JOURNAL OF PROPULSION AND POWER
Vol. 13, No. 4, July–August 1997

Biphase Inverter Based on Cesium Plasma Switches

N. I. Alekseyev,* V. B. Kaplan,† A. M. Martsinovskij,‡ S. V. Electrov§
Ioffe Physico-Technical Institute, St. Petersburg 194037, Russia

For the goals of practical use of cesium switches (a nuclear powerplant for spacecraft with a thermoionic reactor and subsequent current conversion), the study of their performance in a biphase inverter mode is of much interest. Unlike a half-period mode for active load, which so far has received the primary attention, the work of each switch is determined tangibly by the state of its neighbor. The demands on the mutual arrangement of extinguishing and igniting pulses are defined experimentally for either a symmetrical circuit or a nonsymmetrical one with the switches based on various extinguishing principles.

Nomenclature

E_a = modulated voltage of a source
I_a = anode current in a separately regarded plasma switch
$I_{1,2}$ = anode current through switches 1,2
L = inductive load; in case of biphase inverter, one-half of inductive load of primary winding
V_a = anode voltage
$V_g^{(+,-)}$ = ignition and extinguishing pulses to the grid
$V_{1,2}^{(+,-)}$ = ignition and extinguishing pulses to grids 1,2
$\tau[V_g^{(+,-)}]$ = length of pulses

Introduction

PLASMA CESIUM SWITCHES (PS) are a class of plasma full-control three-electrode devices (the control goes by applying short ignition V_g^+ and extinguishing V_g^- pulses to the grid) for the transformation of dc into an alternating one in the conditions of high temperatures and radiation (they are unfit for performance of transistor or solid-state switches). The physical principles for PS on the base of Knudsen arc with pure Cs filling[1–5] and a Cs–Ba mixture[6–9] have been extensively studied.

In the last variant the admixture of Ba ensures high current densities (as high as more than 10 A/cm^2), so that even large-scale aperture grids (~1 mm diam, 1 mm thick) make it possible to shut off (extinguish) the current when a negative voltage pulse V_g^- is applied to the grid and stimulates self-extinguishing (or spontaneous current cutoff). Typical of this mechanism is a long time between the leading front of the pulse and extinguishing (as long as 10–20 μs) and the weak dependence of the current change process on the length of the front. The processes that stimulate instability and self-extinguishing could develop during the grid pulse action.

Some special approaches (honeycomb-type grids of the developed grid surface structure[10,11] or the restriction of the discharge area in the grid plane) permit the use of this control mechanism at much smaller emissions (~1 A/cm^2) in a pure Cs switch.

Different from the self-extinguishing mechanism is a dynamic (or potential) one when the steep-front extinguishing pulse is applied to a small-cell grid (0.1–0.2 mm diam and 10 μm thick). This mechanism works reliably for Cs switches at a current of 1–5 A/cm^2 and a Cs pressure up to 2×10^{-2} torr.[1–5] Typical of this mechanism is fast (within 0.5–2.5 μs) extinguishing, in which the current decreases substantially (more than half) during the negative pulse front time (~0.1–0.2 μs). If the pulse is great enough the plasma cannot make up for the increased ion loss out of intercell spacing of the grid, as the ionization process in Cs is of a stepped, slow character with a typical time of 1–2 μs.

Not taking into account the advantages of using a Cs or Cs–Ba filling,[10,11] we note here that Cs switches give a chance to use both principles at a current of 1–5 A/cm^2 and to compare them.

This paper is devoted to the performance of both types of Cs switches synchronized in a biphase inverter circuit (BI or push–pull mode,[12] (see Fig. 1a). Switches 1,2 are conducting in turn ($V_{1,2}^+$ and $V_{1,2}^-$ in Fig. 1b are the ignition grid pulse and the extinguishing grid, respectively). When a switch starts conducting, its anode voltage V_a drops down to 1–3 V, so that the voltage E_a is almost entirely developed across the primary winding and transferred to the secondary winding load R_L in proper polarity [Fig. 1b, curve $V_L(t)$].

