Originally published as:

Mishin, V. M., Förster, M., Kurikalova, M. A., Mishin, V. V. (2011): The generator system of field-aligned currents during the April 06, 2000, superstorm. - *Advances in Space Research*, 48, 7, 1172-1183

DOI: 10.1016/j.asr.2011.05.029

The generator system of field-aligned currents during the April 06, 2000, superstorm

V. M. Mishin *

*Institute of Solar-Terrestrial Physics, Siberian Branch (SB), Russian Academy of
Sciences (RAS), P.O. Box 4026, Irkutsk 664033, Russia*

M. Förster

*GFZ German Research Centre for Geosciences, Helmholtz Centre Potsdam,
Telegrafenberg, D-14473 Potsdam, Germany*

M. A. Kurikalova, and V. V. Mishin

Institute of Solar-Terrestrial Physics, SB RAS, Irkutsk, Russia

Abstract

Using ground-based magnetometer data of the April 6-7, 2000, superstorm, we obtained maps of ionospheric and field-aligned currents (FACs). Based on these, we deduced the electrical circuit of the disturbed magnetosphere/ionosphere and a conceptual model of its magnetospheric generators, which supply both hemispheres. This model implies that the generator system creates primarily the Region-1 FACs of Iijima and Potemra at both hemispheres, while the Region-2 and Region-0 FACs form by spreading of the Region-1 currents through the ionosphere. This conclusion is supported by observations.

A second prediction of this model turns out to be the following hypothesis, which is also based on the new empirical data. The Region-2 FAC of the dawn side in

the Northern Hemisphere is connected with the global dynamo via the asymmetric ring current of the inner magnetosphere, DRP-1. Coming with the DRP-1 into the dusk side, the Region-2 FAC then splits and connects with the dusk side ionosphere of both hemispheres. This way a part of the dawn side Region-1 current becomes connected with the dusk side dynamo of the opposite hemisphere. The intensity of Region-2 and Region-1 FACs of the dusk side is therefore smaller than on the dawn side of this hemisphere, provided that the conductivity in the magnetically conjugated Region-2 ionosphere is larger than the local. Similarly, the dawn-dusk asymmetry of the FAC intensities may also be caused by an inequality of magnetic field and/or pressure gradient in the northern and southern halves of the plasma sheet where DRP-1 flows. The predicted dawn-dusk asymmetry according to such a model is supported by the observations and appears causally connected with an asymmetry between the hemispheres. This conclusion opens a new approach to study these kinds of FAC asymmetries.

Further analysis led to the additional conclusion, that the global magnetospheric dynamo works as a voltage generator both during relatively quiet (average) conditions as well as under strong disturbance conditions.

Key words: magnetospheric generators, field-aligned currents, superstorm

1 Introduction

The term “generator” (or “dynamo”) is of fundamental importance in electrical engineering, but it is relatively rarely used for describing the physics of the rarefied magnetosphere, where currents flow in circuits with distributed parameters. Some previous discussion on this subject (*Heikkila*, 1984; *Parker*,

* Corresponding author

Email address: mishin@iszf.irk.ru (V. M. Mishin).

1996, 2000; *Vasyliunas*, 2001) concluded finally, that the description of mag-
netospheric electric circuits analogous to electric wire circuits with lumped
parameters is possible, provided that the electric fields and currents are given
from observations and the results obviously justify the specified approxima-
tion.

Siscoe et al. (2002), on the other hand, worked out a MHD model of the
disturbed magnetosphere, where they placed the generator region in the bow
shock and the load region into the dayside magnetopause. This model al-
lowed to bring the reconnection observations at the dayside magnetopause
into accordance with the data of the calculated electric field and currents in
these regions. *Akasofu* (2004) described an electric circuit with a generator
in the plasma sheet and the load in the ionosphere by use of ground-based
magnetometer data for applying the magnetogram inversion technique KRM
(*Kamide et al.*, 1981; *Kamide and Baumjohann*, 1993) and magnetic obser-
vations in the inner magnetosphere (*Iijima et al.*, 1990). Important examples
of effective studies of magnetospheric processes by using terms of electrical
engineering for the description of magnetospheric generators and their elec-
tric circuit schemes were given, e.g., by *Lysak* (1985); *Liu et al.* (1988); *Mac-*
Dougall and Jayachandran (2006); *Siscoe and Siebert* (2007); *MacDougall and*
Jayachandran (2007, and references later down in this paper). This approach,
which is using not only the MHD, but also the above-mentioned basic terms of
electrical engineering, will be likewise essential for the present study. Several
associated topics will be touched, among them our principal one that focus on
the further development of our generator model (see below).

One topic is associated with the substorm current wedge (SCW, *McPherron*
et al., 1973) that plays a central role for the magnetosphere/ionosphere system

under disturbance conditions. For the ionospheric part of the SCW within this conception, a Pedersen or Cowling current forms the observed unloading westward auroral electrojet (WEJ). This is an azimuthal current, directed westward along the Region-1 of Iijima and Potemra (*Potemra*, 1994). This conception is presently dominating in the public literature. However, according to statistical FAC models (*Potemra*, 1994; *Weimer*, 2001; *Papitashvili et al.*, 2002; *Gjerloev and Hoffman*, 2002), meridional Pederson currents rather than azimuthal currents in the auroral zone close neighbouring FAC sheet pairs of Region-1 and Region-0 or Region-1 and Region-2, respectively, although not all these authors use Iijima-and-Potemra's terminology.

The meridional Pedersen currents develop together with Hall currents, which form the observed convectional auroral electrojets (*Kamide and Baumjohann*, 1993; *Baumjohann and Treumann*, 1996). Many observational data suggest, that the basic ionospheric currents in the disturbed nightside auroral zone are meridional currents (*Gjerloev and Hoffman*, 2002; *Akasofu*, 2004; *Lui and Kamide*, 2003; *Liang and Liu*, 2007; *Mishin et al.*, 2008). Therefore, it is likely that the unloading WEJ is essentially an azimuthal Hall current, associated with the mentioned Pedersen current. Such a reasoning corresponds to those models, where the dawn-dusk current disruption (CD) in the plasmasheet causes there a generator, which finds its closure as WEJ in the ionosphere. Here, the closing current is not a Pedersen or Cowling current (like in the SCW model), but rather a Hall current. The data presented in this study will support such a conception. Novel important observations and theoretical arguments supporting this point of view are presented by *Zou et al.* (2009) and *Lyons et al.* (2009).

In the framework of the electric circuit theory with lumped parameters,

58 *Mishin et al.* (2004) and *Förster et al.* (2006) elaborated an empirical model
 59 of FACs, which takes into account all three zones of Iijima-and-Potemra’s pat-
 60 tern, while introducing three additional meso-scale substructures for each of
 61 these regions. These three substructures are attributed in the model of *Mishin*
 62 *et al.* (2004) to a particular unified system of generators. The present study
 63 focus on the further development of this complemented Iijima-and-Potemra
 64 model, pointing out its complex system of generators and interrelationships.

