DEVELOPMENT OF THE INR DTL RF SYSTEM CROWBAR OPERATION

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Abstract

DTL RF system of the INR linear accelerator consists of five RF channels. In turn, each channel maintains two powerful series connected vacuum tubes, installed in anode modulator and RF power amplifier PA. Operation of the both tubes is supplied with crowbar system that defends vacuum tubes from destroying as result of breakdowns in one of them. Since the energy storage in the INR DTL anode modulator is artificial forming line AFL (with impedance value 24 Ohm) in crowbar system can be used series thyristors and starting block, which opens the thyristors, when PA vacuum tube anode pulse current exceeds set-point value. In the paper an analysis of the processes in AFL and crowbar system is considered. Some results of the crowbar system upgrade are presented.

1. INTRODUCTION

In fig.1 the simplified view of the PA and anode modulator vacuum tubes connection with power supply and crowbar are shown. From fig.1 it follows that PA and modulator vacuum tubes are series connected and hence the crowbar system has to defend from breakdowns not only PA and modulator vacuum tubes, PA anode-grid cavity but also the modulator vacuum tube heater and grid bias transformers and the pulse transformer between modulator and pulse driver. To defend the high voltage power supply equipment from damage it was provided by designer fast disconnection high voltage rectifier HVR from 10 kV, 50 Hz network in TD1~20 ms after crowbar thyristors operation with smooth decreasing of voltage at the HVR input. It follows also to take into account that after discharging the AFL (as a result of crowbar operation) a HVR current is increased from (3-4)A during stable operation of the RF channel up to 20A in 10-12 ms after the crowbar operation. At that, due to the energy, stored in the HVR choke, overvoltage takes place in the AFL – its maximum value is increased at 8-10 kV in ~30ms after crowbar operation. At time delay TD1=20ms overvoltage in the AFL doesn't appear.

In addition to the crowbar there is a current protection relay, which also disconnects high voltage rectifier HVR from 10 kV, 50 Hz network in TD2~100 ms if a current at the AFL input exceeds predetermined current value. It is significant that values of breakdown and crowbar current are the same. That is why breakdown in one of the RF channel equipment results in fast falling of the high voltage value at thyristors anode and for successful operation of the crowbar it is necessary to feed a negative voltage E_0 at the cathode of thyristors. Disconnection high voltage rectifier HVR from 10 kV, 50 Hz network in result of the crowbar operation was not happy choice with accelerator operation point of view, because in 20-30 sec after RF channel switching off cavity detuning achieved a few bandwidths and it took near 15-20 min to put into operation the accelerator again[1]. Why was taken such decision? The point is that there was opinion that the crowbar thyristors could not to be closed immediately after AFL discharge and, hence, could create short circuit for the HVR and induction voltage regulator IVR.

Moreover, fast disconnection from high voltage supply excludes repetition of the crowbar operation with full discharge of the AFL, following with RF pulse repetition rate 50Hz, as in ~20ms AFL voltage is practically restored. It was from these considerations that a decision was taken to break off the modulator high voltage supply after crowbar operation.

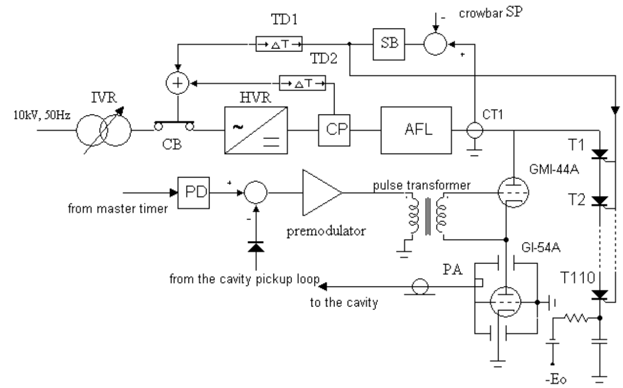

Fig.1 Simplified common view of RF channel with crowbar circuit (PD – pulse driver, CT1 –current transformer, CP-current protection, CB- high-voltage circuit breaker, TD – time delay)

Before considering of the crowbar upgrade it follows to estimate processes in the artificial forming line AFL in order to make sure in correct interpretation of the initial suppositions.

