Substrate Bias Voltage Generation for Pulse Ion Treatment with Electron Tubes in the Mode with Return of Electrons to the Grid

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Abstract – The application of electronic tubes in the overstressed mode with low anode voltage and return of electrons to the grid for generation of substrate bias voltage pulses is considered. This mode is shown to have practical significance at the bias voltages in kilovolt's range in conditions of large substrate ion current fluctuations as it ensures small bias voltage fluctuations and effective use of the primary DC power source voltage. When the substrate current spontaneously rises above the critical value, the tubes automatically decrease the bias voltage and suppress current spikes and arcing in the substrate circuit.

1. Introduction

Ion bombardment of substrates is widely used at coatings deposition and other surface treatments. For this, ion-containing plasma is generated in the vicinity of the substrates and a negative bias voltage is applied to them for ion acceleration. Pulse modulation of the bias voltage is carried out in many modern technological processes as it suppresses arcing on the substrate surface, allows controlling the substrate temperature at the same pulse amplitude by duty cycle regulation and increasing the bias voltage range [1].

In power ion-plasma facilities, the substrate ion current usually has great fluctuations (tens percents relatively the average value) caused by the follows:

- fluctuations of plasma density because of plasma generating discharge instability (the instability is inherent for vacuum cathode arcs and electron beam supported arc-like discharges on molten metal surface in thermo-ion deposition systems, especially at high discharge currents);
- periodical arcing in the plasma-generating system and on the substrate surface;
- short-time switching-off of overloaded power suppliers;
- rotation of substrates with non-uniform surface shape during the technological process.

The fluctuations result in chaotic amplitude modulation of substrate ion current pulses. To ensure the invariability of bias voltage in such conditions, bias voltage suppliers must possess the characteristics of ideal voltage generator with zero internal resistance. But in order to prevent damage or overheating of the substrate surface in the case of very high ion current or arcing, the maximum substrate current must be limited. Such features at the bias voltage of hundreds volts are commonly provided by transistor pulse modulators with the capacitor energy storage and the automatic system for interruption of overcurrent. At kilovolt's bias voltages, modulators on the base of vacuum electron tubes are more preferable because tubes ensure stable work at those voltages in wide range of duty cycle or pulse rate. Moreover, the tubes allow limiting the current by the certain value.

The tubes are traditionally used in pulse radio-systems (in radar's and other pulse modulators, RF switch-mode generators, *etc*) with quite defined hard loads at the fixed operation points. In our case the situation is different since the tube current are determined by the random value of substrate ion current, that is the substrates are a continuously changeable or floating electrical load. Taking this into account, it is needed to choose the right mode of tube operation for effective bias generation, This problem is considered in the paper.

2. Equivalent scheme of the substrate circuit

The equivalent substrate circuit scheme with tube generating bias voltage pulses is shown in Fig. 1.

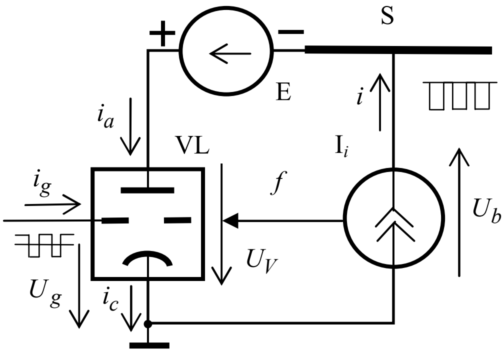

Fig. 1. Substrate circuit scheme with closed tube. E – DC power supply with voltage E, I_i – equivalent ion current generator, VL – electronic tube, S – substrate, i – ion current, i_a, i_g, i_c – current of anode, grid, cathode, accordingly, U_b – substrate bias, U_g – positive voltage of control grid, U_V – tube voltage drop, f – function $U_V=f(i)=f(i_a)$

The substrate being a plasma ion collector is connected to equivalent generator I_i of ion current (the generator imitates the ion-containing plasma). Substrate current i (not U_g or U_V!) controls the tube current ($i_a=i$) and voltage drop U_V. In the scheme, the dependence of U_V on i is depicted by function f being, in fact, an anode current-voltage characteristic.