65 We use ground-based magnetometer data of the superstorm interval of April
 66 06, 2000, based on which we obtain maps of equivalent ionospheric current
 67 (EIC) and field-aligned currents (FACs). This provides the basis for a further
 68 elaboration of the electric circuit scheme and its magnetospheric generators,
 69 expanding hereby the results of *Mishin et al.* (2004, 2010a,b) particularly with
 70 respect to both hemispheres. Analyzing this scheme and data from the liter-
 71 ature, we took into account and expanded some results obtained by *Siscoe*
 72 (1982), *Crooker and Siscoe* (1983), *Cowley* (2000), *Siscoe et al.* (2000), and
 73 *Lysak* (1985). We obtained plots, which show the variations of current in-
 74 tensities within each of the three FAC zones of Iijima and Potemra at the
 75 Northern Hemisphere. They constitute an evidence for our first basic con-
 76 clusion about the global system of magnetospheric generators, namely, that
 77 the generator system of the Northern Hemisphere closes immediately on the
 78 primary Region-1 FACs, while the Region-2 and Region-0 FACs result from
 79 spreading of the Region-1 currents through the ionosphere. This implies that
 80 all three Iijima-and-Potemra regions are formed by one common dynamo sys-
 81 tem in the respective hemisphere. Such a hypothesis (though without taking
 82 into account R0) was already proposed by *Siscoe* (1982) and theoretically
 83 supported in several studies as cited above (see, e.g., *Siscoe et al.*, 2000; *Cow-*

84 *ley*, 2000). Our results support this hypothesis for the first time by means of
85 observations at the Northern Hemisphere.

86 The global current circuit with its generators comprises also Region-2 cur-
87 rents, which connect both hemispheres and hence also the dynamos placed
88 both in the Northern and Southern Hemispheres. These dynamos are con-
89 nected in parallel. We conclude finally, that this global magnetospheric dy-
90 namo as source of the global FAC system can work as voltage generator dur-
91 ing relatively quiet (average) conditions, as well as under strong disturbance
92 conditions.

93 The paper is organized as follows. In Section 2 we present our data base and
94 the timing of the magnetospheric disturbances during this superstorm interval.
95 A description of our scheme of spatial FAC structures and substructures as
96 well as its magnetospheric generators is given in Sections 3 and 4, respectively.
97 Section 5 presents the main findings of this study concerning the variations
98 and the relative differences of the FAC intensities between the dawn and dusk
99 side and between the hemispheres. Section 6 considers the issue of the mag-
100 netospheric generator type. Section 7 finally summarizes these findings and
101 conclusions.

102 **2 Data basis, timing, and peculiarities of the 3-D current system**

103 Fig. 1 shows the time sequence of the solar wind (s.w.) parameters as mea-
104 sured by the WIND spacecraft together with the AE and SYM-H indices (pro-
105 vided by the WDC-C2, Kyoto) for the interval 15-20 UT of the superstorm
106 day April 06, 2000. The s.w. parameters are time shifted by the propagation

April, 06, 2000

Fig. 1. Parameters of the solar wind (from top to bottom) as measured by the WIND satellite and time-shifted to the magnetopause: density n , velocity V , dynamic pressure P_d , the IMF components B_y and B_z in GSM coordinates. The time shift is 12 min until 16:40 UT and 8 min afterwards. Additionally, the AE-index obtained from the WDC-C2 in Kyoto (T. Iyemori) by use of a standard set of nighttime auroral magnetometers and the SYM-H index are shown.

Fig. 2. Distribution of ground-based magnetometer stations used for the present study, plotted in magnetic latitude versus magnetic local time (MLT) dipole coordinates for the circumpolar region of the Northern Hemisphere as far as 40° . The station's coordinates and names according to the numbers are listed in the Appendix.

time from the WIND spacecraft to the dayside magnetopause. This time shift
amounts to 12 min until 16:40 UT and 8 min afterwards (*Huttunen et al.*,
2002). Some precursors of substorm activity can be noticed during the inter-
val from 15:00-16:40 UT, while a sudden, step-like increase of the dynamic
pressure at 16:41 UT to a high pressure level of ~ 13 nPa together with a sud-
den increase of other activity parameters marks the begin of the superstorm
of April 06, 2000 (Fig. 1). It is described in more detail, e.g., in the papers
of *Huttunen et al.* (2002) and *Mishin et al.* (2010b). In the present study we
provide further data about the dynamics of FAC intensities within each of

116 the three different FAC regions of Iijima and Potemra. We use the maps of
 117 EIC and FAC density distribution patterns, obtained by means of the Mag-
 118 netogram Inversion Technique (MIT-2) as described, e.g., by *Mishin* (1990)
 119 and *Mishin et al.* (2001). Data of 120 ground-based magnetometer stations of
 120 the Northern Hemisphere were used for this study as input in MIT-2. Their
 121 locations in geomagnetic coordinates are shown in Fig. 2 and tabulated in the
 122 Appendix. The reference levels to create the “geomagnetic disturbance field”
 123 were determined for all stations from their average value during the quiet time
 124 interval 0130-0200 UT of April 06, 2000.

125 Two examples of the mentioned maps are shown in Fig. 3. In the EIC maps
 126 (left panels), the two thick arrows indicate two regions of more concentrated
 127 current isolines or intense electrojets. One is the westward auroral electrojet
 128 (WEJ), the other points eastward (EEJ). The electrojets are also indicated
 129 in the FAC maps (right panels). The maps of the upper panels represent the
 130 relatively quiet interval (1500-1632 UT), while the lower panels are typical for
 131 the disturbance interval (1641-2000 UT).

132 In both examples one can notice that each electrojet is located between
 133 pairs of upward and downward directed FACs. These facts underline that the
 134 electrojets appear first of all as Hall currents and each pair of antipodal FACs
 135 closes in the ionosphere with meridional Pedersen currents. The ionosphere
 136 acts here as a dissipative medium. From this it follows further, that each
 137 pair of FACs is linked to generators in the magnetosphere, but is not just an
 138 extension of the magnetospheric drift current.

139 The lower panels of Fig. 3 for the time moment 17:30 UT correspond to the
 140 main active phase of this disturbance period (cf. Fig. 1). The WEJ in the maps

of 17:30 UT appears therefore as an unloading electrojet. The conclusion, that the unloading electrojet of the given examples are Hall currents, does not agree with the well-known SCW model (*McPherron et al.*, 1973; *Kan*, 2007), where this WEJ is carried by a Cowling current (see Section 1).

On the whole, the data in Fig. 3 affirm the conclusion about the existence of electric circuits of the disturbed magnetosphere, each of which has its magnetospheric generators and a pair of antipodal FACs which close in the ionosphere by meridional Pedersen currents (*Mishin et al.*, 2010b). This is also supported by the data mentioned in paragraph 4 of the Introduction (Section 1).

