POWERFUL RF TRIODE AS ANODE MODULATOR VACUUM TUBE

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Abstract

For 20 years modulator vacuum tube GMI-44A successfully operated in DTL RF system of INR Linac. The vacuum tube had been designed and manufactured at OKB “Swetlana” (now joint stock company SED-SPb) in the 70-ies - 80-ies of the last century. A quantity of manufactured tubes had achieved nearly 80 and allowed the accelerator operating up to date. In the middle of 80-th manufacture of the tubes was stopped. Attempts of the GMI-44A manufacture restoration or repair were unsuccessful ones.

As it is turned out, the only decision in the circumstances is use of vacuum tube GI-71A (the former name “Katran” [1]) as modulator tube. The tube GI-71A operates for the last ten years in all final RF power amplifiers (FPA) of INR Linac instead of GI-54A.

Use of RF triode GI-27A in anode modulator as control valve was considered in [2], but a creation of the HV modulator pulse was realized by means of the “soft” discharger.

ITRODUCTION

The powerful anode modulator simplified scheme is shown at fig.1, where AFL – artificial forming line (storage device), TRPM – transistor pre-modulator, TR- thyristor regulator of GI-71A filament voltage.

To simplify the subsequent discussion the modulator vacuum tube will be marked as GI-71AM though in the modulator and the FPA the same vacuum tube GI-71A sets in.

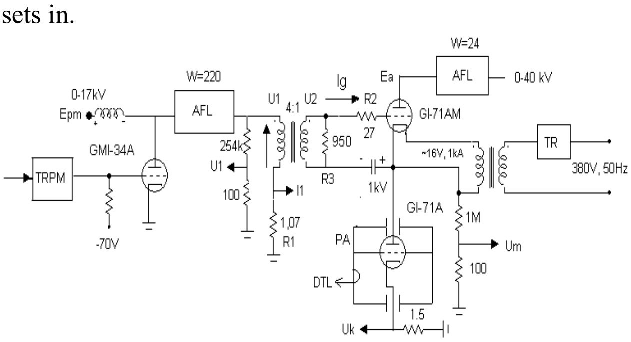

Figure1: Simplified scheme of anode modulator.

At fig.1 pre-modulator devices are additionally represented at the scheme: pulse transformer between output stage of the pre-modulator (at vacuum tube GMI-34A) and GI-71AM input, a source of negative grid bias relatively cathode, resistive dividers, which allows to measure voltages in the main point of scheme, final RF power amplifier (FPA), connected in series with modulator vacuum tube GI-71AM. Resistor R2 limits the grid current value in a case of emergency situation (short circuit of GI-71AM grid-cathode gap) and brings down oscillations in the circuit consisted from pulse transformer secondary winding inductance and capacity grid-cathode *Cgc* of the modulator vacuum tube.

It should be noted that modulator vacuum tube performs several functions such as:

- Creation of PA plate pulse voltage up to 35-40 kV with current 150-200A;
- Control of plate voltage by a signal of negative feedback from the tank;
- Interruption of pulse modulator in the case of breakdowns in PA vacuum tube [3]
- Aging of PA vacuum tube because of series crowbar operation particularities [3] - due to delay between signals from current transformer in the modulator vacuum tube plate network and at the GI-71AM input a part of energy, accumulated in AFL, is delivered in a point of break-down, destroying non uniformity at electrode surface of the FPA vacuum tube.

Before estimate problems, which are appeared after replacement of GMI-44A at GI-71A it follows to compare both vacuum tubes options (see table 1).

Table 1: Tubes Options

	GMI-44A	GI-71AM
Cag, pF	300	80
Cgc, pF	1000	200
Cac, pF	20	3
- Eg, kV	2	1.5
Ea, kV	60	45
Iem, A	500	900
Iao, A*)	140	100
Igo, A*)	1	25
Pa, kW	150	140
Pg, kW	1.5	2
Filament voltage	6V, 50Hz	16V, 50Hz
Filament current	2kA	1kA

*) At voltages Ugk = 500 V and Uak = 6kV

As can be seen from table 1 the vacuum tubes options noticeably differ in values of inter-electrode capacities and grid currents. The last one means, that pre-modulator pulse power needs to be increased 20-30 times. That can be achieved by two ways: increasing of transistor pre-modulator gain and optimization of GMI-34A mode of operation, particularly by means of plate voltage increasing.

Moreover, as follows from table 1 GI-71AM filament options demand changes of the high-voltage filament transformer. It should be noted that GI-71A modes of operation in modulator and in RF final power amplifier are significantly different ones. In FPA there is pulse plate voltage 25-30 kV and automatic pulse grid bias due small resistor in cathode circuit. Value of pulse grid bias doesn’t exceed 400V. During setting GI-71A in anode modulator there are dc plate voltage up to 40kV and dc

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grid bias about 1 kV. The last mode of operation is more difficult than previous one.

PRE-MODULATOR MODE OF OPERATION

Pre-modulator scheme as it looks by the secondary winding of ideal pulse transformer with transformer ratio 4:1 is shown at fig.2.

