magnetospheric shock could be occurred expressly and leave a significant effect on low latitude region. We analyze the SSC and SI event to observe the effect which is the GICs purposely. The intense geomagnetic storm or disturbance from the Sun indirectly leads to a serious harm to the underground based technology system.
Figure 1: The time derivative of the horizontal component, $\frac{dH}{dt}$, of LKW, MND, DAW, and TWV station. It shows the only LKW station experience the GIC on 27 March 2008 magnetic disturbance.

Figure 2: The variation of $H$-component at LKW station with the variation of North-South and the East-West component, $Ex$ and $Ey$ for LKW station on 27 March 2008.
Figure 3: The time derivative of the horizontal component, dH/dt of BCL, LKW, and PTN station. It shows the only LKW station experience the GIC on 24 January 2012 magnetic disturbance.

Figure 4: The variation of H-component at LKW station with the variation of North-South and the East-West component, Ex and Ey for LKW station on 24 January 2012.
Figure 5: The time derivative of the horizontal component, dH/dt of BCL, LKW, and PTN station. It shows the only LKW station experience the GIC on 15 July 2012 magnetic disturbance.

Figure 6: The variation of H-component at LKW station with the variation of North-South and the East-West component, Ex and Ey for LKW station on 15 July 2012.
Figure 7: The time derivative of the horizontal component, dH/dt of BCL, LKW, and PTN station. It shows the BCL, LKW, and PTN station was experiences high dH/dt leading by BCL station with 46.52 nT/min on 17 March 2013.

Figure 8: The variation of H-component at BCL station with the variation of North-South and the East-West component, Ex and Ey for LKW station on 17 March 2013.

Figure 9: The variation of H-component at LKW station with the variation of North-South and the East-West component, Ex and Ey for LKW station on 17 March 2013.

Figure 10: The variation of H-component at PTN station with the variation of North-South and the East-West component, Ex and Ey for LKW station on 17 March 2013.
Figure 11: The time derivative of the horizontal component, dH/dt of BCL, LKW, and PTN station. It shows the BCL, LKW, and PTN station was experiences high dH/dt leading by BCL station with 92.98 nT/min on 2 October 2013.

Figure 12: The variation of H-component at BCL station with the variation of North-South and the East-West component, Ex and Ey for LKW station on 2 October 2013.

Figure 13: The variation of H-component at LKW station with the variation of North-South and the East-West component, Ex and Ey for LKW station on 2 October 2013.

Figure 14: The variation of H-component at PTN station with the variation of North-South and the East-West component, Ex and Ey for LKW station on 2 October 2013.
Figure 15: The time derivative of the horizontal component, dH/dt of BCL and LKW station. It shows the BCL and LKW, the station was experiencing high dH/dt leading by BCL station with 32.79 nT/min on 8 February 2014.

Figure 16: The variation of H-component at BCL station with the variation of North-South and the East-West component, Ex and Ey for LKW station on 8 February 2014.

Figure 17: The variation of H-component at LKW station with the variation of North-South and the East-West component, Ex and Ey for LKW station on 8 February 2014.
Figure 18: The time derivative of the horizontal component, $dH/dt$ of BCL and LKW station. It shows the BCL and LKW, the station was experiencing high $dH/dt$ leading by LKW station with 35.11 nT/min on 16 February 2014.

Figure 19: The variation of $H$-component at BCL station with the variation of North-South and the East-West component, $Ex$ and $Ey$ for LKW station on 16 February 2014.

Figure 20: The variation of $H$-component at LKW station with the variation of North-South and the East-West component, $Ex$ and $Ey$ for LKW station on 16 February 2014.
Figure 21: The time derivative of the horizontal component, $dH/dt$ of BCL and LKW station. It shows the BCL and LKW station was experiences high $dH/dt$ leading by BCL station with 36.24 nT/min on 12 September 2014.

Figure 22: The variation of $H$-component at BCL station with the variation of North-South and the East-West component, $Ex$ and $Ey$ for BCL station on 12 September 2014.

Figure 23: The variation of $H$-component at LKW station with the variation of North-South and the East-West component, $Ex$ and $Ey$ for LKW station on 12 September 2014.
Figure 24: The time derivative of the horizontal component, dH/dt of BCL and LKW station. It shows the BCL and LKW station was experiencing high \( \frac{dH}{dt} \) leading by LKW station with 40.44 nT/min on 23 December 2014.

Figure 25: The variation of H-component at BCL station with the variation of North-South and the East-West component, Ex and Ey for BCL station on 23 December 2014.

Figure 26: The variation of H-component at LKW station with the variation of North-South and the East-West component, Ex and Ey for LKW station on 23 December 2014.
3.2 The North-South and the East-West electric field component, Ex and Ey to the GICs cases.

