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Key Points:
- Quasi-DC driving of FAC corresponds to voltage generator, when ground response is proportional to ionospheric conductance
- Resonant driving corresponds to current generator, when ground response weakly depends on local ionospheric conductance
- Dayside TCVs and Pc5 ULF waves should be considered as a result of current generator

Correspondence to:
V. A. Pilipenko,
space.soliton@gmail.com

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Electromagnetic Fields of Magnetospheric ULF Disturbances in the Ionosphere: Current/Voltage Dichotomy

Vyacheslav A. Pilipenko[1], Evgeniy N. Fedorov[2], Michael D. Hartinger[2,3], and Mark J. Engebretson[4]

[1]Space Research Institute, Moscow, Russia, [2]Institute of Physics of the Earth, Moscow, Russia, [3]Virginia Tech, Blacksburg, VA, USA, [4]Augsburg University, Minneapolis, MN, USA

Abstract A circuit analogy for magnetosphere-ionosphere current systems has two extremes for drivers of ionospheric currents: the "voltage generator" (ionospheric electric fields/voltages are constant, while current varies) and the "current generator" (current is constant, while the electric field varies). Here we indicate another aspect of the magnetosphere-ionosphere interaction, which should be taken into account when considering the current/voltage dichotomy. We show that nonsteady field-aligned currents interact with the ionosphere in a different way depending on a forced driving or resonant excitation. A quasi-DC driving of field-aligned current corresponds to a voltage generator, when the ground magnetic response is proportional to the ionospheric Hall conductance. The excitation of resonant field line oscillations corresponds to the current generator, when the ground magnetic response only weakly depends on the ionospheric conductance. According to the suggested conception, quasi-DC nonresonant disturbances correspond to a voltage generator. Such ultralow frequency (ULF) phenomena as traveling convection vortices and Pc5 waves should be considered as the resonant response of magnetospheric field lines, and they correspond to a current generator. However, there are quite a few factors that may obscure the determination of the current/voltage dichotomy.

1. Introduction: Current/Voltage Dichotomy

When considering time-dependent models of the magnetosphere-ionosphere current system it is physically intuitive to distinguish between generators, which deliver a fixed current, and those in which the voltage is fixed (Lysak, 1985). In general, currents perpendicular to the background magnetic field in the outer magnetosphere with a nonzero divergence close via field-aligned currents (FACs). Two extreme cases are possible, which may be visualized by a circuit analogy with the generator as a battery with an internal resistance. If the internal resistance is small compared to the load on the circuit, the load will receive a fixed voltage; whereas if the load is small compared to the internal resistance, a fixed current, determined by the internal resistance, will be delivered to the load (Lysak, 1990). Invoking the circuit analogy, low internal resistance corresponds to a voltage generator, while high internal resistance corresponds to a current generator.

Magnetosphere-ionosphere transient current systems with typical time scales in the lowest-frequency portion of the ultralow frequency (ULF) band (1–15 min) are often described using this electrical circuit analogy, with the ionosphere functioning as a load and a process in the magnetosphere functioning as a generator. A process outside the ionosphere generates a potential difference that maps along magnetic field lines to the ionosphere, where it drives electric fields. The electric field and corresponding ionospheric potential differences can be regarded as the output voltage of the generator. If the external process driving the electric field behaves as a "voltage generator," then one expects the ionospheric electric field to remain constant while ionospheric current may vary. In contrast, if the external process behaves as a "current generator," one expects current intensities to remain fixed while ionospheric electric fields may vary. As such, these current systems are an important indicator of how the coupled magnetosphere-ionosphere system responds to transient phenomena.

In the case of a magnetospheric current generator the magnetic effect on the ground must be nearly the same under sunlit or dark ionospheres, whereas in the case of a voltage generator the ground magnetic response must be much larger under a highly conductive ionosphere (Lam & Rodger, 2004; Sibeck et al., 1996). The statistical analysis of conjugate magnetometer observations of transient high-latitude current systems in the ULF band: Traveling convection vortices (TCVs; Kim et al., 2013, 2015; Lam & Rodger, 2004; Murr et al., 2002), and sudden commencements (SCs; Engebretson et al., 1999) gave seemingly contradictory results from the view of this paradigm: Some studies associated these disturbances with voltage generators, others current generators.

From the seasonal variation of the magnetic disturbance amplitude it is also feasible to determine whether the nature of this disturbance current system is produced by a voltage or a current generator. If the current system between the magnetosphere and ionosphere is a current generator, magnetic perturbations on the ground will not clearly show a seasonal variation of FACs and ionospheric currents since the amount of total current is almost constant. On the other hand, in the case of voltage generator, the amount of total current strongly varies with seasonal dependence on the ionospheric conductance. Studies using this analysis found global magnetospheric FAC systems (Haraguchi et al., 2004; Shi et al., 2010) and SCs (Shinbori et al., 2012) should be attributed to voltage generators.

Here we indicate another aspect of magnetospheric disturbance interaction with the ionosphere that should be taken into account when considering the current/voltage dichotomy. We show that oscillatory FACs interact with the ionosphere in a different way depending on forced driving or excitation of resonant field line oscillations. We consider a simple "box-model" of the magnetospheric field line Alfven resonator with asymmetric conjugate ionospheres driven by a transverse external current, and compare the ground magnetic responses in both hemispheres.

2. Model of Magnetospheric Field Line Resonator With Asymmetric Ionospheres

The ionospheric and ground response to magnetospheric disturbances is primarily caused by nonsteady FACs transported by transient or standing Alfven waves. Alfven waves carry the FAC $j_z = \mu_0^{-1}\nabla_\perp^2 A$, where $A = (i\omega)^{-1}\partial_z\varphi$ is the parallel component of the vector potential, φ is the electric potential, and μ_0 is the magnetic constant. For Alfven waves running in positive/negative (+/−) directions one may substitute $\varphi \propto \exp(\pm ik_A z)$ in this relationship and obtain $j_z = \pm\Sigma_A\nabla_\perp^2\varphi$, where $\Sigma_A = (\mu_0 V_A)^{-1}$ is the Alfven wave conductance, $k_A = \omega/V_A$ is the Alfven wave number, and V_A is the Alfven velocity.