The main problem to be solved was the study of the transitional process influence on BI. This influence is also a problem in semiconductor inverters,[13] in that even a short conductance of both switches at one time leads to their breaking down, special measures are taken to prevent this from happening. In BIs based on plasma switches the role of inductive load is manifold: extinguishing or ignition of a switch could either promote or disturb the work of the other. In an experimental setup for the Cs–Ba switch push–pull mode study[12] this problem was aggravated with placing both Cs reservoirs in a common temperature reservoir.

Our experiments were carried on with plane–parallel geometry devices placed into glass envelopes.[1–3] The switches under study had their own cesium reservoirs that could be heated or cooled independently within a temperature range, even though both glass devices were placed in a common temperature reservoir.

Current and voltage signals were measured using a gated integration system.

Performance of a Separate PS Loaded with Mixed Ohmic-Inductive Impedance

Although primary attention was concentrated on the qualitative analysis of transitional processes in the modes where each switch element worked reliably, the study was started with individual switches with combined ohmic-inductive loads. First an analysis of the switch with the small-cell grid[1–5] was taken, whose characteristics had been extensively studied previously.

Presented as Paper 94-3887 at the AIAA 29th Intersociety Energy Conversion Engineering Conference, Monterey, CA, Aug. 7–11, 1994; received Aug. 14, 1995; revision received Dec. 4, 1996; accepted for publication Feb. 4, 1997.

*Ph.D. Junior Researcher, Low-Temperature Plasma Laboratory.
†Ph.D. Senior Researcher, Low-Temperature Plasma Laboratory.
‡Ph.D. Head of Sector, Low-Temperature Plasma Laboratory.
§Junior Researcher, Low-Temperature Plasma Laboratory.

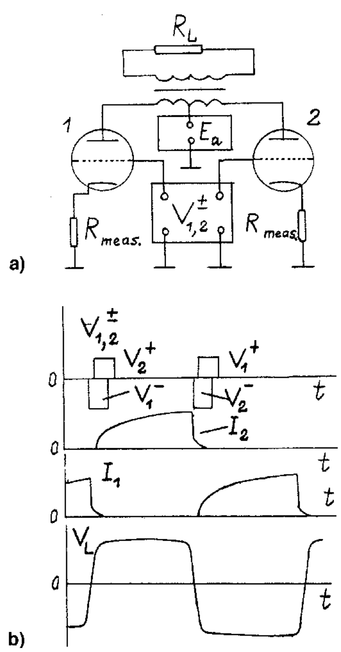

Fig. 1 a) Biphase inverter circuit and b) operation. Control pulses $V_{1,2}^{(+,-)}$; currents $I_{1,2}$ through the switches 1,2; V_L, the voltage across the secondary winding.

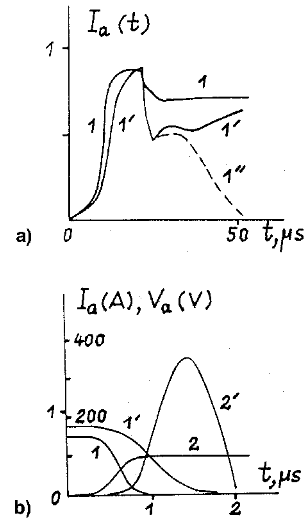

Fig. 2 a) Ignition and b) extinguishing currents (1-1″) and voltages (2,2′) across a switch loaded with pure ohmic (1,1′) and combined (2,2′: L = 0.8 mH) impedance. P_{Cs} = 7 × 10^{-3} torr; E_a = 80 V (except 1″; 1″, L = 0.8 mH; E_a = 30 V).

