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

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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
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1996, 2000; Vasyliunas, 2001) concluded finally, that the description of magnetospheric 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 approximation.

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 allowed 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 observations 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 electric circuit schemes were given, e.g., by Lysak (1985); Liu et al. (1988); MacDougall 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,
Mishin et al. (2004) and Förster et al. (2006) elaborated an empirical model of FACs, which takes into account all three zones of Iijima-and-Potemra’s pattern, while introducing three additional meso-scale substructures for each of these regions. These three substructures are attributed in the model of Mishin et al. (2004) to a particular unified system of generators. The present study focuses on the further development of this complemented Iijima-and-Potemra model, pointing out its complex system of generators and interrelationships.

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

The global current circuit with its generators comprises also Region-2 currents, which connect both hemispheres and hence also the dynamos placed both in the Northern and Southern Hemispheres. These dynamos are connected in parallel. We conclude finally, that this global magnetospheric dynamo as source of the global FAC system can work as voltage generator during relatively quiet (average) conditions, as well as under strong disturbance conditions.

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

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

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

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

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

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

The lower panels of Fig. 3 for the time moment 17:30 UT correspond to the 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:

$$\Delta = \delta I/I \leq 10\%$$  \hspace{1cm} (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
Region, and $\delta I$ the full FAC of opposite sign in the same Region. According to this definition (1), within each specific area of downward or upward FAC, an intrusion of current with opposite sign $\delta I$ from adjacent areas can take place. Such a definition corresponds to the simplifying assumption, that $\delta I$ describes the possible error of the calculated value $I$. This “error” includes the known trends to a spiral distribution of the FAC density, which (trends) are inevitably abandoned within the limits of the Iijima-and-Potemra model approach. The maps allowed to deduce in this way the FAC intensities ($I$) of each Region, i.e. the integrated values of the total of upward and the total of downward (into the ionosphere) currents in the corresponding half-regions. Thus we estimated the FAC intensities ($I$) of each region both on the dawn and dusk side independently. We calculated also the difference currents ($dI$) between the dawn side current intensities and those on the dusk side for each Region. The graphic display of these differences (Figs. 5, 6), which reveals the dawn-dusk asymmetry mentioned above already, will be dealt with in the subsequent Sections 5 and 7.

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

In each region of the FAC maps in Fig. 3, right panels, one can notice the presence of medium-scale heterogeneities, which are indicated by symbols like R.N± with a ”+“ sign for inflowing FAC into the ionosphere and a ”-“ sign for outflowing FAC. In the symbols, ”R“ stands for the Iijima-and-Potemra FAC Region number (R = 0, 1, or 2), and N = 1, 3, or 2 designate the dayside, nightside, or intermediate MLT sectors, respectively. For example, “1.3+” means Region-1 current in the nighttime MLT sector with downward FAC (into the
An idealized schematic distribution of the R.N FAC sectors is shown in Fig. 4, panel (d) in magnetic latitude versus magnetic local time (MLT) coordinates. This scheme reflects the intrinsic regularity of the spatial distribution of FAC substructures within the three main FAC Regions of Iijima and Potemra. This scheme does not need to persist all the time in all its parts and it might get disordered under certain conditions, but it reflects a statistical average or idealized pattern. Identified substructures are indicated by its 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.
4 Magnetospheric generators

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

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

In an analogous manner, we consider the FAC pair 1.1+ and 1.1- as currents, which flow out of the dawn-dusk current disruption at the dayside magnetopause. It is known, that in this dayside region with \( N=1 \) the electric field is directed from dawn to dusk and this magnetospheric region is also generated by reconnection processes, but on the dayside magnetopause (Siscoe et al., 2000; Cowley, 2000). We find therefore, that the FAC pair 1.1+ and 1.1- can be ascribed to generator I, which is due to reconnection processes at the dayside magnetopause.

The reconnection at the dayside magnetopause creates also open magnetic flux \( \Psi \) in the tail lobes. This open flux is transported by the solar wind in
antisolar direction and crosses each perpendicular slice plane of the tail, one
of which is illustrated in Fig. 4 (Dungey, 1961). In doing so, it excites emf in
the mantle (marked by arrows) and creates therefore a volumetric generator in
the tail lobes. We assume that a dusk-dawn current is induced in the mantle
as indicated by those arrows in Fig. 4, which closes in the plasma sheet as
dawn-dusk current. The middle part of the tail volume corresponds to the
intermediate MLT sector with N=2. The volumetric generator is indicated
with the Roman figure II (see Fig. 4, panels a and b).

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

5 FAC intensity variations in each current region

In the scheme of Fig. 4, each generator and the generator system as a whole
is connected by FACs to the ionospheric Region-1. These FACs feed meridional
Pedersen currents, which on their turn supply Region-2 and Region-0 FACs.
It means that all three Iijima-and-Potemra regions in the schematic view of
Fig. 4 are caused by a common unified system of magnetospheric generators,
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 $I_{Ri+}$ ($I_{Ri-}$) indicate total integrated downward (upward) FAC intensities, where “i” ($i = 0, 1, \text{or} 2$) 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).

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

To check this statement, Fig. 5 shows the variation of the FAC intensities of the Northern Hemisphere, i.e., the integrated FAC densities over each area of the three regions, separately for the dawn (right panel) and dusk side (left 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).

