OPERATION OF THE 400-750KV PULSE VOLTAGE MULTI-CASCADE DISCRIMINATOR

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1. INTRODUCTION

The multi-cascade discriminator (MD) of the amplitude of pulsed 400-750kV voltage is an important part of the pulse high-voltage generator at the high-current linac injector of the Moscow meson factory [1]. It was invented and designed at the Efremov Institute of Electrophysical Apparature (Leningrad). It was partially tested at the factory [2] and successfully ran at 1 Hz repetition rate [3] in the adjusting mode of the accelerator. However the transition to 50Hz repetition rate gave rise to certain drawbacks, such as the current overloading of the inductivities, breakdown of the diodes and insufficient voltage. Analytical and experimental researches were conducted, and the required changes were made on their basis. These changes allowed the discriminator to operate with high reliability. The main results are set forth in this report.

2. ANALYSIS OF THE MULTI-CASCADE DISCRIMINATOR OPERATION

The periodic process is considered when at the end of each period all inductivity currents and the capacitors voltages revert to their values in the beginning of the period. The period is divided into 2 parts; in the first part currents and voltages grow, in the second part they revert to original values.

2.1. DISCRIMINATION OF PULSED VOLTAGE

The principal scheme of the device for limitation of positive voltage impulses is shown in fig. 1a. When the applied voltage exceeds the sum of $\mathbf{C_1 \div C_n}$ voltages and drop of voltages on all diodes $\mathbf{V_1 \div V_n}$, these diodes conduct the I_i pulse current, which slightly increases the charges of capacities during the time of the pulse $\mathbf{t_i}$ by $\boldsymbol{\delta U_i = I_i t_i / C_i}$. The sum voltage instability is equal to their sum on all capacitors, i.e. $\boldsymbol{\delta U = n I_i t_i / C}$, if capacities are identical. During the impulse the voltage which approximately repeats the general impulse form is applied to each inductivity; its magnitude is proportional to this cascade capacity voltage. As a result, j-inductivity current will be augmented by

$$\mathbf{I_j = U_0 k_{uj} t_i k_i / L_j},$$

where $\mathbf{U_0}$ is reference voltage of the discriminator, $\mathbf{k_{uj}}$ is coefficient which demonstrates how many times the j-capacity voltage is less than $\mathbf{U_0}$; $\mathbf{k_i = 1 + (t_b + t_e)/t_i/2}$ allows for a role of fore and back fronts in the inductivity current increasing, $\mathbf{L_j}$ is inductivity of the corresponding cascade (see Fig. 2a).

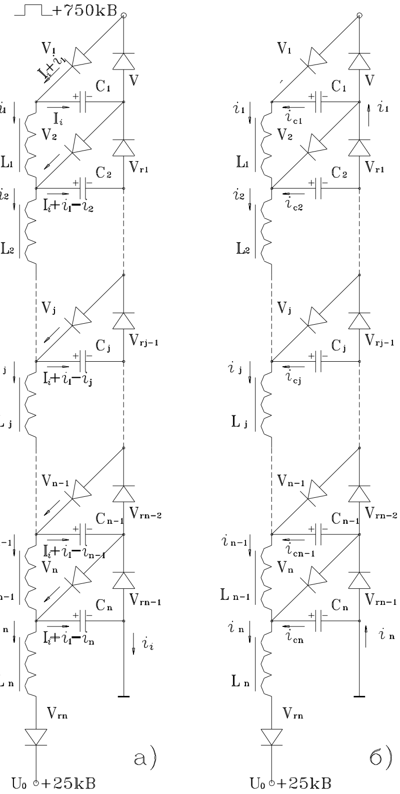

Fig. 1.