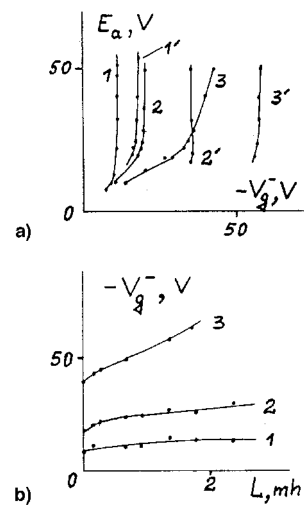

Fig. 3 a) Dependence of minimal extinguishing pulse $|V_g^-|$ on modulated voltage E_a (extinguishing efficiency) with pure ohmic (1,2,3) and combined (1′-3′) impedance. $I_a(A)$: 1,1′, 0.35; 2,2′, 0.46; 3,3′, 0.68; 1′,2′,3′, L = 0.8 mH; P_{Cs} = 8 × 10^{-3} torr. b) Extinguishing efficiency as a function of the inductive component L of the load. P_{Cs} = 8 × 10^{-3} torr; E_a = 70 V; $I_a(A)$: 1, 0.3; 2, 0.6; 3, 1.1.

Unlike BI, which is to be considered later, most of the source voltage in the conducting state was developed across the ohmic load. This enabled us to compare extinguishing and ignition kinetics in cases of pure ohmic (curves 1,2 in Fig. 2b, 1 in Fig. 2a) and combined (1′,2′ in Fig. 2b, 1′ in Fig. 2a) impedance with regard to a common initial state. In Fig. 2b the curves 1,1′ represent a time variation of anode current and 2,2′ that of anode voltage; the curves 1,1′ in Fig. 2a illustrate the ignition process (current $I_{1,2}$ measuring shunts are connected between the cathodes and ground. Thus, initial current jerk during the first ~20 μs corresponds a grid current during the length of the pulse V_g^+). The inductive load was 1 mH and the source voltage was $E_a \approx$ 80 V. It could be seen that the inductive load moderated the current change notably (1′, Figs. 2a and 2b). Herewith, the anode voltage during ~2–4 μs could considerably exceed E_a (2′, Fig. 2b) and reach 500–800 V. Such an overload was important to avoid leading to either a control loss or a reignition of the discharge.

The grid control efficiency (defined as the minimal extinguishing pulse to the grid $|V_g^-|$ as a function of modulated voltage E_a) is shown in Fig. 3a (pressure $P_{Cs} \approx 8 \times 10^{-3}$ torr) at various currents I_a. One can see the following facts from Fig. 3:

1) Combined load curves 1′,2′,3′ are cut short toward small voltages E_a because no conductive state is realized there: the ignition pulse is too short and the anode current through the inductive load L has no time to become great enough, whereas the anode voltage (at floating grid potential) is too small to take up the discharge.

2) Curves 1′–3′ (Fig. 3a) are shifted with regard to the ohmic load curves 1–3 (Fig. 3b) by 15–20 V. Independence $|V_g^-|(E_a)$ (see curves 1′–3′ in Fig. 3a) is hardly connected with the plasma beam discharge features (unlike the ohmic load case[14]), but emerges from the fact that extinguishing is mainly determined by an inductive eruption $V_a >> E_a$.

Given in Fig. 3b are extinguishing efficiencies as functions of L for a set of I_a. It is seen that sensitivity of the switch to additional inductive load increases with the current. For currents I_a > 1 A/cm^2, the maximum value of L was 1.5–2 mH. The inductive eruption then reached ~1200 V. At a greater voltage a spot breakdown from the grid to the cathode was observed. The study of safety against spot ignition for greater currents was not carried out through the limited cathode emission.

It may be said that no effects of this type were observed in a BI mode and all of the problems turned out to be connected with the fast transitional process: extinguishing a switch-ignition of the other one.

Symmetrical Biphase Inverter Scheme

The circuit is shown in Fig. 1. The secondary winding ohmic load value was 300 Ω. A routine procedure of forcing the circuit into the BI mode was as follows: after cathode emissions had been adjusted, the switches were tested in a half-period mode and necessary extinguishing pulses were set with reserve; then a temporal arrangement of the pulses was regulated for each transitional tact to bring the circuit into biphase mode. Because it was possible to determine with disturbed modulation which four stages (two ignitions and two extinguishing) destroyed the performance, we usually began with an acquired BI mode and observed the temporal trends of operation against the arrangement of the leading fronts of pulses.

