The model of electrophysical processes increasing effectiveness of electric power technology based on electron beams

B N Kazmin, I V Trifanov, D R Ryzhov, M V Savelyeva
Reshetnev Siberian State Aerospace University
31, “Krasnoyarskiy Rabochiy” prospect, Krasnoyarsk, 660037, Russia.

E-mail: sibgau-uks@mail.ru

Abstract. The research focuses on electrophysical model of processes increasing energy efficiency of electric power technology based on electron beams that are generated by crossed electric field. The energy of beams is transformed with compression and simultaneous deceleration with crossed electric field into electric power to transfer into users’ electric power grid. We perform computer modeling of the processes to confirm the energy efficiency of the proposed model.

We suggest examining techniques and means to generate electron (ion) beams and transform their energy into electric power, and obtaining models to increase energy efficiency of these electric power processes.

It is possible to specify electromagnetic processes in electron (ion) beams of low-energy plasma, generated in plasmatrons with electron (ion) guns with electric and magnetic lenses [1, 2], applying Maxwell-Lorentz electromagnetic field equation [3] by means of electric currents in electron beams \( I_{eb} = I_c + I_{cond} + I_{sh} \): convection \( I_c \), conductivity \( I_{cond} \) and shift \( I_{sh} \). Vlasov-Poisson simultaneous equations can describe electrodynamics of plasma processes obtained from Vlasov-Maxwell simultaneous equations [4, 5].

Electron (ion) beams with high energy density are widely used in various energetic technologies both in aerospace industry and in many other industries in Russian economy [1, 6, 7, 8].

The technology “to generate electric power” [6, 7] is known, due to it an electric arc ionizes power fluid and generates electron beams with anode bed of an electron gun; anode bed crosses with arc electric field. A model to generate electron beams in “the crossed electric fields” is less electric power consuming and technically less complicated in comparison with conventional methods of generating electron beams in electric and magnetic fields. [1, 2].

To increase energy efficiency of electric power technology transforming energy generated in crossed electric fields of electron beams into electric capacitance is realized with crossed electric fields.

It is possible to realise a model of electric physical processes increasing energy efficiency of electric power technology to produce electric power with generating electron beams in the crossed electric fields and transforming energy of electric beams into electric capacitance in the crossed electric fields while using electric plant.

The results were obtained within the project No. 72 of the state task No. 2014/211 of the Ministry of Education and Science of the Russian Federation.
Fig. 1 presents a functional diagram of the electric plant. 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 «+» 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 like Faraday cup [5] transforming electron beam charge 3 into equivalent electric current that generates a direct axis component of electric field $E_l$ on decelerating circuit resistance. The component decelerates electron beam 3. Power transformer – converter (PTC) 6 in the primary circuit has got inductive windings $L_1$ and $L_2$, inductive circuit $L_2$ is aligned to output frequency $\omega_p$ resonantly. PTC 6 secondary circuit is connected with electric power consumer line 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.

The electric plant according to the proposed technique to generate electric power operates in the following way. The necessary voltage is fed to Aa and Ka electrodes of an electric arc with CVSC 1; power fluid filling a vacuum chamber (VC) is ionised under the ark influence. The impact of half-wave voltage $U_A$ fed to output anode $A_{eg}$ of an electron gun 2 generates anode electric field crossed with the electric arc field. Electron beams 3 are generated in this “crossed field” and they direct to a work space 4, where “the crossed electric field” impacts on electron beam 3.

1) We introduce a new term – “the crossed electric field”, by analogy with the term “the crossed electric and magnetic field” used in science-technical literature; here we could also apply terms “orthogonal electric field” or “normal” and “tangential component” of electric field but not for the proposed engineering solution. The fields can be non-orthogonal and working frequencies of the crossed fields are different in the proposed model. Generating electron beams in the crossed electric field are unsophisticated and more energy-efficient than in the “the crossed electric and magnetic field” [1, 2, 15].
Figure 1. Functional diagram of an electric plant realising a model of electrophysical processes of electric power technology based on electron beams in the crossed electric fields.

