Energy regeneration model of self-consistent field of electron beams into electric power

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Abstract. We consider physic-mathematical models of electric processes in electron beams, conversion of beam parameters into electric power values and their transformation into users’ electric power grid (onboard spacecraft network). We perform computer simulation validating high energy efficiency of the studied processes to be applied in the electric power technology to produce the power as well as electric power plants and propulsion installation in the spacecraft.

Energy regeneration model of electron (ion) beams greatly determines energy efficiency of electric power technology [3], where the beams are generated with electric arc plasma guns and electron guns with electric, magnetic and electromagnetic lenses by ionising the power fluid with electric arc and forming beams of the charged plasma [1, 2].

Self-consistent field energy [4, 5] generated by interaction of electric charges of electron (ion) beams is transformed and used in many technological processes: generation, amplification and transformation of microwave oscillation, as well as it is applied for wakefield acceleration of the charged particles in colliders [6] and in other processes [1].

To regenerate energy of the charged plasma beams into electric energy their kinetic energy of self-consistent field [3, 6] is mainly used. Potential energy of self-consistent field is practically not applied. Using potential energy significantly increases energy efficiency of electric power technologies, as the amount of potential energy in the charged plasma beams is practically equal to the amount of kinetic energy [1, 2] according to law of conservation of energy.

The chain diagram of the electric power plant to realise the proposed model of energy regeneration of self-consistent field of electron beams into electric power is in Figure 1.

The plant contains controlled voltage switch converters (CVSC) 1 transforming ac voltage into dc voltage, the last energises electrodes of electric arcs of electric guns (EG) 2. Electric arc anode (Aa) is connected with a «+» of CVSC terminal, cathode is connected with «─» to electric plant earth. AC voltage $U_A$ of cyclic output frequency $\omega_p$ of users’ electric power grid (UEPG) (onboard power system of a vehicle) energises output anodes of electric guns. Electric guns generate electron beams (EB) 3 pulsating with $\omega_p$ frequency.

Working spaces (WS) 4 are made of electron conductor material, therefore double electric layer (DEL) appears on their inner surface, it generates radial component of electric field $E_r$. The radial component field density is $10^2...10^3$ times higher than EG 3 field density, therefore, it compresses an electron beam transversally. Decelerating electrodes (DE) 5 look

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like Faraday cup [7] transforming electron beam charge 3 into equivalent electric current that generates a direct axis component of electric field $E_l$ on decelerating circuit resistance to decelerate electron beam 3. Power transformer – converter (PTC) 6 in the primary circuit has got inductive windings $L_1$ and $L_2$, inductive circuit $L_2$ with condenser $C_p$ is aligned to output frequency $\omega_p$ resonantly. PTC 6 secondary circuit is connected with users’ electric power grid via electric power meter Wh of overcurrent type. Generating capacitance (GC) working at cyclic frequency $\omega_p$ supplies the energy to the users’ electric power grid.

**Figure 1.** Chain diagram of an electric plant realising energy regeneration model of self-consistent field of electron beams into electric power in the crossed electric fields.

The beam electrons having the same accelerating potential of anode field of an electric gun seem to obtain similar velocity; dispersion of electron velocity distribution function relatively to their saturation state is low ($\sigma << 1$). Therefore, beam electrodynamics and its self-consistent field can be described with Vlasov-Poisson simultaneous equations obtained from Vlasov-Maxwell equations by linear approximation of the function of the charged particles distribution due to velocity [4, 5].

Vlasov-Poisson equations are simultaneous equations for every component of an electron beam. We consider a beam within nonrelativistic limit:

$$\frac{\partial f_\alpha}{\partial t} + \mathbf{v} \frac{\partial f_\alpha}{\partial x} + \frac{q_\alpha}{m_\alpha} \mathbf{E} \cdot \frac{\partial f_\alpha}{\partial \mathbf{u}} = 0,$$

(1)
Poisson equation is also applied \((\nabla \cdot \mathbf{E} = -\nabla^2 \varphi = \rho / \varepsilon)\), as well as differential form of Poisson equation \([9]\) for a self-consistent electric field \((\text{div} \mathbf{E} = -\text{divgrad} \varphi = \nabla^2 \mathbf{U} = \rho / \varepsilon)\), Laplace equation in Cartesian axials \((\nabla^2 \mathbf{U} = \partial^2 \mathbf{U} / \partial x^2 + \partial^2 \mathbf{U} / \partial y^2 + \partial^2 \mathbf{U} / \partial z^2 = 0)\).