Let's denote in this section (Figs. 4 and 5) as 1 the switch conducting at the moment concerned, and the other denoted as 2. A specially designed four-pulse generator allowed the alteration of a shift between the leading front of pulses V_1^-, V_2^+ within a range of -3; 3 μs, the length of $V_{1,2}^-$ up to 20–30 μs, and that of $V_{1,2}^{+-}$ to 20 μs. Like the case of ohmic load, we were only interested in fast extinguishing. It is this case that was usually realized at a pause (dead time) between the conducting states of switches 1 and 2 (see currents I_1, I_2 and voltages V_{a1}, V_{a2} in Fig. 4), so that the extinguishing of 1 was over before the ignition of 2, and conversely. Fast extinguishing led to shock excitation of a circuit inductive load–transformer stray capacity with an oscillation period of 5–6 μs, first wave amplitude V_{a1} of 150–200 V. Like a half-period mode, overvoltage V_{a1} did not cause a reignition of the discharge and the loss of control; however, negative periods of the anode voltage detained the current increase in switch 2. Therefore, it was necessary that the increase in I_2 be supported along with the ignition pulse [$\tau(V_2^+) > 1/\gamma$] during the oscillation dampening time $1/\gamma$. The value of γ depended on the current I_2, since the increase in I_2 resulted in the decrease in equivalent resistance of a switch and Q-factor. In the circuit under study $\gamma^{-1} \approx$ 8–10 μs $\approx$ two oscillation periods (the ignition pulse amplitude was ~5–6 V). Thus, with the length $\tau(V_2^+) \sim$ (15–20) μs the oscillations were put down effectively and did not suppress the ignition of 2. If the leading front of V_2^+ comes ahead of that of V_1^- (overlap), no oscillations arose, but at a small overlap (0–2 μs) the modulation broke down because the extinguishing of 1 turned out to be too sensitive to the additional power put into the discharge at the ignition of switch 2. Indeed, the increase in I_2 brought about emf = $L\,dI_2/dt$ in the coil and an increase in V_{a1} as high as $V_{a1} = E_a + L(dI_2/dt - dI_1/dt) \approx 2E_a$ (at $V_{a2} \approx E_a - L\,dI_2/dt \approx 0$: $dI_1/dt \to 0$). The modulation restored again with a further increase in overlap (curve 2 in Fig. 5), but time variation of the current had a different shape. Ohmic resistance of both devices shunted the transformer coil so that the eruption of the anode voltage V_{a1} that follows the ignition of switch 2 was smaller and had more slope than in the case of a pause.

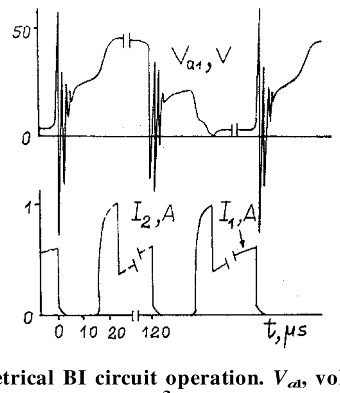

Fig. 4 **Symmetrical BI circuit operation. V_{a1}, voltage across the switch 1; $I_{1,2}^-$ currents. $P_{Cs} = 10^{-2}$ torr. E_a = 30 V; repetition period ~1.2 ms; the length of the pause 4 15 μs.**

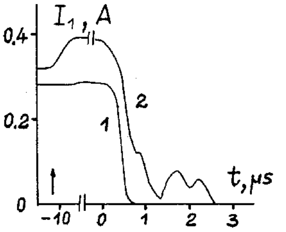

Fig. 5 **Extinguishing in the case of overlap (2) and pause (1); P_{Cs} = 7 × 10^{-3} torr; E_a = 20 V, I_a = 0.4 A.**

Switch 1 had enough time to reach a new stationary state with slightly more voltage and current. Therefore, the decrease in I_1 during the extinguishing process was slow, and a greater pulse $|V_1^-|$ was needed compared to the case of pause (curve 1). This mode is less efficient as the source spends a part of its power for heating ohmic elements of the primary winding.