Let us consider Alfvenic disturbances in a simple "magnetospheric box" model: homogeneous plasma with constant V_A immersed in a straight magnetic field B_0. In the near-equatorial magnetosphere, the axis X corresponds to Earthward radial direction, Y denotes the azimuthal direction, and Z corresponds to the field-aligned direction. Field lines with length $2l$ are terminated by conjugate Southern (S) and Northern (N) ionospheres with Pedersen/Hall conductances $\Sigma_{P,H}^{(S)}$ and $\Sigma_{P,H}^{(N)}$. The oscillations are driven by an external transverse current $j_x^{(d)}$. These oscillations are described by the following system of equations

$$\begin{aligned} \partial_z E_x &= i\omega B_y, \\ \partial_z B_y &= i\frac{\omega}{V_A^2}E_x - \mu_0 j_x^{(d)}. \end{aligned} \qquad (1)$$

where E corresponds to electric field and B to magnetic field. Excluding from the system (1) the variable $B_y = \partial_z E_x/(i\omega)$ we obtain the wave equation

$$\{\partial_z^2 + k_A^2\}E_x = -i\omega\mu_0 j_x^{(d)}. \qquad (2)$$

The impedance-type boundary conditions at conjugate ionospheres $z = \mp l$ are

$$B_y = \mp\mu_0\Sigma_P^{(S,N)}E_x \qquad (3)$$

The interaction of Alfven wave with the ionosphere is characterized by the reflection coefficient

$$R_{S,N} = \frac{\overline{\Sigma}_P^{(S,N)} - 1}{\overline{\Sigma}_P^{(S,N)} + 1}, \qquad (4)$$

where $\overline{\Sigma}_P^{(S,N)} = \Sigma_P^{(S,N)}/\Sigma_A$ is the ratio between the ionospheric Pedersen conductance and wave conductance.

Depending on the ratio between Σ_P and Σ_A two types of Alfven resonance modes are possible (Kivelson & Southwood, 1988):

- The half-wave for which $R_S R_N > 0$, that is the reflection coefficients from the conjugated ionospheres are either both positive $R_S > 0,\ R_N > 0$ (e.g., at dayside where $\overline{\Sigma}_P^{(S,N)} > 1$), or both negative, $R_S < 0, R_N < 0$ (e.g., at nightside where $\overline{\Sigma}_P^{(S,N)} < 1$). The real part of the fundamental eigenfrequency of the Alfven resonator is described by homogeneous Equation (2) $\Omega_A = \pi V_A/2l$.
- The quarter-wave mode, $R_S R_N < 0$, i.e. when one ionosphere is high-conductive ($\overline{\Sigma}_P > 1$), whereas the other one is low-conductive ($\overline{\Sigma}_P < 1$). The real part of the fundamental eigenfrequency of a quarter-wave mode is $\Omega_A/2 = \pi V_A/4l$.

If the distribution of Alfven velocity along a field line is uniform, the real part of the fundamental eigenfrequency of the Alfven resonator does not depend on ionospheric conductivity. Moreover, nonuniform distribution leads only to weak dependence on ionospheric conductivity in the majority of practically important cases. The exception may occur near the terminator, where $R \to 0$.

Let the driving current be localized at the magnetospheric equator ($z = 0$), namely, $j_x(z) = I_e\delta(z)$. Integrating equation (1) across the region occupied by a driver, the conditions on a jump of transverse magnetic and electric fields can be obtained. Therefore, at $z = 0$ the wave fields should match as follows

$$\{E_x\}|_{z=0} = 0, \quad \{B_y\}|_{z=0} = -\mu_0 I_e. \tag{5}$$

where $\{\dots\}$ denote a jump across the source region.

Steady state solutions of (1) for $E_x(z) \propto \varphi$ and $B_y(z) \propto \psi$ are

$$\begin{aligned} \varphi_{S,N}(z) &= \mp V_A \left[\exp\{\mp ik_A(z \pm l)\} - R_{S,N}\exp\{\pm ik_A(z \pm l)\}\right] \\ \psi_{S,N}(z) &= \exp\{\mp ik_A(z \pm l)\} + R_{S,N}\exp\{\pm ik_A(z \pm l)\}. \end{aligned} \tag{6}$$

The upper/lower signs correspond to S/N hemispheres. These solutions satisfy the boundary conditions at the ionosphere $z = \mp l$

$$\psi_{S,N} = \mp \mu_0 \Sigma_P^{(S,N)} \varphi_{S,N} \tag{7}$$

and describe the field-aligned structure of a disturbance.

The field-aligned distribution of wave electric and magnetic fields above and below the source of disturbances is

$$E_x(z) = \begin{cases} A_S\varphi_S(z) & \text{at} \quad -l \le z \le 0, \\ A_N\varphi_N(z) & \text{at} \quad 0 \le z \le l. \end{cases}$$
$$B_y(z) = \begin{cases} A_S\psi_S(z) & \text{at} \quad -l \le z \le 0, \\ A_N\psi_N(z) & \text{at} \quad 0 \le z \le l. \end{cases} \tag{8}$$

To find the amplitudes $A_{N,S}$ of excited disturbance, we substitute (8) into the merging condition (5) and obtain the system

$$\begin{cases} \varphi_N(0)A_N - \varphi_S(0)A_S = 0, \\ \psi_N(0)A_N - \psi_S(0)A_S = -\mu_0 I_e, \end{cases} \tag{9}$$

The coefficients A_N, A_S can be found from the solution of the system (9) as follows

$$A_S = -\frac{\mu_0 I_e}{\Delta}\varphi_N(0); \quad A_N = -\frac{\mu_0 I_e}{\Delta}\varphi_S(0) \tag{10}$$

where Δ is the determinant of the system (9)

$$\Delta = \varphi_S(0)\psi_N(0) - \varphi_N(0)\psi_S(0) \tag{11}$$

Substituting this solution into (8) we obtain

$$E_x(z) = -\frac{\mu_0 I_e}{\Delta}\begin{cases} \varphi_N(0)\varphi_S(z) & \text{at} \quad -l \le z \le 0, \\ \varphi_S(0)\varphi_N(z) & \text{at} \quad 0 \le z \le l. \end{cases}$$
$$B_y(z) = -\frac{\mu_0 I_e}{\Delta}\begin{cases} \varphi_N(0)\psi_S(z) & \text{at} \quad -l \le z \le 0, \\ \varphi_S(0)\psi_N(z) & \text{at} \quad 0 \le z \le l. \end{cases} \tag{12}$$