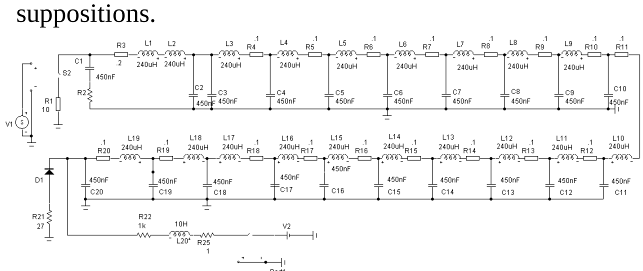

Fig.2 Micro Cap 7 model of the artificial forming line

2. MODELING OF PROCESSES IN THE AFL BY MEANS OF MICRO CAP 7

The MC-7 model of the INR DTL AFL is presented in fig.2. It consists of 19 cells with C=450nF, L=240μH, time of discharge ~ 400 μs and impedance ~ 24 Ohm. At that, to improve the modulator pulse form the first twocells are combined into one cell. HV rectifier is represented as source V2, choke L20 and resistor R22, thyristors - as resistor R1 and V-switch S2, the high voltage circuit-breaker – as T-switch Part 1 that turns off HV supply from the AFL in TD1=20 ms after switch S2 turning on. Resistor R2 limits starting value of thyristors current, circuit R21, D1 intends for dissipation stored in the AFL energy during crowbar operation. At that if $R_2<\rho$, where ρ is AFL impedance, there is a danger of repeated starting of the thyristors as the voltage $U_{C1}>0$ during a crowbar operation.

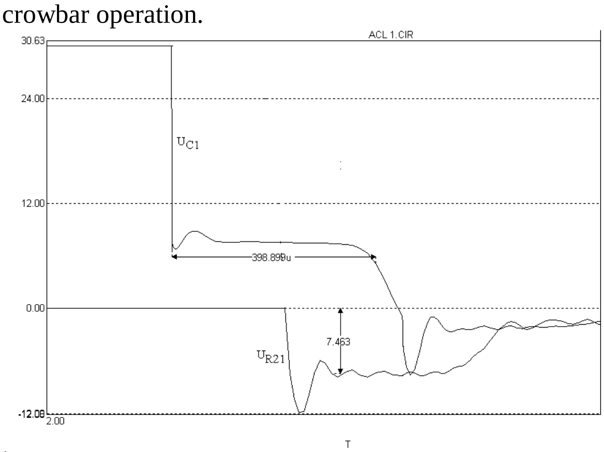

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Fig.3 Transients in the AFL, R1=6 Ohm, R21=30 Ohm.

In Fig.3 transients in the AFL model after the switch S2 is closed are shown. It follows from them that after AFL discharging a negative voltage appears at thyristors anode providing their safe closing. Hence, the thyristors are open only for the AFL discharging time and there is not a danger of short circuit creating. Moreover, after the AFL discharging thyristors are switched over from source with internal resistance 24 Ohm (AFL impedance) to the source with internal resistance 500 Ohm (HVR impedance). Thus, one could say that crowbar operation is stopped after AFL discharging and, hence, suggestion about possibility of short circuit as result of crowbar operation, mentioned above, is wrong. As an example, in fig.4 snapshot of the real process in the AFL is presented. The upper trace corresponds to the thyristors current (value of thyristors current ~ 300A at AFL voltage 15 kV), lower trace –anode modulator pulse.

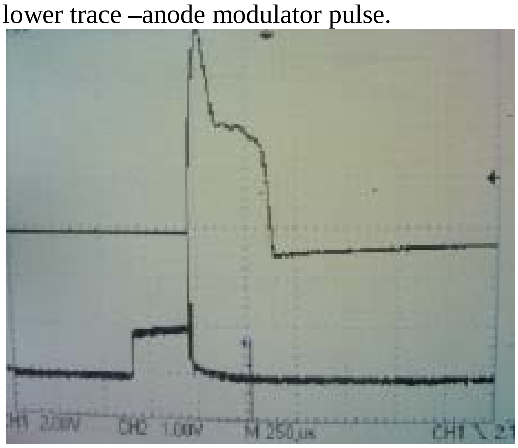

Fig.4. Snapshot of crowbar operation.

