Field-aligned currents (FACs) behaviour during the arrival of interplanetary magnetic shock

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Abstract. In this paper, our study is focused on the FACs behavior during the SC event. SC consists of two events which are storm sudden commencement (SSC) and sudden impulse (SI) event. The difference between these two events is that the interplanetary shock due to SSC leads to geomagnetic storm while during SI event, there is no geomagnetic storm afterward. We performed the statistical analysis between the FACs value and the temporal variation of SYMH index (dSYMH/ dt) during SC events from 2008 until 2015. The dSYMH/ dt describe the interplanetary shock signature during the SC events. The results showed that the dSYMH/ dt during SSC event has a better correlation than the dSYMH/dt during SI events. It suggested that during the SSC onset, there is the magnetic reconnection process between magnetosphere and ionosphere. So, the enhancement of ground magnetic field is contributed by both magnetospheric and ionicpheric currents. However, during the SI onset, least connection process happen between magnetosphere and ionosphere thus, the ground magnetic disturbance was mainly associated with the magnetospheric current.

1. Introduction
Field-aligned currents (FACs) illustrates the coupling process between magnetosphere and ionosphere by which the energy associated with the solar events (solar flares, coronal mass ejection (CME) and coronal holes (CH)) are transferred and are converted into an ionospheric electric current. Generally, during the magnetic reconnection process, the value of FACs is enhanced [1]. Most of the study on FACs have only been carried out during the substorms [1]–[4], which are frequently occurred in auroral region. Plus, the substorm activity occurs when the magnetosphere-ionosphere is energized through the interplanetary convection electric field that governed by the negative value of interplanetary magnetic field (IMF) Bz component [5]. However, too little attention has been paid to compare the behavior of FACs during the SC events associated with the interplanetary shock waves. So, the present study thoroughly examined the magnetic reconnection process specifically during SC onset based on FACs value. SC is a clear onset in the magnetic field variation when the magnetospheric compression associated with interplanetary shock waves occurs. The SC event is categorized into two events which are storm sudden commencement (SSC) and sudden impulse (SI) event. The difference between these two events is that the interplanetary shock due to SSC leads to geomagnetic storm while during SI event,
there is no geomagnetic storm afterward. The compression of Earth’s magnetosphere due to interplanetary shocks yields to the enhancement of magnetopause current, ring current intensification, and equatorial electrojet, thus resulting in the important role of SC events to GIC activities in this region [6]–[9].

2. Data analysis

2.1. Solar wind an IMF data
Measurements of the solar wind and interplanetary magnetic field (IMF) parameters, including the solar wind velocity and orientation of IMF are made by Advanced Composition Explorer (ACE) satellite. ACE measurements are obtained from OMNI database that available online (http://nssdc.gsfc.nasa.gov/omniweb/). ACE satellite, which is located at LI point to 17 RE of the Earth, provides the measurement values for the solar wind and IMF near the outer boundary of Earth’s magnetosphere.

2.2. Ground magnetic indices
In order to study the geomagnetic activity, different magnetic indices are analyzed. AU and AL indices are used to understand the influence of SI event impact to auroral electrojets. These indices are derived from magnetometer stations located in the auroral zone in the northern hemisphere. AU index is an indicator of the eastward auroral electrojet which flows on dayside and AL index represents the westward auroral electrojet which flows on nightside. Besides that, these indices are a good indicator to measure substorm activity in the auroral zone. Symmetric disturbance field in H (or known as SYM-H afterward) describes the variation of the ring current in the magnetosphere and tail current. The SYM-H index is made by averaging the horizontal magnetic field measured by several low-latitude and mid-latitude magnetometers in order to avoid the contamination of auroral and equatorial electrojets. Increase pattern of SYMH shows the compression phase of geomagnetic storm and it also shows the eastward magnetopause current. Westward ring current and main phase of the geomagnetic storm are represented by the decreasing pattern of SYMH. These indices (AU, AL, and SYMH) are obtained from World Data Center for Geomagnetism that operated by Kyoto University, Japan (http://wdc.kugi.kyoto-u.ac.jp/).