The ratio between electric fields $E_N = E_x(l)$ and $E_S = E_x(-l)$ in the Northern and Southern ionospheres can be derived from ((4), (6), (11), and (12)) as follows:

$$\frac{E_N}{E_S} = \frac{1 - i\overline{\Sigma}_P^S \tan(k_A l)}{1 - i\overline{\Sigma}_P^N \tan(k_A l)}. \tag{13}$$

Similarly, the ratio between the magnetic fields $B_N/B_S = B_y(l)/B_y(-l)$ in conjugate ionospheres is

$$\frac{B_N}{B_S} = -\frac{\overline{\Sigma}_P^N}{\overline{\Sigma}_P^S}\frac{1 - i\overline{\Sigma}_P^S \tan(k_A l)}{1 - i\overline{\Sigma}_P^N \tan(k_A l)}. \tag{14}$$

Different situations are possible, as follows from these relationships ((13) and (14)), depending on the time scale of disturbance τ and the local field-line resonant period T_A.

2.1. Ratio Between Ground Disturbances at Conjugate Points

The magnetic X-component (N-S) $B^{(g)}$ on the ground produced by an azimuthal (E-W) magnetic disturbance B above the ionosphere is described by the well-known formula (Alperovich & Fedorov, 2007; Hughes & Southwood, 1976)

$$B_S^{(g)} = B_S \frac{\Sigma_H^{(S)}}{\Sigma_P^{(S)}} \exp\left(-kh\right) \quad B_N^{(g)} = B_N \frac{\Sigma_H^{(N)}}{\Sigma_P^{(N)}} \exp\left(-kh\right). \tag{15}$$

where h is the height of the ionospheric conductive sheet, and k is the horizontal wave vector of disturbance. The ratio between the ground magnetic responses at the conjugate points is

$$\frac{B_N^{(g)}}{B_S^{(g)}} = \frac{B_N}{B_S}\frac{\Sigma_H^{(N)}}{\Sigma_P^{(N)}}\frac{\Sigma_P^{(S)}}{\Sigma_H^{(S)}}. \tag{16}$$

By analogy to electric circuits, we denote a magnetospheric generator "current" if change of ionospheric conductivity leads only to weak variations of the ionospheric current and magnetic field, while electric field in the ionosphere changes inversely proportional to conductivity. On the contrary, if upon change of the ionospheric conductivity, the electric fields are almost constant, whereas the currents and magnetic fields are proportional to the conductivity, the magnetospheric generator is to be considered as a voltage generator. In this consideration we take into account that the ratio of Pedersen to Hall conductivity $\overline{\Sigma}_H/\overline{\Sigma}_P$ is nearly constant ~ 1.5–2.0 throughout daytime and nighttime.

2.2. Nonresonant Driving of FAC

In the case of quasi-DC forced driving, when $\omega \ll \Omega_A$ (or $k_A l \ll 1$), from (12) the electric fields, Hall currents, and magnetic fields in conjugate ionospheres can be obtained

$$E_{S,N} = -\frac{I_e}{\Sigma_P^{(S)} + \Sigma_P^{(N)}}, \quad I_H^{(S,N)} = \mp\Sigma_H^{(S,N)} E_{S,N}, \quad B_{S,N} = \mp\mu_0 \Sigma_P^{(S,N)} E_{S,N}. \tag{17}$$

From (15) the magnetic response on the ground can be evaluated

$$B_{S,N}^{(g)} = \mp\mu_0 I_e \frac{\Sigma_H^{(S,N)}}{\Sigma_P^{(S)} + \Sigma_P^{(N)}} \exp(-kh). \tag{18}$$

From ((13), (14), and (16)) the ratio between ground magnetic disturbances at conjugate points follows

$$\frac{B_N^{(g)}}{B_S^{(g)}} = \frac{\overline{\Sigma}_H^{(N)}}{\overline{\Sigma}_H^{(S)}} \tag{19}$$

Let us consider as an example the situation when the ionospheric conductivities are strongly asymmetric, $\Sigma_P^{(N)} >> \Sigma_P^{(S)}$. Then upon a quasi-DC driving in the high-conductive Northern Hemisphere the ground magnetic response does not depend on local ionospheric conductivity, $B_N^{(g)} \propto \Sigma_H^{(N)}/\Sigma_P^{(N)}$, which corresponds to a voltage generator. However, in the low-conductive Southern Hemisphere the ground magnetic response is proportional to the local ionospheric conductance $B_S^{(g)} \propto \Sigma_H^S$), which corresponds to a current generator.

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2.3. Resonant Driving of FAC for Asymmetric Conjugate Ionospheres

In the case of resonant driving, when the frequency of oscillatory driver matches the local field line frequency of a magnetic shell, $\omega \rightarrow \Omega_A$ (or $k_A l = \pi/2$) and $\tan(k_A l) \rightarrow \infty$, the explicit equations for electric currents, electric and magnetic fields above the ionosphere, and magnetic response at the ground can be obtained. Substituting $\varphi_{S,N}$ and $\psi_{S,N}$ from (6) into (11) we obtain the determinant

$$\Delta = \frac{4V_A(\overline{\Sigma}_P^{(S)} + \overline{\Sigma}_P^{(N)})}{(\overline{\Sigma}_P^{(S)} + 1)(\overline{\Sigma}_P^{(N)} + 1)}. \tag{20}$$