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

Fig. 6 illustrates the previously (Section 2) mentioned asymmetry between the dawn-side and dusk-side FAC densities. It shows the differences of the
integrated FAC intensities between the dawn side currents and those on the
dusk side, which were shown in Fig. 5 independently on the right and left
hand panel, respectively. During the prestorm interval (1500-1632 UT) an
asymmetry I.R(dusk)>I.R(dawn) can be noticed; during the storm interval
(1641-2000 UT) the sign of the asymmetry varies with time, as Fig. 6 shows
more clearly. We presume that this asymmetry between the dawn and the dusk
side can be explained by FACs, which connect both hemispheres (beside of the
FACs that close entirely within the Northern Hemisphere via the ionosphere
and the northern half of the plasma sheet with DRP-1). The principal cause for
this asymmetry could be, for instance, the disparity between the conductances
of both hemispheres within the Region-2+ footpoints, i.e., Σ_N ≠ Σ_S, where Σ
stands for the height-integrated ionospheric conductance within these named
zones.

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

We selected the Region-2 FAC due to two reasons. Firstly, it is this FAC
that connects the DRP-1 of the inner magnetosphere with the ionosphere and, secondly, just this FAC is continued by R1– FAC in the auroral ionosphere, where the Harang discontinuity and substorm onsets are usually observed (e.g. Zou et al., 2009; Lyons et al., 2009). Due to these reasons, and remembering the well-known Vasyliunas (2001) equation for FAC density, which expresses the FAC density through magnetic field and pressure gradients of the plasma sheet in the equatorial plane, we expect the R1 and R2 FACs to be both variable and different between the Northern and Southern Hemispheres.

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

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

We performed numerical experiments using MIT-2 and identical Northern Hemisphere input magnetometer data with varying ionospheric conductance
models: spatial homogeneous and inhomogeneous ones. With conductances in the homogeneous model of $\Sigma_P = 7 \, \text{S}$ and $\Sigma_H = 14 \, \text{S}$, the calculated average FAC intensity values for the Northern Hemisphere turned out to be about twice as large as those calculated with the standard inhomogeneous model. Nevertheless, the experiments showed, that the fact of dawn-dusk differences in the FAC intensities persisted and even the sign of the differences mostly remained the same, independent of the conductivity distribution options. We conclude that the observed asymmetry cannot be related to errors of the conductance model, which is inevitably a coarse approximation only at the present stage of global modelling. This conclusion is in line with the results of Lu et al. (2001).
The described global dynamo electric circuit is shown schematically in Fig. 7. The global dynamo feeds two generator halves: one for the Northern (top) and one for the Southern Hemisphere (bottom). The left half represents the dawn side, the right half the dusk side. The symbols with large and small initial letters of the type R1+, r1+, etc. correspond to the Northern and Southern Hemisphere, respectively. The letters “R” and ”r” in these symbols stand for the Regions R0, R1, or R2; the signs “+” and “−” correspond to downward and upward FACs in the ionosphere, respectively. This notation is similar to that in Figs. 3 and 4 with the exception, that the differentiation into substructures “N” (as in “R.N”) are absent here. This means that the scheme of Fig. 7 is the same for all three values of N (i.e., N=1, 2, or 3). The circuit of Fig. 7 differs from that in Fig. 4 in two points: it describes both hemispheres as two parts of one global dynamo and, secondly, it comprises now an additional electric link of the two hemispheres, which is shown in Fig. 7 by the two thin lines, connecting block r2+ with block R2+. In the case considered above with $\Sigma_N < \Sigma_S$, the additional FAC flows from the North to the South Hemisphere (R2− to r2+).

6 Current or voltage generator?

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

The global dynamo consists of two coexistent dynamos in the Northern and Southern Hemisphere, respectively. Each of these two is assembled of three generators and each of the resulting six generators feeds the whole ionosphere. But the main part of the load of each individual generator is attributed to
some particular portion of the whole magnetosphere. The ratio $\alpha$ between the internal generator’s resistance, $R_i$, and its associated load resistance, $R_e$, is therefore different for each generator and depends on many various factors. This way the value $\alpha$ (i.e., discriminating between current generators and voltage generators) for the resulting global generator can adopt various values, depending, e.g., on the dipole tilt angle (which causes a strong UT and seasonal variation), the phases and strength of disturbances, the IMF $B_y$ and $B_z$ conditions and so forth.

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

Relating to this, let us consider the conditions under which the global FAC dynamo acts as voltage or current generator. For this purpose, we examine the Ohm’s law in terms of $Q = U^2/R$, where $U$ is the overall potential drop of the global dynamo, and $R = R_i + R_e$ is the sum of the generator’s internal resistance (i) and the load or external resistance (e). We assume that the observed range of magnetospheric power values $Q$ extend from $\sim 2 \cdot 10^{10} W$ for the most quiet conditions to $\sim 2 \cdot 10^{13} W$ during superstorms. Considering further that the cross-polar cap potential reaches saturation values up to about $U \leq 200 \text{ kV}$ during extreme conditions and that it has values of about $U \geq 10 \text{ kV}$ for quiet conditions, we get resistance values $R$ between $5 \cdot 10^{-3} \Omega$ and
2 \cdot 10^{-3} \, \Omega \) for quiet and strongly disturbed conditions, respectively. Therefore, while the global dynamo intensifies by a factor of 1000, the full resistivity of its current circuit diminishes only slightly or, considering the precision of calculations, does not change significantly.

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

7 Conclusions

The main results of the present study are the following.

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

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

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

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

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

According to the described electric circuits of the global dynamo system, this dawn-dusk asymmetry results from an asymmetry between electrody-
namic parameter distributions of the two hemispheres and vice versa. This conclusion sheds light on the long-standing discussion about these two kinds of asymmetries and allows a new approach to their detailed study.

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

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

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

We hope that our results may be used for the formulation and interpretation
of further global MHD modelling efforts of the disturbed magnetosphere. An
associated paper, based on the data of a substorm event during the storm of
Aug 02, 2002, is prepared for publication elsewhere.

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