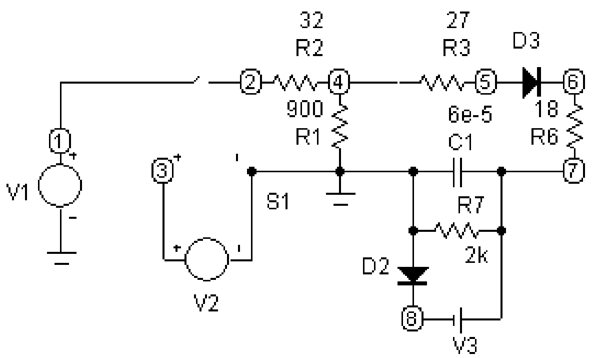

Figure 2: Pre-modulator output stage model.

At the scheme *R6* is an input impedance of the modulator vacuum tube GI-71AM, *R2* – AFL wave impedance, *V1* – GMI-34A plate voltage, *V3* – negative bias source, *V2* – *SV*-switch, operating with repetition rate 50 Hz and pulse length 400µs, *R3*-resistor limiting grid current, *R1* – additional resistor in secondary winding of pulse transformer.

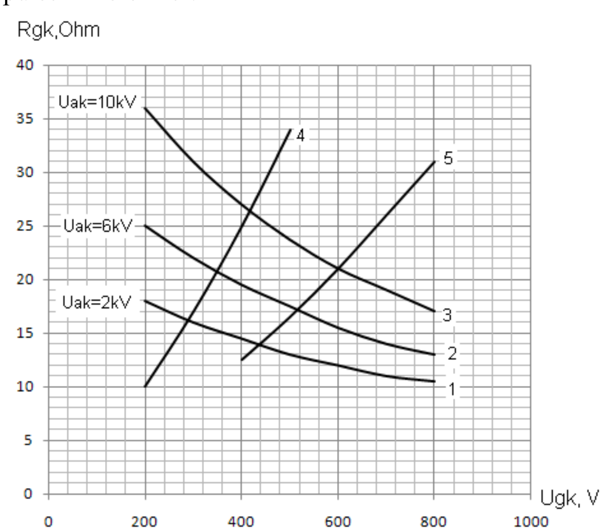

Figure 3: Example of pre-modulator options calculation.

The pre-modulator scheme allows determining real values of pulse voltage *Ugk* (U_{R6}). At that it should be noted that input impedance of vacuum tube GI-71A depends on both from grid-cathode voltage *Ugk* and anode-cathode voltage *Uak*. As a consequence, it is impossible to determine the main options of pre-modulator analytically.

Example of pre-modulator options calculation, such as GI-71A input impedance, *Ugk* voltage and plate current Iao, is shown at fig.3, where curves 1-3 represent the GI-71A input impedance as a function of the *Ugk* and *Uak* voltages.

The curves are created from known dependecies *Ig=f(Ugk)* of vacuum tube GI-71A. Curves 4,5 correspond to the pre-modulator options, presented at fig.3, where voltage *Ugk* value was calculated for different values of *R5*.

The curve 4 corresponds value of V3 = 2500V, the curve 5 – 3500V. Taking into account the pulse transformer ratio, plate voltage of vacuum tube GMI-34A for curve 4 is equal 10 kV and for curve 5 – 14 kV.

Intersection points of curves 1-3 and 4,5 determine values of *Ugk* and *Rgk* and, hence, values of grid current *Ig* = *Ugk/Rgk* and GI-71AM plate current *Iao* – from known plate-grid dependencies *Iao* = *f(Ugk)*. Below, in table 2 some results of such calculations are presented.

Table 2: Results of Calculations

	U1=2500V			U1=3500V		
Uak, kV	2	6	10	2	6	10
Rgk, Ohm	16	21	26	12.5	17	21
Ugk, V	290	350	420	400	520	600
Ig, A	18.1	16.6	16.1	32	30.6	28.5
Ia, A	50	70	120	65	120	170

It follows from table 2 that due to nonlinearity of GI-71A input impedance, *Ugk* value increases on 50%, when *Uak* value changes from 2kV to 6kV. At that, grid current value change is minor – 10% only. All this takes place at unchangeable value of GMI-34A plate voltage.

In order to move from static options to the real ones it is possible to make use the procedure, presented in [4]. According to that of it follows, first of all, to set FPA input options such as RF voltage value *Ug* at the GI-71A grid and plate voltage *Ea*, which provide required level of RF power in the DTL cavity.

Calculation model, presented in [4], allows determining FPA vacuum tube mode of operation in full, including plate current constant component *Iao*. Returning to GI-71A static options it is easy to determine *Ugk* and *Uak* values, matching calculated above value *Iao*. Then it is not difficult to define *R6* value and GMI-34A plate voltage, which provide demanded value of *Ugk*.

As to GI-71AM plate voltage *Eao* its value is determined as *Eao=Ea + Uak + W Iao*, where *W* is the wave impedance of *AFL* at GI-71AM plate.