During discharge of the AFL through the crowbar thyristors energy, stored in the capacities, is dissipated mainly in the thyristors (R1) and resistor R21. But due to time delay between times of crowbar switching on and high voltage circuit breaker (CB) switching off, the AFL has time to restore a charge of the AFL capacities and, hence, there is a danger of repeated breakdowns.

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3. BRIEF REVIEW OF BREAKDOWNS

It should be remembered that the crowbar was first of all designed and produced for protection of powerful vacuum tubes, installed in the anode modulator (GMI-44A) and RF power amplifier (GI-54A). High-speed crowbar operation had to defend the vacuum tubes from destroying in result of AFL discharge at shorted vacuum tube. However, as may be seen from fig.1, both modulator and PA vacuum tubes are connected series and conditions for breakdowns are different.

3.1 Modulator vacuum tube breakdown

Breakdown in the modulator vacuum tube GMI-44A really can happen only in the time interval between RF pulses, when anode-cathode gap is under full high voltage of the AFL (30 - 40 kV). At that, if the crowbar were switched off, the PA vacuum tube would under nearly full AFL voltage without RF exciting. As follows from measurements, the PA vacuum tube direct current with RF exciting nearly three times higher than without one. It means that modulator vacuum tube breakdown current is limited and can't result in the modulator vacuum tube destroying. Surely, it's true, if there isn't PA vacuum tube inside self-exciting, which can result in impairment of the vacuum and following breakdown. But this process takes a time and can't happen during one pulse. Besides, a danger of the inside self exciting is much less in the new vacuum tubes GI-71A (former name "Katran" [2]), which during last years have been installed in the half of the RF power amplifiers instead of GI-54A, which manufacture was stopped nearly 15 years ago.

3.2 RF power amplifier breakdowns

In contrast to the previous case sparks or breakdowns in the RF power amplifier PA vacuum tube GI-54A (GI-71A) or PA anode-grid cavity can be only during RF pulse, when there are anode pulse voltage and RF driver supply. As the long-term experience has showed, the most part of crowbar operation is caused by breakdowns in the PA anode-grid cavity. The main reasons of that are the following:

- breakdowns in the coaxial transmission line CTL between PA and accelerator cavity;
- overvoltage at the falling edge of RF pulse in the PA cavity [3] in process of RF channel operation and, particularly, due to accelerator cavity detuning;
- self-exciting of the amplitude or phase control system;
- interdependence of the RF channel equipments, which have common electric power networks, master oscillator driver and master timer;

All above-mentioned reasons can create conditions for breakdowns in the PA anode-grid cavity because of peculiarity of the anode cavity structure. It represents so called half-wave coaxial line, where the inner stem of the line is under both HV pulse and RF voltages. At that, while the PA vacuum tube anode-grid RF voltage doesn't exceed a value of modulator pulse voltage (25-30 kV), RF voltage between inner stem and sidewall of the PA cavity can be a few times higher.

In rise of breakdown, due to the high value of the GMI-44A emission current at low plate voltage, the breakdown current is limited by the AFL impedance only. It means that if the crowbar is switched off, breakdown current value, discharging the AFL, is very close to the thyristors current during crowbar operation. At that, if the breakdown takes place (due to overvoltage) at falling edge of RF pulse in the PA cavity [3], modulator vacuum tube GMI-44A is already closed, and there is no signal for crowbar operation. But the breakdown results in to ionization of the gap and to the following breakdown during the next RF pulse with crowbar operation. Moreover, if the crowbar is switched off modulator pulse becomes negative during breakdown (see fig.5). Likely reason – positive charged ions motion in the broking gap.