A summary of the previous terms of reliable performance is as follows:

1) A slight pause has to exist (>2–3 μs) between the leading front of the extinguishing pulse to the grid of the conductive switch and the front of ignition pulse to the neighboring one.

2) The ignition pulse length has to make up $\tau(V_g^+) \sim$ 10–15 μs at typical I_a.

Biphase Inverter with Nonsymmetrical Switches

The study of BI with cesium switches based on the self-extinguishing principle was performed by using PS with a small-cell grid of restricted area (diaphragm) as an example. In the device used, the area restriction factor was ~25 (the grid diaphragm diameter of ~2 mm and the cathode diameter of ~10 mm). Control features and physical processes that develop when negative pulse is applied to this grid are considered separately.[15] Here we confine ourselves to the following:

1) Because of the multiple increases in the density of current through the grid, this density could get close to the random current value. The cathode emission of ≥0.5 A/cm^2 at a pressure of ~10^{-2} torr ensured the self-extinguishing branch of the grid control so that the extinguishing efficiency $|V_g^-|(E_a)$ upgraded with the current (with emission or up the I-V characteristic at a given emission).

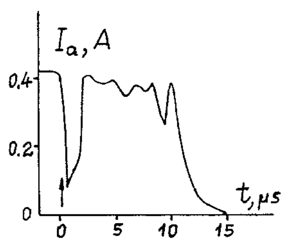

Fig. 6 **Typical current variation on self-extinguishing (switch of restricted area grid). Arrow shows the front of V_g^-. P_{Cs} = 1.33 × 10^{-2} torr, E_a = 20 V; $I_a^{(0)} \approx$ 0.42 A; $|V_g^-|$ = 30 V.**

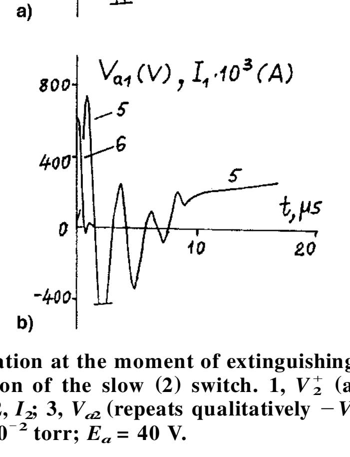

Fig. 7 **Operation at the moment of extinguishing the fast switch (1), the ignition of the slow (2) switch. 1, V_2^+ (arbitrary units). $|V_2^+| \sim$ 6 V; 2, I_2; 3, V_{a2} (repeats qualitatively $-V_{a1}$); 5, V_{a1}; 6, I_1; P_{Cs} = 1.1 × 10^{-2} torr; E_a = 40 V.**

2) Unlike small-cell grid PS (Ref. 1), no maximum possible time of extinguishing existed. When working for active impedance (Fig. 6) the current could almost reach its initial value after a lapse of 1–2 μs and be invariable for some time (as long as 15–20 μs) until the moment of extinguishing. It was natural then to expect minor current dynamic change from the inductive component of the impedance.

3) As compared to the small-cell grid switch,[1–5] the ignition was slow and its start delayed 2–3 μs (Fig. 7, curve 2) with regard to the leading front of ignition pulse (curve 1).

4) Fast extinguishing could be obtained in the switch of the restricted area grid as well, but greater pulses $|V_g^-|$ were needed and will not be commented on in this paper.

Since the shoulders of the circuit are no longer equivalent, we considered separately the processes of extinguishing 1 (small-cell grid) and the ignition of the switch 2 (diaphragm).

This study has shown that the demands on the mutual pulse arrangement were exorbitant in this nonsymmetrical case [transition (1-2) and the opposite transition moment (2-1)].