During the period of time cations of the ionised power fluid come to the arc cathode \((C_A)\) charging it positively. The cations have a mass of thousand times bigger than electrons have, therefore they do not practically change their trajectory of movement within an electric arc.

Radial component \(E_r\) of the crossed field generated by double electric layer in WS 4, compresses an electron beam transversely due to taper pencil along the beam movement. Beam compression coefficient 3 in WS 4 is

\[ C_{cb} = \frac{d_{input}}{d_{output}}, \]

where: \(d_{input}\) and \(d_{output}\) are diameters of input and output inlets in WS 4 accordingly.

Electron beam compression can be realized with electric, magnetic, electro-magnetic “quadrupole electron lenses” allowing to control electron beam compression 3 in an electric plant, though it requires to consume additional energy. Therefore, our invention proposes an energy-efficient technical solution: to compress electron beam with the field of double electric layer generated due to electrophysical properties of materials without additional energy consumption [2].

Compressing electron beam 3 results in electron approach to each other and increase in charge density in a beam

\[ \rho_{eb} = \rho_e C_{cb} \approx C_{cb} 3e/4\pi r_e^3, \]

where: \(e=1.6 \times 10^{-19}\) C – electron charge; \(r_e\) – an average distance among electrons in a beam; \(4\pi r_e^3/3\) – volume an electron has got in a ray; the increase in energy of electron interaction in a beam – potential energy in an electron beam

\[ W_{ep} = q_{ep}^2/\varepsilon r_e = \rho_{ep}^2 V_{ep}^2/\varepsilon r_e, \]
where: \( q_{eb} = \rho_{eb} V_{eb} \) – the total charge of electrons in a beam; \( V_{eb} = s_{eb} l_{eb} \) – volume, beam area and length of electron beam, accordingly; \( \varepsilon \) – dielectric permittivity of medium in an electron beam.

Increasing charge density consequently results in increasing electric current intensity and beam power 3

\[
I_{eb} = \rho_{eb} \nu_b s_{eb},
\]

where: \( \nu_b = (2eU_b/m_e)^{1/2} \) – electron velocity in a beam, \( s_{eb} \) – an area of beam radial section.

Potential power generated by electric charges of an electron beam compressed in WS 4.

\[
S_{eb} = I_{eb} U_b = I_{eb} W_{el} q_{eb}
\]

Direct axis component \( \mathbf{E}_d \) of the crossed field in WS 4 is generated by equivalent electron current obtained from charges \( q_{eb} \) of a beam 3 with Faraday cup [8] in an electrode 5. Electron current running along decelerating electrode circuit resistance 5 generates decelerating potential, that decelerates electron ray transforming potential energy of electron interaction compressed in WS 4 of an electron beam into its kinetic energy, equivalent power to the electric user power grid via \( L_2 \) PTC 6. The circuit load of decelerating electrode is tank circuit of decelerating electrode is tank resistance generated by inductance \( L_2 \) and condenser \( C_p \). Current resonance \( (I_L = I_C) \) in a contour improves oscillation form decreasing energy loss to higher harmonic components and together compensates reactive power increasing power coefficient \( \cos \varphi \) in the electric current practically up to "1". Decelerating potential of the component \( \mathbf{E}_d \) of the crossed field in WS 4 is generated in antiresonant contour, magnetic flux vector is generated by inductance \( L_2 \)

\[
\mathbf{F}_e = I_{eb} \mu_\mu \exp(j \omega_{el} t) \mathbf{H}_\mu = \omega_p L_2 I_{eb} \exp(j \omega_{el} t) \mu_\mu
\]

where: \( \mu \) – magnetic inductive capacitance of coil flux guide material PTC 6; \( \mu_\mu \) and \( l_\mu \) – cross section and coil flux guide length PTC 6, accordingly; transformed potential power is obtained through \( L_2 \):

\[
S_{ebt} = \omega_p L_2 I_{el}^2.
\]