Thick solid black lines in the FAC maps of Fig. 3 show the boundaries of the three Iijima-and-Potemra FAC regions, which correspond to the characteristics of each Region as given by *Potemra* (1994). We used additionally two rules supplementing each other: 1) The boundary of Region-0 should coincide with the high-latitude boundary of Region-1 of downward FAC on the dawn side (morning sector) and upward FAC on the dusk side (evening sector). 2) The terms “morning sector” and “evening sector” are conditional as the boundary between sectors divides two Region-1 FAC areas of predominantly different sign. “Predominantly” means, that the boundaries of each of these areas of the Iijima-and-Potemra Regions should be determined so that the integrated currents satisfy the condition:

$$\Delta = \delta I / I \leq 10\% \quad (1)$$

Here I describes the full downward ($I+$) or full upward ($I-$) FAC of the corresponding area in the MLT sector of the considered Iijima-and-Potemra

165 Region, and δI the full FAC of opposite sign in the same Region. According
 166 to this definition (1), within each specific area of downward or upward FAC,
 167 an intrusion of current with opposite sign δI from adjacent areas can take
 168 place. Such a definition corresponds to the simplifying assumption, that δI
 169 describes the possible error of the calculated value I . This “error” includes
 170 the known trends to a spiral distribution of the FAC density, which (trends)
 171 are inevitably abandoned within the limits of the Iijima-and-Potemra model
 172 approach. The maps allowed to deduce in this way the FAC intensities (I) of
 173 each Region, i.e. the integrated values of the total of upward and the total
 174 of downward (into the ionosphere) currents in the corresponding half-regions.
 175 Thus we estimated the FAC intensities (I) of each region both on the dawn
 176 and dusk side independently. We calculated also the difference currents (dI)
 177 between the dawn side current intensities and those on the dusk side for each
 178 Region. The graphic display of these differences (Figs. 5, 6), which reveals
 179 the dawn-dusk asymmetry mentioned above already, will be dealt with in the
 180 subsequent Sections 5 and 7.

181 **3 Spatial substructures of the Iijima-and-Potemra FAC regions**

182 In each region of the FAC maps in Fig. 3, right panels, one can notice the
 183 presence of medium-scale heterogeneities, which are indicated by symbols like
 184 R.N $\pm$ with a ”+“ sign for inflowing FAC into the ionosphere and a ”-“ sign for
 185 outflowing FAC. In the symbols, ”R“ stands for the Iijima-and-Potemra FAC
 186 Region number (R = 0, 1, or 2), and N = 1, 3, or 2 designate the dayside, night-
 187 side, or intermediate MLT sectors, respectively. For example, “1.3+” means
 188 Region-1 current in the nighttime MLT sector with downward FAC (into the

189 ionosphere along magnetic field lines at the Northern Hemisphere).

190 An idealized schematic distribution of the R.N FAC sectors is shown in
191 Fig. 4, panel (d) in magnetic latitude versus magnetic local time (MLT) co-
192 ordinates. This scheme reflects the intrinsic regularity of the spatial distribu-
193 tion of FAC substructures within the three main FAC Regions of Iijima and
194 Potemra. This scheme does not need to persist all the time in all its parts
195 and it might get disordered under certain conditions, but it reflects a statisti-
196 cal average or idealized pattern. Identified substructures are indicated by its
197 numbers R.N and also by its FAC sign in Fig. 3, right panels.

Fig. 3. Examples of equivalent ionospheric current (EIC) patterns (left panels) and of the spatial distribution of field-aligned current (FAC) density (right panels). The dials show geomagnetic latitude versus magnetic local time (MLT) with the outer boundary at 50° , midday (12 MLT) on top, dusk (18 MLT) to the left, etc. . The blue and black isocontours in the EIC maps distinguish clockwise and anticlockwise current vortices, respectively, while the blue and black isolines of the FAC pattern indicate correspondingly downward and upward currents. Thick solid black lines show the boundaries of Iijima-Potemra's FAC regions. The symbols of type R.N+ (or R.N-) have the following meaning: R stands for the Iijima-Potemra FAC region ($R = 0, 1$, or 2), and $N = 1, 3$, or 2 designate the dayside, nightside, or intermediate MLT sectors, respectively. For example, “1.2+” means “Region-1, intermediate MLT sector (near the dawn-dusk meridian) with downward (along magnetic field lines into the ionosphere at the Northern Hemisphere) FAC”. An idealised scheme of the FAC regions and its substructures is shown in Fig. 4, panel (d). The same classification of FAC regions is used in the schematic view of magnetospheric generators in Fig. 4.

Fig. 4. Schematic sectional view of the system of three magnetospheric generators for southward IMF. The three panels show the Northern Hemisphere part of the magnetosphere as seen from the dusk side (sun is to the left along the X-axis, the Y-axis points toward dusk) with sections in the equatorial plane and in an YZ-plane of the tail. The solid line “1” (yellow) in the equatorial plane of the first panel indicates the current in the bow shock, which is closed by the current “2” at the magnetopause (e.g. *Siscoe et al.*, 2000). The arrows with the Roman figures “I” and “III” show the current direction of the generators I and III, respectively. The Roman figure “II” indicates the cut through the volumetric generator II, at which the closed circle of the mantle current and the currents of the plasma sheet (PS) and the low-latitude boundary layer (LLBL) are drawn. The concentric circles in the equatorial plane delimit the ionospheric R0, R1, and R2 current regions of Iijima and Potemra. The thick continuous lines with arrow heads show the FACs, which connect the generator regions with the ionosphere by inward/outward (downward/upward) flowing currents. Panel (a) shows FACs 1.1 of generator I and 1.2 of generator II. The 1.2 currents are closed in the generator region II via meridional ionospheric currents, 0.2 FACs and the perpendicular currents DRP-2 in the tail lobe. Panel (b) shows the nighttime 1.3 FAC system of generator III. These FACs continue in the ionosphere as meridional currents toward higher and lower latitudes. They are closed via the 0.3 FACs to the nighttime part of the mentioned DRP-2 currents in the tail lobe and 2.3 FACS and DRP-1 currents in the inner magnetosphere, respectively. Panel (c) is a simplified version of the previous panel (b). It does not include the partial ring current DRP-1 and the R2 FACs. Panel (d) shows a schematic representation of the spatial substructures of the Iijima-and-Potemra FAC regions. Each of the three main regions split up into three medium-scale heterogeneities on both the dawn and dusk sides. They comprise the dayside, nightside, and intermediate MLT sectors. All three substructures can appear simultaneously, but need not necessarily persist all the time.

198 4 Magnetospheric generators

199 Which physics is behind the “R.N”-type FAC structures?

200 The answer to this question might be obvious, when applying it to the
201 FAC pair 1.3+ and 1.3- in the nighttime Region-1. These two FAC maxima
202 can certainly be ascribed to currents, which flow from the edges of the current
203 disruption region of the plasma sheet in the magnetospheric tail. The electric
204 field of this region is directed from dawn to dusk. Assuming that the current
205 disruption of the plasma sheet region is equivalent to feeding an oppositely
206 directed current (dusk-dawn) to this region, then we find fulfilled the condition
207 $\vec{j} \cdot \vec{E} < 0$, i.e. a generator (named “generator III” in Fig. 4) is situated in this
208 region with $N=3$. The current disruption in the tail is generated by nightside
209 reconnection and the generator III is created by this process in the nighttime
210 part of Region-1, where the corresponding ionospheric Region-1 FACs are
211 mapped (*McPherron et al.*, 1973).

212 In an analogous manner, we consider the FAC pair 1.1+ and 1.1- as cur-
213 rents, which flow out of the dawn-dusk current disruption at the dayside mag-
214 netopause. It is known, that in this dayside region with $N=1$ the electric field
215 is directed from dawn to dusk and this magnetospheric region is also gen-
216 erated by reconnection processes, but on the dayside magnetopause (*Siscoe*
217 *et al.*, 2000; *Cowley*, 2000). We find therefore, that the FAC pair 1.1+ and
218 1.1- can be ascribed to generator I, which is due to reconnection processes at
219 the dayside magnetopause.

