Characteristic of the Disturbed Days Ionospheric Current System in the 180-Degree Magnetic Meridian

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Abstract. The behavior of the ionospheric current during disturbed days using 10 geomagnetic observatories along 180-degree magnetic meridian was analysed. Separation of external and internal current during geomagnetic storm on 12 April until 15 April 2012 data was carried out using spherical harmonic analysis method. The contour of day to day variation of total current, external current and internal current were distinguished based on geomagnetic storm phase. These current then were correlate with the solar wind parameter, IMF Bz, and geomagnetic indices in order to identify their relationship. The results reveal that these current intensities were found higher during the initial phase. This due to the enhancement of the magnetic field during the initial phase caused by the increment of solar wind dynamic pressure and southward IMF Bz. Hence, the induced current identified in the internal current. This study demonstrated that the electric current induction can be obtained from the weak geomagnetic storm.

1. Introduction

A magnetic field recorded in ground-based magnetometer consists of a summation of various sources of signals. The geomagnetic variation field is comprised of contribution in external currents in the ionosphere and magnetosphere and internal (earth’s dynamo core, magnetization field of rocks in the crust and induced current generated by external field) currents in the Earth. The most significant contribution is from the current generated from fluid dynamo process in the Earth’s core that produce magnetic field up to ~ 30000-60000 nT on the surface called as main-field. The others source only up to few percents contributes in the geomagnetic field [1]. One of the sources from the external field is electric current flowing in the ionosphere that referred as solar quiet(Sq) current. Sq is a dynamo current driven by thermo-tidal action in the ionospheric E-region between 90 and 130km. The term Sq is due to the solar regular variation in sunlit direction during a quiet day. This resultant current would be
controlled by ionospheric conductivity and the electric field [2]. During geomagnetically disturbed condition, the magnetic field from the external source is mainly contaminated from ionosphere and magnetosphere current (solar wind variation depends on the direction of interplanetary magnetic field) and the increasing of internal current (telluric current) induced from the external source. Thus, by separating these field, the magnetic variation can be inferred in the purely original source.

A spherical harmonic analysis is a mathematical modeling technique for separating external/internal field in Sq analysis has been adequately demonstrated in [3][4][5][6]. However, these studies have examined only separating current only during quiet days. Although there is some research has been carried out on separation external and internal current during the disturbed period[7][8][9], however, the effect of day to day geomagnetic storm variation on the longitudinal variation on these current has not been closely examined.[9] studies external/internal field associated with Dst index (disturbance time index) during a geomagnetic storm. They found that the large contribution on the internal field is during the main phase of the geomagnetic storm. However, this analysis only limited a few stations in latitudinal variation. A geomagnetic storm is a temporary disturbance of the Earth’s magnetosphere caused by intense energy from solar wind that interacts with the Earth’s magnetic field. One of the factors that cause the magnetic storm is solar Coronal Mass Ejection(CME).

In this study, the aim was to examine the day to day characteristic of ionospheric current during the disturbed period of the geomagnetic storm due to CME on 13 April 2012. The geomagnetic data used from 12 April until 15 April 2012 were obtained from 10 geomagnetic stations located longitudinally along the 180° magnetic meridian. In addition, these regions actually were not have been studied yet particularly in external/internal current analysis. Separation of external current and the internal current was carried out by employing the spherical harmonic analysis. These results were then distinguished based on the geomagnetic phase such as initial phase, main phase and recovery phase to differentiate their physical mechanism. In order to analyze the characteristic of these current and to identify any possible factors, the data of solar wind parameters, interplanetary magnetic field, and geomagnetic indices were provided.