Substituting Δ from this equation together with $\varphi_{S,N}$ and $\psi_{S,N}$ from (6) at $z = \pm l$ into (12), we get for ionospheric electric field $E = E_x$

$$E_S = -i\Sigma_A^{-1} I_e \frac{\overline{\Sigma}_P^{(N)}}{\overline{\Sigma}_P^{(S)} + \overline{\Sigma}_P^{(N)}}, \quad E_N = -i\Sigma_A^{-1} I_e \frac{\overline{\Sigma}_P^{(S)}}{\overline{\Sigma}_P^{(S)} + \overline{\Sigma}_P^{(N)}}, \tag{21}$$

and magnetic field $B = B_y$ in the ionosphere

$$B_S = -B_N = i\mu_0 I_e \frac{\overline{\Sigma}_P^{(N)}\overline{\Sigma}_P^{(S)}}{\overline{\Sigma}_P^{(S)} + \overline{\Sigma}_P^{(N)}}. \tag{22}$$

Combining ((21), (22), and (15)) we find the magnetic response at the ground as follows:

$$B_S^{(g)} = i\mu_0 I_e \frac{\overline{\Sigma}_P^{(N)}\overline{\Sigma}_H^{(S)}}{\overline{\Sigma}_P^{(S)} + \overline{\Sigma}_P^{(N)}} \exp(-kh), \quad B_N^{(g)} = -i\mu_0 I_e \frac{\overline{\Sigma}_H^{(N)}\overline{\Sigma}_P^{(S)}}{\overline{\Sigma}_P^{(S)} + \overline{\Sigma}_P^{(N)}} \exp(-kh). \tag{23}$$

From the Ohm's law we find the height-integrated Hall I_H currents

$$I_H^{(S)} = -iI_e \frac{\overline{\Sigma}_P^{(N)}\overline{\Sigma}_H^{(S)}}{\overline{\Sigma}_P^{(S)} + \overline{\Sigma}_P^{(N)}}, \qquad I_H^{(N)} = -iI_e \frac{\overline{\Sigma}_H^{(N)}\overline{\Sigma}_P^{(S)}}{\overline{\Sigma}_P^{(S)} + \overline{\Sigma}_P^{(N)}} \tag{24}$$

Thus, in the case of resonant Alfven eigenoscillation excitation ($\omega \rightarrow \Omega_A$) as follows from (23) the ratio of ground magnetic responses in conjugated points is as follows:

$$\frac{B_N^{(g)}}{B_S^{(g)}} \simeq \frac{\overline{\Sigma}_H^{(N)}}{\overline{\Sigma}_P^{(N)}} \frac{\overline{\Sigma}_P^{(S)}}{\overline{\Sigma}_H^{(S)}} \tag{25}$$

The ratio of ground magnetic responses in conjugated points does not depend on variation of the ionospheric conductance, which corresponds to the current generator regime. The change from voltage to current generator regime upon transfer from nonresonant to resonant driving is similar to the antireflective coating in optics, where the input impedance of a multi-layered system changes dramatically when the wavelength of incident light is a multiple of the layer width.

In comparing the properties of current and voltage generators it is useful to introduce an effective conductivity for the generator, which plays the same role as the internal resistance of a battery in the circuit analogy. Formally, regimes of current and voltage generators are determined by the ratio between an internal generator resistance and a load resistance. For FAC generator, the local ionospheric resistance $\propto \Sigma_P^{-1}$ plays the role of a load resistance, whereas the wave resistance $\propto \Sigma_A^{-1}$ and the resistance of conjugated ionosphere plays the role of a source resistance.

For illustration, let us suppose that ionospheric conductivities are strongly asymmetric: Northern conductivity is much larger than that of the conjugated Southern ionosphere, $\Sigma_{P,H}^{(N)} \gg \Sigma_{P,H}^{(S)}$. Then from (23) it follows

$$B_S^{(g)} \simeq i\mu_0 I_e \Sigma_H^{(S)} \exp(-kh), \quad B_N^{(g)} \simeq i\mu_0 I_e \Sigma_H^{(N)} \frac{\overline{\Sigma}_P^{(S)}}{\overline{\Sigma}_P^{(N)}} \exp(-kh). \tag{26}$$

It follows from equation (26) that in the considered case of strongly asymmetric conductivities, the magnetic field response in the high-conductive Northern ionosphere $B_N^{(g)} \propto \Sigma_P^{(S)}(\overline{\Sigma}_H^{(N)}/\overline{\Sigma}_P^{(N)})$ does not depend on local (N) conductivity, that is, it behaves as a current generator. At the same time, the magnetic field response in the low-conductive Southern ionosphere $B_S^{(g)} \propto \Sigma_H^{(S)}$ is proportional to local (S) ionospheric conductivity, that is it behaves as voltage generator.

2.4. Field-Aligned Magnetosphere-Ionosphere Currents

Let us find the relationship between the FACS flowing into conjugate ionospheres $j_z = j_\parallel$ and a driver current I_e. The continuity equation for the disturbance of FAC with a transverse wave vector k is as follows:

$$ikj_x + \partial_z j_z = 0, \tag{27}$$

where $j_x = I_e(k)\delta(z)$. Integration of (27) along z across some vicinity of a magnetospheric driver results in the following relation $\{j_z\}|_{z=0} = -ikI_e$. The ratio between FACs flowing into the conjugate ionospheres can be found using the Ampere law $j_z = \mu_0^{-1} ikB_y$ as follows:

$$j_\parallel^{(N)}/j_\parallel^{(S)} = B_N/B_S. \tag{28}$$

In the case of quasi-DC driving, FAC is constant along a field line between a driver and ionosphere, $j_\parallel^{(N)} = j_\parallel(+0)$ and $j_\parallel^{(S)} = j_\parallel(-0)$. From (17) and (28) one can find

$$j_\parallel^{(N)} = -j_\parallel^{(S)} \frac{\Sigma_P^{(N)}}{\Sigma_P^{(S)}} \tag{29}$$

The FACs flowing into the Northern and Southern Hemispheres are found from ((28) and (29)) as follows:

$$j_\parallel^{(S)} = ikI_e \frac{\Sigma_P^{(S)}}{\Sigma_P^{(S)} + \Sigma_P^{(N)}}, \quad j_\parallel^{(N)} = -ikI_e \frac{\Sigma_P^{(N)}}{\Sigma_P^{(S)} + \Sigma_P^{(N)}} \tag{30}$$

