

Instead of the foreword

In the 70^s... 80^s I was an enthusiast of buildings with tubes of any kind. Later my hobby's interest has shifted to other areas. I left however, with a large dowry of tubes such as triodes, tetrodes, pentodes, multi-grids tubes (hexodes, octodes) and multiple tubes in the same glass balloon, of all kinds. In these circumstances, from time to time, I want to realize assemblies that include such devices. I also belong to the category of those, who conceive their own schemes. In these circumstances, it is very advantageous to do studies on CAD (SPICE) simulation, available after unprecedented development (after the 90's) of personal computers. Seeing endeavors of several enthusiasts of electronic tubes to bring these devices simulators, I decided to involve myself, to improve vacuum tube models for SPICE simulations. Later, seeing that I'm not always satisfy of the models developed by others (Norman Koren, Eugen Karpov and so on) I approached increasingly often issues of designing mathematical models of electronic tube, I started to put them in SPICE simulators and to use them. This handout is my first article in this field and I sincerely hope, it will bring many news to support the activities of builders tubes enthusiasts , which I wish them pleasant reading. Because I have not been able to publish in web format this text translated into English, I have prepared and attached a pdf file here with the English translation for all those interested who do not speak Romanian.

The author

1. The current of control grid of electron tubes.

Sometimes is necessary to take account of current that appears on the control grid of a vacuum tube, where assemblies are made with these electronic devices. It is generally ineffective if the effective voltage grid control always remains negative. However, there are some applications of electron tubes, especially in power electronics (generators or schemes in pulse mode) where this is not possible permanently. Therefore it takes mathematical regressions able to approximate as accurately circuit current that arises in the control grid, based on data provided by the manufacturer catalog tube. These regressions can then be used for adequate bond SPICE models of these tubes. By similar regressions can also be shaped, screen grid current of a tetrode or pentode. How should therefore vary a mathematical function curve to match current variation in the control grid circuit of a tube? To answer this question, consider and study the characteristic curves of several tubes.

Fig. 1.1 shows the variation of anode and first grid current of high power Russian triode ГИ7Б, used in generating continuous wave mode with $\lambda = 18,5$ cm.

Fig. 1.2 shows the characteristic curves of anode and first grid currents of ГИ7Б tube, used as a pulse triode.

Fig. 1.3 shows the characteristic curves of anode and first grid currents of Russian pentode 6Ж5П (connected as triode) in pulse mode.

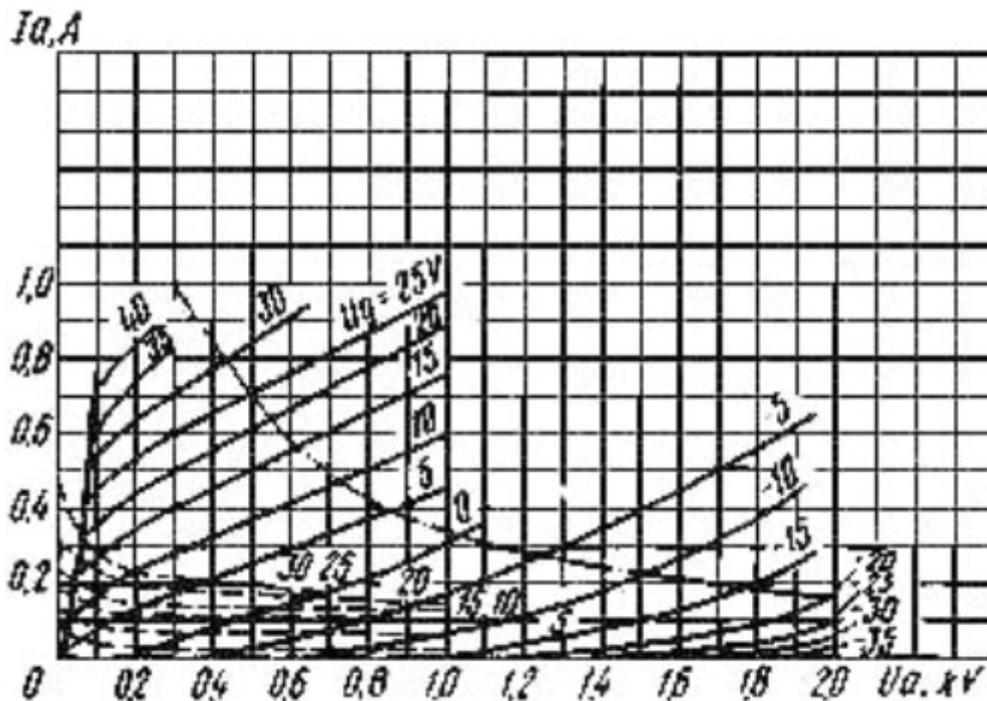


Fig. 1.1 – Anodic & grid current characteristics at high power triode ГИ7Б used in a generator of continuous wavelength, $\lambda = 18.5$ cm

2. The current of screen grids of pentodes and tetrodes.

Analyzing current variation of tetrode and pentode screen grids, it follows that their evolution is similar to the first grid currents, if used triode in continuous waveform generation, or pulse generator system.

Fig. 2.1 shows the characteristics of screen grid currents of ГУ50 tube (largely equivalent of EL152) connected as a pentode in power amplifiers. Examples may continue in a similar manner.

After 1990, with the evolution of computing technology applied to PC-s, the fans of vacuum tube audio amplifiers developed computational techniques based on mathematical regressions, which could simulate in PSPICE technology, specific models of these devices. Fortunately for them, in most classical audio amplifiers the control grid currents were negligible, and the screen grid of the final pentodes have not too much influence in the final power amplification.

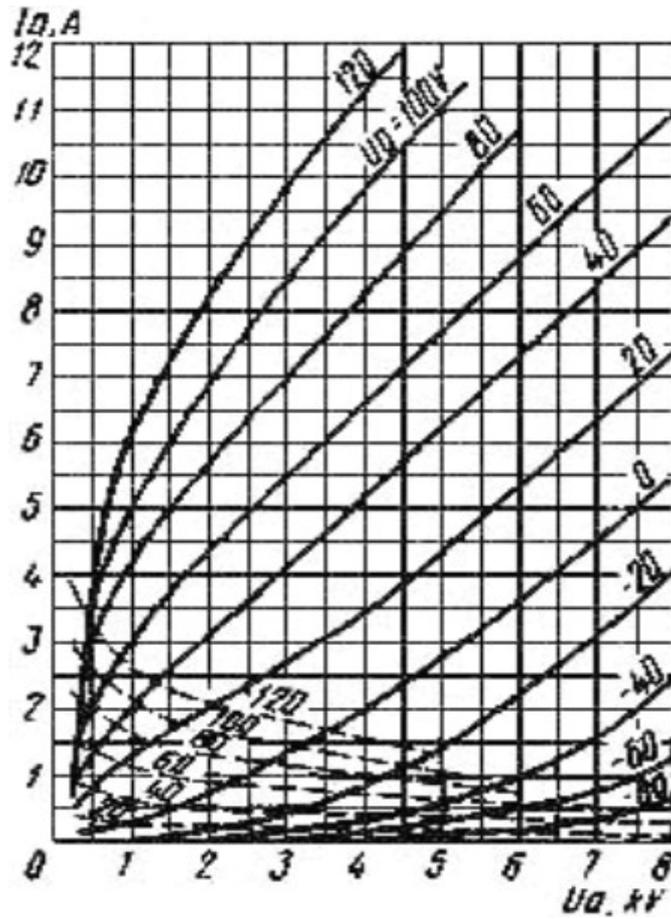


Fig. 1.2 – Anode and grid characteristics to high power triode ГИ7Б, in pulse generator mode.