220 The reconnection at the dayside magnetopause creates also open magnetic
221 flux Ψ in the tail lobes. This open flux is transported by the solar wind in

222 antisolal direction and crosses each perpendicular slice plane of the tail, one
 223 of which is illustrated in Fig. 4 (*Dungey*, 1961). In doing so, it excites emf in
 224 the mantle (marked by arrows) and creates therefore a volumetric generator in
 225 the tail lobes. We assume that a dusk-dawn current is induced in the mantle
 226 as indicated by those arrows in Fig. 4, which closes in the plasma sheet as
 227 dawn-dusk current. The middle part of the tail volume corresponds to the
 228 intermediate MLT sector with $N=2$. The volumetric generator is indicated
 229 with the Roman figure II (see Fig. 4, panels a and b).

230 Thus the position of the three mentioned generators in the magnetosphere
 231 is shown in Fig. 4. The electric circuits of the Northern Hemisphere includ-
 232 ing its generators are shown there as well (*Mishin et al.*, 2004, 2010b). We
 233 assume for this study, that due to the widespread character of ionospheric
 234 conductance, each generator closes through the whole ionosphere. The three
 235 generators constitute a common system for the three zones in the Northern
 236 Hemisphere, and together with the three similar generators in the Southern
 237 Hemisphere (not shown) they constitute a unified system - the global dynamo.
 238 Further details are given in the caption of Fig. 4.

239 5 FAC intensity variations in each current region

240 In the scheme of Fig. 4, each generator and the generator system as a whole
 241 is connected by FACs to the ionospheric Region-1. These FACs feed meridional
 242 Pedersen currents, which on their turn supply Region-2 and Region-0 FACs.
 243 It means that all three Iijima-and-Potemra regions in the schematic view of
 244 Fig. 4 are caused by a common unified system of magnetospheric generators,
 245 shown there for the Northern Hemisphere only. An expected implication of

Fig. 5. Integrated downward or upward total currents (FAC intensities I) of the Iijima-and-Potemra Regions are drawn versus UT. The left and right panels are for the dusk sector and dawn sector, respectively. The symbols $I.R_i+$ ($I.R_i-$) indicate total integrated downward (upward) FAC intensities, where “i” ($i = 0, 1$, or 2) stands for the FAC Region number. The green lines are summations of Region-2 and Region-0 total currents to be compared with the Region-1 contributions (in black).

246 this argument is the equality of the FAC intensities between Region-1 and the
 247 sum of Region-2 and Region-0, $I(R1) = I(R2) + I(R0)$. In accordance with the
 248 model scheme (Fig. 4), such an equality is fulfilled for both the dawn and the
 249 dusk side independently, which should be true for both hemispheres. These
 250 two halves (dawn and dusk side) seem to vary in a self-contained manner.

251 To check this statement, Fig. 5 shows the variation of the FAC intensities
 252 of the Northern Hemisphere, i.e. the integrated FAC densities over each area
 253 of the three regions, separately for the dawn (right panel) and dusk side (left
 254 panel), respectively. In the dawn side, the inflowing (downward at the North

Fig. 6. Difference of the integrated FAC intensities (total currents) of the dusk- and the dawn-side as shown in Fig. 5 , i.e., the FAC intensities of the various regions and the summations of Region-2 and Region-0 current (in green) of the dawn side (right panel in Fig. 5) are subtracted from those on the dusk side (left panel in Fig. 5). The difference currents are interpreted as hemispheric imbalances of the FAC flows, resulting in interhemispheric FACs, which connect both hemispheres (see text).

255 Hemisphere) FAC of Region-1 is shown together with the outflowing (upward
 256 FACs) of Region-2 and Region-0. In the dusk side, on the other hand, the
 257 outflowing Region-1 and the inflowing Region-2 and Region-0 FACs are shown
 258 correspondingly. The result of the comparison in each side gives in fact an
 259 evidence of the approximative equality of $I(R1) = I(R2) + I(R0)$ within the
 260 probable precision (error bars) of the method for both the dawn and the dusk
 261 sides.

262 Fig. 6 illustrates the previously (Section 2) mentioned asymmetry between
 263 the dawn-side and dusk-side FAC densities. It shows the differences of the

264 integrated FAC intensities between the dawn side currents and those on the
 265 dusk side, which were shown in Fig. 5 independently on the right and left
 266 hand panel, respectively. During the prestorm interval (1500-1632 UT) an
 267 asymmetry $I.R(\text{dusk}) > I.R(\text{dawn})$ can be noticed; during the storm interval
 268 (1641-2000 UT) the sign of the asymmetry varies with time, as Fig. 6 shows
 269 more clearly. We presume that this asymmetry between the dawn and the dusk
 270 side can be explained by FACs, which connect both hemispheres (beside of the
 271 FACs that close entirely within the Northern Hemisphere via the ionosphere
 272 and the northern half of the plasma sheet with DRP-1). The principal cause for
 273 this asymmetry could be, for instance, the disparity between the conductances
 274 of both hemispheres within the Region-2+ footpoints, i.e., $\Sigma_N \neq \Sigma_S$, where Σ
 275 stands for the height-integrated ionospheric conductance within these named
 276 zones.

277 The observed disparity in Fig. 6 is, as mentioned already, most likely due to
 278 the fact, that the electric circuit of the generator system comprises (as distinct
 279 from the scheme in Fig. 4) an additional FAC of Region-2, which links the two
 280 hemispheres. As shown in Fig. 4, which displays the generator system of the
 281 Northern Hemisphere only, the R2- FAC of the dawn side in the Northern
 282 Hemisphere is connected with the dynamo system via the asymmetric ring
 283 current DRP-1 and the R2+ FAC of the dusk side. In this schematic view, the
 284 connecting FACs don't ramify to the Southern Hemisphere, if the system is
 285 completely symmetric or, in other words, if $\Sigma_N = \Sigma_S$. However, by assuming
 286 additionally, that the global dynamo system consists of two symmetric halves
 287 in both the Northern and Southern Hemisphere, and there exists an inequality
 288 like $\Sigma_N < \Sigma_S$, then we should expect a different situation (see below).

289 We selected the Region-2 FAC due to two reasons. Firstly, it is this FAC

290 that connects the DRP-1 of the inner magnetosphere with the ionosphere and,
 291 secondly, just this FAC is continued by R1- FAC in the auroral ionosphere,
 292 where the Harang discontinuity and substorm onsets are usually observed (e.g.
 293 *Zou et al.*, 2009; *Lyons et al.*, 2009). Due to these reasons, and remembering
 294 the well-known *Vasyliunas* (2001) equation for FAC density, which expresses
 295 the FAC density through magnetic field and pressure gradients of the plasma
 296 sheet in the equatorial plane, we expect the R1 and R2 FACs to be both
 297 variable and different between the Northern and Southern Hemispheres.

298 For $\Sigma_N < \Sigma_S$, the Region-2 FAC of the Northern Hemisphere will split at
 299 the dusk side and a substantial part of it will close as R2+ current through
 300 the Southern ionosphere, i.e., will get lost partly for the Northern Hemisphere.
 301 Thus, when $\Sigma_N < \Sigma_S$, the asymmetry is of the type dawn<dusk, while for
 302 $\Sigma_N > \Sigma_S$ the opposite (dawn>dusk) applies. Asymmetric conditions in the
 303 distribution of FACs and electric potentials of both hemispheres were men-
 304 tioned already, e.g., by *Lu et al.* (1994); *Papitashvili et al.* (2002); *Lukianova*
 305 *et al.* (2008) and *Shi et al.* (2010).