In the regime of resonant driving of FACs, the magnitudes of magnetic fields in the conjugate ionospheres are the same. Therefore, from (28) one can find $j_\parallel^{(N)}/j_\parallel^{(S)} = -1$. Using (22) and (28) FACs are found as

$$j_\parallel^{(N)} = -j_\parallel^{(S)} = kI_e \frac{\overline{\Sigma}_P^{(N)} \overline{\Sigma}_P^{(S)}}{\overline{\Sigma}_P^{(S)} + \overline{\Sigma}_P^{(N)}}. \tag{31}$$

As an example, let us consider a case of strongly asymmetric ionospheres, $\overline{\Sigma}_P^{(N)} >> \overline{\Sigma}_P^{(S)}$. From the above relationships it follows that FACs into both high-conductive Northern Hemisphere and low-conductive Southern ionosphere are proportional to Pedersen conductivity of the low-conductive Southern Hemisphere, $j_\parallel^{(N)} = j_\parallel^{(S)} \propto \overline{\Sigma}_P^{(S)}$.

2.5. Radar Measurements of Ionospheric Electric Fields in Conjugate Ionospheres

HF radar sounding of the ionosphere provides a possibility to monitor the ionospheric electric field and plasma velocities. The dense array of SuperDARN radars in both Northern and Southern Hemispheres may give a possibility to measure ionospheric electric field response in conjugate ionospheres. The relevant magnitudes of electric fields in conjugate ionospheres are to be as follows.

In the case of quasi-DC forced driving, when $\omega \ll \Omega_A$ (or $\tau \gg T_A$), we arrive from ((13) and (14)) at the ratio between electric disturbances at conjugate ionospheres

$$\frac{E_N}{E_S} \simeq 1, \qquad \frac{B_N}{B_S} \simeq -\frac{\overline{\Sigma}_P^{(N)}}{\overline{\Sigma}_P^{(S)}}. \tag{32}$$

This relationship follows from the equipotentiality of magnetospheric field lines for a quasi-DC electric field.

In the case of resonant Alfven eigenoscillations, when $\omega \to \Omega_A$ (or $\tau \simeq T_A$), from (21) we get

$$\frac{E_N}{E_S} \simeq \frac{\overline{\Sigma}_P^{(S)}}{\overline{\Sigma}_P^{(N)}}, \qquad \frac{B_N}{B_S} \simeq -1. \tag{33}$$

The relationships ((32) and (33)) may be verified by comparing amplitudes of ionospheric electric field disturbances detected simultaneously by SuperDARN radars in Northern and Southern Hemispheres. Also, the correspondence between disturbance E-field and local ionospheric conductance may be validated by EISCAT radar observations.

2.6. Wave Energy Absorption in Asymmetric Ionospheres

The Poynting flux of electromagnetic energy along a field line into the ionosphere is $S_z = E_x \times B_y/(2\mu_0)$. Therefore, in the case of quasi-DC forced driving, when the ratio between electric and magnetic disturbances at conjugate ionospheres is described by (32)

$$\left|\frac{S_N}{S_S}\right| \simeq \frac{\overline{\Sigma}_P^{(N)}}{\overline{\Sigma}_P^{(S)}} \tag{34}$$

Thus, in this case the absorption is higher where the conductance Σ_P is higher. Indeed, under the same electric field more intense currents are excited in a more-conductive ionosphere.

In the case of resonant driving, when the ratio between electric and magnetic disturbances at conjugate ionospheres is described by ((21) and (22)), we get

$$\left|\frac{S_N}{S_S}\right| \simeq \frac{\overline{\Sigma}_P^{(S)}}{\overline{\Sigma}_P^{(N)}} \tag{35}$$

The absorption is to be higher at the less conductive end of a field line. This conclusion may be comprehended by comparing Pedersen currents in both hemispheres

$$I_P^{(S)} = -\mu_0^{-1} B_S, \quad I_P^{(N)} = \mu_0^{-1} B_N, \quad I_P^{(N)}/I_P^{(S)} = -1. \tag{36}$$

The ratio between the Joule losses under the same Pedersen current is inversely proportional to the ratio of Pedersen conductances.

Consideration of the damping of field line oscillations based on the impedance-type relationship for Alfven waves in the upper ionosphere (3) led many years ago to the same conclusion (Newton et al., 1978). Indeed, more energy is necessary to keep the same amount of current flow through a low conductivity ionosphere.

3. Comparison With Observations

The solution of the problem of the excitation of FAC in the magnetospheric resonator shows that the field-aligned structure and dependence on the ionospheric conductance may look like a voltage or current generator, depending on the periodicity of the driver regime τ and the local eigenperiod of the magnetospheric resonator T_A. For a quasi-DC forced driving, the structure of the disturbance corresponds to the voltage regime: The ground magnetic response is proportional to the ionospheric conductance. In the case of resonant driving with $\tau \simeq T_A$, the structure of the excited disturbance corresponds to a current generator, when the ground magnetic response practically does not depend on the ionospheric conductance. The current/voltage generator paradigm was regularly tested with observations at conjugate points or with examination of seasonal effects. Here we compare the results of conjugate observations of quasi-DC and transient (TCVs and ULF waves) high-latitude current systems.

3.1. Magnetospheric Global FAC Systems

Numerous studies of large-scale magnetospheric FACs were performed using magnetic field gradients measured by low-orbiting satellites Christiansen et al. (2002). The statistical results obtained correspond to a quasi-steady (as compared with Alfvenic time) case. Typically, empirical modeling of quasi-steady magnetosphere-ionosphere current system indicated that this FAC are driven by a voltage generator. Here we mention just a few.