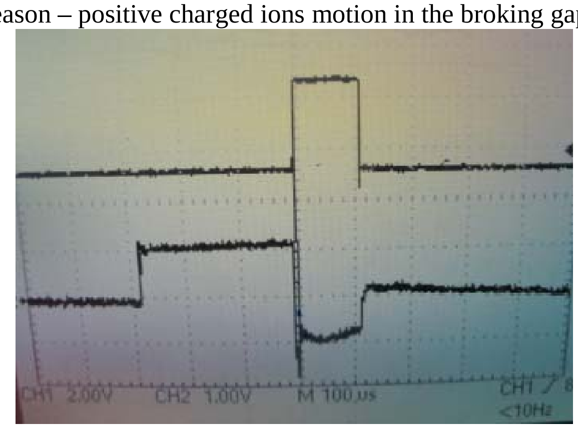

Fig.5.Upper trace – breakdown current, lower trace – anode modulator pulse.

4. CROWBAR UPGRADE

As follows from foresaid, the existing crowbar successfully carries out its function (see fig.4) with full discharge of the AFL after breakdown beginning. The negative sides of this crowbar are long restoration time after breakdown and a danger of the breaker CB destroying due to frequent operation.

The main purpose of the crowbar upgrade has been directed at keeping of the positive side of the existing crowbar – fast interruption of the breakdown. As the most part of breakdowns happens in the RF power amplifier during anode modulator pulse, another way of crowbar realization can be considered. Instead of full discharge of the AFL, interruption of premodulator output signal immediately after breakdown beginning is put into operation. At that, modulator vacuum tube is closed, breakdown is stopped (see fig.6) and the AFL remains charged without overvoltage. Moreover, starting with the next pulse, time delay of the master timer pulses for 3-5 sec is input, in order to restore electric strength of the broking gap. During this time the accelerator tank tuning remains unchangeable but it is sufficient for considerable deionization of the sparking gap. If in 3-5sec the breakdown will be repeated CB is disconnected and the anode modulator is switched off.

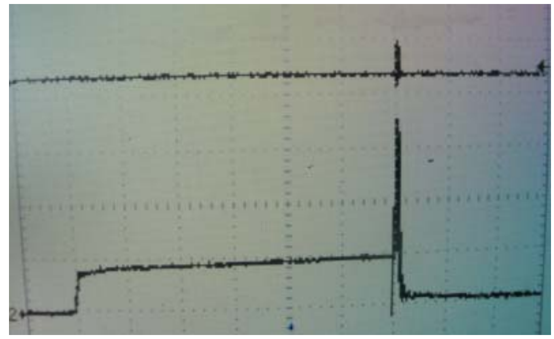

Fig.6 Result of breakdown interruption. Upper trace – breakdown current, lower trace-modulator current. 1 dev-50μs.

In fig.7 the new crowbar system is presented. First of all, the main part of the crowbar with series connection of thyristors is excluded from it and a new circuit is added. It consists of the interrupt location, which involves the device, named "breaker", controlling two electronic switches. The fast switch after the pulse driver PD interrupts driver (within the limits of the RF pulse) immediately after breakdown beginning. The slow switch interrupts master timer pulses, following with the repetition rate 50Hz, for 3-5 sec. In case of the second breakdown - after restoration of master timer pulses, the breaker gives a command to switch off HV supply.

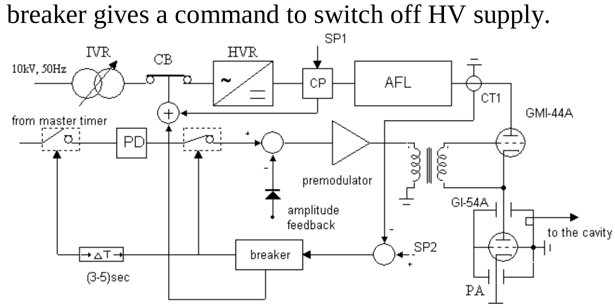

Fig.7. New crowbar structure

At present time the new crowbar systems are installed at all DTL RF channels, but efficiency of the new system can be estimated during the long-term tests only.

5. REFERENCIES.

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