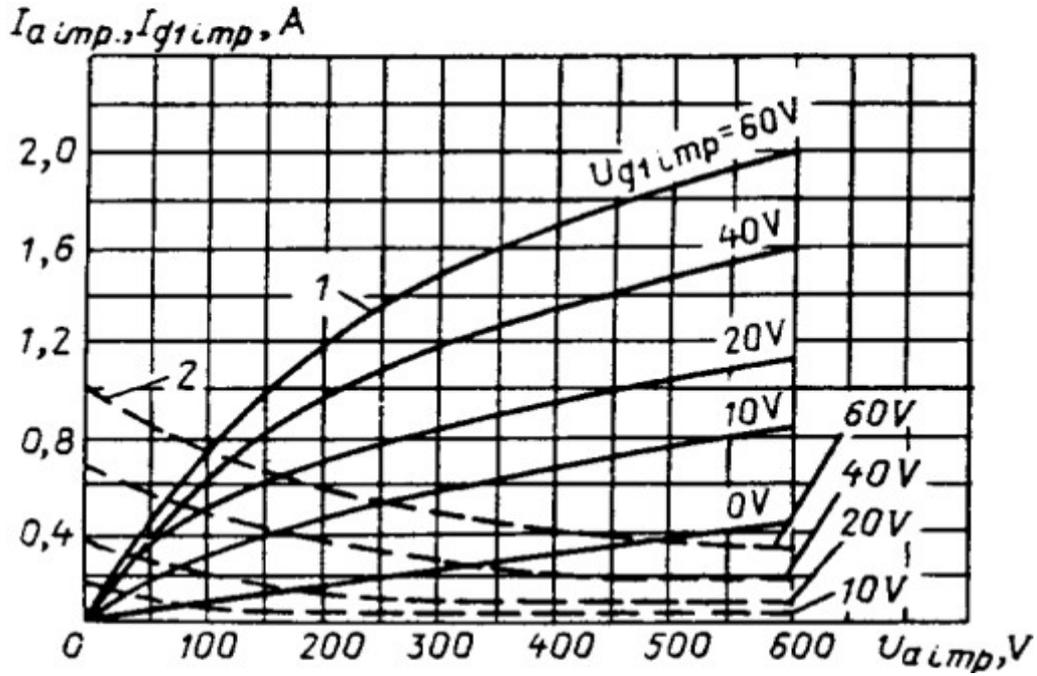


Fig. 1.3 – Current characteristics of anodic & first grid, to pentode 6Ж5П (as a triode pulse mode connected)

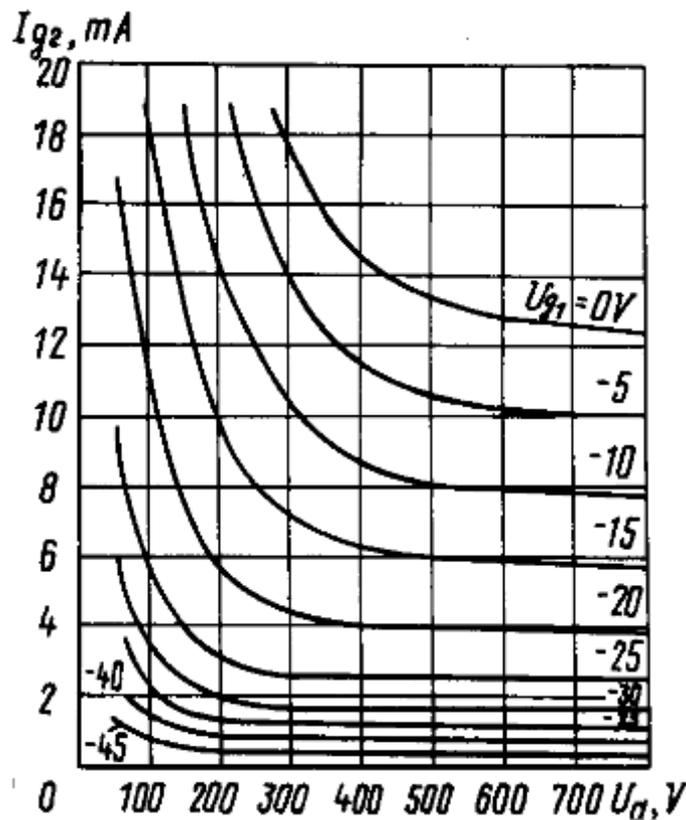


Fig. 2.1 – Characteristics of the screen grid current, Russian pentode 6Y50

3. Modeling currents of the first grid and screen grids.

As a result of regressions (equations) introduced in the 90's by the manufacturer amateur of tube audio amplifiers Norman Koren, continuously improved by the others, have been used models of most vacuum tubes amplifiers simulation schemes. With all the benefits of these regressions to simulate the tubes, they may not be simulated (true reality) of schemes other than tube audio amplifiers. Thus, neglecting the role of screen grid currents and / or control grid of a tube, Koren decided that to simulate the screen grid current of audio amplifiers, is sufficient to apply the old model regressions for triode – „*We continue to use equation (3) for pentode screen grid current for three reasons: 1. Screen current is not as critical to the tube performance as plate current. 2. Good data on screen current is scarce. 3. The model should be kept as simple as possible for use with evaluation version of PSpice.*” – I quote from the reference article [1]. Figure 3.1 shows the variation of currents gride with equation (3) of that article, which is transcribed here in the next relationship:

$$I_{G2} = (E_G + E_{G2}/\mu)^{3/2} / k_{G2} \text{ if } E_G + E_{G2}/\mu = 0; I_{G2} = 0 \text{ otherwise} \quad (3.1)$$

The simple comparison of the curves shown in Fig. 3.1 with the curves shown in Fig. 3.2 taken from the data sheet, leads to the conclusion that the relation (3.1) above (see equation (3) of that article) does not accurately describe the current variation in a screen grid pentode, because it heavily depends of the dynamic anodic voltage.