It should be noted the increasing role of capacitor C1 in connection with grid current growth.

Values of the grid current, resister R7 and capacity C1 determine the low limit of negative bias voltage. If assume, that the external negative bias source is disconnected, then negative bias voltage will be result of capacitor *C1* charging by grid current. Really in a steady state the next ratio takes place:

$$(E_{go}+\Delta Uc)(1-e^{\frac{-1}{FTc_c}})=\Delta Uc\ ,$$

where *Ego* – negative bias, that appears as a result of capacitor *C1* charging, *F* – a pulse repetition rate, *Tc* = *C1*R7* – capacitor *C1* discharge time constant,

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$\Delta U_C = \frac{1}{C_1}\int_0^{\tau} I_g(t)dt$ where τ is the pulse length of grid current.

Assuming grid current value constant along pulse length it is easy to get an expression, determining a low level of the bias voltage:

$$E_{go} = \frac{I_g}{C_1} T_u e^{-\frac{t}{FT_C}} (1 - e^{-\frac{t}{T_C}})^{-1}$$

For example, for *Ig=30A, C1=60nF, F=50Hz, Tc=0,12s,* τ *= 400µs* value of negative bias achieves *Ego~ -1100V.*

SOME RESULTS OF GI-71AM TESTING

During the year new modulator vacuum tube GI-71A had been installed in four of the six regular RF channels with output pulse RF power 1MW (the fifth RF channel), 1,2 MW (the first RF channel), 1,8MW (the fourth RF channel and 2,2 MW (the sixth reserve channel).

Maximum operating time of the vacuum tube has been about 2000 hours to date. Failure of the vacuum tubes has not been noted. Unexpectedly the modulator speed of response has been noticeably increased after replacing GMI-44A at GI-71AM. It allowed giving up from additional feedback circuit around modulator [5].

The most reliable operation takes place in the first and fifth RF channels, where GI-71AM plate voltage does not exceed 28 kV. With increasing GI-71AM plate voltage the series crowbar system [3] operation can be disturbed. The fact is that crowbar operation is caused by anode-grid breakdowns in FPA vacuum tube GI-71A or anode grid cavity, whereupon open vacuum tube GI-71AM is proved under full plate voltage. If the modulator vacuum tube is not closed by the series crowbar system, plate current will be increased several times up to 400-500 A, until the artificial forming line will be discharged. It means that breakdown pulse width will achieve 400 µs instead of 10 µs in a case of proper operation of the crowbar system.

There are two main reasons of the crowbar failure.

- Lack of aged vacuum tube GI-71AM because neither manufacturer (S.E.D-S.Pb) nor user (INR RAS) has equipment for aging of vacuum tubes GI-71A. That is why vacuum tube aging takes place during beam sessions only.
- Overvoltage in pre-modulator networks as a result of GI-71AM grid current interruption by the series crowbar system.
- Unknown processes in the vacuum tube GI-71AM after breakdowns in the FPA causing short circuit vacuum tube GI-71AM cathode at the ground.

It should be recalled that FPA operates with ground grid and breakdowns take place between the inner tube of coaxial plate-grid cavity (or vacuum tube plate) and ground.

At fig.4 snapshot of processes which accompany FPA breakdown are shown. From them follows that despite of modulator input pulse cutting off modulator vacuum tube GI-71AM is open until full discharge of the forming line.

Moreover grid-cathode gap is also broken down and capacitor C1 (see fig.2) is discharged through broken gap supporting GI-7AM open.

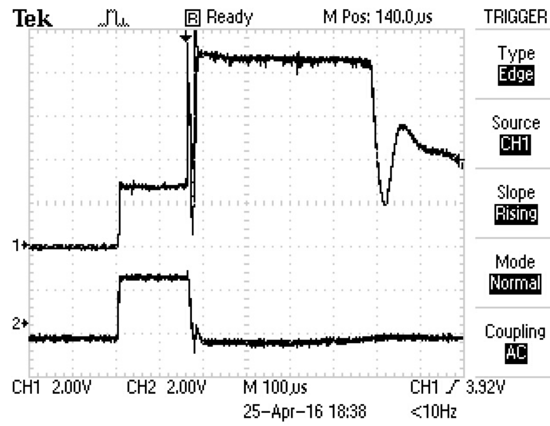

Figure 4: Snapshot of process during breakdown in FPA. Upper trace – plate current, lower trace – pulse at the GMI-34A input (see fig.1).

Unfortunately cathode and grid of vacuum tube GI-71A are under high pulse voltage and real processes at the electrodes can't be watched by the simple way.

Now we consider a few ways of the problem deciding, particularly installation of solid-state opening switch [6] in GI-71AM plate circuit and correcting circuits, limiting value of overvoltage at the GI-71AM grid. We don't also eliminate a possibility of GI-71A design changing. In particular there is agreement with SED-SPb about placing magnetic discharge vacuum pump at grid electrode of GI-71A.

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