Transition 1-2

Because of a delayed increase in current I_2 there was a pause when both elements were not conducting for some time, no matter which front (of V_1^- or V_2^+) came on earlier. The currents and anode voltages are shown in Fig. 7 in the case of V_1^- leading front (preceding extinguishing of 1, curve 6) being ahead of that of V_2^+ (curve 1) by $\div 2$ μs; however, the kinetics did not change notably if V_1^- were behind. Although the value of delay $t(I_2) - t(V_2^+)$ (Fig. 7a) and the I_2 increase rate depended on the phase of V_{a1} (curve 3), the pulse V_2^+ of 12–15 μs length was always enough for reliable ignition of switch 2.

Transition 2-1

Because extinguishing of switch 2 had delayed the self-extinguishing character and the current I_2 did not change notably

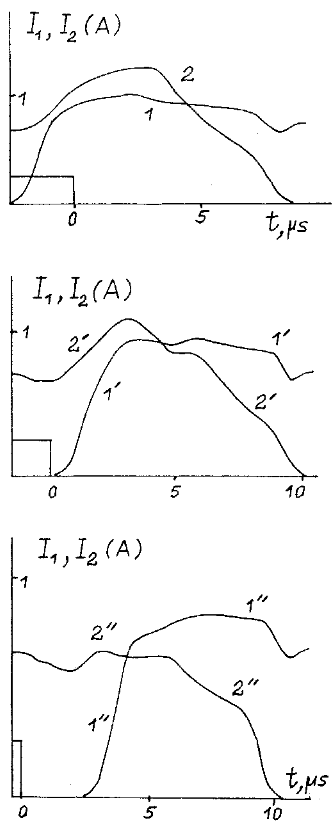

Fig. 8 Operation at the moment of extinguishing the slow switch, the ignition of the fast switch (currents). 1,1′,1″, I_1; 2,2′,2″, I_2; $P_{Cs} = 8 \times 10^{-3}$ torr; $E_a = 60$ V; step shows schematically the position of the front of V_2^-.

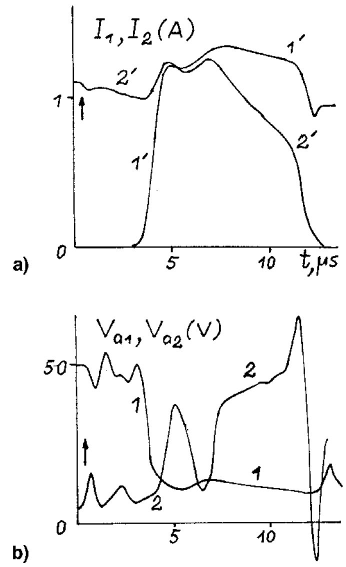

Fig. 9 Operation at the moment of extinguishing the slow switch, the ignition of the fast switch: a) 1′, I_1; 2′, I_2 and b) 1, V_{a1}; 2, V_{a2}; $|V_1^+| \sim 6$ V; $|V_2^-| = 40$ V. Arrow shows the V_2^- leading front.

within the first 3–4 μs, bulk conductance remained for some time, even at a pause between the leading fronts of V_1^- and V_2^+ [$t(V_1^-) < t(V_2^+)$]. The time variation of I_2 is shown in Fig. 8 (2,2′,2″) depending on the current I_1 increase start in neighbor switch (1,1′,1″). Unlike the case of ohmic load, some increase in I_2 above the stationary value could be observed (if the stationary current was smaller than emission owing to a backstream random current from the plasma). It was always connected with the ignition start of the switch 1, leading to a substantial voltage outbreak V_{a2} (Fig. 9b, curve 2). The process had a complicated impact upon the factors that determine the further variation of the current: the current density through the diaphragm and local concentration of the plasma at whose background the instability developed. Yet a comparison to the same initial state of the device loaded with ohmic impedance had shown that no significant extinguishing efficiency change occurred.

The study of nonsymmetrical circuit enabled some results to be suggested in the case of using two switches based on self-extinguishing processes, e.g., the inherent ignorance of performance concerning the arrangement of control pulses.