On the other hand, the first of the three grounds put forward by Koren, is no longer present when talking about another application of a tube, outside amplifiers. However for a wave generator (for example) or a processing circuit pulse, must consider the actual variation of the first grid and screen grid currents of a possible pentode, or tetrode, or only the comand grid current variation of a triode. One of the first consequences of ignoring, or deformation grids currents of any kind, is a cathode current model different from the real one, unable to correctly simulate, automatic bias voltage of the grid. It can be ignored in amplifiers, by replacing automatic bias voltage, with constant bias voltage sources, as actually practiced in the vast majority of schemes of audio Hi-Fi amplifiers. Any other application of a pentode, which includes at least one cathode resistor circuit, can not be simulated in a PSPICE simulator.

The 2-nd reason put forward by Koren in the article quoted, for not having sought a variation faithful regression to solve current screen grid (especially) but the first grid also, is not applicable because there were

in the 90's and more (so in the current era) modern highly effective means for checking and tracing (possibly automatic) the actual variation of grid currents.

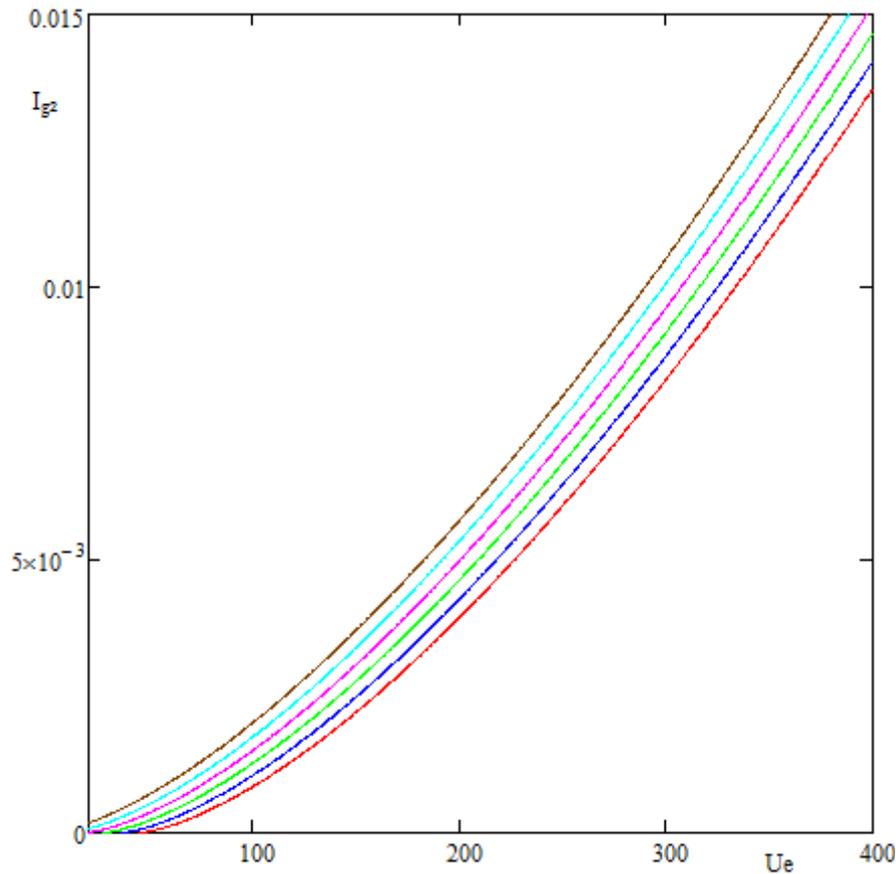


Fig. 3.1 – Variation of screen grid current of a 6Ж5Π pentode, according to the relationship (3.1) proposed by Koren.

The 3-rd reason of Koren in the above quotation, which was probably a little more difficult to overcome in the 90's, but is no longer also an impediment, since the development of all aspects of current assets design and simulation electronics, computer assisted. Therefore, both professionals and amateurs will find data sheets of electron tubes, or uses an automatic tracer curves of variation of a screen grid pentode, or control grid of a triode. To illustrate, take the case of Russian pentode 6Ж5Π, for which the screen grid characteristics are drawn with dotted lines in Figure 3.2. Considering the group of equations (5) of Article [1], further enhanced by other contributions [2] we have:

$$E_1 = \frac{E_{G2}}{k_p} \cdot \ln \left[e^{k_p \cdot \left(\frac{1}{\mu} + \frac{E_{G2} + V_{ct}}{E_{G2}} \right)} + 1 \right] \quad (3.2)$$

$$I_p = \frac{1 + \text{sgn}(E_1)}{k_{GI}} \cdot \arctan \left(\frac{E_p}{k_{VB}} \right) \cdot E_1^X \quad (3.3)$$

Determine by specific mathematical methods, the following set of specific factors of vacuum tube model:

$$\begin{aligned} k_p &= 1599,3 \\ k_{GI} &= 589,8 \\ k_{VB} &= 21,35 \\ \mu &= 61,04 \\ V_{ct} &= 1,142 \\ X &= 1,416 \end{aligned} \quad (3.4)$$

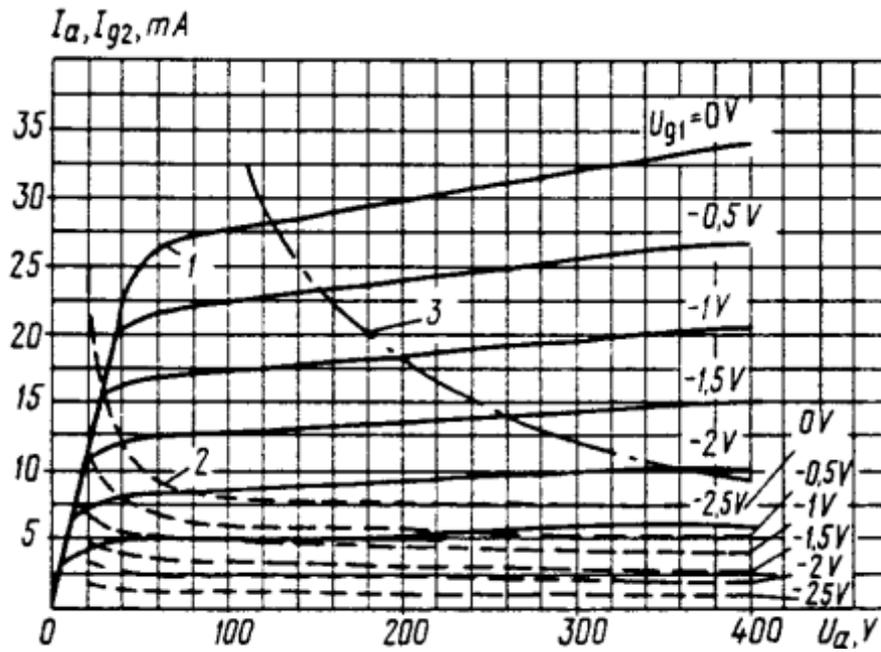


Fig. 3.2 – Variation screen grid and anode current (dotted line) for pentode 6Ж5П as data sheets

Figure 3.3 shows the anode characteristics of the model diagram. For comparison, the dashed lines are the corresponding curves in the data sheet, revealed point by point. It was represented with blue stripe, the hyperbole of anodic current of maximum dissipation.