306 Following the above reasoning, the dawn-dusk FAC asymmetry can in prin-
 307 ciple be induced by any North-South asymmetry of the ionospheric current
 308 distribution, the divergence of which constitutes the FAC system. That means,
 309 the proposed model of the global dynamo system with the mentioned addi-
 310 tional Region-2+ FACs, which connect both hemispheres, enables to explain
 311 at least qualitatively the observational facts of the dawn-dusk disparity and
 312 variability of the FAC intensities.

313 We performed numerical experiments using MIT-2 and identical Northern
 314 Hemisphere input magnetometer data with varying ionospheric conductance

Fig. 7. The electric circuit of the global dynamo system. Thin lines symbolize electric equipotential connections, thick lines the ionospheric resistors (see text for explanations).

315 models: spatial homogeneous and inhomogeneous ones. With conductances in
 316 the homogeneous model of $\Sigma_P = 7$ S and $\Sigma_H = 14$ S, the calculated average
 317 FAC intensity values for the Northern Hemisphere turned out to be about
 318 twice as large as those calculated with the standard inhomogeneous model.
 319 Nevertheless, the experiments showed, that the fact of dawn-dusk differences
 320 in the FAC intensities persisted and even the sign of the differences mostly
 321 remained the same, independent of the conductivity distribution options. We
 322 conclude that the observed asymmetry cannot be related to errors of the con-
 323 ductance model, which is inevitably a coarse approximation only at the present
 324 stage of global modelling. This conclusion is in line with the results of *Lu et al.*
 325 (2001).

326 The described global dynamo electric circuit is shown schematically in
 327 Fig. 7. The global dynamo feeds two generator halves: one for the Northern
 328 (top) and one for the Southern Hemisphere (bottom). The left half repre-
 329 sents the dawn side, the right half the dusk side. The symbols with large and
 330 small initial letters of the type R1+, r1+, etc. correspond to the Northern and
 331 Southern Hemisphere, respectively. The letters “R” and ”r” in these symbols
 332 stand for the Regions R0, R1, or R2; the signs “+” and “-” correspond to
 333 downward and upward FACs in the ionosphere, respectively. This notation is
 334 similar to that in Figs. 3 and 4 with the exception, that the differentiation into
 335 substructures “N” (as in “R.N”) are absent here. This means that the scheme
 336 of Fig. 7 is the same for all three values of N (i.e., N=1, 2, or 3). The circuit of
 337 Fig. 7 differs from that in Fig. 4 in two points: it describes both hemispheres
 338 as two parts of one global dynamo and, secondly, it comprises now an addi-
 339 tional electric link of the two hemispheres, which is shown in Fig. 7 by the
 340 two thin lines, connecting block r2+ with block R2+. In the case considered
 341 above with $\Sigma_N < \Sigma_S$, the additional FAC flows from the North to the South
 342 Hemisphere (R2- to r2+).

343 **6 Current or voltage generator?**

344 Now we will come to a different, but associated topic: What is the type of
 345 the global dynamo?

346 The global dynamo consists of two coexistent dynamos in the Northern and
 347 Southern Hemisphere, respectively. Each of these two is assembled of three
 348 generators and each of the resulting six generators feeds the whole ionosphere.
 349 But the main part of the load of each individual generator is attributed to

350 some particular portion of the whole magnetosphere. The ratio α between the
 351 internal generator's resistance, R_i , and its associated load resistance, R_e , is
 352 therefore different for each generator and depends on many various factors.
 353 This way the value α (i.e., discriminating between current generators and
 354 voltage generators) for the resulting global generator can adopt various val-
 355 ues, depending, e.g., on the dipole tilt angle (which causes a strong UT and
 356 seasonal variation), the phases and strength of disturbances, the IMF B_y and
 357 B_z conditions and so forth.

358 These arguments give a comprehension about the diversity of situations,
 359 where the global dynamo in different observational periods as well as in differ-
 360 ent numerical experiments may appear on the one hand as current generator
 361 and on the other hand as voltage generator. The significant intensification of
 362 FACs, e.g., at the transition from winter to summer conditions, as in the data
 363 of *Shi et al.* (2010), gives evidence in favour of the voltage generator. Data
 364 of an opposite sense, i.e., in favour of a current generator, were presented by
 365 *MacDougall and Jayachandran* (2007).

366 Relating to this, let us consider the conditions under which the global FAC
 367 dynamo acts as voltage or current generator. For this purpose, we examine
 368 the Ohm's law in terms of $Q = U^2/R$, where U is the overall potential drop
 369 of the global dynamo, and $R = R_i + R_e$ is the sum of the generator's internal
 370 resistance (i) and the load or external resistance (e). We assume that the
 371 observed range of magnetospheric power values Q extend from $\sim 2 \cdot 10^{10} \text{ W}$
 372 for the most quiet conditions to $\sim 2 \cdot 10^{13} \text{ W}$ during superstorms. Considering
 373 further that the cross-polar cap potential reaches saturation values up to about
 374 $U \leq 200 \text{ kV}$ during extreme conditions and that it has values of about $U \geq$
 375 10 kV for quiet conditions, we get resistance values R between $5 \cdot 10^{-3} \Omega$ and

376 $2 \cdot 10^{-3} \Omega$ for quiet and strongly disturbed conditions, respectively. Therefore,
 377 while the global dynamo intensifies by a factor of 1000, the full resistivity
 378 of its current circuit diminishes only slightly or, considering the precision of
 379 calculations, does not change significantly.

380 It is well known, on the other hand, that the R_i values increase during
 381 the transition from quiet to superstorm conditions. Considering this fact and
 382 the above mentioned data of *Papitashvili and Rich* (2002), we conclude that
 383 $R_i < R_e$ holds also during superstorms. It is therefore most likely that during
 384 disturbed condition such as during quiet conditions the global dynamo will
 385 act as voltage generator rather than as current generator.

386 7 Conclusions

387 The main results of the present study are the following.

388 The electric current in the disturbed magnetosphere/ionosphere system of
 389 the Northern Hemisphere is described for the April 06, 2000, superstorm pe-
 390 riod. The empirical conceptual model describes three generator regions: at the
 391 nightside, the dayside and at intermediate MLT sectors, respectively (*Mishin*
 392 *et al.*, 2004, 2010b). We used the terms of electric engineering theory with
 393 lumped parameters, but did not confine to that alone.

394 We note that for the event considered the currents in the ionosphere are
 395 mainly meridional Pedersen currents, which connect two neighbouring, oppo-
 396 sately directed FAC regions of Iijima and Potemra. This is true even for the
 397 unloading westward auroral electrojet that is carried by a Hall current. The
 398 latter requires a substantial addition to the well-known SCW model, where

399 this electrojet is carried by a Cowling current.

400 We obtained primarily plots of the temporal variation of FAC intensities for
401 each of the three FAC regions of Iijima and Potemra in the Northern Hemi-
402 sphere. Here we could show for the first time, that during the superstorm
403 disturbance there persists an approximate equality between the Region-1 cur-
404 rent intensity and the sum of both Region-2 and Region-0 current intensities
405 at the dawn and dusk side independently.

