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Effect of an external circuit on the stability of thermionic energy converter steady states

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Abstract. The possibility of creating an alternating current source based on a thermionic energy converter is because, under certain conditions, an electron instability can develop in such a diode in the collisionless mode, leading to a sharp current cut-off. To implement this effect, it is enough to short electrodes through inductance. To select the optimal operation mode of the generator, it is necessary to study external inductance influence on the development of the instability. This problem is theoretically studied in the proposed work, and both over-neutralized and under-neutralized modes are considered. Dispersion equations are obtained. It is shown that when external inductance is included an instability threshold can be moved below the Pierce one. Besides, this type of instability can develop only for inductance values from a limited range.

Keywords: thermionic energy converter, plasma diodes

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Влияние внешней цепи на устойчивость стационарных режимов термоэмиссионного преобразователя энергии

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Аннотация. Возможность создания источника переменного тока на основе термоэмиссионного преобразователя энергии обусловлена тем, что в бесстолкновительном режиме в таком диоде при определенных условиях может развиваться электронная неустойчивость, приводящая к резкой отсечке тока. Для выбора оптимального режима работы генератора необходимо изучить влияние внешней индуктивности на развитие неустойчивости. В данной работе рассматриваются перекомпенсированный и недокомпенсированный режимы. Для них получены дисперсионные уравнения и показано, что неустойчивость может развиваться только при значениях внешней индуктивности из ограниченного диапазона.

Ключевые слова: электронная неустойчивость, плазменный диод, плазменные колебания

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Introduction

Thermionic energy converter (TEC) is used for direct conversion of heat into electrical energy, and is usually a DC source. A concept of AC source based on TEC has been proposed after the study carried out at the Ioffe Institute [1, 2]. This was made possible due to the fact that, under certain conditions, an electron instability develops in the TEC leading to a sharp current cut-off. To implement this effect, the TEC should be in the collisionless (Knudsen) mode, and the electrodes must only be shorted through inductance. The operability of such a device was confirmed experimentally [2]. Thus, both obtaining of electric energy and conversion of DC voltage into AC one are carried out directly in the TEC. There is no need for additional voltage converters. As a result, there are prospects to reduce weight characteristics, to reduce cost as well as to increase reliability of the power plant based on TEC. However, in order to develop the generator it is important to optimize operation modes of the device.

In this paper, we present results of studying the stability features of TEC stationary states and investigate at what values of an external inductance the instability can occur in the diode from external circuit system.

Materials and Methods

This paper considers a collisionless (Knudsen) diode with surface ionization (KDSI) in which electrons are supplied from the hot emitter by thermal emission and ions are supplied by surface ionization.

There are two modes of operation: over-neutralized and under-neutralized. In the first case, more ions than electrons enter from the emitter (the neutralization parameter $\gamma = n_{i,0} / n_{e,0} > 1$, where $n_{i,0}$ ($n_{e,0}$) is the ion (electrons) density escaping from the emitter surface, at the emitter). As a rule, self-consistent stationary solutions are characterized by potential distributions (PD) that have a broad quasi-neutral plateau in the most part of the inter-electrode gap, while there is potential jump in small near-electrode regions. There is a monotonic potential distribution if $\gamma > 1$. It consists of zone with a sharp potential jump near the emitter, a plateau zone with a zero electric field and a potential jump near the collector that has the same sign as that at the emitter. On the contrary, in the case of $\gamma < 1$ PDs vary non-monotonically: a virtual cathode (VC) is formed near the emitter, reflecting a portion of electrons back to it. There is a strong potential jump and a quasi-neutral plateau region. The potential jump near the collector is of the same sign as that at the VC outside. These are PDs with virtual cathode (VCPD).

At the KDSI, the velocity distribution functions of electrons (EDF) and ions escaping from the emitter surface are semi-Maxwellian with the emitter temperature T_E. The charged particle densities in the stationary mode depend only on the potential at the current point and on the potentials at the points of particle reflection from the potential barriers. For the case of KDSI, one can obtain analytical expressions for charged particle densities for any type of PD [4].