2.2 DISCHARGE OF CAPACITIES BETWEEN IMPULSES

Between impulses all capacitors return charges in a reference supply source when average current $\mathbf{I_n = n I_i t_i f}$ running, where f is pulse repetition rate (see Fig. 1b). The numeration of cascades starts from the output. Let us consider the first cascade. The inductivity current should be diminished by magnitude $\mathbf{I_1 = U_0 k_{u1} t_i k_i / L_1}$; the negative voltage $\mathbf{U_2 - U_1 + U_{r1} + R_1 i_{l1}}$ (where $\mathbf{U_2}$ and $\mathbf{U_1}$- voltage on capacities $\mathbf{C_2}$ and $\mathbf{C_1}$ accordingly, $\mathbf{U_{r1}}$ - voltage drop on the diode $\mathbf{V_{r1}}$, $\mathbf{R}$ - ohmic resistance of the inductivity wiring, $\mathbf{i_{l1}}$ - momental value of a current in $\mathbf{L_1}$) is applied to the inductivity. For MD parameters it is possible to assume with satisfactory accuracy that $\mathbf{R}$ is a small value, the current is changing linearly during $\mathbf{t_1}$ when the charge $\mathbf{Q = I_i t_i}$ passes through the inductivity.

Hence $\boldsymbol{\delta U_1 = U_2 - U_1 = I_1 L_1 / t_1 - U_{r1}}$ and $\mathbf{Q = I_1 t_1 / 2}$. Having made necessary transformings, we get

$$\mathbf{t_1 = 2 L_1 I_i / (U_0 k_i k_{u1})}, \ \boldsymbol{\delta U_1 = (U_0 k_i k_{u1})^2 t_i / (2 I_i L_1) - U_{r1}}$$

For the second cascade it is necessary to take into account, that there pass charge $\mathbf{2Q}$, hence

$$\mathbf{t_2 = 4 L_2 I_i / (U_0 k_i k_{u2})}, \ \boldsymbol{\delta U_2 = (U_0 k_i k_{u2})^2 t_i / (4 I_i L_2) - U_{r2}}$$

and for j-cascade, accordingly, charge $\mathbf{jQ}$ and

$$\mathbf{t_j = j 2 L_j I_i / (U_0 k_i k_{uj})}, \ \boldsymbol{\delta U_j = (U_0 k_i k_{uj})^2 t_i / (j 2 I_i L_j) - U_{rj} - R I_j / 2},$$

if $\mathbf{t_j < 1/f}$. The diagrams of currents are shown in Fig. 2b and 2c.

It is necessary to take into account that $\boldsymbol{\delta U_j}$ will be in all previous cascades, i.e., with coefficient j in a total MD voltage loss.

If $t_j > 1/f$, then $\delta U_j + U_{rj} + RI_{mj}$ gets such value, that during $1/f-t_i$ the j-inductivity current has changed by I_j; here the average current $I_{aj}=jQf$. Then, neglecting t_i in comparison with $1/f$, we receive

$$\delta U_j=U_0t_ifk_ik_{uj}-U_{rj}-R_jjQf$$

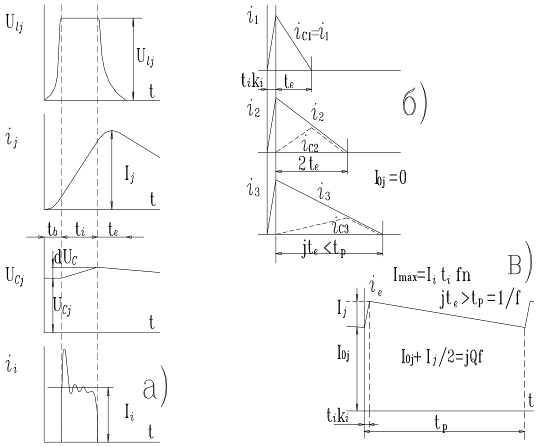

Fig. 2.