Conclusions

The results obtained show that the push–pull mode is realized successfully in the switches based on either the same or different principles of control, and restricted to laboratory conditions and comparatively low total currents. The performance study of a full-scale model for an order of magnitude higher currents is possible.

References

[1]Kaplan, V., Martsinovskij, A., Makarov, A., Novikov, A., Serbin, V., Tzirkel, B., and Yuriev, V., *Soviet Physics—Technical Physics*, Vol. 22, No. 2, 1977, pp. 159–176.

[2]Bakst, F., Kaplan, V., Kostin, A., Martsinovskij, A., Rasulov, F., Sveshnikova, Y., and Yuriev, V., "Stationary Conductive State of a Grid-Control Switching Element," *Soviet Physics—Technical Physics*, Vol. 23, No. 11, 1978, pp. 1301–1313.

[3]Bakst, F., and Kostin, A., "Theory of Switching Transients in Cesium Grid Triodes," *Soviet Physics—Technical Physics*, Vol. 29, No. 1, 1984, pp. 1–6.

[4]Kaplan, V., Martsinovskij, A., Rasulov, F., and Yuriev, V., "Kinetic of Negative Grid Pulse Influence upon Discharge Plasma," *Journal de Physique (Paris)*, Vol. 40, No. C-7, 1979, pp. 495–497.

[5]Bakst, F., Martsinovskij, A., and Yuriev, V., "Low-Voltage Arc Plasma in Three-Electrode System," *Journal de Physique (Paris)*,

Vol. 40, No. C-7, 1979, pp. 497–499.
[6]Kaibyshev, V., Kusin, G., and Melnikov, M., ''Effect of a Third Electrode on a Low-Voltage Arc,'' *Soviet Physics—Technical Physics*, Vol. 20, No. 2, 1975, pp. 203–207.
[7]Kaplan, V., Martsinovskij, A., Mustafaev, A., Sitnov, V., and Ender, A., ''Spontaneous Current Cutoff in a High-Current Low-Pressure Cesium-Barium Triode,'' *Soviet Physics—Technical Physics*, Vol. 24, No. 3, 1979, pp. 325–328.
[8]Wernsman, B., El-Genk, M., and Kaibyshev, V., ''Experimental Investigation and Analysis of Operation Characteristics of a Planar Cs-Ba Tasitron,'' *Review of Scientific Instruments*, Vol. 65, No. 11, 1994, pp. 3449–3459.
[9]Wernsman, B., and El-Genk, M., ''Experimental Investigation of Current Modulation in a Planar Cs-Ba Tasitron,'' *IEEE Transactions on Plasma Science*, Vol. 23, No. 1, 1995, pp. 198–203.
[10]Alekseyev, N., Martsinovskij, A., and Kaplan, V., ''An Investigation of the Physical Processes in a Plasma Switch with a Thick Grid. I. The Stationary Conducting State,'' *Technical Physics*, Vol. 37, No. 9, 1992, pp. 930–937.
[11]Alekseyev, B., Martsinovskij, A., and Kaplan, V., ''An Investigation of the Physical Processes in a Plasma Switch with a Thick Grid. II. Pulsed Quenching of the Discharge,'' *Technical Physics*, Vol. 41, No. 6, 1996, pp. 551–558.
[12]El-Genk, M., Kaibyshev, V., Murray, C., Wernsman, B., and Djashiashvili, Y., ''Preliminary Performance Results of the Cs-Ba Tasitrons Inverter,'' *IEEE Transactions on Electron Devices*, Vol. 40, 1993, pp. 1335–1339.
[13]Bedford, B., and Hoft, R., *Principles of Inverter Circuits*, Wiley, New York, 1964.
[14]Bakst, F., ''Role of Collective Interactions in the Diffusion of an Electron Through Exited Atomic or Ionic States in Plasma,'' *Soviet Technical Physics Letters*, Vol. 5, No. 2, 1979, pp. 425, 426.
[15]Alekseyev, N., Martsinovskij, A., Kaplan, V., and Rasulov, F., *Technical Physics* (to be published).