2.3. Calculation of field-aligned currents (FACs)
As the current requires a closed loop to circulate, the field-aligned currents (FACs) close the magnetospheric current loops to let it flow into and out the ionosphere. Regarding this process, it allows the solar energy transfer from the magnetosphere into the ionosphere. To calculate the FACs, we apply the formula (1) suggested by [1], [10].

\[
FAC = 0.0328 \left[ n_p^2 V_{sw} B_T \sin \left( \theta \right) \right]^{1/2} + 1.4
\]

FAC is measured in µAm⁻² based on the solar wind density in cm⁻³ (np), solar wind speed in km/s (Vsw), total of interplanetary magnetic field: 

\[
B_T = \sqrt{B_y^2 + B_z^2}
\]

and the angle of the magnetic field, \((B_y/B_z)\):

- If \(B_z > 0\) \(\Rightarrow \theta = \tan^{-1} abs \left( \frac{B_y}{B_z} \right)\)
- If \(B_z < 0\) \(\Rightarrow \theta = 180 - \tan^{-1} abs \left( \frac{B_y}{B_z} \right)\)

3. Result and discussion
Figure 1 shows the different behavior of solar wind speed, \(V_{sw}\), \(B_z\) component of interplanetary magnetic field (IMF) and ground magnetic SYMH index during SSC and SI events. The red-dashed boxes in both events represent the arrival of the interplanetary shock at 0914UT during SSC event and at 1214UT during SI event. The most obvious differences are the orientation of IMF \(B_z\) and the decreasing pattern of SYMH index. During SSC event, the IMF \(B_z\) turn southward after the short compression based on the positive IMF \(B_z\) at the moment of the interplanetary shock. The IMF magnitude during the southward pointing allows the solar wind energy transfer from the magnetosphere into the ionosphere and
subsequently led to the magnetic field disturbances as seen in the negative value of SYMH index at around 2 hours after the SSC event. Meanwhile, during SI event, the IMF $B_z$ remained at the positive value for about 8 hours after the interplanetary shock, which inhibits the magnetosphere-ionosphere coupling process happened. However, these sudden shocks have caused similar magnetospheric compression strength of 30nT/min based on dSYM/dt during both events. Since the reconnection between solar – earth magnetic field happened during SSC event, we can clearly see that higher FACs value during this event compared to SI event with 12.1µAm$^{-2}$ and 8.2µAm$^{-2}$ respectively.

![Figure 1](image1.png)

**Figure 1.** An example of SSC (left panel) and SI event (right panel) on 12 March 2012 and on 23 December 2014 respectively. From top panel to bottom: solar wind speed ($V_{sw}$), IMF $B_z$, ground magnetic index (SYMn) with its temporal variation (dSYM/dt) in red line and field-aligned currents (FACs). Both squared red-dashed lines represent the arrival of interplanetary shock (SSC and SI).

The study of field-aligned currents (FACs) was very important to describe the solar energy transfer from magnetosphere into the ionosphere. The FAC value was controlled by the solar wind and the orientation of IMF $B_z$ [1], [10]. In this study, we investigated the magnetic reconnection process specifically during SSC onset and SI onset by performing the correlation coefficient as shown in Figure 2. We calculated the correlation between the FACs value and the temporal variation of SYMn index (dSYM/dt) during SC events from 2008 until 2015. Bear in mind that SC onset was associated with the interplanetary shocks events and the dSYM/dt described the interplanetary shock signature mainly to the equatorial region [11]. The correlation was categorized into three parts: 1) overall SC onset (1st panel), 2) SSC onset (2nd panel) and 3) SI onset (3rd panel). In overall, there is a correlation between dSYM/dt and FACs during all SC events. However, when we specifically classified the calculation into SSC and SI onsets, we have found a significant result where during SSC onset the correlation was higher than during SI onset. These correlation values explained that during the SSC onset, there was the magnetic connection between magnetosphere and ionosphere. So, the enhancement of ground magnetic field was contributed by both magnetospheric and ionospheric currents. However, during the SI onset, very low positive correlation was observed. Meaning that small reconnection process happen between these two layers and thus, the ground magnetic disturbance was mainly associated with the magnetospheric
current. During the arrival of interplanetary shock, the generated magnetopause compression waves extend across the magnetosphere, thus enhancing the current connecting the magnetosphere and ionosphere [12].

![Image of correlation between dSYMHDt and FACs](image)

**Figure 2.** The correlation between the dSYMHDt and FACs during SC (consisting of SSC and SI) events from 2008 until 2015 (in left panel). The second and third panels are the correlation during SSC and SI onset.

4. **Conclusion and future recommendation**

This study shows that stronger reconnection process between magnetosphere-ionosphere happened during SSC event compared to SI event. Recently, the study on the arrival of the interplanetary shock during SC event was related to the GIC risk in equatorial region [7], [11], [12] As the equatorial dB/dt level was similar despite SSC and SI events, these results depict that strong GIC activity may occur in equatorial region even with less contribution from the ionospheric current [11]. In other words, the ground technological system in equatorial region was exposed to the high risk of GIC even during quiet geomagnetic activity [11], [13]. So, the study on FACs will be more interesting if we extend the investigation to the GIC risk assessment in equatorial region.

5. **References**

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