2. Data and Methods

2.1. Geomagnetic Data

The minute geomagnetic data were extracted from ten geomagnetic observatories along 180° Magnetic Meridian obtained from Magnetic Data Acquisition System of Circum-pan Pacific Magnetometer Network (MAGDAS/CPMN) and International Real-Time Magnetic Observatory Network (INTERMAGNET). The map and details of the stations are shown in Figure 1 and Table 1 respectively. In this study, the geomagnetic coordinate is deployed due to the most natural phenomenon in the magnetic field. Geomagnetic field components of horizontal(H), declination (D) and vertical (Z) were carried out in this analysis.
2.2. **IMF, Solar Wind Parameters, and Geomagnetic Indices Data**

To investigate the possible mechanism that influences the behavior of current during the geomagnetic storm; the solar wind parameter, interplanetary magnetic field, and geomagnetic indices were applied. The data of solar wind parameters: solar wind speed (Vsw) and solar wind pressure (Pdyn), interplanetary magnetic field (IMF Bz) and geomagnetic indices (Kp*10 index, Ap index, Dst index, AL, and AU index) were obtained from OMNIWeb Plus website at https://omniweb.gsfc.nasa.gov/. The data of solar wind parameters and IMF Bz were present in a minute to show the real-time of disturbance.

For estimating the rate of solar wind input energy transfer into the magnetosphere, the Akasofu’s epsilon [10] was used from the equation:

$$\text{Input Energy (\epsilon)} = V_{sw} \times B^2 \times F(\theta) I_0^2$$  \hspace{1cm} (1)

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**Figure 1:** Map of geomagnetic observatories used.

**Table 1:** Details of stations used.

| Station Name       | Abbrev. | Array   | Geographic | Geomagnetic | Time Zone (GMT) |
|--------------------|---------|---------|------------|-------------|-----------------|
|                    |         |         | Lat. (°)   | Long. (°)   |                 |
| Irkutsk            | IRT     | Intermagnet | 52.27      | 104.45      | 42.37 177.3     | +8               |
| Beijing Ming Tombs | BMT     | Intermagnet | 40.3       | 116.2       | 30.51 187.59    | +8               |
| Lanzhou            | LZH     | Intermagnet | 36.1       | 103.84      | 26.17 176.51    | +8               |
| Phuthuy            | PHU     | Intermagnet | 21.03      | 105.95      | 11.06 178.33    | +7               |
| Dalat              | DLT     | Intermagnet | 11.94      | 108.48      | 2.13 181.0      | +7               |
| Bac Liue           | BCL     | MAGDAS   | 9.32       | 105.71      | -0.6 178.11     | +7               |
| Langkawi           | LKW     | MAGDAS   | 6.3        | 99.78       | -3.42 172.35    | +8               |
| Pontianak          | PTN     | MAGDAS   | -0.07      | 109.31      | -10.0 181.71    | +7               |
| Learmonth          | LRM     | Intermagnet | -22.22     | 114.1       | -32.06 187.07   | +8               |
| Gingin             | GNG     | Intermagnet | -31.36     | 115.71      | -41.14 189.16   | +8               |
where $V_{sw}$ is a solar wind speed, $B$ is an interplanetary magnetic field, $I_0$ is 7 Earth radii, $R_e$ and $F(\theta)$ is a function IMF clock angle $\theta$ (By/Bz).

2.3. Spherical Harmonic Analysis

In order to separate current, the mathematical model called as spherical harmonic analysis is applied. As devised by Gauss, 1839 was ascribed by [11], the magnetic potential function, $V$ at any location on the earth can be expressed as in converging series of terms:

$$V = a \sum_{n=1}^{\infty} \left[ \left( \frac{r}{a} \right)^n S_n^e + \left( \frac{r}{a} \right)^{n+1} S_n^i \right]$$

These series allow a separation of the external and internal current source over a sphere (radial distance, $r$) by two series of terms. First term is $r^n$ that has increasing power of $r$, that means as $r$ direction increases, the field would increase; approaching into an external current source. The other series of the term is $(1/r)^n$, that increase with reciprocal power of $r$. As the $r$ increase, the term becomes smaller as if the field approaching the internal current source in reduced $r$ direction. Thus, such series represent the magnetic potential function, $V$ in the ionospheric current analysis is a combination of external (ionospheric source) and internal (induced) source of the geomagnetic field.