The study of Haraguchi et al. (2004) statistically examined the dependence of the intensities of dayside large-scale FACs on the ionospheric conductance using the data of DMSP-F7 satellite. In the dayside region, intensity of FAC R1 (current flows into/away the ionosphere in the prenoon/postnoon sector) and cusp current R0 had a high correlation with ionospheric conductivity, suggesting that R0 and R1 FACs are driven by a voltage-like source. Shi et al. (2010) statistically investigated features of FAC distribution in plasma sheet boundary layers in the magnetotail using the curlometer technique to calculate the current from four-point magnetic field measurements. The results showed that the FAC distribution in the plasma sheet boundary layer had dusk-dawn and north-south asymmetry. The occurrence and polarities of FACs in the Northern Hemisphere were found to be different from those in the Southern Hemisphere. The interhemispheric difference between the FAC densities suggests that an important source of these currents must be a voltage generator. These observational results match the model prediction on nonresonant driving of FACs.

3.2. TCV and SCs

TCVs are specific daytime high-latitude structures driven by magnetospheric FACs (Engebretson et al., 2013; Friis-Christensen et al., 1988). The terrestrial manifestation of a TCV is an isolated magnetic impulse event (MIE)—a perturbation of the geomagnetic field with a duration of ∼5–10 min and with amplitude of ∼100 nT (Lanzerotti et al., 1990; Vorobjev, 1993). TCVs can be manifested not only in the form of a solitary pulse, but also in the form of a quasiperiodic sequence of pulses. Typical double vortex TCV structure of Hall currents is formed around a pair of upward and downward FACs between the ionosphere and the magnetosphere (McHenry & Clauer, 1987).

The physical mechanism of excitation of a TCV and its interaction with the ionosphere is not uniquely determined. Various driving mechanisms of TCVs were claimed, such as the pulsed reconnection of the interplanetary and magnetospheric magnetic fields (Lanzerotti et al., 1986), pulsed variations in the dynamic pressure of the solar wind (Glassmeier, 1992), or sporadic regions of hot plasma in the ion foreshock (hot flow anomalies; Murr & Hughes, 2003). Probably, there are different types of TCVs, but we refer to TCV events as those associated with smaller spatial scale upstream pressure variations from the ion foreshock as compared with an interplanetary shock and large dynamic pressure variations of the pristine solar wind.

The statistical study of Lanzerotti et al. (1991) provided a comprehensive analysis of conjugate aspects of TCV/MIE events. This study, which used data from the Iqaluit-South Pole conjugate pair, found that TCVs/MIEs were of similar magnitude in the two hemispheres and that the same sense of current was flowing into the conjugate locations. A study of TCVs at the same conjugate pair by Murr et al. (2002) showed that the amplitudes of the magnetic perturbations were similar in the two hemispheres in the sunlit and dark ionospheres. Lam and Rodger (2004) also observed that conjugate TCVs were of similar intensity in both hemispheres regardless of any difference in conductivity. They found no statistical difference between events occurring during conditions when one hemisphere was dark and other events when both were dark or light. During solstice conditions, the hemisphere conductances ought to differ by at least a factor of 10. Using this assumption and finding no statistical difference between the two ensembles, they concluded that these TCV events were associated with current generators. Modeling studies by Zhu et al. (1999) predicted that for a voltage driven precipitation source, large differences in amplitude and structure would be observed by magnetometers in sunlit and dark conditions. Their model suggested that the amplitude of magnetic perturbations will be nearly 3 times larger in an ionosphere with $\Sigma_P \simeq 7$ mho compared to that with $\Sigma_P \simeq 2$ mho. The fact that observational studies did not find such large hemispheric differences argues against a voltage driven precipitation source.

Based on these observational results, it seems likely that TCVs are to be associated with a current generator. Thus, according to our model, TCVs are to be excited at resonant field line. Indeed, in at least some observational studies the pressure disturbances that drive TCVs have been associated with resonant oscillations (Shen et al., 2018; Shi et al., 2014).

However, TCV magnetograms do not always appear as resonant oscillations, but rather as impulsive or heavily damped oscillations. Nonetheless, it is possible that resonant effects play a significant role in the TCV formation. Though TCVs are generated by some extra-magnetospheric transients, the epicenters of TCV-associated FACs are found well inside the magnetosphere. The position of TCVs relative to particle precipitation boundaries obtained from low-altitude DMSP satellite measurements was investigated by Yahnin et al. (1997) and Moretto and Yahnin (1998). The TCVs occurred within the poleward part of the belt of trapped energetic electrons, which suggests that TCVs map to the central plasma sheet within the magnetosphere, but not at the magnetopause. Numerical 3-D modeling showed that the generation of TCVs and the associated FACs in the dayside magnetosphere by an interplanetary tangential discontinuity originated at latitudes ∼ 40–50°, well inside the magnetopause (Chen et al., 2000).

A possible way to reconcile the intermagnetospheric TCV response with a magnetosheath source is the assumption that the FACs which drive the vortex-like TCV are produced in the Alfven field line resonance region, where the initial impulse duration matches the Alfven eigenperiod, that is $\tau \simeq T_A$. However, TCVs differ from resonant ULF waves in the following aspect. In order to drive a resonant system till saturation level, a driver must be applied continuously during a time period about $T_A Q$ (where Q is the quality factor of a resonant system). A realistic value for dayside Alfvenic resonator in the Pc5 band is $Q \simeq 5$–10. The actual driving time of TCV is much less than that, but TCV still can be excited because the driver intensity is much stronger than that of Pc5 wave driver. Thus, TCVs are likely a spatially localized phenomenon, and most probably associated with a nearly standing resonant Alfvenic mode. Therefore, the match of its conjugate features to the current generator agrees well with the theoretical predictions for resonant driving of the magnetospheric Alfven resonator.

Another transient disturbance with a similar time scale is SC. An SC is a complicated transient response of the magnetosphere-ionosphere system to an interplanetary shock. It consists of a magnetic field compression transported to the ground by a fast compressional mode wave and a global vortex-like disturbance produced by a FAC system at the magnetopause. Moreover, during SC ionospheric electrojet and magnetospheric electron precipitation into the ionosphere suddenly intensify. All these factors make the determination of ground magnetic response owing to FAC complicated. The SC-associated compression of the magnetosphere can excite damped Psc5 pulsations deep in the magnetosphere at a latitudinally narrow resonant magnetic shell (Samsonov et al., 2011). Beyond this narrow region, no resonant response to SC pulse is observed, evidencing that $\tau \neq T_A$. The main impulse (MI) of SC is believed to be produced by a vortex-like ionospheric current system driven by a large-scale FAC (Curto et al., 2007). The important difference between this FAC and the TCV-associated FAC is the larger spatial scale in SC events. This FAC is thus a global transient response at the magnetopause to an interplanetary shock and is not related to resonant Alfvén oscillations.