The solution of the equations \([8]\) for sinusoidal distribution of electron beam charges results in distribution of a potential \(\varphi(x,t)\) of a self-consistent electric field of an electron beam.

\[
\varphi(x,t) = \rho / 4 \pi r \int dV = (\rho V / 4 \pi r) \cdot \exp(j \omega \tau) \quad (2)
\]

Where: \(q_\alpha\) - charge of an \(\alpha\) component and \(m_\alpha\) - mass of particles of an \(\alpha\) component of an electron beam, \(\mathbf{E}(x,t)\) - self-consistent electric field vector; \(\varphi(x,t)\) - self-consistent electric field potential and \(\rho_\alpha\) - charge density of an \(\alpha\) component in an electron beam; \(\rho V= q_\alpha\) - electric charge of an \(\alpha\) component of an electron beam with \(V\) volume; \(r\) - vector-range among electrons of a beam; \(\omega_p\) - cyclic operation frequency modulating electron beam within an electron gun of electric arc plasmatron \([1]\).

Potential distribution of a self-consistent electric field results in adequate intensity distribution of a self-consistent electric field, capacity and energy of an electron beam \([4, 5, 8]\):

\[
\mathbf{E}(x,t) = -\text{grad} \varphi(x,t); \quad W_q = q_\alpha \varphi(x,t) = q_\alpha^2 / 4 \pi r \varepsilon; \quad S_q = W_q \cdot f_p; \quad (3)
\]

where: \(W_q\) and \(S_q\) - capacity and energy accordingly, they are generated by electron beam charges; \(f_p = \omega_p / 2\pi\) - operational frequency of anode field of electron gun modulating an electron beam.

The chain diagram of the electric plant is presented by Fig. 1. The diagram demonstrates simulation of the processes generating electron beams and transforming their energy into electric power parameters.

Ionising working fluid by electric arc plasmatron in the anode field of an electron gun removes electrons out of electric arc area gathering electrons into a beam. The beam is modulated by the operating frequency \(\omega_p\), that directs to a working space of a polarisable electrode. Electric power consumption of the process is:

\[
W_{\text{cons}} = q_{\text{eb}} (U_{\text{arc}} + U_A) = q_{\text{eb}} U_A (1 + K_{W_{\text{arc}}}); \quad S_{\text{cons}} = I_A U_A (1 + K_{S_{\text{arc}}}); \quad (4)
\]

where: \(q_{\text{eb}}\) - charge of an electron beam; \(U_{\text{arc}}\) - operational voltage of an arc (approximately 50 V); \(U_A\) - voltage of an output anode of an electron gun, it can change within a range of 500V up to 5000V; \(K_{W_{\text{arc}}} = 2.5\) \(U_{\text{arc}}/U_A\); \(K_{S_{\text{arc}}} = \text{consumption coefficient of energy or capacity, accordingly, to an electric arc relatively to capacity consumption of anode field of a gun 2}\).

Potential energy of electron range of self-consistent field generated by Coulomb and Lorentz orthogonal forces within an electron beam 3, in the first approximation, is the same, as a beam 3 is in electrodynamic balance under the impact of these forces, and a total beam energy 3 and its capacity equal to the sum of their effective values \([2, 8]\):

\[
W_{\text{gen}} = (W_C^2 + W_{\text{eb}}^2)^{1/2} \approx \sqrt{2} q_{\text{eb}}^2 \varepsilon r_e; \quad S_{\text{gen}} = W_{\text{gen}} f_c; \quad (5)
\]

where: \(W_C = F_C r_c = (q_{\text{eb}}^2 \varepsilon r_e^2) r_e = q_{\text{eb}}^2 \varepsilon r_e\) - energy component of self-consistent field of beam 3, generated by Coulomb forces; \(W_{\text{eb}} = F_L r_e = q_{\text{eb}} [v_e \times B_e] r_e \approx q_{\text{eb}}^2 \varepsilon r_e\) - energy component of beam 3, generated by Lorentz forces; \(B_e = \mu_e v_c / 2\pi r_e\) - self-consistent field density generated by an electron of beam 3 in the nearby electron.
Energy of the charged particle range and their kinetic energy in the electron beam generated by anode field of the electron gun is

\[ W_{eb} = W_{qeb} + W_k = \frac{1}{2} q_{eb}^2 / e r_e + N_{eb} m_e v_e / 2 = 2 q_{eb} U_A; \]  

(5a)

where: \( W_{qeb} = \frac{1}{2} q_{eb}^2 / e r_e = q_{eb} U_A \) – potential energy of electron range in a beam generated by an electron gun; \( \varepsilon \) – dielectric permittivity in the electron beam environment; \( N_{eb} \) – the amount of electrons in a beam having potential of anode field \( U_A \) of an electron gun is characterised by quadratic dependence on electron beam charge. Therefore, there is an aerie generated by an anode field of the electron gun.

\[ \Delta W = \text{generated by anode field of the electron gun} \]

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above physic-mathematical models of electron beams and regeneration processes of their energy into the equivalent electric power transformed into the network of 50 Hz.