The bias voltage value is $U_b=E-U_V$ and any changes of U_V result in the same changes of U_b with the minus sign if DC voltage E is constant. Ratio $K_E=U_b/E$ determines the coefficient of employing voltage E for generation of the bias voltage.

3. Features of tube characteristics and choice of tube operation mode for bias generation

To choose the tube operation mode with minimal fluctuations of U_b and maximal K_E, consider features of the tube anode characteristics. Fig. 2 shows such characteristics for a high power triode. They are approximated by straight lines for plot simplification. The positive grid voltage U_g is a parameter. The anode characteristics of other grid tubes are close to the shown ones; in the case of tetrode or pentode parameter U_g relates to the screen grid voltage.

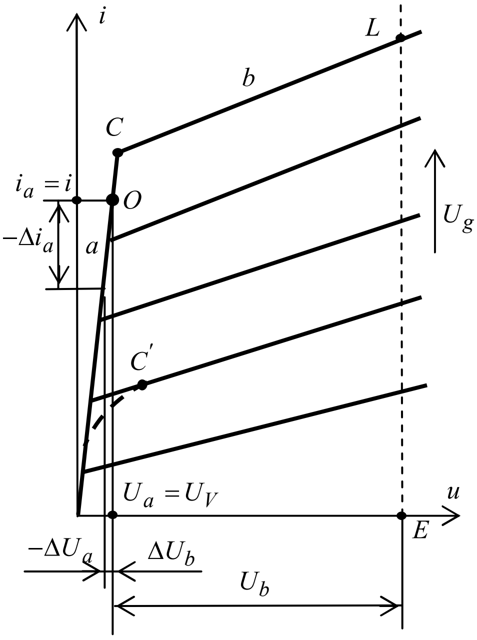

Fig. 2. Anode characteristics of vacuum grid tube (triode). Letter O means a tube operation point

Curves $i_a(U_a)$ have two parts (a and b) crossing in critical point C. The real curves have a smooth bend between the parts as the dashed line shows it in Fig. 2. Letter C' means a point where part b begins to transform to part a.

The ratio U_a/U_g affects the behavior of $i_a(U_a)$. The first almost vertical part (a) being at low U_a/U_g is a line of anode current fall. This line accords with the saturation mode at which the tube conductivity is maximal. The work on part a ensures the highest values of K_E. The strong fall of i_a is caused by redistribution of the cathode current $i_c=i_g+i_a$ between the grid and the anode in favor of grid.

In the theory of RF tube generators, the line of critical regime (borderline) is superimposed on the anode characteristics. This line goes through points C and separates the overstressed (low U_a, high i_g) and understressed (high U_a, low i_g) regimes for the grid. The grid and anode voltages are close in those points; therefore the critical regime line is usually associated with the so-called line of equal voltages. Accordingly, $U_a/U_g<1$ on part a and $U_a/U_g>1$ on part b. As a result, grid current i_g is a large fraction of i_c on part a but a small fraction on part b. For many tubes, especially, triodes, the lines of critical regime and equal voltages practically coincide with the earlier said line of anode current fall.

Part a relates to the tube operation mode, at which the cathode electrons go to the positive grid not only due to the direct hit on grid windings but also due to return from the grid-anode gap. The returning electrons pass by grid windings at the beginning of their way to the anode. Then they go back to the grid as the grid potential, which is higher than the anode one, attracts them. The anode potential greatly affects the current distribution between the grid and the anode at low U_a. The theory of the mode is presented in [2].

The anode voltage automatically gets such a value that equalizes anode current i_a with ion current i. Since the rest of cathode electrons i_c-i_a goes to the grid, it serves as an absorber of excess electrons. Quite low U_g is sufficient for equalizing i_a and i if the corresponding positive voltage is applied to the grid (see operation point O in Fig. 2).

Plots in Fig. 2 shows decreasing the ion current leads to decreasing the anode current by $-\Delta i_a$ and according decreasing the anode voltage by $-\Delta U_a$ as well as increasing the bias voltage by ΔU_b. Values of ΔU_a and ΔU_b are relatively small if the current changes within limits of part a. The amplitude of positive grid pulses may be kept constant but must ensure the position of point C on the current scale above the operation point at the maximal acceptable value of the ion current.