Shinbori et al. (2012) examined the seasonal variations of the MI amplitude, normalized by current SYM-H index. The size of the diurnal variation was found to increase significantly during the summer, compared with that during the winter. This seasonal variation was interpreted that magnetic disturbance at nightside supposedly generated by primary FACs during the MI phase was intensified by increased ionospheric conductivities during the summer. Judging from such seasonal variation it was concluded that the MI current system in the ionosphere and magnetosphere is caused by a voltage generator rather than a current generator. Yumoto et al. (1996) also found a hemispheric difference in SC at midlatitudes: Their amplitude was significantly larger in the summer hemisphere than in the winter one. Keeping in mind all the uncertainties of the above analysis, these results fit the assumption that an SC is a quasi-DC driver of magnetospheric FACs at middle latitudes. Thus, a strong dependence on conductance corresponds to the regime of a voltage generator, natural for a nonresonant disturbance. However, at auroral latitudes, the time scale of MI growth may be less that the resonant period of Alfven field line oscillations, $\tau < T_A$. This case should be considered separately with account of specific features of the auroral ionosphere-magnetosphere system as discussed in the section 4.

3.3. ULF Waves

Theoretical models describe the resonant excitation of Alfven standing waves and associated FACs by an external pressure pulse (e.g., Lee & Lysak, 1989) and by running waves on the magnetospheric boundary (e.g., Wright & Rickard, 1995). The consideration of the current/voltage dichotomy for ULF waves (Pc3–5 pulsations) should be done with great care. In general, the field of ULF waves is composed from fast magnetosonic (compressional) mode and Alfven mode. For example, according to the LEO satellite observations, Pc3 waves in the upper ionosphere are predominantly composed from compressional mode besides a narrow region of Alfven resonance (Pilipenko & Heilig, 2016). The transmission mechanisms of the compressional mode and Alfven mode through the ionosphere are very different (Pilipenko et al., 2011). While a FAC carried by an Alfven wave cannot penetrate into the insulating atmosphere and spreads over the ionosphere as Pedersen and Hall currents, the magnetic field compression transported by a fast mode wave “feels” the ionosphere only weakly. Both modes, azimuthally large scale, produce a main ground response in the same X-component. Therefore, a discrimination of fast and Alfven modes is to be done before analysis.

For high-frequency ULF waves (Pc3 band) the description of Alfven wave interaction with relationship (3) becomes insufficient, and additional effects should be taken into account. Important effect is the “shielding” of ULF pulsations by a highly conductive ionosphere (Takahashi et al., 1994). Distortion of the ground-based spatial structure of Pc3 waves was described using a numerical model of the Alfven wave transmission through the ionosphere in (Pilipenko et al., 2000). The predicted decrease of the ground response is most pronounced when the wave frequency and ionospheric conductivity are higher. From a physical point of view, the effect is caused by excitation of a surface-type diffusive mode in the ionosphere. Yoshikawa et al. (2002) interpreted an attenuation of the magnetic field amplitude on the ground as a result of an enhancement of inductive rotational Hall currents for high-frequency and highly conducting ionosphere. The shielding effect may cause a significant north-south difference in the amplitude of the ground Pc3 magnetic signal in the case of non-symmetric conjugate ionospheres. Therefore, the conjugate properties of Pc 3 pulsations are not described by our model and mainly controlled by the shielding effect.

Asymmetry of ground amplitudes of Pc3 Alfven oscillations, with the ground signal being weaker under a higher-conductivity ionosphere, were indeed observed upon observations at conjugate ionospheres. The north-south asymmetry of the amplitude of Pc3 pulsations was studied using data from magnetically conjugate stations Kotzebue-Macquarie Islands (LT difference of 2.5 hr) by Obana et al. (2005). The north to south power ratio showed a maximum in the northern winter and a minimum in the northern summer. The "seasonal variation" implies that Pc3 waves incident from the magnetosphere are more strongly shielded when the ionospheric conductivity is higher. Seasonal and diurnal variations of Pc3 magnetic pulsation powers have been examined using magnetic data from conjugate stations Syowa and Tjornes by Saito et al. (1989). The magnetic pulsation powers were found to be relatively higher at the winter hemisphere station than at the summer station. The power density ratio between the conjugate stations, which is associated with the seasons and local time, can be attributed to the effects of sunlight in the ionosphere, that is, Pc3 pulsations are shielded when the waves propagate from the magnetosphere to the ground through the sunlit ionosphere. A conjugate study of Pc3–4 pulsations at high latitudes by Engebretson et al. (2000) also showed statistically reduced amplitude in sunlit hemisphere.

In the Pc5 band the shielding effect becomes much less significant. However, a specific difficulty in analysis of conjugate studies of Pc5 pulsations is that resonant frequency-dependent amplification occurs in a small latitudinal region ($\sim$ 200 km). The conjugate observation results are expected to be strongly influenced by uncertainties in the difference between the pulsation resonant peak and an observation site. Therefore, any conclusions on Pc5 asymmetry strictly speaking demands a thorough determination of resonant wave structure in both hemispheres, for example, with the gradient method.

The north-south asymmetry of the amplitude of Pc5 pulsations was studied by Obana et al. (2005) using magnetic field data from the conjugate Kotzebue-Macquarie Islands stations at $L \simeq 5.4$. The power ratio showed a "regular offset," probably caused by a regular shift of statistical position of the wave resonant peak and the station location. The relative stability of the offset during seasonal variations may provide indirect evidence of the independence of ground magnetic signal on the ionospheric conductance. Thus, this feature of conjugate Pc5 waves may be interpreted as an indirect manifestation of a current generator regime.