Now it is possible to write the expression for a total loss of MD voltage, if k - the number of the cascade, after which $t_j > 1/f$,

$$\Delta U=\sum_{j=1}^{j=k} j((U_0k_ik_{uj})^2t_i/(j2I_iL_j)-U_{rj}-R_jI_{aj})+\sum_{j=k+1}^{j=n} j(U_0t_ifk_ik_{uj}-U_{rj}-RI_{aj})$$

The j-capacity voltage (let $j < k$) is determined as

$$U_j=U_0-\sum_{m=j}^{m=n}(\delta U_m)=U_0k_{uj}=U_0-\sum_{m=k+1}^{m=n}(U_0t_ifk_ik_{um}-R_mmQf)-\sum_{m=j}^{m=k}((U_0k_ik_{um})^2t_i/(m2I_iL_m)-R_mI_{am})+U_r(n+1-j)$$

Let us consider the important case, when the parameters L, R, U_r for all cascades are identical. Then, accepting the symbols: $\Delta U_r=\Delta U/(nU_0)$, $\Delta U_L=U_0t_ik_i^2/(2I_iL)$, $t_0=2LI_i/(U_0k_i)$, and accordingly $t_j=t_0(j/k_{uj}$, $I_0=U_0t_ik_i/L$, $I_j=I_0k_{uj}$, $\delta U_j=U_0\Delta U_Lk_{uj}^2/j-U_r$ or $\delta U_j=U_0k_fk_{uj}-U_r-RI_{aj}$, where $k_f=t_ik_if$, we receive the loss of voltage in relative units

$$\Delta U_r=(\Delta U_L/n)\sum_{j=1}^{j=k}k_{uj}^2+(k_f/n)\sum_{j=k+1}^{j=n}(jk_{uj})-(U_r/U_0)(n+1)-(R/(U_0n))\left(\sum_{j=1}^{j=k}(jI_j/2)+Qf\sum_{j=k+1}^{j=n}j^2\right)$$

and the j-capacity voltage, $j < k$ (relative units)

$$U_j/U_0=k_{uj}=1-k_f\sum_{m=k+1}^{m=n}k_{um}-\Delta U_L\sum_{m=j}^{m=k}(k_{um}^2/m)+U_r(n+1-j)+(R/U_0)\left(Qf(n-k)+I_0/2\sum_{m=j}^{m=k}k_{um}\right)$$

The simplest cases are of certain interest:

1). A repetition rate is small, for all cascades $t_j < 1/f$, $I_{aj}=Ij/2$, and let $k_{uj}\sim 1.0$, then

$$\Delta U_r = \Delta U_L-(U_r/U_0)(n+1)-RI_0(n+1)/(4U_0)$$

$$k_{uj}=1-\Delta U_L\sum_{m=j}^{m=n}(1/m)+(U_r/U_0)(n+1-j)+(RI_0/2U_0)(n+1-j)$$

For ideal MD, when U_r and R are neglectedly small, the loss of voltage is determined by the first member. It does not depend on cascade number and is inversely proportional to I_i and L; the condition of acceptable loss determines the value of inductivity. The diode voltage drop and ohmic resistance, on the contrary, equalize the voltages on capacities and moderate the total loss of voltage. With the growth of cascade number this tendency has a stronger effect.

2). The repetition rate is large, $t_1 > 1/f$, let $k_{uj}\sim k_{uf}$ and $I_{aj}=jQf$, then

$$\Delta U_r=k_f(n+1)/2k_{uf}-(U_r/U_0)(n+1)-(RQf/(U_0n))\sum_{j=1}^{j=n}j^2$$

$$k_{uj}=1-k_fk_{uf}(n+1-j)+(U_r/U_0)(n+1-j)+(R/U_0)Qf(n+1-j)$$

Here for ideal MD the loss of voltage grows linearly with the number of cascades and does not depend on the value of inductivity. The influence of diodes has the same nature, the influence of resistance has a stronger effect as the cascade number grows.

In order to take into account precisely all the parameters of the multi-cascade discriminator, the PC computation code for currents and voltages in all correlated cascades was developed. The fastest convergence of results is received for the initial state, when the capacitor voltages equal zero, and with each impulse they receive a charge I_it_i. The formed voltages were observed after approximately 70 impulses, i.e. a few seconds later. The MD experimental values agree well with the computer calculations.