406 This equality of current intensities means, that the mentioned three genera-
407 tors in the Northern Hemisphere are parts of one and the same comprehensive
408 dynamo system. This generator system first generates the Region-1 currents,
409 which then spread through the ionosphere to feed both the Region-2 and
410 Region-0 FACs. This conclusion is obtained here for the first time empirically,
411 but it supports theoretical results found previously by, e.g., *Siscoe* (1982),
412 *Siscoe et al.* (2000) and *Cowley* (2000).

413 We found and described for the first time the previously unknown asymmet-
414 ric characteristics of the dawn and dusk side FAC intensities. The disbalance
415 appears to be quite strong and its sign varies. This asymmetry is interpreted
416 in terms of FACs, which connect both hemispheres. It represents an addi-
417 tion to the model of generators as shown in Fig. 4 that describes solely those
418 FACs, which are closed in the ionosphere of the Northern Hemisphere. The
419 completed model of the global dynamo system consists of three generators in
420 the Northern and three analogous generators in the Southern Hemisphere as
421 well as FACs, which connect both hemispheres.

422 According to the described electric circuits of the global dynamo system,
423 this dawn-dusk asymmetry results from an asymmetry between electrody-

424 namic parameter distributions of the two hemispheres and vice versa. This
425 conclusion sheds light on the long-standing discussion about these two kinds
426 of asymmetries and allows a new approach to their detailed study.

427 Numerical experiments showed (cf. Section 5, page 21) that the discovered
428 asymmetry cannot be caused by the uncertainty of the model's conductances,
429 which are of course only approximate at the present stage.

430 We concluded that the global magnetospheric dynamo works as voltage
431 generator during relatively quiet conditions as well as during heavily disturbed
432 conditions.

433 On the whole, we give only a qualitative, conceptual explanation of the
434 stated observations (Figs. 5 and 6) using a set of assumptions that allows
435 the simplest description of these observations in terms of electric engineering.
436 A more or less complete description of the problem under consideration is
437 possible, of course, only within the framework of a corresponding MHD mod-
438 elling. On the other hand, the schematic in Fig. 7 suggests a new approach to
439 the problems, which are well known as long-standing, but still unsolved ones
440 as, e.g., the inequality of downward and upward (or dawn-dusk) FACs in the
441 Iijima-and-Potemra regions of one and the same hemisphere and the problem
442 of the electric connectivity between the two hemispheres. There are further
443 questions like that on the type of the magnetospheric dynamo(s) as voltage or
444 current generator(s) and the problem of the source for the three Iijima-and-
445 Potemra regions, i.e., is it a common global dynamo or does it consist of three
446 different generators. Our new approach underlines the close link of the named
447 problems.

448 We hope that our results may be used for the formulation and interpretation

449 of further global MHD modelling efforts of the disturbed magnetosphere. An
450 associated paper, based on the data of a substorm event during the storm of
451 Aug 02, 2002, is prepared for publication elsewhere.

452 **Acknowledgement**

453 Work at ISTP was supported by the Russian Foundation for Basic Research
454 (RFBR) under grant No. 08-05-90207 Mong_a and No. 09-02-00082a.

455 Work at the GFZ German Research Centre for Geosciences Potsdam was sup-
456 ported by the Deutsche Forschungsgemeinschaft (DFG).

457 We thank the World Data Center for Geomagnetism (WDC-2), Kyoto, for
458 providing the AE and SYM-H indices. The authors thank the following col-
459 leagues and teams for supplying MIT input data: D. McComas, R. Lepping,
460 K. Ogilvie, J. Stenberg and A. Lasarus (WIND data); H. Gleisner (DMI,
461 Denmark), A. Viljanen (IMAGE project), K. Yumoto (project 210MM), T.
462 Iyemori (WDC-C2, Kyoto), J. Posch (project MACCS), O. A. Troshichev
463 (AARI St.-Peterburg), E. P. Kharin (WDC-B), S. I. Solovjov (Jakutsk), B.
464 M. Schevtsov and A. V. Vinnitzky (IKIR), the teams of INTERMAGNET,
465 GIMA (Alaska), CANOPUS (CARISMA) (D. Milling), S. Khomutov (obser-
466 vatory Novosibirsk), and O. Kusonsky (observatory Arti).

467 We thank also the collaborators of the MIT team: A. D. Bazarzhapov, Yu. A.
468 Karavaev, T. I. Saifudinova, L. A. Saprionova, and M. Tolochko for fruitful
469 discussions and the technical support.

470 **Appendix**

471

Table A.1

List of the Northern Hemisphere geomagnetic observatories used for this study.

#	Name	diplat	diplong	#	Name	diplat	diplong
1	Chokurdakh	64.54	216.56	61	Lerwick	60.29	95.97
2	Magadan	54.45	223.75	62	Lovoe	56.91	113.26
3	Onagawa	32.25	220.11	63	Mbour	17.67	67.83
4	Petropavlovsk	48.35	232.37	64	Meanook	61.46	321.68
5	Tixie Bay	64.15	202.31	65	Memambetsu	37.95	221.75
6	Zuriynka	60.09	221.38	66	Narsarsuaq	67.27	48.94
7	Arti	49.66	147.62	67	Nagycenk	45.67	107.90
8	Contwoyto Lake	72.61	318.79	68	Newport	54.86	319.07
9	Dawson City	67.61	286.62	69	Niemegk	50.56	105.51
10	Eskimo Point	69.19	344.33	70	Nurmijarvi	57.16	119.89
11	Fort Simpson	67.69	308.91	71	Ottawa	53.64	8.30
12	Fort Smith	66.93	321.31	72	Poste-de-la-Baleine	63.57	6.14
13	Gillam	64.46	344.46	73	Resolute Bay	82.61	334.09
14	Island Lake	61.94	344.81	74	Sitka	61.41	295.32
15	McMurray	63.69	323.58	75	Sodankyla	63.51	125.46
16	Pinawa	58.23	343.58	76	San Pablo-Toledo	40.75	85.20
17	Rabbit Lake	65.81	332.47	77	Saint Johns	54.60	35.50
18	Rankin Inlet	70.97	346.62	78	Surlari	41.50	116.05
19	Ammassalik	70.62	61.64	79	Tamanrasset	22.81	91.62
20	Attu	74.68	43.65	80	Thule	85.16	36.51
21	Danmarkshavn	77.89	101.36	81	Tihany	44.79	108.79
22	Frederikshab	68.53	44.20	82	Tucson	39.43	328.81
23	Godthab	70.85	42.97	83	Victoria	54.47	311.84
24	Kullorsuaq	81.33	49.23	84	Wingst	52.69	102.73
25	Scoresbysund	73.00	84.91	85	Yellowknife	69.12	316.78
26	Sukkertoppen	72.19	42.35	86	Andenes	66.63	118.24
27	Sondre Stromfjord	73.51	46.60	87	Bear Island	71.04	126.32
28	Savissivik	83.46	39.63	88	Dombas	60.72	106.82
29	Umanaq	77.16	49.01	89	Hankasalmi	58.64	122.50
30	Upernavik	79.56	46.71	90	Hornsund	73.64	127.74