The dH/dt illustration presents the comparison between LKW stations and other low latitude stations where a comparison was made based on the availability of data. The value of dH/dt exceeding 30 nT/min is taken apart further more detailed by plotting the variation of the North-South and East–West electric field, Ex, and Ey to estimate the GIC value of each station.

By working the plane wave method, a few parameters need to be prepared and substituted in the formula. There is a constraint to get the constant $a$ and $b$ but the author comes out with a mathematical equation with the constant was being excluded in the equation to give some idea on how the GICs equations look likes for each of low latitude station. The constant $a$ and $b$ is the parameter on the power grid topology and the value is depending on the power transmission system. The $a$ and $b$ parameters realized to be dissimilar to one and another power grid transmission. Plus, the power grid system also different depending on the location of the station itself. This equation also required the value of underground conductivity, where it needs a method to calculate the underground conductivity. So far, the spherical harmonic analysis (SHA) has been used for a long time ago to calculate the underground conductivity. Based on the SHA approached, the maximum value of the underground conductivity is around 0.1975 s/m for the depth of 973 km conducted well in Malaysia region in the year of 2016 and 2017 [22]. In this study, the conductivity value is very likely can be used for LKW station but it not suitable for other stations. However, the plane wave method decided the conductivity value is assumed to be uniform, not directly proportional to the depth. However, the value of the underground conductivity might be change depending on the Sun activities. Based on that reason, the conductivity value was excluded in the GICs calculation due to the analysis made is in different years. A further experiment to continue this study was properly planned to conduct a direct measurement under high voltage power transmission line in nearest time. The value of $a$ and $b$ can be acquired from a long-term measurement located at LKW station to get the accurate value. The GIC calculation is important because the currents are able to trigger and disrupting the transformer on the power grid system. The transmission structure easily can distract from the unusual current flow in the winding of the transformer. Other than that, the undesired current might heating the structure of the transformer, reduced the lifespan of the transformer, and the road to the worst case is the whole transmission system is expected can deliver instability voltage to lead a serious harm which is power blackout in particular time.

By applying SHA concept, we manage to obtain the value of the underground conductivity with the downward increased pattern, which is directly proportional to the depth. The SHA approached presented in this analysis is based on the 2-D electrical conductivity – depth estimation because it uses the vertical and horizontal geomagnetic component as the primary data to extract the value of underground conductivity. While, the underground conductivity required to implement the plane wave method is 1-D conductivity, where it contradicts with the SHA method. However, the 1-D conductivity can be obtained by using only vertical geomagnetic component or the second approach is uses the ratio of the vertical and horizontal component as the primary data to compute the conductivity value. We also found the method to modify the 2-D SHA method to obtain a uniform underground conductivity is by applying the C-responds approached according to [24]. Outweighed by the reason, we found [25] was conducted the GICs calculation at mid-low-latitude regions by implementing the plane wave method. The value of the underground conductivity used in their analysis was obtained experimentally using the magneto-telluric equipment where the equipment having a limited capability to deeply penetrated. Hence, the value of underground conductivity used is
around 0.001 s/m with respect to the depth below than 100 km. The below table shows the typical model of the underground conductivity using SHA concept.

Table 3: Typical the underground conductivity – depth estimation Earth model.

| Depth (km) | Conductivity (s/m) |
|-----------|-------------------|
| 100 km    | $\sigma = 0.017$ s/m |
| 350 km    | $\sigma = 0.0455$ s/m |
| 650 km    | $\sigma = 0.1294$ s/m |
| 950 km    | $\sigma = 0.1983$ s/m |

The underground conductivity model in Table 3 shows the downward increased patterns to the depth. It explained that, the increasing of depth (km), the more conductive that area. However, this analysis was decided to perform the GICs equations for each of GICs event without substitute the underground conductivity value where the value lets as the constant parameter. The value of underground conductivity change will cause the Ex and Ey value also changed. Due to that reason, the underground conductivity was excluded from the equation.

The GICs equation provided below is the estimation of current itself. Against, there are three constant parameters were excluded from the GICs equation. The constant $a$, $b$, and underground conductivity, $\sigma$ value were unsubstituted in the equation due to explanation in sub-section ii and sub-section iii. However, the GICs equation represents each event are still continued. Only the stations experience GICs that provide the equation. The Ex and Ey value were taken on the same time with the maximum amplitude of dH/dt. The variation of Ex and Ey seemed smaller if compared with the previous work. We believed that issues raised up due to unsubstituted underground conductivity value plane wave equation. The equation prepared as follows;
Table 4: The equation formed using the plane wave method, with a constant parameter for LKW station, as the majority of GICs event experiences on.