3. THE PROTON INJECTOR DISCRIMINATOR

For the discriminator considered the parameters have the following values: U_0=25kV, n=32, L=10H, U_r=60V, R=50Ohm, I_i=2,5A, k_i=1,5, t_i=85mcsec. Then the main magnitudes for 50Hz repetition rate are equal: ΔU_L=9,56%, t_0=0,00133s; I_0=0,319A; k_f=0,64%.

Table 1.

f (Hz)		10	25	50	100
U_2 (kV)	Precisely approx.	20,9 21,5	20,9	20,3 20,6	18,2 18,3
U_1 (kV)	Precisely approx.	19,3 20,2	19,3 20,1	18,8 19,4	17,0 17,5
U (kV)	Precisely approx.	768 768	768 765	749 742	691 695

In Table 1 the results of calculations made in accordance with the mentioned formulas and by the computer are compared. It can be seen that assumptions made when deducing the formulas are justified.

In Table 2 the dependence of output voltage (relative units derived from $\mathbf{nU_0}$) on **L** value and voltages on the first two capacities for two modes is shown when **f**=10 and **f**=100Hz; the other parameters are invariable.

Table 2

L (H)		2	5	10	20	50	100
U_r	10Hz	.746	.884	.951	.992		
(rel. units)	100Hz	.746	.839	.855	.860	.862	.862
U_2 (kV)	10Hz	10.4	16.6	21.5	23.3		
	100Hz	10.4	15.8	18.3	18.6	18.7	18.8
U_1 (kV)	10Hz	8.4	14.5	20.2	22.3		
	100Hz	8.4	13.9	17.5	18.0	18.5	18.6

4. INDUCTIVITY

For multi-cascade discriminators, when current in last inductivity does not drop to 0, currents in first and last inductivities differ **n** times, where **n** is cascade number. Therefore inductivity wiring requirements are completely different. The last inductivity current is the greatest one, it is equal

$$\mathbf{I_{an}=nI_it_if.}$$

Active current in first inductivity is much less because current continues only during $\mathbf{t_I}$ time, and so there is no need to have such large wire cross-section as for the last inductivity. All inductivity wirings were changed for the new ones in proton injector discriminator.

If, as it is for injector, inductivities have magnetic cores it is possible to rise their values for the first cascades by decreasing air gaps of cores. This action will reduce voltage loss of first condensators. However, it is necessary to mean, that non-identical inductivities will destroy linear voltage distribution through cascades, and especially will shorten separate cascades pulse front duration, that is very important for diodes.

5. DIODES

Experimental and analytical study has shown that charging diodes $\mathbf{V_1 \div V_n}$, see Fig.1 a, work in much harder conditions than discharging ones, as just after passing of $\mathbf{I_i}$ pulse current they should go to a closed state during back front of high voltage pulse. Diodes КД203Д used in the beginning were not reliable for **f**>10 Hz and were changed for КД206Д diodes with shorter reverse time, the latter diodes do not demand voltage distributor.

Assemblies of 59 this type diodes (for 25kV voltage) can work up to **f**=100 Hz.

6. CONCLUSION

The exact calculation of MD voltage loss has urged us to increase the number of cascades up to 32.

In addition the assemblies of КВИ-3 capacitors with equivalent capacitance ~ 1000pF were mounted in bridge to all diodes (both direct and inverse). They serve to eliminate the cascades overvoltage when breakdowns in accelerating tube or high-voltage transformer occur.

For trouble-free operation at **f**=100Hz the inductivities should be different. It is necessary to connect each of the last 8 inductivities in bridge to the same inductivity (thereby it may be possible to eliminate their overcurrent); and for the first 8 inductivities it is necessary to increase their value 5-10 times (at the expense of the gap decreasing in a magnetic conductor), and thus to diminish voltage losses on the first capacities.

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