Kinetic energy taken from electrons of a beam 3 while it is decelerated by the component \( \mathbf{E}_d \) of field in WS 4 is also transformed via \( L_2 \) as kinetic power

\[
S_{ebt} = U_{el}^2 / \omega_p L_2 = (m_e (\nu_{el}^2 - \nu_b^2)/2)^2 / \omega_p L_2,
\]

where: \( U_{el} = m_e (\nu_{el}^2 - \nu_b^2)/2 \) – decelerating electrode voltage 5 as the result of deceleration a beam 3 of the component \( \mathbf{E}_d \) of the field in WS (PIT 4); \( \nu_{el} \) – electron velocity of a beam 3; the electrons belong to the decelerating electrode 5. We can consider equal both potential \( S_{eql} \) and kinetic \( S_{elb} \) powers, generated by orthogonal Coulomb-Lorentz force in an electron beam 3 for the first approximation, as a beam 3 in electrodynamic balance under the force impact, and the total of the generation by the compressed beam 3 equals to the sum of effective ranges composing powers:

\[
S_G = (S_{ebt}^2 + S_{elb}^2)^{1/2} = \sqrt{2} S_{ebt}.
\]

The energy of electron ray generation producing the generation power \( S_G \) is:

\[
W_G = \sqrt{2} W_{el} = \sqrt{2} q_{el}^2 / \varepsilon \nu_{el}.
\]

Output power necessary to generate an electron ray 3 with electron gun 2 is obtained from electric user power grid via inductance circuit \( L_1 \)

\[
S_{consump} = \omega_p L_1 I_{el}^2 = S_\Sigma + S_\lambda = U_A I_A (1 + K_{S3l}),
\]

where: \( I_{el} = I_A (1 + K_{S3l}) \) – the require current intensity for an electric gun; \( S_\Sigma \) and \( S_\lambda \) - power output of electric arc and anode field of EG 2, respectively; \( K_{S3l} = 2.2 U_d / U_A \) – power output coefficient per electric arc in relation to power output of anode field of gun 2. The relevant magnetic flux within a coil flux guide of PTC 6 is generated to transfer current out of the grid.
\[ F_{eb} = I_{eb} \mu_s / I_\mu \]  

(12)

The expressions (6 and 12) describing \( F_e \) and \( F_{eg} \) magnetic flux vectors reveal that vectors are performed by the dissimilar current \( I_{en} \) and \( I_{\text{gI}} \), therefore, vectors \( F_e \) and \( F_{eb} \) are opposing to one another. Vector \( F_{eb} \) transferring power to EG \( (\text{Эп})_2 \) is balanced by vector \( \Phi_e \) generating power. Generating power by the proposed electric plant requires vector \( \Phi_e \) of magnetic flux exceeds vector \( F_{eb} \) of magnetic flux:

\[ \frac{F_e}{F_{eb}} \geq 1 \text{ или } I_{eb} = C_{en} \rho_{e} v_0 s_{en} / I_{\text{gI}} = I_A (1 + K_{\text{SII}}) \geq 1. \]  

(13)

Satisfying the condition the electric power meter Wh of overcurrent type registers the amount of electric power produced by the plant while the current comes to the users’ grid (onboard grid of a space vehicle).

The expression (13) results in necessary coefficient of electron ray compression to generate the required amount of power \( S_{\text{Gen}} \) by the electric plant and relevant coefficients to transform power generation \( K_{SG} \) and power of electron beam \( K_{SP} \).

\[ K_{en} \geq I_A (1 + K_{\text{SII}}) / \rho_{e} v_0 s_{en} \]  

(14)

\[ K_{\text{SII}} = K_{SG} / \sqrt{2} = S_{\text{en}} / S_{\text{arp}} = U_A K_{C_b} \rho_{e} v_0 s_{eb} / U_A I_A (1 + K_{\text{SII}}) \]  

(15)

Electrons performing the work within the outer electric circuit under the impact of potential difference between decelerating electrode 5 and cathode \( \text{КД} \) of electric gun 2 come to the cathode and recombine cations to atoms and molecules of working fluid under reionisation by electric arc between anode \( A_a \) and cathode \( C_a \) to start a new cycle of generating electric power and its transforming into users’ grid (onboard grid of a space vehicle [9]).