For the convenience, we turn to dimensionless quantities, and choose the electron energy at the emitter $W_E = kT_E / 2$ and the Debye-Hückel length $\lambda_D^E = \left[2\tilde{\epsilon}_0 W_E / (e^2 n_{e,0})\right]^{1/2}$ (here e is electron charge and $\tilde{\epsilon}_0$ is vacuum permittivity) as units of energy and length. Then the dimensionless potential η is normalized to kT_E / e.

In the over-neutralized mode with MPD the particle densities are given by

$$n_e(\eta) = n_{e,0}\, exers(\eta),$$
$$n_i(\eta,\eta_C) = \gamma n_{e,0}\left[2\exp(-\eta) - \exp(-\eta_C) exers(\eta_C - \eta)\right]. \quad (1)$$

Here η_C is the potential difference between the electrodes, and the function $exers(x) = \exp(x)\,[1 - erf(\sqrt{x})]$. The relationship between the neutralization parameter γ and the plateau potential η_p is determined from the quasi-neutrality condition.

$$exers(\eta_p) - \gamma\left[2\exp(-\eta_p) - \exp(-\eta_C) exers(\eta_C - \eta_p)\right] = 0. \quad (2)$$

In the under-neutralized mode with VCPD the particle densities are given by

$$n_e(\eta,\eta_m) = n_{e,0}\exp(\eta_m) exers(\eta - \eta_m)$$
$$n_i(\eta,\eta_C) = \gamma n_{e,0+}\begin{cases}\left[2exers(-\eta) - \exp(-\eta_C) exers(\eta_C - \eta)\right], & \eta < 0,\\ \left[2\exp(-\eta) - \exp(-\eta_C) exers(\eta_C - \eta)\right], & \eta > 0.\end{cases} \quad (3)$$

We need to solve a system of two equations to calculate the minimum potential η_m and plateau potential η_p. The first of equations corresponds to the condition of quasi-neutrality at the plateau $\eta = \eta_p$, and the second one corresponds to the condition of zero total charge on the VC outer part, i.e. between points η_m and η_p, where the electric field strengths vanish:

$$\exp(\eta_m) exers(\eta_p - \eta_m) - \gamma\left[2\exp(-\eta_p) - \exp(-\eta_C) exers(\eta_C - \eta_p)\right] = 0,$$
$$\exp(\eta_m)\left[iers(\eta_p - \eta_m) - 1\right] - \gamma\left\{2[iers(-\eta_m) - \exp(-\eta_p)] + \right.$$
$$\left. + \exp(-\eta_C)\left[iers(\eta_C - \eta_p) - iers(\eta_p - \eta_m)\right]\right\} = 0. \quad (4)$$

Here, the function $iers(x) = (2/\sqrt{\pi})(\sqrt{x}) exers(x)$. One can find more detailed consideration of all types of PD in the KDSI in [4].

In our work, we study the electron instability of solutions both with MPD, and with VCPD. In this case, the ions can be considered as immovable. We derive formulas for the diode impedance taking into account the presence of inductance in the external circuit, and use them to study dispersion characteristics of the diode.

In the over-neutralized mode with MPD and in the under-neutralized mode with VCPD, a flow of accelerated electrons with small energy dispersion enters the plasma.

Therefore, we assume that a mono-energetic electron flow enters from the emitter at a velocity which value will be determined below for each mode.

Results and Discussion

Stability of solutions with MPD in the over-neutralized mode for a diode included in an external circuit without reactive elements was studied in [5]. The PD was represented as

$$\eta(\zeta,\tau) = \eta_0(\zeta) + \tilde{\eta}(\zeta)\exp(-i\Omega\tau), \quad |\tilde{\eta}(\zeta)| \ll \eta_0(\zeta). \quad (5)$$

Here $\eta_0(\zeta)$, $\tilde{\eta}(\zeta)$ and Ω are the unperturbed PD, the potential perturbation amplitude, and the complex frequency respectively. Evolution of small potential perturbation was tracked.