Figure 3.4 shows the diagram of the cathode current characteristics obtained by adding the current model of the anode and screen grid, for all intents characteristics. For comparison, the dashed lines are the corresponding curves for cathodic currents, obtained by summing over the entire area of the anode current and the current screen grid of the tube data sheet. It was represented with blue stripe, the hyperbole of catodic current of maximum dissipation. (maximum anodic current dissipation, plus maximum current screen grid dissipation). In order to achieve the model, we used the following equations:

$$E_2 = \frac{E_{G2}}{\delta} \cdot \ln \left[e^{\delta \cdot \left(\zeta + \frac{E_{G1} + \epsilon}{E_{G2}} \right)} + 1 \right] \quad (3.5)$$

$$I_k = \alpha \cdot \arctan \left(\frac{E_p}{\beta} + \gamma \right) \cdot E_2^\kappa \quad \text{if } E_2 \geq 0; \quad I_p = 0 \quad \text{otherwise} \quad (3.6)$$

Determine by specific mathematical methods, the following set of specific factors of vacuum tube model:

$$\begin{aligned} \alpha &= 0,0013 \\ \beta &= 190,41 \\ \gamma &= 1,922 \\ \delta &= 9518,6 \\ \epsilon &= -1,998 \\ \zeta &= 0,0437 \\ \kappa &= 2,084 \end{aligned} \quad (3.7)$$

Figure 3.5 shows the screen grid characteristics of the model diagram. For comparison, the dashed lines are the corresponding curves in the data sheet, revealed point by point. It was represented with blue stripe, the hyperbole of screen grid current of maximum dissipation. The curves were obtained from the equation:

$$I_{g2} = \frac{-2}{k_{G1}} \cdot \arctan \left(\frac{E_p}{k_{VB}} \right) \cdot E_1^X + \alpha \cdot \arctan \left(\frac{E_p}{\beta} + \gamma \right) \cdot E_2^\kappa \quad \text{if } I_{g2} \geq 0; \quad I_{g2} = 0 \quad \text{otherwise} \quad (3.8)$$

In equation (3.8) E_1 is given by (3.2) and E_2 is given by (3.5).

Now let's see how it can be modeled the grid control current, in the event of a triode. The equations for the anodic current model, will be in this case:

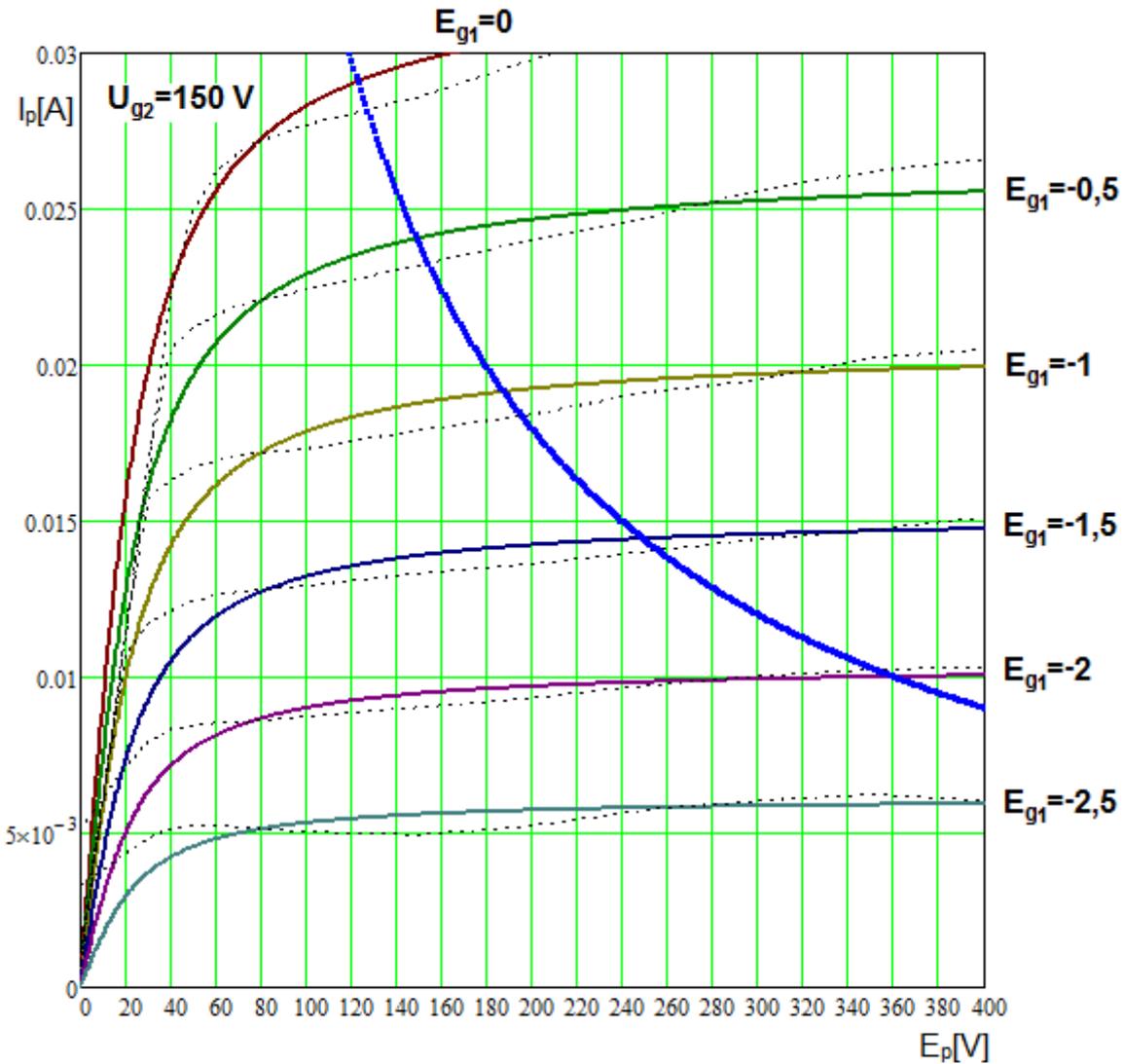


Fig. 3.3 – 6Ж5П pentode, anode current variation, according to the model.

$$E_1 = \frac{E_p}{k_p} \cdot \ln \left(e^{k_p \left(\frac{1}{\mu} + \frac{E_{G1} + V_{ct}}{\sqrt{k_{VB} + E_p^2}} \right)} + 1 \right) \quad (3.9)$$

$$I_p = \frac{1 + \text{sgn}(E_1)}{k_{G1}} \cdot E_1^X \quad (3.10)$$

Let's analyze high power Russian triode ПИ7Б, in pulse mode. According to relations (3.9) and (3.10) can be found the following solution:

$$\begin{aligned} k_p &= 560,1 \\ k_{G1} &= 66,42 \\ k_{VB} &= 1000669 \\ \mu &= 81,66 \\ V_{ct} &= -13,55 \\ X &= 1,185 \end{aligned} \quad (3.11)$$

Fig. 1.2 shows the datasheet characteristic curves for the anode and first grid currents (dashed lines) of ПИ7Б triode, used as a pulse triode.