The expressions (2, 3, 9, 10, 13, 14 and 15) demonstrates the generated power depends on electron ray compression coefficient \( C_{eb} \), therefore changing \( C_{eb} \) controls power transformation coefficient and the amount of generated power according with the proposed energy production technique.

When changed automatically with frequency \( \omega_r \) of polarity of half-wave voltage \( U_A \) on output anodes \( A_{\text{eg}} \) of electric gun 2, the different electron gun generates an electron beam 3 the described above processes happen where beam energy converts into electric power and further the different symmetrical branch of PTC 6 transforms it to the users’ electric power grid. As a result we have full-wave transformation of electron beam (3) energy into electric power; its quality corresponds to the requirements of GOST 13109-97 [10]. The working fluid is not spent; there are no harmful wastes and emissions having negative impact on the environment, though they are typical to the power generating industry [11] burning fuel.

Fig. 2 presents the electric parameters obtained with computer modeling in Delphi [12, 13, 14, 16] of electrophysical processes of electric power technology based on electron beams in the crossed electric fields. The technology is realised with the electric power plant demonstrated by Fig. 1.
Figure 2. The results of modeling processes of electric power technology based on electron beams in the crossed electric field.

\[ S_{\text{cons}}(1\text{A}) \text{ and } S_{\text{cons}}(2\text{A}) \] - power consumption to generate an electron beam under the dynamic current of electron gun 1A and 2A accordingly;

\[ C_{\text{SD}} \] - coefficient of power consumption per electric arc relatively to power consumption in electric gun;

\[ S_{\text{eb}}(1\text{A}) \text{ and } S_{\text{eb}}(2\text{A}) \] - electric beam power under the dynamic current of electric gun 1A and 2A accordingly;

\[ S_{\text{G}}(2\text{A}) \] - the generation power under the dynamic current of electron gun 2A;

\[ C_{\text{eb}} \] - coefficient of electron beam power transformation.

Proportionally to the compression coefficient compression of electron beams 3 in WS 4 by the field of double electric layer not requiring additional electric energy consumption; it increases the energy efficiency of the proposed technology to produce electric energy.

Current resonant condition, compensating reactive power within the electric circuit decelerating the compressed electron beam 3 and converting equivalent power produced by the energy of the compressed beam, increases the electric circuit power coefficient up to \( \langle 1 \rangle \). The power decelerates electron beam and transforms its energy to the users' electric power grid.

Therefore, deceleration and simultaneous electron beam compression applied according to the proposed model of electric power technology of energy production give the possibility to use both kinetic and potential energy of electron beam electric charges, consequently, to generate electric power with higher electric efficiency; the power is equal to the energy of the compressed electron beam. \([15]\)

The proposed model of electrophysical processes increasing power generating technologies can be used for both electric power production \([7]\) and aerospace engineering \([8]\).
Summing it up we could state the following:

1. The proposed model to generate electron beams within “the crossed electric field” their energy regeneration within “the crossed electric field” into electric power transformed into users’ electric power grid allows to increase energy efficiency of electric power technology based on electric beams.

2. Applying the crossed electric field of electric gun ionising power fluid together with anode field of electron gun generating electron beam with simultaneous electron mass transfer, enables to generate electron beams of higher intensity with higher energy efficiency technically simpler than the traditional technology based on electric and magnetic fields.

3. Compressing electron beam by the field of double electric layer not requiring additional energy consumption increases energy parameters of an electron beam and efficiency of the proposed model to generate electric power proportionally to compression coefficient.

Decelerating and simultaneous compressing an electron beam within the crossed electric field allows to transform both kinetic and potential energy of the interacted charges of an electron beam; therefore it transforms energy of the compressed electron beam into equivalent electric power with high energy efficiency to the users’ electric power grid.

4. Current resonant condition within electric circuit decelerates the compressed electron beam and approaches the electric circuit power coefficient to «1» decelerating electron beam and transforming equivalent power to the users’ electric power grid.

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