In this case, the potential perturbation in the plasma does not affect the EDF at the emitter $f_0(u_0)$ The following equation was obtained for the potential perturbation amplitude:

$$\tilde{\eta}'(\zeta) + \int_0^\infty du_0 u_0 f_e^0(u_0)\int_0^\zeta \frac{dx}{u^3(x,u_0)}\int_0^x dy \exp\{i\Omega[\sigma(\zeta,u_0) - \sigma(y,u_0)]\}\tilde{\eta}'(y) = -\frac{i}{\Omega}\tilde{j}. \quad (6)$$

Here $u(\zeta,u_0)$ and $\sigma(\zeta,u_0)$ are the electron velocity at point ζ and its motion time from emitter to point ζ in field with potential $\eta_0(\zeta)$, and $\tilde{j}$ is an amplitude of the total current-density perturbation. At $\eta_p \gg kT_E / W_p$ the EDF at the emitter can be approximated by δ-function: $f_e^0(u_0) = n_E\delta(u_0 - u_E)$ with $n_E = n_{e,0}$, $u_E = \sqrt{(kT_E/m)}$. Then in Eq. 6 one gets rid of one integration. Equation (6) allows one to find the perturbation potential amplitude for the mode without reflection of electrons from potential barriers at any form of $\eta_0(\zeta)$.

The boundary conditions for perturbations at the emitter are the same as in the Pierce diode, where the monoenergetic electron flow moves through a uniform background of immovable ions, and $\eta_0(\zeta) \equiv 0$:

$$\tilde{\eta}(\zeta)|_{\zeta=0} = 0, \qquad \tilde{j}_e(\zeta)|_{\zeta=0} = 0. \tag{7}$$

Here $\tilde{j}_e$ is a perturbation amplitude of the electron convection current-density.

In studying an effect of the external circuit on stability features of the diode it is convenient to consider the impedance of the diode $Z(\Omega,\sigma) = -\tilde{\eta}(\Omega,\sigma)/\tilde{j}$; here $\tilde{\eta}(\Omega,\sigma)$ is an amplitude of the collector potential perturbation.

When the unperturbed potential of the collector coincides with the plateau potential, the situation is close to the Pierce diode: the electric field in almost the entire gap vanishes. Some differences are that the EDF at the plateau is slightly different from the mono-energetic one, and the near-emitter region, where the potential and charged particle densities vary greatly, has a width although small compared to δ, but finite. When $\eta_p \gg kT_E/W_p$, where $W_p = kT_E/2 + e\Phi_p$ is the kinetic energy of the plasma electrons, the thermal spread of electron velocities can be neglected. In [5] it was shown that the EDF at the emitter should be chosen as following:

$$f_e^0(v) = n_e\delta\left(v - \sqrt{kT_E/m}\right).$$

When deriving an equation for the potential perturbation we follow [5]. The electron energy W_p in plasma and Debye-Hückel length $\lambda_D^p = \left[2\tilde{\varepsilon}_0 W_p/(e^2 n_p)\right]^{1/2}$ are used as energy and length units. Note, that plasma energy and Debye-Hьckel length parameters are connected with the emitter ones by formulas [5]

$$W_p = W_E + e\Phi_p, \quad \lambda_D^p = \lambda_D^E\left([1+2\eta_p(\gamma)]/exers[\eta_p(\gamma)]\right)^{1/2}. \tag{8}$$

Here $\eta_p = e\Phi_p/kT_E$ is the plasma potential calculated in the "emitter" units.