The magnetic potential that computed from the daily mean values in UT time that represent both external and internal current in spherical harmonic can be expressed by:

$$V_n^m = C + a \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left\{ \left( \frac{\alpha}{r} \right)^n + \left( \frac{\alpha}{r} \right)^{n+1} \right\} \cos(m\phi) + \left( \frac{\beta}{r} \right)^n \sin(m\phi) \right\} P_n^m(\theta)$$

where $C, a, r, \theta$ and $\phi$ denote as constant of integration, the geocentric radius, the earth radius, the geomagnetic colatitude and the local time of the geomagnetic station. The $a_n^{me}, a_n^{mi}, b_n^{me}$ and $b_n^{mi}$ represent as Legendre polynomial coefficients where e and i representing as the external and internal values respectively. $P_n^m(\theta)$ is Legendre polynomial function of colatitude $\theta$ only. The integers $n$ and $m$ are called as degree and order respectively; where $n$ has a value of 1 or greater, and $m$ is always less than or equal to $n$ ($m \leq n$). In the present analysis, the magnetic potential computed in order $m=4$ and degree $n=12$.

The equivalent current function, $J(\phi)$ for an hour of a day can be obtained from:

$$J(\phi) = \sum_{m=1}^{4} \sum_{n=m}^{12} \left( u_n^m \cos(m\theta) + v_n^m \sin(m\theta) \right) P_n^m$$

For the representation of external current;

$$u_n^m = - \left( \frac{5R_e}{2\pi} \right) \left( \frac{2n+1}{n+1} \right) a_n^{me} \left( \frac{\alpha}{R_e} \right)^n$$
\[ V_n^m = -\left(\frac{5R}{2\pi}\right)\left(\frac{2n+1}{n+1}\right)b_n^m \left(\frac{a}{R}\right)^n \]  

(6)

and also for the internal current;

\[ U_n^m = -\left(\frac{5R}{2\pi}\right)\left(\frac{2n+1}{n}\right)a_n^{mi} \left(\frac{R}{a}\right)^n \]  

(7)

\[ V_n^m = -\left(\frac{5R}{2\pi}\right)\left(\frac{2n+1}{n+1}\right)b_n^{mi} \left(\frac{R}{a}\right)^{n+1} \]  

(8)

where R is the Earth radius in kilometers and a is the radius of a sphere at which current could flow. Since the value of a is approximately equal to R, thus ratio a/R is 1.

3. Results and Discussion

The first set of analysis was to examine the variation of external source based on solar wind parameters, interplanetary magnetic field, and geomagnetic indices. Figure 2 shows the variation of interplanetary magnetic field (IMF Bz), solar wind input energy ($\varepsilon$), solar wind speed ($V_{sw}$), solar wind dynamic pressure ($P_{dyn}$), and geomagnetic indices (AL, AU, Kp, Ap, and Dst index) during the minor geomagnetic storm that been analysed on 12 April 2014 until 15 April 2014. The graph of variations was distinguished based on geomagnetic storm phase as demonstrated in Dst index plot. The geomagnetic indices of Kp, Ap, and Dst index were applied to measure the rate of disturbance in geomagnetic field in middle and low latitude. The AL and AU indices used to be proxy of auroral disturbance in high-latitude. AU is proxy of eastward auroral electrojet that flow in dayside and AL is proxy of westward auroral electrojet in nightside. These indices were included due to the possibility of the auroral electrojet that can travel equatorward during high magnetic activity[12].