| Date     | GICs equation for LKW station |
|----------|-------------------------------|
| 27-Mar 08| $GIC = a\left(\frac{0.0004}{\sqrt{\sigma}}\right) - b\left(\frac{0.0031}{\sqrt{\sigma}}\right)$ |
| 24-Jan 12| $GIC = a\left(\frac{0.0033}{\sqrt{\sigma}}\right) - b\left(\frac{0.0041}{\sqrt{\sigma}}\right)$ |
| 15-Jul 12| $GIC = a\left(\frac{0.0047}{\sqrt{\sigma}}\right) - b\left(\frac{0.0029}{\sqrt{\sigma}}\right)$ |
| 17-Mar 13| $GIC = a\left(\frac{0.0004}{\sqrt{\sigma}}\right) + b\left(\frac{0.0031}{\sqrt{\sigma}}\right)$ |
| 2-Oct 13 | $GIC = a\left(\frac{0.0047}{\sqrt{\sigma}}\right) + b\left(\frac{0.0071}{\sqrt{\sigma}}\right)$ |
| 8-Feb 14 | $GIC = a\left(\frac{0.0022}{\sqrt{\sigma}}\right) - b\left(\frac{0.0049}{\sqrt{\sigma}}\right)$ |
| 16-Feb 14| $GIC = a\left(\frac{0.0027}{\sqrt{\sigma}}\right) - b\left(\frac{0.0031}{\sqrt{\sigma}}\right)$ |
| 12-Sep 14| $GIC = a\left(\frac{-0.0037}{\sqrt{\sigma}}\right) - b\left(\frac{0.0047}{\sqrt{\sigma}}\right)$ |
| 23-Dec 14| $GIC = a\left(\frac{0.00311}{\sqrt{\sigma}}\right) - b\left(\frac{0.0009}{\sqrt{\sigma}}\right)$ |

Table 5: The equation formed using the plane wave method, with a constant parameter for BCL station, as the station also experiences the GICs event in this period of studies.

| Date     | GICs equation for BCL station |
|----------|-------------------------------|
| 17-Mar 13| $GIC = a\left(\frac{0.0034}{\sqrt{\sigma}}\right) + b\left(\frac{0.0019}{\sqrt{\sigma}}\right)$ |
| 2-Oct 13 | $GIC = a\left(\frac{0.0010}{\sqrt{\sigma}}\right) - b\left(\frac{0.0062}{\sigma}\right)$ |
| 8-Feb 14 | $GIC = a\left(\frac{0.0039}{\sqrt{\sigma}}\right) + b\left(\frac{0.0024}{\sqrt{\sigma}}\right)$ |
| 16-Feb 14| $GIC = a\left(\frac{0.0082}{\sqrt{\sigma}}\right) - b\left(\frac{0.0071}{\sqrt{\sigma}}\right)$ |
| 12-Sep 14| $GIC = a\left(\frac{-0.0037}{\sqrt{\sigma}}\right) - b\left(\frac{0.0047}{\sqrt{\sigma}}\right)$ |
| 23-Dec 14| $GIC = a\left(\frac{0.0026}{\sqrt{\sigma}}\right) - b\left(\frac{0.0037}{\sqrt{\sigma}}\right)$ |
Table 6: The equation formed using the plane wave method, with a constant parameter for PTN station, as the low latitude station rarely experiences the GICs event.

| Date       | GICs equation for PTN station                                               |
|------------|-----------------------------------------------------------------------------|
| 17-Mar13   | \( GIC = a(0.0043 \sqrt{\sigma}) - b(0.0010 \sqrt{\sigma}) \)           |
| 2-Oct13    | \( GIC = a(0.0019 \sqrt{\sigma}) + b(0.004 \sqrt{\sigma}) \)            |

Briefly discussion on the variation of the Ex and Ey that becoming an important parameter to plug in into the GIC equation. For the four years analysis based on different phases of SC, the LKW station is the most experiences GIC event, followed by BCL and PTN station. While, the MND, DAW, and TWV do not experience on the GIC event. By thoroughly looking, the value of Ex and Ey responded with the positive and negative number. Most of the Ey variation at LKW station is negative except on 2 October 2013. On the other hand, The Ey variation at BCL station was responded with the negative value except for 17 March 2013. While the PTN station a contradict version based on two events. On the same time, we manage to observe the variation of Ex that usually demonstrates a positive value but it shows the opposite sign for two events on 12 September 2014 and 23 December 2014 for LKW and BCL station respectively. The matter that needs to be exposed is the positive and the negative value of Ex and Ey is represent the power transmission system connected trend. The trend of the power transmission structure has been marked as an issue that needs to be proposed for further investigation. Need to be reminded that, the topology of the power transmission structure is not to be similar to other where is based on region. The maximum amplitude of dH/dt is mainly related to the variation of Ex and Ey as the peak point of electric field component can be observed in the variation. Consequently, the GIC equation provided in the table is verifiable by conducting a direct measurement under high voltage power transmission line for a long-term analysis. Previously, the studies on the GICs values were used both approaches namely calculation and experimentally measurement.