If the operation point rises above critical point C and passes to part b at the same grid voltage, changes of ΔU_a and ΔU_b become much larger since the slope of part b is small. Moreover, the bias voltage becomes zero when the current reaches point L.

Part b relates to the tube operation mode, at which the cathode electrons go to the positive grid only due to the direct hit on grid windings and the anode captures all electrons passing between the grid windings. No electrons return to the grid from the grid-anode gap. This operation mode is called as a mode of direct electron interception (capture) by the grid; its theory is presented in [2].

Due to weak change of the current on part *b* at significant increase of anode voltage (certainly, if the grid voltage is constant) the tube works on this part as a current limiter. It provides automatic suppress of current spikes and acing in the substrate circuit.

All above said points at expedience of employing the tube operation on part *a* of anode characteristic for effective generation of the substrate bias voltage pulses with practically constant amplitude. In this case the tube works in the overstressed grid regime or free anode current passage mode.

The important issue relates with power dissipated by the grid and the anode. The following parameters are used commonly: P_g – the average value of power dissipated by grid ($P_g=i_gU_gD$, where $D=\tau F$ is the duty cycle, τ is the pulse duration, F is the pulse rate); $P_{g.per}$ – the maximal permissible power dissipated by grid; P_a – the average value of power dissipated by anode ($P_a=i_aU_aD$); $P_{a.per}$ – the maximal permissible power dissipated by anode.

In the pulse radio-systems with hard loads the operation point of tubes working in switch-mode is set up in the vicinity of fixed point *C* to provide the non-high grid power P_g at the minimal power P_a dissipated by anode.

In our case with the soft load the position of point C may be either fixed or movable (in dependence of the control algorithm) but without fail it must be above the continuously changeable operation point position. Then the operation point is in the limits of part *a* in spite of the current fluctuations. The value of P_g depends on the distance between points *O* and *C*. When the grid has a constant positive potential and the substrate current suddenly falls down to very low value, practically all cathode electrons go to the grid and the value of P_g is the highest. On the contrary, P_g is low when the operation point is close to or above point *C* where i_g is not large. The value of P_a is very low when the tube operates on part *a* of anode characteristic. If a spontaneous spike of current or arc occurs, the operation point quickly passes to part *b* and the anode voltage sharply rises. This leads to increase of P_a, but further decrease of P_g.

4. Safe tube exploitation during substrate bias generation

Safe tube exploitation means the tube operation when $P_g<P_{g.per}$ and $P_a<P_{a.per}$, respectively.

One can propose two approaches to ensure the safe regime for the grid. The first approach employs a feedback system for continuous monitoring of the substrate current and regulation of the amplitude of positive grid pulses to save the position of point C on the current scale slighter above the instantaneous substrate current value. The system must have the fast reaction and be workable in the wide frequency band. Additionally, the system must contain a threshold subsystem for suppressing the current spikes and arcs. Obviously, such approach is very complicated and needs careful tuning of the system.

The second approach employs natural properties of grid tubes operating on part *a* of anode characteristic in the overstressed mode with return of electrons to the grid. In this case the amplitude of positive grid pulses is kept constant but it should be chosen as for the worst grid regime (U_a=0, i_a=0, $i_g=i_c$), at which all cathode electrons goes to the grid. The grid pulse amplitude U_g must satisfy the equation (1):

$$U_g \le P_{g.per} / Di_g\big|_{U_a=0}. \tag{1}$$

Then we can determine the point *C* position on the current scale with help of the tube anode characteristic for the chosen value of U_g as a parameter. Point *C* determines the critical value of the anode current ($i_{a.cr}$), above which the tube begin to limit the current. Using the value of the maximal acceptable substrate current ($i_{s.m}$), that is a parameter of plasma technology facilities, determine the minimal needed number of the parallel-connected tubes (*N*) for generation of the bias voltage pulses accordingly (2):

$$N\big|_{\text{minimal integer}} \ge i_{s.m} / i_{a.cr}. \tag{2}$$

Consider the issue of the safe regime for the anode. Violation of the condition $P_a<P_{a.per}$ takes place when the tube passes to part *b* of anode characteristic and works in the current limitation regime with high anode voltage. Although such situation occurs during substrate current spikes and arcing, non-frequent similar events do not create the problem since the anode does not heat up to high temperature during one or several pulses. Moreover, the pulse modulation is the good means to eliminate arcing. The problem arises when the value of *E* is enough high and either overcurrent occurs at each pulse or the substrate circuit has the sustained short. Preliminary ion treating of the substrate at low duty cycle or pulse rate is often used to decrease the frequency of arcing. Automatic switch-off of DC power source or opening the tube by applying negative voltage to the grid is provided to protect the tube and the pulse modulator from short circuits.