On 12 April 2014, the sudden commencement (SC) occurs at 04UT followed by prolonged initial phase. During the SC, at a prior time, the Dst index have a small increase, then as the IMF Bz is turned to southward; there is a small drop in Dst index and the geomagnetic indices of Kp and Ap are increases with the value -4 and 22nT. Simultaneously, the input energy abruptly increases up to 1.5x10^{19} erg/s and solar wind dynamic pressure enhance up to 8.77nPa. The increment is due to pressure from the shock hits the magnetosphere and cause the magnetopause current (Chapman Ferarro current) increase. Moreover, it also causes the horizontal magnetic field component in ground-based having a positive sudden increase[13]. This SC, however, was not so related to the solar wind speed due to slow solar speed range (~300km/s). As soon as the Bz is positive and gradually varying, all the parameters have been in lower variation and having a prolonged initial phase for about few hours.

Later, at 15UT on the same day, the IMF Bz changes to direction into southward and all the parameters varies abruptly indicating the main phase process is started. During the main phase, as the Bz is negative, the magnetic reconnection occurred and magnetosphere convection enhanced. The ring current growth and cause the negative perturbation in the Earth’s magnetic field[14]. As shown in Figure 2, the magnitude of input energy transfers into magnetosphere increases and peak about 1.75x10^{19} erg/s. The solar wind speed experiences the high-speed solar wind that increases up to ~600 km/s. In contrast, the value of solar wind dynamic pressure was enhanced but not so high compared during SC time. Moreover, the value of AL and AU index was found increased at 19UT. However, the AL index shows a higher variation index (large decrease) compared to the AU index. This due to the increment of westward auroral electrojet current in nightside. Note that at 19UT, all selected stations having
nighttime. Based on the Dst index, the value of the index was gradually decreased until -60nT at 04UT on 13 April 2014. This decrease is caused by the growth of ring current. At the same time, the Kp*10 index and Ap index increased with the value of 50 and 48nT respectively, representing the geomagnetic disturbance is weak storm type G1. Further, as the Bz is northward the magnetic field begins to recover over within three days. At this phase, the energy transfer becomes weaken.

Figure 2: The variation of the IMF Bz, input energy, solar wind speed, solar wind dynamic pressure including geomagnetic indices including AL, AU, Kp, Ap and Dst index during 12 April 2014 until 15 April 2014 in UT hours.

Figure 3 shows the contour map of day to day current intensity of equivalent current, external current and internal current over four days of geomagnetic storm phases. The Dst index is included in the graph is used to illustrate the phase of the geomagnetic storm. The purple lines indicating the starting process of initial phase and recovery phase and the red line represents the prior of the main phase of geomagnetic storms happen. Two-current vortices form that are oppositely directed at 00UT to 10UT, demonstrating the equivalent current of the daytime ionosphere. The positive peaks of the current indicating the current flows in the counter-clockwise direction in the northern hemisphere. And also negative peaks in southern hemisphere represent the current flows in a clockwise direction. Near to equatorial station (BCL and LKW), the current lines are close together denoted as equatorial electrojet current. However as shown in the external plot, the value was very low due to computation in spherical harmonics regarding the highest order[6].
In the view of the current pattern and their intensity based on geomagnetic phase, the initial phase shows highest current intensity and greater peak compared during the main phase and recovery phase. Referring to total current result (upper panel), the value of this current is higher compared to external and internal current mainly during the initial phase. The intensity of the total current is representing the summation of external and internal current. During the initial phase, the intensity of all currents shows the highest value. The maximum of the total current in the northern hemisphere is $18.3 \times 10^6$ A and in the southern hemisphere is $-13.8 \times 10^6$ A at peak of current vortices. For the the external current, the value in the northern is peak at value $12 \times 10^6$ A and the southern peak value is $-11 \times 10^6$ A. The lowest current is at internal current where the northern peak is $9 \times 10^6$ A and southern peak is $-9 \times 10^6$ A. It can be seen contribution of initial phase physical process that causes the enhancement of magnetic field. Note that, the data are computed from daily average, thus it can reduce the effects of the magnetospheric source. The values of calculated current also reached up to $\sim 10^7$ A using equations (5) until (7). These measured values were generally agreement with results obtained by [15] that studied the equivalent current during the quiet days using the same equations.