3.3 GIC penetration based on skin depth.

On the whole, becoming another relevant question, how far the GICs can penetrate into the Earth Lithosphere and what is approached to estimate the depth of penetration. More so, we carried out this issues by explaining the electromagnetic waves propagate in Ultra-Low frequencies (ULF) range in between 300 Hertz - 3 kiloHertz. Previously, the ULF propagation used for earthquake prediction using three different model so-called ULF emission, micro-fracturing, and the ULF polarization. In this context, the ULF propagate landward experiences a basic process of wave propagation where the wave incident at the Earth surface and reflect windward. The wave then propagates to transmit the magnetic field depending on the Earth conductivity. Loses of the magnetic field intensity is should have in the middle of the incident and reflect wave process. However, the Earth underground conductivity plays a significant role in deciding the ration of the reflected waves. A direct hypothesis can be made. If the underground conductivity is infinite value, the incident and the reflected magnetic field is approximately similar. While, if the underground conductivity is a finite number, which is not uniform, the reflected magnetic field intensity can be properly observed by depending on the skin depth. How far (km) the electric current can flow around the surface so-called skin depth. The less skin depth, the far current able to flow. The frequency and the resistivity of the layer of Lithosphere is dependence parameter to the skin depth. The skin depth is directly proportional to the resistivity but
inversely proportional to the frequency. It brings an explanation the short period variation, closely related to the frequency value might able to penetrate to the shallow depth and vice versa.

Table 7: The skin depth calculation based on the conductivity and the period of the wave propagation. This table was fully copied and rewrite from [26] without changing any parameter, values, or formula.

| Skin depth \( \delta \) (km) | Conductivity (s/m) |
|-----------------------------|--------------------|
|                            | \( 10^1 \) | \( 10^2 \) | \( 10^3 \) |
| \( T \) (period) | Sec | 10 | 5.03 | 15.91 | 50.32 |
|                  | 45  | 10.68 | 33.76 | 106.76 |
|                  | 150 | 19.40 | 61.64 | 194.92 |
| Min             | 50  | 87.18 | 275.66 | 871.73 |
|                  | 150 | 150.99 | 477.46 | 1509.88 |

\[
\delta = \left( \frac{T}{\pi \mu \sigma} \right)^{1/2}
\]

Table 7 shows the significant parameter to calculate the skin depth in km using equation 3. This table was properly constructed by [26]. The underground conductivity value was divided into three range while the period, \( T \) obtained by considering the ULF value is below than 10 Hertz. Extracted information from this established table, the more conductive region might produce a thin skin depth while the less conductive region performs a high skin depth value. The way to mitigate the skin depth is the period must be short, refer the table 7. Other than that, the permeability also plays a significant role to reduce skin effect but for ULF wave propagation, the permeability used is the physical constant of the free space (\( \mu = 4\pi \times 10^{-7} \)). The changing of permeability value can be only for material for design concept but not appropriate with this topic. Based on the summary provided before, the GICs current able to penetrated unlimited depth only depending on the underground conductivity. Merely, the SHA method only can provide the maximum value of the underground conductivity around 950 km down to Earth Lithosphere.

**Conclusion**

A long-term analysis has been done well and the GIC estimation is managed to conduct even the equation consist of the constant parameter. The issue easily can be solved by conducting a direct measurement on that particular area. Remaining investigation on the variation of \( Ex \) and \( Ey \) with the variation of solar wind parameter and the solar activities was planned to conduct in order to strengthen the understanding of the relationship between an upper part that contribute to the geomagnetically induced current event. Several conclusions can be underlined, namely;

a) The value of \( Ex \) and \( Ey \) is varied and peak at the point of the maximum amplitude of the time derivative of the horizontal component (nT/min).
b) The changing of conductivity may allow the \( Ex \) and \( Ey \) also changed. The underground conductivity was excluded in the equation due to uncertainties issues.
c) The estimation of the GIC value is depending on the \( Ex \) and \( Ey \) value also the underground conductivity.
d) The more conductive region, the more current may deeply penetrate.
e) The GIC value calculated in this study applies only to that particular station provided due to the calculation is based on the magnetic field on the same date.

f) The Ex and Ey value obtained in this study represent the value of the time derivative of the horizontal component of each station.

g) The GICs estimation can be verified by conducting the long-term direct measurement under high voltage power transmission at each of station.

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