5. The preferable tubes for bias pulse generation

The preferable tubes for bias pulse generation in the mode with return of electrons to the grid are power triodes with the right control characteristics (with the positive grid) since they have the highest values of $P_{g.per}$ as compared with grid tetrodes and pentodes. The triodes with low μ-coefficient (~20–30) are better since their grid current $i_g|_{U_a=0}$ is less than in the case of triodes with high μ. Table 1 presents parameters of some Russian tubes suitable for generation of bias pulses with high *D* (up to 0.99) and short pauses between pulses (such regime provides the most intensive ion treatment) [3].

Table 1. Parameters of some tube for bias generation

Tube type	GU-4A	GU-22A	GU-30A	GU-55A	GU-62A
U_a, kV	6	10	7,5	12	10
$P_{a.per}$, kW	20	20	60	60	40
$P_{g.per}$, kW	0.8	0.6	2.5	2.4	1.8

Table 2. Parameters of GU-22A working at

U_g, V	i_g, A	i_a, A	P_g, kW	P_a, kW	KP
100	1,2	0,6	0.12	0.06	10
200	1,8	3,4	0.36	0.68	19
220*	2*	4*	0.44*	0.88*	18*
250	2,3	5	0.58	1.25	17,4
300	3	6	0.90	1.80	13,3
400	4,5	9,6	1.80	3.84	10,7
500	5,6	13,2	2.80	6.60	9,4
600	7,7	16,5	4.60	9.90	7,1
D=1. Power amplification coefficient $K_P=i_aU_bD/P_g$ was calculated for U_b=2 kV					

Table 3. Parameters of GU-22A working at

Ug, V	ig, A	Pg, kW
100	1,3	0.13
200	2	0.40
220*	2,3*	0.51*
235*	2,4*	0.56*
250	2,7	0.68
300	3,5	1.05
400	4,7	1.89
500	6,6	3.30
600	10	6.00
D=1.		

One can see, there are many tubes for work at voltages up to 10 kV. Coefficient K_E for these tubes is about 0.9 and even higher at E in kilovolt's range.

Now, consider in detail the parameters of triode GU-22A taken as an example. Let the operation mode be heaviest with $D\approx 0$ that is as for DC regime. Table 2 present parameters of GU-22A working on the line of equal voltages; Table 3 presents parameters for operation at zero anode voltage and zero substrate current. In the latter case $i_g=i_c$ and U_g must be ≤235 V to avoid grid overheating. When $U_a>0$, the temperature regime of grid is lighter (compare values of P_g in tables for U_g=220...235 V). The parameters marked by asterisks (*) should be used as operation's ones. The tube provides work with the substrate ion current of up to 4 A and the bias voltages up to 10 kV. The power amplification coefficient K_P=18 at the bias voltage of 2 kV and the higher U_b the higher value of K_P is. If the substrate current rises up to 6 A, the tube decreases U_b down to zero.

Experiments with triode GU-22A have confirmed the presented data. The pulse modulator with the switch-unit containing 3 parallel-connected triodes working in the overstressed mode with return of electrons to the grid was made. Its parameters are as follows: U_b=2...6 kV, $i\leq 10$ A, D=0,1–0,9, F=0.1–10 kHz. The grid driver was made on the base of IGBT transistors. The modulator is successfully employed in thermoion facilities for deposition of coatings with ion bombardment.

6. Conclusions

The grid tubes may be used in the overstressed mode with return of electrons to the grid for generation of substrate bias voltage pulses in the kilovolt's range in conditions of large ion current fluctuations. The tubes provide the acceptable values of coefficient of employing DC power source voltage (K_E~0.9) and amplification coefficient (K_P~20) The most preferable tubes are triodes with low μ-coefficient.

References

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