Eventually, as the main phase started (red line), the value of all current gradually decreases. It is apparent that the current reduced due to negative perturbation on the geomagnetic field due to the enhancement of ring current. When the Bz is changing to negative value started at 15UT, the storm started to occur during nighttime. As can be seen in Figure 3 in total current and external current graph, there is a small current vortex occurred in the mid-latitude station in the northern hemisphere. This current might be attributed to movement of auroral electrojet to the equatorward. But in this case, it reaches only in mid-latitude. The main phase process ends at 04UT on 13 April 2014 where it is noon time. At the present time, the peak of total current decrease with the value of $14 \times 10^6$ A in the northern hemisphere and $-8 \times 10^6$ A in the southern hemisphere. The peak of external current value for northern and southern hemisphere are $7 \times 10^6$ A and $-5 \times 10^6$ A respectively. The value in internal current also reduced with about $\pm 1 \times 10^6$ in both hemispheres compared to the external current. Later, as the recovery phase started, the total current and external current changes gradual increase until 15 April that represents regular daily variation. This is due to the dissipation of transfer energy. However, in contrast with total and external current, the internal current changes gradually to a lower value. Hence, for this reason, the increment during initial phase showing that there is a telluric current induced by the external source. Moreover, the behavior of internal current during the last day of recovery phase show that internal source with the small value of induced current.

Clearly, as expected, the enhancement during the initial phase in the external current is comprised of the magnetospheric current that depends on the IMF direction and the ionospheric current that have varied in their ionospheric conductivity. Current flowing in the magnetosphere and ionosphere also can be induced in the ground. The changing of the magnetic field can cause current induction in any conductive place. During nighttime, the currents can receive a contribution from the magnetosphere. The smaller current vortices in nightside can be attributed to the westward auroral electrojet indicate by AL indices in Figure 2. This auroral electrojet driven magnetospheric field-aligned current can be propagated to lower latitude in the conducting E-region [16]. The value of northern hemisphere also was found higher compared to southern due to April month used in this study where the spring equinox in the northern hemisphere and autumn equinox in the southern hemisphere. In addition, the low current intensity at the equatorial station in southern hemisphere shown in the external current plot could be attributed to the interhemispheric current that cancels out the external current in that particular hemisphere [17]. Moreover, the concentration of current is less in the southern hemisphere due to only four stations used.
Figure 3: The contour of day to day variation of total current (upper), external current (middle) and internal current (bottom) during 12-15 April 2012. The Dst index is used to represent the flow of geomagnetic storm occurred.
4. Conclusion
The present study was set out to determine external/internal current separation during the disturbed period and correlate with the solar wind parameter, IMF, and geomagnetic indices in order to identify their relationship. The result has shown that the variation of the total, external and internal current based on geomagnetic storm phase are associated with these parameters. The representation of current computed from the longitudinal stations also shows the real situation of current vortices during a geomagnetic storm. The results of current separation have been indicating that external current is from magnetospheric current and ionospheric current source while the internal current from the Earth’s main field and also induced current by an external source. During the initial phase, these current enhanced due to reconnection process and generating the induced current in the internal current. Even though the data was obtained from daily means baseline that reduced the magnetospheric source, the results however also show the induction of currents in the external and internal currents. Overall, the presented results show that the SHA method can be used to determine the current induction mainly during initial phase due to external source obtained from a weak geomagnetic storm event. The findings of the study can extend our knowledge of the behavior purely current. The study was limited to only one case of a geomagnetic storm. More cases of the geomagnetic storm are required to better understand the characteristic of separated current associated with the external source. The fewer stations used in southern hemisphere also cause the concentration of current was reduced. Thus, it is preferable using more stations to study the high resolution of current features. Further work in determining the conductivity needs to be carried out in order to identify the characteristic of an internal source. It would be interesting also to further research on understanding the effect of geomagnetically induced current (telluric current) in the internal field.

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