Figure 3.6a shows the anode characteristics of the model diagram. For comparison, the dashed lines are the corresponding curves in the data sheet, revealed point by point. It was represented with blue stripe, the hyperbole of anodic current of maximum dissipation.

Figure 3.6b shows the diagram of the cathode current characteristics obtained by adding the current

model of the anode and screen grid, for all intents characteristics. For comparison, the dashed lines corresponding of curves for cathodic currents, obtained by summing over the entire area of the anode current and the screen grid current of the tube data sheet. It was represented with blue stripe, the hyperbole of cathodic current of maximum dissipation (maximum anodic current dissipation, plus maximum screen grid current dissipation). In order to achieve the model, we used the following equations:

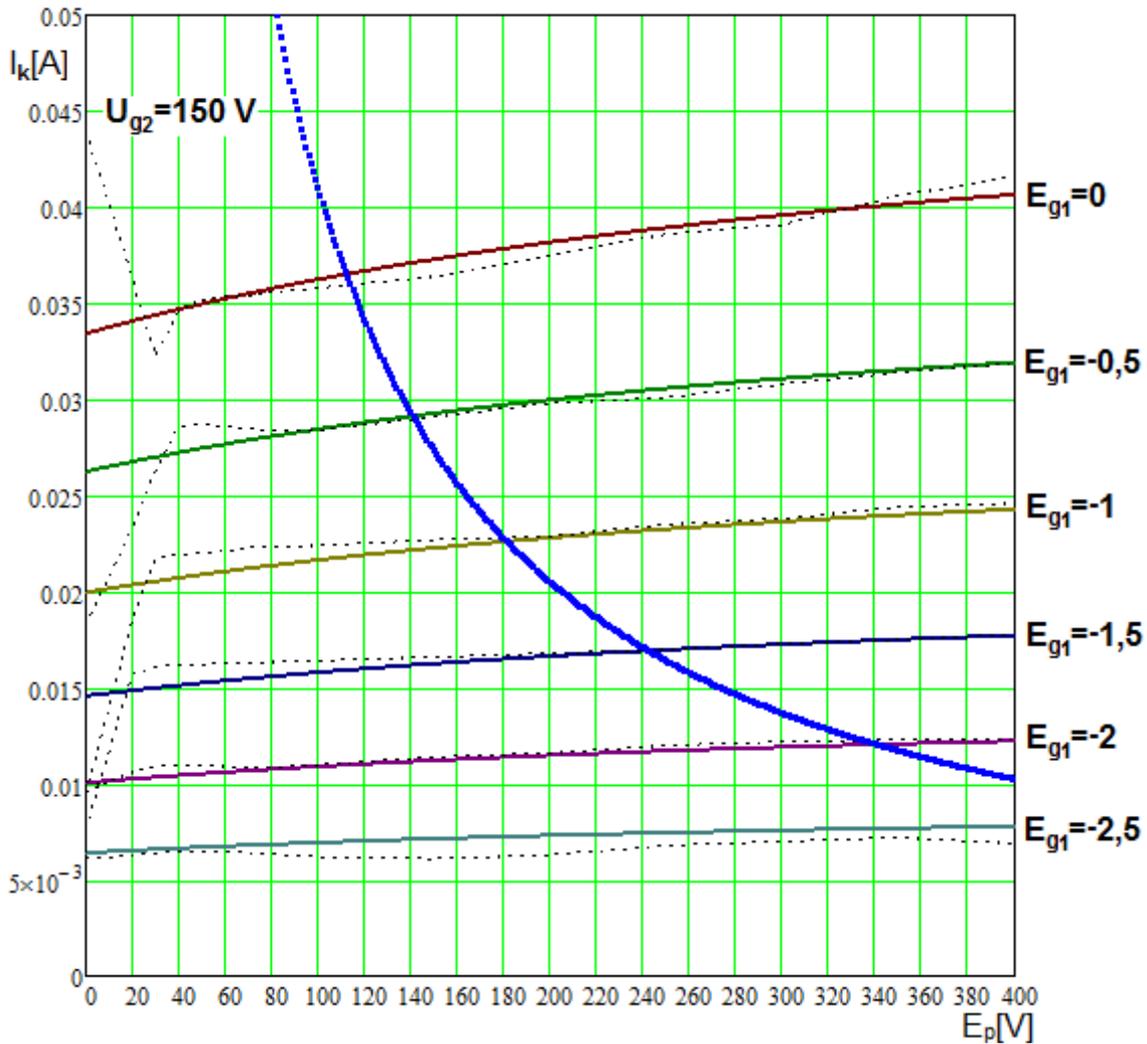


Fig. 3.4 – 6Ж5П pentode, cathode current variation, according to the model.

$$E_2 = \frac{E_p}{\delta} \cdot \ln \left[e^{\delta \cdot \left(\zeta + \frac{E_{g1} + \varepsilon}{\sqrt{\beta + E_p^2}} \right)} + 1 \right] \quad (3.12)$$

$$I_k = \alpha \cdot E_2^\kappa \text{ if } E_2 \geq 0; I_p = 0 \text{ otherwise} \quad (3.13)$$

According to relations (3.12) & (3.13) we can find the solution:

$$\begin{aligned} \alpha &= 0,0383 \\ \beta &= 93541 \\ \delta &= 1913,4 \\ \varepsilon &= -10,69 \\ \zeta &= 0,0116 \\ \kappa &= 1,1512 \end{aligned} \quad (3.14)$$

Figure 3.6c shows the control grid characteristics of the model diagram. For comparison, the dashed lines are the corresponding curves in the data sheet, revealed point by point. It was represented with blue stripe, hyperbole of screen grid current of maximum dissipation. The curves were obtained from the equation:

$$I_{g1} = \frac{-2}{k_{G1}} \cdot E_1^X + \alpha \cdot E_2^\kappa \text{ if } I_{g1} \geq 0; I_{g1} = 0 \text{ otherwise} \quad (3.15)$$