For ULF waves with frequencies much less than the Alfven field line eigenfrequency the dependence of ground power on the ionospheric conductance should correspond to the case of voltage generator. For example, Pc3–4 pulsations in the polar cap cannot be eigenoscillations of open field lines. Indeed, suppression of Pc3–4 wave activity in the polar cap during the polar night was observed by Chugunova et al. (2008). This effect indicates that the polar cap Pc3–4 wave driver corresponds to a voltage generator.

3.4. Additional Factors Influencing Ground Magnetometer Observations

There are additional factors that may obscure the observed relationship between the ground magnetic response and the ionospheric conductance, which should be taken into account (Hartinger et al., 2017). Interpreting ground based magnetometer measurements is fraught with contention, in part, due to the lack of direct information about the ionospheric conductivities. Many researchers have pointed out that difficulties could arise from assumptions commonly used to interpret ground magnetometer observations: making measurements made at positions fixed relative to the FAC. These assumptions can significantly alter expectations for whether magnetic perturbations are associated with a current or voltage generator.

Though the model considered here is homogeneous, in reality the plasma distribution along a field line must be inhomogeneous: The plasma density N_e in the upper ionosphere at the sunlit end of a field line should be higher than at the dark end. As a result, the Alfven wave conductance, $\Sigma_A \propto \sqrt{N_e}$, must be higher at the sunlit end. Thus, the contrast in the ratio Σ_P/Σ_A, which determines the reflection condition and ground response (but not solely Σ_P), is to be less distinct between (N) and (S) ionospheres. This partly equalizes the ground response in conjugate ionospheres even in the case of a voltage generator.

Auroral electron precipitation tends to reduce hemispheric conductivity asymmetries produced by solar illumination. A typical ratio of summer to winter conductivities outside the auroral oval is closer to 10, whereas inside the oval is roughly just a factor of 2. Even when one auroral station is in darkness while the other is in sunlight, rather than differing by an order of magnitude, $\Sigma^{(N)}$ and $\Sigma^{(S)}$ are usually much closer to a factor of 2. It is important for the considered problem, because the "epicenters" of the Pc5 power (Kozyreva et al., 2016) and TCV amplitude (Sibeck et al., 1996) are typically located near the equatorward auroral oval boundary.

Moreover, at auroral latitudes the occurrence of auroral acceleration region must be taken into account upon consideration of the magnetospheric driver internal resistance and the load resistance.

The model considered has a passive ionosphere, whose conductances do not evolve due to the current/voltage imposed on the ionosphere. However, very intense FAC, transported by an Alfven wave, can pump/deplete the ionospheric plasma or modify the ionosphere via the modulated precipitation of particles (e.g., Michell et al., 2008; Pilipenko et al., 2014). Such extreme events of the ionospheric conductance modification by a magnetospheric driver is not considered by the linear theory.

A steep gradient of the ionospheric conductance, for example, at the auroral oval boundary or cusp boundary, can substantially distort a ground magnetic response. A numerical model for the study of the 3-D currents driven by a localized source in two hemispheres with different ionospheric conductivities (Benkevich & Lyatsky, 2000) showed that interhemispheric FACs arise near the terminator, leading to the formation of TCV-like vortices in equivalent ionospheric currents, which can be detached from a source and lie several degrees equatorward of it.

4. Discussion

For magnetospheric FAC generator, the local ionospheric resistance $\propto \Sigma_P^{-1}$ plays the role of a load resistance, whereas the wave resistance $\propto \Sigma_A^{-1}$ and the resistance of conjugated ionosphere plays the role of a source resistance. Morphologically, it is supposed that the magnetospheric current generator corresponds to a case, when the recorded ground magnetic field does not depend on the local ionospheric conductivity. Following this definition, we may face the situation (e.g., strongly asymmetric conductivities) when Alfven field line resonance behaves as voltage generator under low local conductance, and as current generator under high conductance.

A close analogy to the considered effect is the Lecher line in the UHF radio signal transmission. Lecher line acts like a parallel resonant circuit, appearing as a high impedance at its resonant frequency and low impedance at other frequencies. Transmission line stubs like Lecher lines resonate at odd-number multiples of their fundamental resonant frequency.

Formally, in the model considered, the magnetic field and plasma are assumed to be laterally homogeneous. In reality, external MHD disturbance (surface or fast compressional modes) can excite FAC only thanks to mode coupling in an inhomogeneous system. However, the spectral MHD theory (e.g., Krylov et al., 1979) states that frequency and field-aligned structure of Alfvenic-type oscillations excited by an external MHD disturbance are described by ordinary differential 1-D equations, identical to uncoupled Alfven mode.

Though upon consideration of SC at low latitudes, the inequality $\tau \gg T_A$ still holds, but at auroral latitudes the opposite condition may exist, when $\tau \ll T_A$. The presented model considers only the steady state periodic disturbances, comprising both hemispheres. However, SC pulse cannot be treated this way. Typically, when SC impulse impinges one of the ionospheres, the conjugate ionosphere does not influence this process. For an adequate treatment of such phenomenon, the consideration of nonsteady problem is necessary. However, such a problem is beyond our consideration and will be considered elsewhere.

5. Conclusion

Here we have indicated an important aspect of the magnetosphere-ionosphere interaction, which should be taken into account when considering the ground response to magnetospheric FAC driving. We have shown with a simple box model of the magnetosphere that nonsteady FACs interact with the ionosphere in a different way in cases of a forced driving or resonant excitation. A quasi-DC driving of FAC corresponds to a voltage generator regime, when the ground magnetic response is proportional to the ionospheric Hall conductance. The resonant excitation corresponds to the current generator regime, when the ground magnetic response practically does not depend on the ionospheric conductance. According to the suggested conception such magnetospheric phenomena as TCVs and Pc5 waves should be considered as a resonant response of magnetospheric field lines and they correspond to a current generator. Quasi-DC nonresonant disturbances such as global magnetospheric FAC systems and SCs correspond to a voltage generator. This classification scheme interprets well the observed features of TCVs and Pc5 waves in conjugate hemispheres and their seasonal variations. The suggested approach to the current/voltage dichotomy may be applied to improve global MHD simulations that often use an assumption of static current systems when coupling to ionospheric models.

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