The diode impedance is made up of the impedance $Z_E(\Omega)$ of the emitter region $(0, \zeta_E)$ and one of the plateau region $Z_p(\Omega)$ (ζ_E, δ). In the near-emitter region, the unperturbed PD is approximated by a straight line: $\eta_0(\zeta) = \kappa\zeta$. It is found that ζ_E magnitude is well described by the formula $\zeta_E = 0.62\gamma^{-0.28}(\lambda_D^E/\lambda_D^p)$ for γ values from 2 to 10. The following expression is obtained for $Z_E(\Omega)$:

$$Z_E(\Omega,\zeta_E) = \frac{i}{\Omega}\left\{\zeta_E - \frac{\pi}{2\alpha^3}\int_{\alpha\sqrt{u_{em}}}^{\alpha} dy\, y^2 \int_{\alpha\sqrt{u_{em}}}^{y} dx\, x^2 T_{11}(y,x)\exp\left[i\Omega\frac{1}{2\alpha}(y^2 - x^2)\right]\right\}. \tag{9}$$

Here $\alpha = 2/\kappa$, $u_{em} = \sqrt{(W_E/W_p)}$ is a characteristic electron velocity at the emitter, $T_{11}(y,x) = J_1(x)N_1(y) - J_1(y)N_1(x)$, and J_1 and N_1 are Bessel and Neumann functions of index 1.

The following expression is obtained for $Z_p(\Omega, \delta)$:

$$Z_p(\Omega,\delta) = -\frac{1}{2\Omega(1-\Omega^2)}\left[\frac{1-\Omega}{1+\Omega}(1+g_+)\{1-\exp[i(1+\Omega)(\delta-\zeta_E)]\} - \right.$$
$$\left. -\frac{1+\Omega}{1-\Omega}(1+g_-)\{1-\exp[-i(1-\Omega)(\delta-\zeta_E)]\} + 2i\Omega^2(\delta-\zeta_E)\right]. \tag{10}$$

Here

$$g_+ = (1+\Omega)[(1-\Omega)f_1 + if_2], \quad g_- = (1-\Omega)[(1+\Omega)f_1 - if_2],$$
$$f_1 = -i\Omega Z'_E(\zeta_E) - 1, \quad f_2 = i\Omega Z''_E(\zeta_E), \tag{11}$$

and $Z'_E(\zeta_E)$ and $Z''_E(\zeta_E)$ are the values of the 1st and 2nd derivatives of the impedance Z_E at the right boundary of the region $(0, \zeta_E)$. In the case under consideration

$$f_s = \frac{\pi}{2a}\int_{\sqrt{V}a}^{a} dx\, x^2 T_{s1}(a,x)\exp\left\{\frac{i\Omega}{2a}(x^2 - a^2)\right\}, \quad s = 1,2. \tag{12}$$

The matching condition for a diode with an inductive external circuit is

$$Z_E(\Omega,\zeta_E)+Z_p(\Omega,\delta)-i\Omega L=0. \tag{13}$$

This equation with $L=0$ was solved in [5]. The dispersion curves, i. e. the dependences of the eigen-mode growth rate Γ and frequency Ω on the dimensionless inter-electrode gap δ were plotted. It turned out that both these dependencies are close to the similar dependences for the Pierce diode. The instability threshold is close to that for the Piers diode $\delta_{th}^{P}=\pi$. The picture of the KDSI generation regions is similar to that for the Pierce diode, too [3], but, unlike the latter, in the KDSI the generation regions are localized. This is due to the fact that the real part of the emitter region impedance is positive.

We have studied solutions of the dispersion equation (13) when inductance is present in the external circuit. It is shown that, same as in the Pierce diode [6], an external inductance leads to the appearance of a new instability branch. In addition, it can intersect Γ = 0 axis at δ values below δ_{th}^{P}. This means that by varying the inductance it is possible to change the emission current value at which sharp current cut-off occurs, i.e., to optimize the TEC operation regimes. It is also shown that instability can develop only at values of the external inductance lying in a limited range. For example, at γ = 10 this range is 0 < *L* < 2.5 (see Fig.1, *a*). It should be noted, that new branch are corresponded frequencies higher the plasma frequency.