Figure 2. Results of simulating processes to generate electron beams within the crossed electric field and their energy regeneration into electric power transformed into users’ electric power grid (onboard flying vehicle network):

$I_{Gmin}$ (A) – electric current intensity in generation mode; $S_{cons}$ (kVA) – power used to generate an electron beam; $S_{Gmin} = I_{Gmin} \times U_{Ap}$ (kVA) – minimum power in generation mode; $S_{Gp}$ (kVA) – power in operation mode of generation; $K_{SGmin} = S_{Gmin} / S_{cons}$ – minimum coefficient power regeneration in generation mode; $K_{RSp} = S_{Garc} / S_{cons}$ - coefficient of power regeneration in operation mode of generation, expression (13); $U_{Ap}$ (V) – operation voltage at the output anode of electron gun.

Therefore, decelerating with simultaneous keeping an electron beam in the compressed condition by “the crossed electric field” applied according to the proposed regeneration model of kinetic and potential energy of electron range of self-consistent field of electron beam into electric power transformed to the users’ electric power grid (onboard flying vehicle network), it is possible to produce electric power with high efficiency; the electric power is equivalent to electron beam energy, where the beam is in the compressed condition.

The proposed model can be applied to produce electric power [11].

Summing it up, we could point out:

Firstly, it is technically simpler and more energy efficient to apply the models of the crossed electric field of electric arc, ionising working fluid, with anode field of an electron gun generating an electron beam and performing its mass transfer. It gives the chance to generate electron beams with current of higher intensity in accordance with the conventional generating electron beams in electric and magnetic fields.

Secondly, it significantly increases energy efficiency of the proposed model to generate electric power if we use the model of the cross electric field with double electric
layer keeping an electron beam in the compressed condition with the field decelerating the beam. The field is generated by an electron beam to regenerate potential and kinetic energy of electron beam to electric power transformed to the users’ electric power grid (onboard flying vehicle network).

Thirdly, double electric layer is generated due to electrophysical properties of materials, therefore its application to keep an electron beam in the compressed condition is not energy consuming, consequently, it increases energy efficiency of the proposed model to generate electric power.

References
[1] Enciklopediya nizkotemperaturnoj plazmy (Encyclopedia of Low-Temperature Plasma)/4 vol. Edited by V.E-Fortov. Moscow: Nauka, 2000
[2] Bolshoj Enciklopedicheskij Slovar. Fizika (Big Encyclopaedic Dictionary. Physics / Editor-in-Chief A.M. Prohorov. Moscow: Ross. Encyclopedia, 1998 – 994 p.
[3] Smirnov V.M., Perelygin S. F., Kondakov V. V. Ocenka perspektiv preobrazovaniya energii plazmy v elektricheskuyu v zamknutyh magnitnyh lovushkah. Godovoj otchet po NIR kafedry fiziki plazmy za 2008 g. Moscow: NIYAU MIFI, 2009. - s. 5-6. (Estimating the prospects of plasma energy conversion into electric energy in closed magnetic hooks/Annual report on the research by the Department of plasma physics for 2008. Moscow: National Research Nuclear University (Moscow Engineering Physics Institute), 2009. - p. 5 - 6.)
[4] Vlasov A.A. Teoriya vibracionnyh svojstv ehlektronnogo gaza I ee prilozheniya (Theory of vibration properties of electron gas and its application) Moscow: Moscow State University – 1945 – issue 75, book 2, part 1.
[5] Vlasov A.A. Statisticheskie Funkcii Raspredeleniya (Statistical distribution function. 2 Ed., corr. Vlasov A.A. 2014. – 360 p.)
[6] Aleksandrov A.F., Kuzelev M.V.. Teoreticheskaya plazmennaya ehlektrotekhnika. Uchebnoe posobie. MGU imeni M.V. Lomonosova, Fizicheskiy fakultet, 2011. - 167 s. (Theoretical plasma electrical engineering. Tutorial. Moscow: Lomonosov Moscow State University, Faculty of Physics, 2011. - 167 p.)
[7] Yandex. Ru/ cilindr Faradeya (Faraday Cup)/ stu.scask.ru/book.ar1.php?id=26.
[8] Shimoni K. Teoreticheskaya elektricheskaya / M., «Mir», 1964. - 773 s. (Shimoni K. Theoretical electrical engineering/Moscow: Mir, 1964. - 773 p.)
[9] Kazmin B.N., Trifanov I.V. Ob ehlektronnom generatore ehlektroenergii // B.N. Kazmin, I.V. Trifanov /Vestnik SibGAU. Vyp. 1(34). 2011. - s. 25–28. (About electronic generator of electric power // B.N. Kazmin, I.V. Trifanov / Vestnik SibSAU. Issue 1(34), 2011. - p. 25–28.
[10] Arhangelskiy A.Ya. Delphi 7 : spravoch. posobie. Moscow : Binom-Press, 2004. – 1024 s. (Archangelsky A.Ya. Delphi 7: resource book. Moscow: Binom-press, 2004. – 1024 p.)
[11] Patent № 2505915 RF, MIPK H02N 3/00./ Elektronnyy generator elektroenergii (Electron electric power generator) / B.N. Kazmin, Trifanov I.V., Oborina L.I., Dubova E.D., Sterechov I.V. Published 27.01.2014. Bulletin № 3.