31	Eagle	68.02	283.77	91	Kevo	65.73	127.55
32	Fort Yukon	69.11	277.80	92	Kilpisjarvi	65.77	121.92
33	Gakona	65.19	281.47	93	Kiruna	64.71	120.67
34	Poker	67.45	276.88	94	Leknes	65.86	115.12
35	Abisko	65.39	119.76	95	Lovozero	63.13	132.69
36	Budkov	47.46	105.79	96	Lycksele	61.85	116.99
37	Belsk	49.23	113.01	97	Longuearbyen	74.64	130.23
38	Brorfelde	54.16	105.95	98	Maisach	65.83	124.65
39	Baker Lake	72.29	340.71	99	Muonio	64.50	123.38
40	Beijing Ming Tombs	32.39	196.92	100	New Aalesund	75.66	129.31
41	Boulder	47.68	334.11	101	Oulujarvi	60.71	124.19
42	Barrow 1	71.81	260.87	102	Pello	63.37	123.03
43	Bay St. Louis	38.64	352.25	103	Rorvik	63.19	110.39
44	Cambridge Bay	76.43	324.61	104	Soroya	67.02	124.41
45	Chambon-la-Foret	48.09	94.14	105	Tromso	66.60	120.96
46	College	67.19	276.68	106	Uppsala	57.52	113.11
47	Del Rio	37.16	340.02	107	Gjoa Haven	76.56	338.80
48	Eskdalemuir	55.96	91.56	108	Igloolik	77.61	1.32
49	Fort Churchill	66.85	344.78	109	Pangnirtung	73.89	24.95
50	Fredericksburg	46.48	5.97	110	Repulse Bay	74.79	354.53
51	Fresno	43.51	318.09	111	Moscow	50.75	129.06
52	Fürstenfeldbruck	46.95	102.89	112	Cape Chelyuskin	69.45	184.16
53	Godhavn	75.95	45.15	113	Dikson	65.48	168.61
54	Guimar-Tenerife	31.39	70.60	114	Vize	71.47	168.44
55	Hartland	51.97	88.50	115	Alert	87.12	116.09
56	Hel	52.19	112.17	116	Dourbes	49.79	97.11
57	Hurbanovo	45.70	109.35	117	Ebro	41.30	90.33
58	Iqaluit	71.71	20.05	118	Leirvogur	67.12	78.20
59	Irkutsk	43.91	186.00	119	Manhay	49.83	98.22
60	Kakioka	29.95	219.22	120	Valentia	53.71	83.09

References

- Akasofu, S.-I., Several controversial issues on substorms, *Space Sci. Rev.*, *113*, 1–40, 2004.
- Baumjohann, W., and R. A. Treumann, *Basic Space Plasma Physics*, Imperial College Press, London, 1996.
- Cowley, S. W. H., Magnetosphere–ionosphere interactions: A tutorial review, in *Magnetospheric Current Systems, Geophysical Monograph*, vol. 118, edited by S.-I. Ohtani, R. Fujii, M. Hesse, and R. L. Lysak, pp. 91–106, American Geophysical Union, 2000.
- Crooker, N. C., and G. L. Siscoe, Ring coupling model: Implications for substorm onset, *Geophys. Res. Lett.*, *10*(8), 761–764, 1983.
- Dungey, J. W., Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, *6*, 47–48, 1961.
- Förster, M., V. M. Mishin, P. Stauning, J. Watermann, T. I. Saifudinova, and A. D. Bazarzhapov, Plasma convection in the Earth’s magnetosphere and ionosphere during substorms, *Adv. Space Res.*, *38*(8), 1750–1754, 2006.
- Gjerloev, J. W., and R. A. Hoffman, Currents in auroral substorms, *J. Geophys. Res.*, *107*(A8), doi:10.1029/2001JA000194, 2002.
- Heikkila, W. J., Magnetospheric topology of fields and currents, in *Magnetospheric currents, Geophysical Monograph*, vol. 28, edited by T. A. Potemra, pp. 208–222, American Geophysical Union, 1984.
- Huttunen, K. E. J., H. E. J. Koskinen, T. I. Pulkkinen, A. Pulkkinen, M. Palmroth, E. G. D. Reeves, and H. J. Singer, April 2000 magnetic storm: Solar wind driver and magnetospheric response, *J. Geophys. Res.*, *107*(A12), 1440, doi:10.1029/2001JA009154, 2002.
- Iijima, T., T. A. Potemra, and L. J. Zanetti, Large-scale characteristics of

498 magnetospheric equatorial currents, *J. Geophys. Res.*, *95*(A2), 991–999,
499 1990.

500 Kamide, Y., and W. Baumjohann, *Magnetosphere-Ionosphere Coupling*,
501 Springer Verlag, Berlin-Heidelberg, 1993.

502 Kamide, Y., A. D. Richmond, and S. Matsushita, Estimation of ionospheric
503 electric fields, ionospheric currents, and field-aligned currents from ground
504 magnetic records, *J. Geophys. Res.*, *86*(A2), 801–813, 1981.

505 Kan, J. R., On the formation of near-Earth X-line at substorm expansion
506 onset, *J. Geophys. Res.*, *112*, A01207, doi:10.1029/2006JA012011, 2007.

507 Liang, J., and W. W. Liu, A MHD mechanism for the generation of the merid-
508 ional current system during substorm expansion phase, *J. Geophys. Res.*,
509 *112*, A09208, doi:10.1029/2007JA012303, 2007.

510 Liu, Z. X., L. C. Lee, C. Q. Wey, and S.-I. Akasofu, An equivalent circuit
511 approach, *J. Geophys. Res.*, *93*(A7), 7266–7375, 1988.

512 Lu, G., A. D. Richmond, B. A. Emery, P. H. Reiff, O. De La Beaujardiere, F. J.
513 Rich, W. F. Denig, H. W. Kroehl, L. R. Lyons, J. M. Ruohoniemi, E. Friis-
514 Christensen, H. Opgenoorth, M. A. L. Persson, R. P. Lepping, A. S. Rodger,
515 T. Hughes, A. McEwin, S. Dennis, R. Morris, G. Burns, and L. Tomlin-
516 son, Interhemispheric asymmetry of the high-latitude ionospheric convec-
517 tion pattern, *J. Geophys. Res.*, *99*(A4), 6491–6510, 1994.

518 Lu, G., A. D. Richmond, J. M. Ruohoniemi, R. A. Greenwald, M. R. Hairston,
519 F. J. Rich, and D. Evans, An investigation of the influence of data and model
520 inputs on assimilative mapping of ionospheric electrodynamics, *J. Geophys.*
521 *Res.*, *106*(A1), 417–433, 2001.

522 Lui, A. T. Y., and Y. Kamide, A fresh perspective of the current system and
523 its dynamo, *Geophys. Res. Lett.*, *30*(18), 1958, doi:10.1029/2003GL017835,
524 2003.

525 Lukianova, R., C. Hanuise, and F. Christiansen, Asymmetric distribution of
 526 the ionospheric electric potential in the opposite hemispheres as inferred
 527 from the SuperDARN observations and FAC-based convection model, *J.*
 528 *Atmos. Sol.-Terr. Phys.*, *70*(18), 2324–2335, 2008.

529 Lyons, L. R., C.-P. Wang, M. Gkioulidou, and S. Zhou, Connections between
 530 plasma sheet transport, Region 2 currents, and entropy changes associated
 531 with convection, steady magnetospheric convection periods, and substorms,
 532 *J. Geophys. Res.*, *114*, A00D01, doi:10.1029/2008JA013743, 2009.