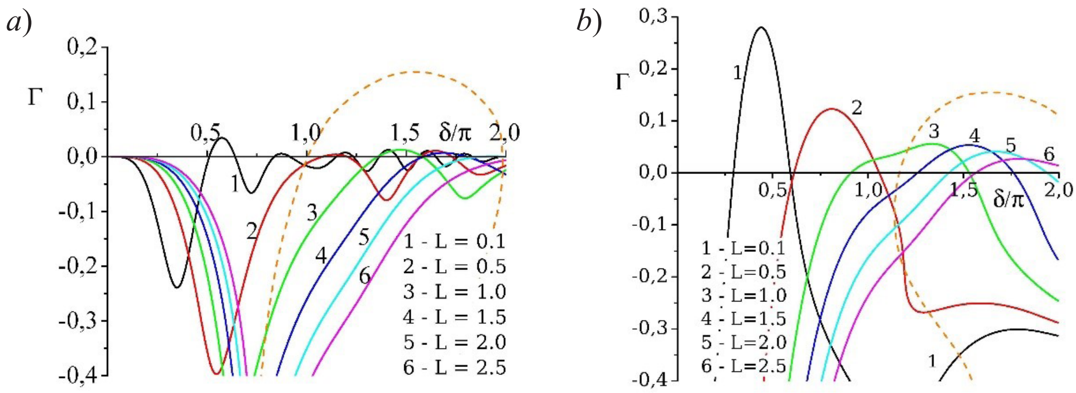

Fig. 1. The growth rate Γ vs δ for various values of an inductance L = 0.1 (1), 0.5 (2), 1.0 (3), 1.5 (4), 2.0 (5), 2.5 (6); dashed curve is the 1st aperiodic Pierce branch in over-neutralized regime, γ = 10 (*a*), and in under-neutralized regime, γ = 0.002 (*b*)

When studying stability of PDs with VC, one can exclude the area between the emitter and the position of VC top ζ_m due to the small width of this area and study an equivalent problem, when the emitter is placed in a point with coordinates (ζ_m, η_m). Current supplied by "new" emitter corresponds to flow of the electrons which overcame the potential barrier η_m occurring in the stationary field, i.e. the current is $j_m = j_E \exp(\eta_m)$ [7, 8]. In this case, we can assume that during the initial stage of the instability development, perturbation of the VC top position and of the electric field at this top are zero.

The following equation is obtained for the potential perturbation amplitude:

$$\begin{aligned}&\tilde{\eta}'(\zeta)+\int_0^\infty du_1 u_1 f_e^0(u_1)\int_0^\zeta \frac{dx}{u^3(x,u_1)}\int_0^x dy\exp\{i\Omega[\sigma(\zeta,u_1)-\sigma(y,u_1)]\}\tilde{\eta}'(y)=\\&=-\frac{i}{\Omega}\tilde{j}\int_0^\infty du_1 u_1 f_e^0(u_1)[\exp\{i\Omega\sigma(\zeta,u_1)\}-1].\end{aligned} \tag{14}$$

Here u_1 is the electron velocity at the "new" emitter. The "current" term in the right part of Eq.(14) is due to the fact that in this case it must be taken into account a perturbation of the lower bound of the velocity region at the emitter, over which the integration takes place when density is calculated. It should be noted, that in this approximation, the potential in the plasma is actually increased by the VC height $|\Phi_m|$, and is $\Delta\Phi = \Phi_p - \Phi_m$. When ΔΦ turns out to be large enough, the thermal velocity spread of electrons in the plasma can be neglected and the EDF at the new emitter can be chosen in the form $f_e^0(u_1) = (j_m / e)\,\delta(u_1)/u_1$.