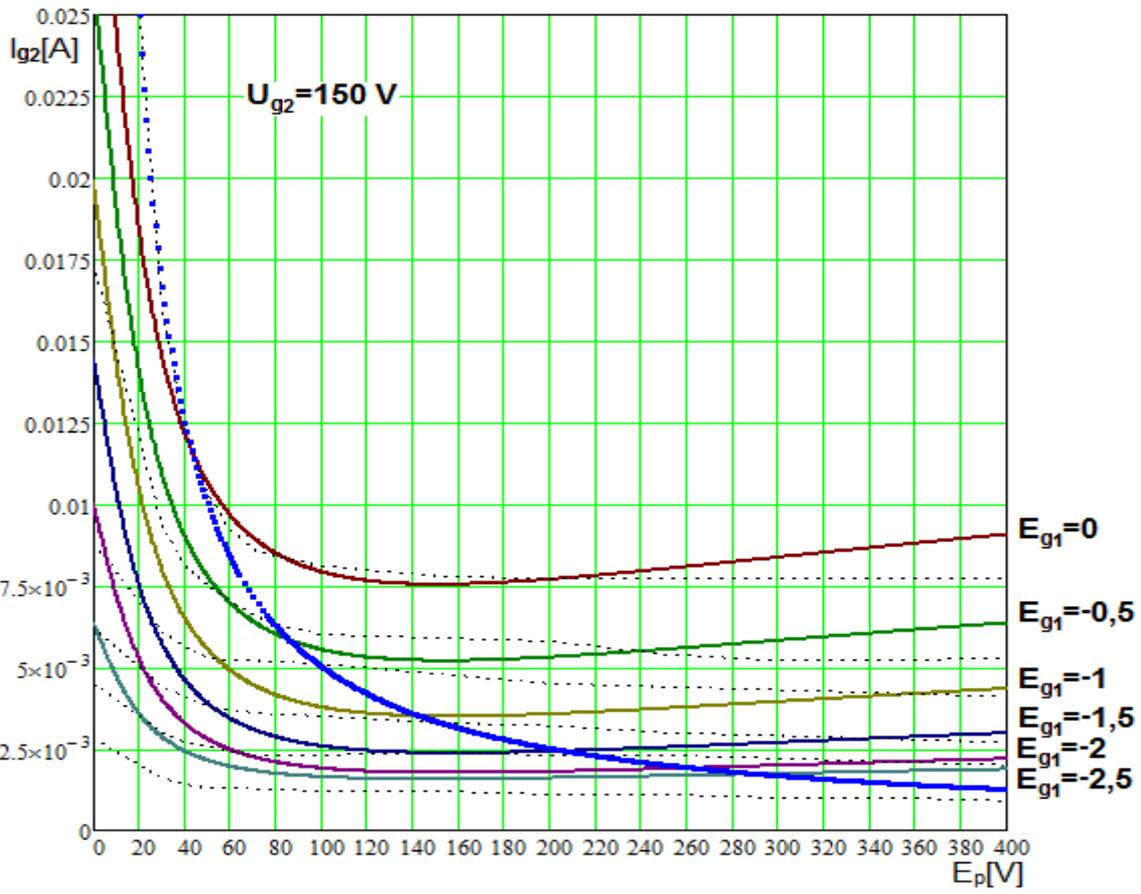


Fig. 3.5 – Pentode 6Ж5П, screen grid current variation, according to the model

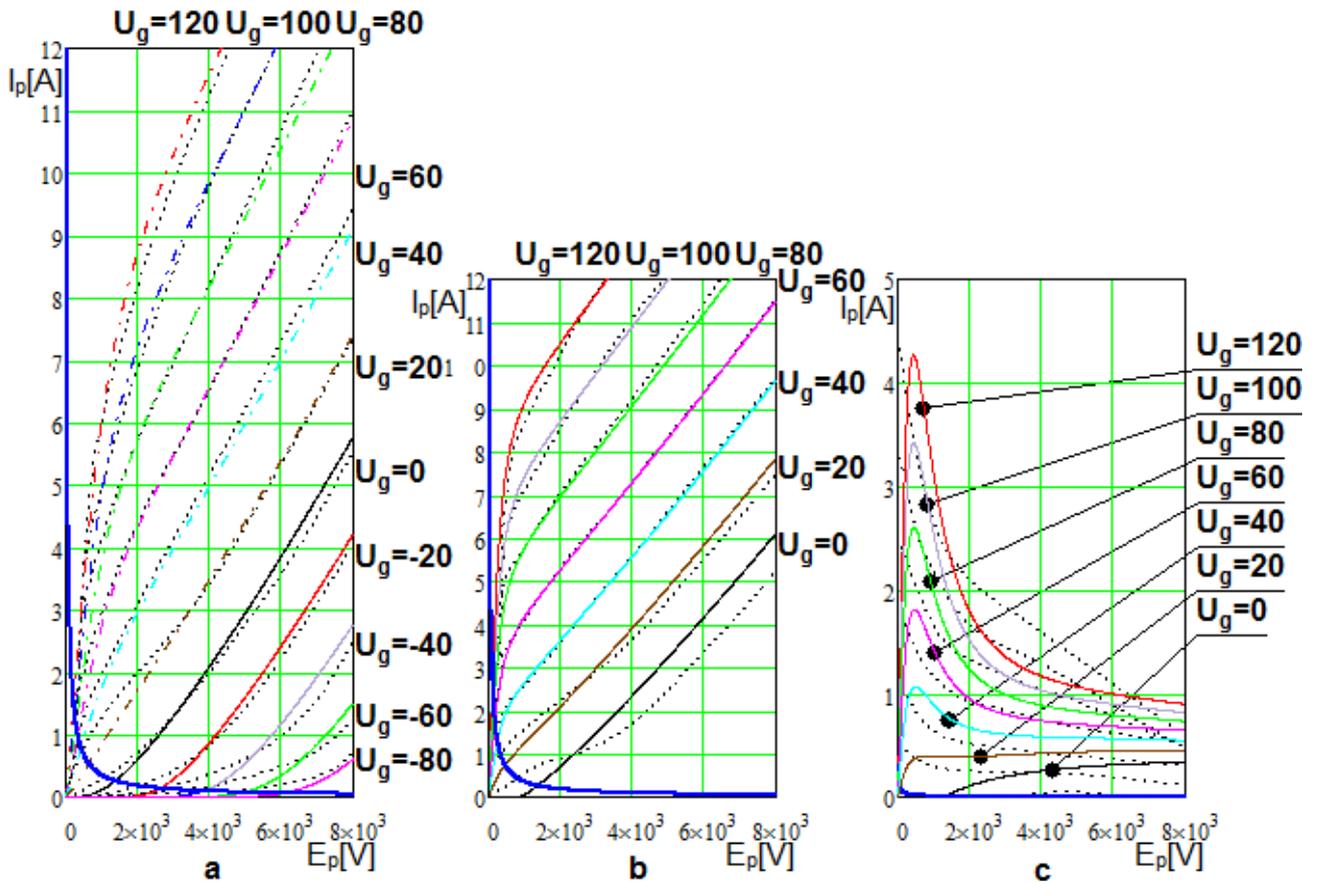


Fig. 3.5 – Model for determining anode, cathode & grid current characteristics of high power Russian triode ГИ7Б, for use in pulse mode.

4. About practical results

Figure 4.1 shows in Multisim the simulation of a tracer of characteristics that check the 6Ж5Π – tube model, from anodic current characteristics viewpoint. The settings are made to -2 V bias voltage on control grid (indicated by virtual voltmeter U1) and 150 V, voltage on the screen. XSC1 virtual oscilloscope, traced anodic current characteristic (numerically equal to the voltage drop across the resistor R1, of 1Ω) appropriate in these circumstances. XSC2 virtual oscilloscope indicates the voltage supplied form, of virtual linear variable V3, with amplitude of 300 V. The n°. 1 scale indicator of virtual oscilloscope XSC1 was fixed on 250 V voltage corresponding position on the X axis (channel B of the oscilloscope) and as shown on the Y axis (channel A of the oscilloscope) indicate a current of 9,778 mA.