533 Lysak, R. L., Auroral electrodynamics with current and voltage generators, *J.*
 534 *Geophys. Res.*, *90*(A5), 4178–4190, 1985.

535 MacDougall, J. W., and P. T. Jayachandran, Polar cap voltage saturation, *J.*
 536 *Geophys. Res.*, *111*, A12306, doi:10.1029/2006JA011741, 2006.

537 MacDougall, J. W., and P. T. Jayachandran, Reply to comment by G. L.
 538 Siscoe and K. D. Siebert on “Polar cap voltage saturation”, *J. Geophys.*
 539 *Res.*, *112*, A06228, doi:10.1029/2007JA012263, 2007.

540 McPherron, R. L., M. P. Russell, and M. P. Aubry, Satellite studies of mag-
 541 netospheric substorms on August 15, 1968. 9. Phenomenological model for
 542 substorms, *J. Geophys. Res.*, *78*(16), 3131–3152, 1973.

543 Mishin, V. M., The magnetogram inversion technique and some applications,
 544 *Space Sci. Rev.*, *53*, 83–163, 1990.

545 Mishin, V. M., T. I. Saifudinova, A. D. Bazarzhapov, C. T. Russell,
 546 W. Baumjohann, R. Nakamura, and M. Kubyshkina, Two distinct substorm
 547 onsets, *J. Geophys. Res.*, *106*(A7), 13,105–13,118, 2001.

548 Mishin, V. M., V. V. Mishin, and D. S. Shirapov, Electric fields and field-
 549 aligned currents, in *Auroral Phenomena and Solar-Terrestrial Relations*,
 550 *CAWSES Handbook-001*, edited by L. M. Zelenyi, M. A. Geller, and J. H.
 551 Allen, pp. 128–133, 2004.

552 Mishin, V. M., L. A. Sapronova, T. I. Saifudinova, R. Lukianova, and
 553 Y. Kuzminykh, The Hall's and Cowling's currents contribution into the
 554 westward auroral electrojet during substorm - unloading phase, in *Physics*
 555 *of Auroral Phenomena, Proceedings of the XXXI Annual Seminar in Ap-*
 556 *atity, Russia*, pp. 42–45, Kola Science Centre, Russian Academy of Science,
 557 2008.

558 Mishin, V. M., A. D. Bazarzhapov, U. Sukhbaatar, and M. Förster,
 559 Electric circuits of the disturbed magnetosphere-ionosphere system
 560 and their generators, *GiA*, 50(8 (Special Issue 2)), 988–996, doi:
 561 10.1134/S0016793210080098, English translation in: ISSN 0016-7932, Ge-
 562 omagnetism and Aeronomy, Pleiades Publishing Ltd., 2010a.

563 Mishin, V. M., M. A. Kurikalova, and M. Förster, Electric circuits and their
 564 generators in the Earth's magnetosphere: The concept of electric circuits
 565 as applied to the first phase of the April 6, 2000, superstorm, *GiA*, 50(8
 566 (Special Issue 2)), 978–987, doi:10.1134/S0016793210080086, English trans-
 567 lation in: ISSN 0016-7932, Geomagnetism and Aeronomy, Pleiades Publish-
 568 ing Ltd., 2010b.

569 Papitashvili, V. O., and F. J. Rich, High-latitude ionospheric convection mod-
 570 els derived from Defense Meteorological Satellite Program ion drift obser-
 571 vations and parameterized by the interplanetary magnetic field strength
 572 and direction, *J. Geophys. Res.*, 107(A8), 1198, doi:10.1029/2001JA000264,
 573 2002.

574 Papitashvili, V. O., F. Christiansen, and T. Neubert, A new model of field-
 575 aligned currents derived from high-precision satellite magnetic field data,
 576 *Geophys. Res. Lett.*, 29(14), 1683, doi:10.1029/2001GL014207, 2002.

577 Parker, E. N., The alternative paradigm for magnetospheric physics, *J. Geo-*
 578 *phys. Res.*, 101(A5), 10.587–10.625, 1996.

579 Parker, E. N., Newton, Maxwell and magnetospheric physics, in *Magneto-*
 580 *spheric current systems*, *Geophysical Monograph*, vol. 118, edited by S.-I.
 581 Ohtani, pp. 1–10, American Geophysical Union, 2000.

582 Potemra, T. A., Sources of large-scale Birkeland currents, in *Physical Signa-*
 583 *tures of Magnetospheric Boundary Layer Processes*, edited by J. A. Holtet
 584 and A. Egeland, pp. 3–27, Kluwer Academic Publishers, 1994.

585 Shi, J. K., Z. W. Cheng, T. L. Zhang, M. Dunlop, Z. X. Liu, K. Torkar,
 586 A. Fazakerley, E. Lucek, H. Rème, I. Dandouras, A. T. Y. Lui, Z. Y. Pu,
 587 A. P. Walsh, M. Volwerk, A. D. Lahiff, M. G. G. T. Taylor, A. Grocott,
 588 L. M. Kistler, M. Lester, C. Mouikis, and C. Shen, South–north asymmetry
 589 of field-aligned currents in the magnetotail observed by Cluster, *J. Geophys.*
 590 *Res.*, *115*, A07228, doi:10.1029/2009JA014446, 2010.

591 Siscoe, G. L., Polar cap size and potential: A predicted relationship, *Geophys.*
 592 *Res. Lett.*, *9*(6), 672–675, 1982.

593 Siscoe, G. L., and K. D. Siebert, Comment on “Polar cap voltage satura-
 594 tion” by J. W. MacDougall and P. T. Jayachandran, *J. Geophys. Res.*, *112*,
 595 A06227, doi:10.1029/2006JA012242, 2007.

596 Siscoe, G. L., N. U. Crooker, G. M. Erickson, B. U. Ö. Sonnerup, K. D. Siebert,
 597 D. R. Weimer, W. W. White, and N. C. Maynard, Global geometry of
 598 magnetospheric currents, in *Magnetospheric Current Systems*, *Geophysical*
 599 *Monograph*, vol. 118, edited by S.-I. Ohtani, R. Fujii, M. Hesse, and R. L.
 600 Lysak, pp. 41–52, American Geophysical Union, 2000.

601 Siscoe, G. L., G. M. Erickson, B. U. Ö. Sonnerup, N. C. Maynard, J. A.
 602 Schoendorf, K. D. Siebert, D. R. Weimer, W. W. White, and G. R. Wil-
 603 son, Hill model of transpolar potential saturation: Comparisons with MHD
 604 simulations, *J. Geophys. Res.*, *107*(A6), 1075, doi:10.1029/2001JA000109,
 605 2002.

606 Vasyliunas, V. M., Electric field and plasma flow: What drives what?, *Geophys.*
607 *Res. Lett.*, *28*(11), 2177–2180, 2001.

608 Weimer, D. R., Maps of ionospheric field-aligned currents as a function of the
609 interplanetary magnetic field derived from Dynamics Explorer 2 data, *J.*
610 *Geophys. Res.*, *106*(A7), 12,889–12,902, 2001.

611 Zou, S., L. R. Lyons, M. J. Nicolls, C. J. Heinselmann, and S. B. Mende,
612 Nightside ionospheric electrodynamics associated with substorms: PFISR
613 and THEMIS ASI observations, *J. Geophys. Res.*, *114*, A12301, doi:
614 10.1029/2009JA014259, 2009.