The boundary conditions for perturbations at the emitter differ from the Peirce-like ones (7) and have the form

$$\tilde{\eta}(\zeta)\,|_{\zeta=0} = 0, \qquad \tilde{\eta}'(\zeta)\,|_{\zeta=0} = 0. \tag{15}$$

When calculating the impedance, we approximate the PD on the external part of the VC by the law, which corresponds to the vacuum diode with zero electric field strength at the emitter:

$$\Phi(z) = \alpha z^{4/3}, \qquad \alpha = \left(\frac{3}{2}\right)^{4/3}\left(\frac{m j_m^2}{2e\epsilon_0^2}\right)^{1/3}. \tag{16}$$

This approximation describes well the behavior of the PD to the right of the VC top [7]. For the position of emitter region boundary ζ_E, electron velocity at the plateau u_p and electron transit time through the emitter layer σ_E we have

$$\zeta_E = \left(2^{5/4}/3\right)(\eta_p - \eta_m)^{3/4}, \quad u_p = \left(6^{2/3}/2\right)\zeta_E^{2/3}, \quad \sigma_E = (6\zeta_E)^{1/3}. \tag{17}$$

Here units of length and energy are selected using the emitter parameters, but only with the replacement η_p with $\Delta\eta = \eta_p - \eta_m$.To go to plasma units, we need decrease ζ_E by ratio of the plasma and emitter Debye-Hückel lengths: $\lambda_D^E/\lambda_D^p = (\eta_p - \eta_m)^{-3/4}\exp(-\eta_m/2)$.

To study the diode generation regions and plasma dispersion, let's consider its impedance. As in the over-neutralized mode, it is composed of the impedances of the emitter layer $Z_E(\Omega, \zeta_E)$ and that of the plateau region $Z_p(\Omega, \delta)$. In this case, we have the following expression for $Z_E(\Omega, \zeta_E)$:

$$Z_E(\Omega,\zeta_E) = \frac{1}{\Omega^4}\left[\frac{i}{6}(\Omega\sigma_E)^3 + i\Omega\sigma_E + 2 + \left(i\Omega\sigma_E - 2\right)\exp(i\Omega\sigma_E)\right]. \tag{18}$$

The impedance of the plateau region $Z_p(\Omega, \delta)$ is determined by the formulas (10) and (11), but only with other functions f_1 and f_2:

$$f_1 = \frac{1}{\Omega^2\sigma_E^2}\left[1 + (i\Omega\sigma_E - 1)\exp(i\Omega\sigma_E)\right],$$
$$f_2 = \frac{-4}{\Omega^2\sigma_E^5}\left[2 + (\Omega^2\sigma_E^2 + 2i\Omega\sigma_E - 2)\exp(i\Omega\sigma_E)\right]. \tag{19}$$

Regions of the KDSI generation for solutions with VCPD in the under-neutralized mode with a purely active external circuit were studied in [7]. It turned out that these regions are localized. This is because the real part of the emitter layer impedance is positive. The $\Omega(\delta)$ dependences turn out to be close to those in the over-neutralized mode. The $\Gamma(\delta)$ dependences are similar to those in the over-neutralized mode, but are shifted in the region of negative Γ values. Besides, all bifurcation points on aperiodic branches that are the oscillatory branch start lie below the $\Gamma = 0$ axis. The instability threshold is shifted to the right of the δ_{th}^P point by a value, approximately equal to ζ_E. When there is inductance in the external circuit, new eigen-mode similar to that in over-neutralized mode appears, and it has frequency higher than the plasma frequency. Its $\Gamma(\delta)$ dependence can intersect $\Gamma = 0$ axis at δ values below the Pierce threshold (see Fig.1, *b*). For example, at $\gamma = 0.002$ it happens when $L \approx 1.4$.

Conclusion

In order to create an alternative current directly in the TEC, its electrodes are bridged over an inductance with a magnitude of about several units of μH [2]. Feasibility of such a generator is based on the electron instability development in collisionless plasma diodes resulting in the current cut-off effect. We have demonstrated that presence of an external inductance induces a new unstable eigen-mode, which can make the instability threshold lower than the Pierce one. Thus, by varying the external inductance one can control current density magnitude at which the cut-off occurs and affect the generator performance.

In order to calculate the optimum magnitude of the inductance one has to calculate the non-linear time-dependent process in the KDSI plasma taking into account a time variation of the collector potential caused by the presence of an inductance.

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