Figure 4.2 shows, how the characteristics tracer, check the cathodic current characteristic for 6Ж5Π tube model. The settings are made for the same parameters (-2 V to grid control & 150 V to screen grid). XSC1 virtual oscilloscope, traced the cathodic current characteristic (numerically equal to the voltage drop across the resistor R3, of 1Ω) appropriate in these circumstances. The n°. 1 scale indicator of virtual oscilloscope XSC1 was fixed on 250 V voltage corresponding position on the X axis (channel B of the oscilloscope) and as shown on the Y axis (channel A of the oscilloscope) indicate a current of 11,602 mA.

Figure 4.3 shows, how the characteristics tracer, check the screen grid current characteristic for 6Ж5Π tube model. The settings are made for the same parameters (-2 V to grid control & 150 V to screen grid). XSC1 virtual oscilloscope, traced the screen grid current characteristic (numerically equal to the voltage drop across the resistor R2, of 1Ω) appropriate in these circumstances. The n°. 1 scale indicator of virtual oscilloscope XSC1 was fixed on 250 V voltage corresponding position on the X axis (channel B of the oscilloscope) and as shown on the Y axis (channel A of the oscilloscope) indicate a current of 1,824 mA.

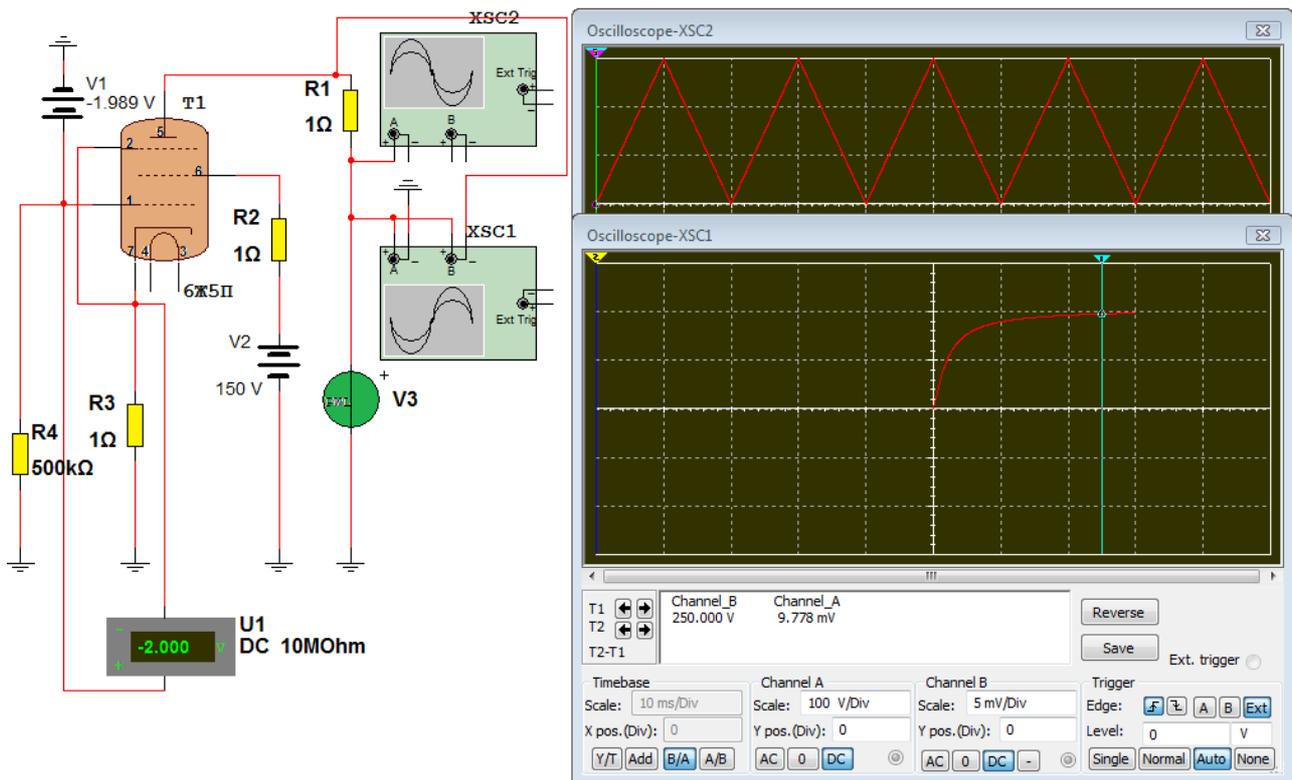


Fig. 4.1 - Automatic plotting simulation of the anodic current characteristic of 6Ж5Π tube model, setting for -2 V bias voltage of command grid & 150 V voltage on the screen grid.

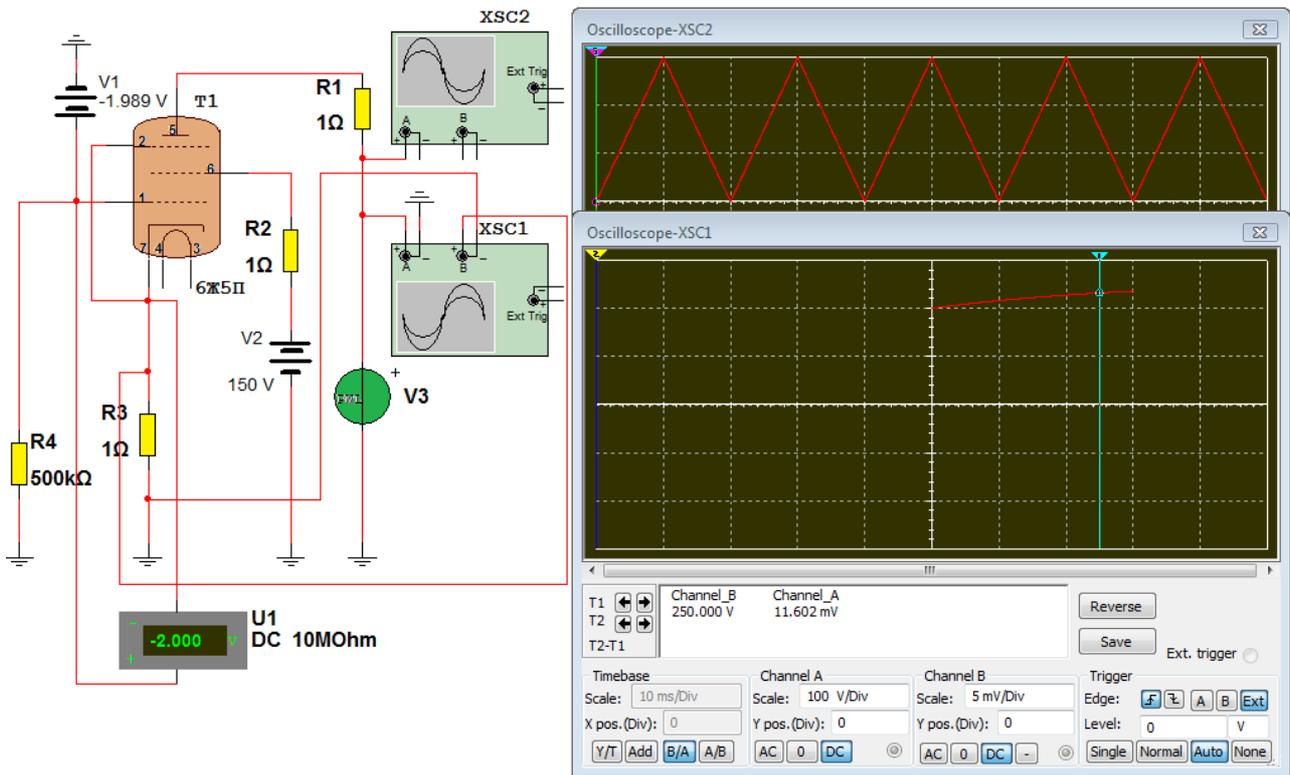


Fig. 4.2 - Automatic plotting simulation of the cathodic current characteristic of 6Ж5Π tube model, setting for -2 V bias voltage of command grid & 150 V voltage on the screen grid.

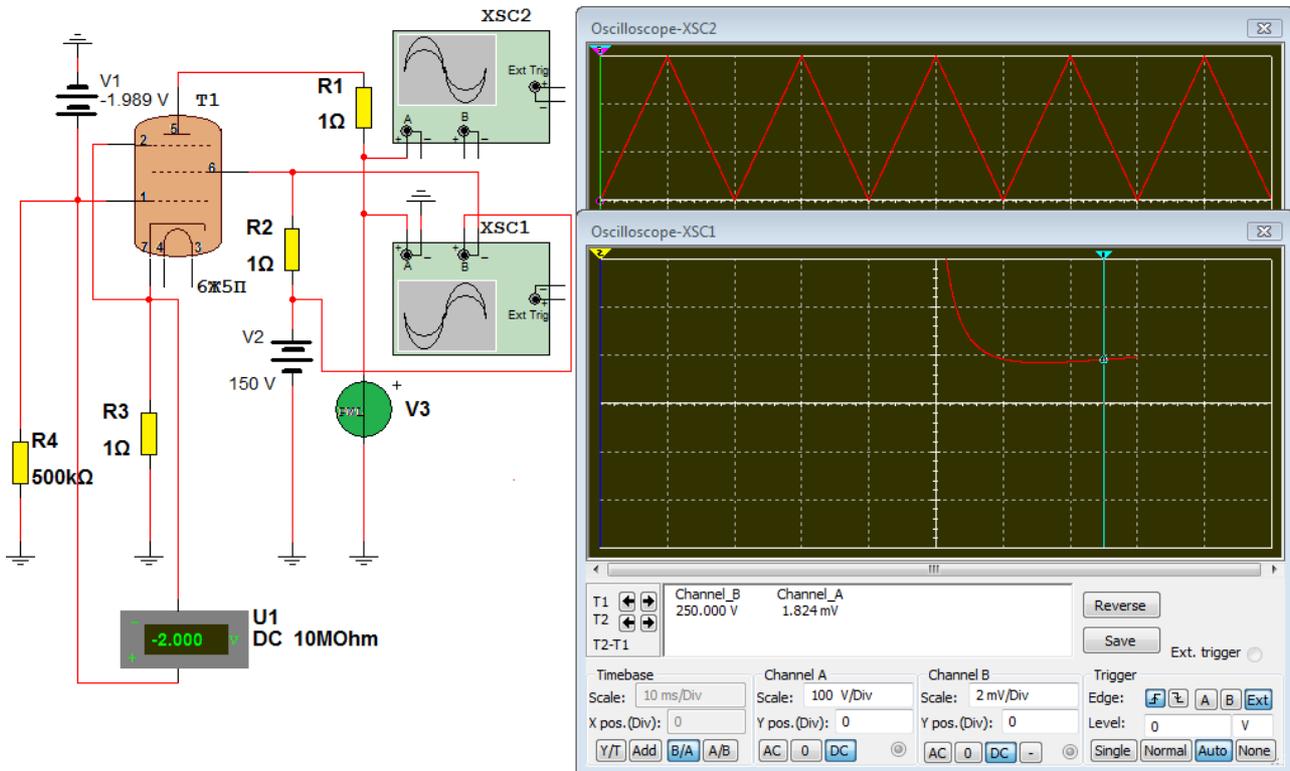


Fig. 4.3 - Automatic plotting simulation of the screen grid current characteristic of 6Ж5Π tube model, setting for -2 V bias voltage of command grid & 150 V voltage on the screen grid.

The results of these simulations, I think they are more than convincing. I have not made similar simulations of ГИ7Б triode, because it is not part of my tube "heritage" and so I was not directly concerned. This task, remains as a theme for the readers directly interested in putting of this tube model, on simulator.

5. Instead of conclusions

All calculations and graphical representations in this article, were made with MathCAD 14.

The models presented above, have been implemented and simulated in various schemes on SPICE simulator MultiSim 11 from National Instruments. There were no reported malfunctions.

It is noteworthy good enough accuracy of coincidence curves in the data sheet homonymous with the model, in the median range considered.

On the other hand, it is clear that attempts to use simplified models of triodes and pentodes, in accordance only with Norman Koren equations and its recommendations in Article [1] to simulate schemes other than those of audio amplifiers, will few succeed. Only in the presence of variations as accurate as possible of the cathodic currents, control grid currents, screen grid currents and suppressor grid currents (only in applications where it is not directly related to the cathode) will be able to simulate schemes such wave generators, or pulse circuits with tubes.

It remains to be solved (in terms of the possibility of complete simulation applications of electron tubes) modeling problem of anodic current characteristics, sufficiently loyal to contain also the portions of negative resistances, especially in tubes with more than three electrodes.

Because the modern age of computers, coincides with the period after the invention of the transistor, many technical aspects of electron tubes remained unexplored and unresolved. It seems that enthusiasts and hobby-ists of electronics, disagree that vacuum tubes only remaine museum objects, and increasingly more choose to use these devices in different areas of electronics. Therefore I think it is the task of these enthusiasts and hobby-ists (or vacuum tube passionate professionals) to perform research and theoretical studies necessary to bring any electron tubes on PSPICE simulators. Many were, and are considering this goal. Among them, I hope to make a modest contribution in this area, through this article.

April 2015
Nicolae Olaru

References :

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4. Pentode 6Ж5П data sheets – <http://musicangel.ru/mess232.htm>