NUMERICAL SIMULATION OF THE MARX–GENERATOR BEHAVIOR ON NONLINEAR LOAD - HIGH-CURRENT VACUUM DIODE

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One of the microsecond high-current beam generation techniques is the implementation of Marx Generator (MG) discharge on the cold diode working under explosive electron emission condition. However at the pointed above-mentioned condition such a diode is a strongly nonlinear load (in a sense of voltage-current characteristic). Therefore there is a problem of the load matching MG to a high-voltage vacuum diode with the purpose of the most effective transfer of the energy accumulated in the MG and getting the greatest possible voltage amplitude value on the diode (for given MG). The no less important problem is the shaping diode voltage pulse by close to rectangular.

In this paper mathematical modeling and numerical simulation data of processes which take place at MG discharge on a high-current vacuum diode are submitted. As the base accelerator operating model on the basis of which the parameters of an equivalent MG circuit and vacuum diode were determined, the accelerating complex was served, the construction of which is explicitly explained in [1, 2]. In the complex located in open air, the following beam parameters were reached: energy – 1.2 MeV, current - up to 15 kA, pulse duration at the pulse base – 10–12 µs. The generator was a multistore construction, on each of its eight floors there was a block of condensers with a capacity of 0.64 µF at voltage 125 kV everyone. The grouping of condensers by their sequential and parallel connection ensures the capacity $C_1 = 0.04$ µF in discharge. The MG limiting voltage is 4 MV, the accumulated energy is 320 kJ. The specific feature of its construction is a height of 12.7 m and remoteness from the accelerator (20 m), that stipulated its natural inductance $L_1 = 101.3$ µH and inductance of the connecting line with the diode $L_2 = 52.1$ µH. Then the equivalent circuit MG before and after discharge can be presented (Fig. 1).

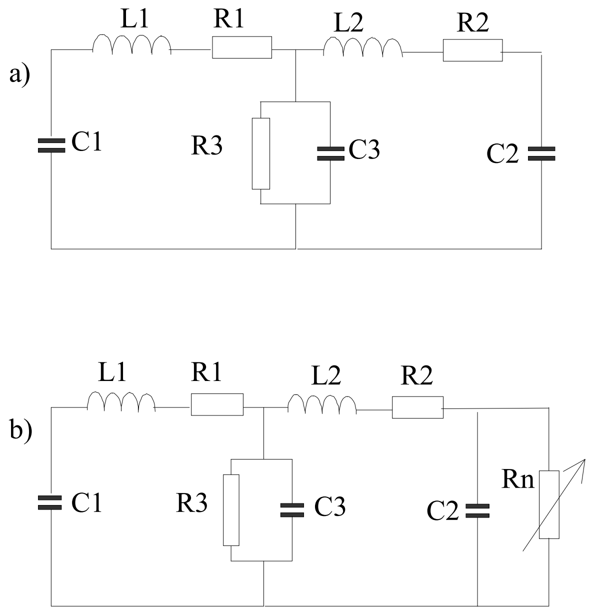


Fig. 1. An equivalent circuit of the generator before discharge (a) and after discharge (b).

Here in addition to described above, the labels R_1 - active resistance of connecting wires and discharge gaps, R_2 – active resistance of the connecting line with the diode, C_3 – generator parasitic capacity, C_2 – diode and connecting line capacity, R_3 – charge-uncharged resistance MG are entered. Calculations, measuring and the estimates of the indicated magnitudes have given the following results C_2=300 pF, C_3=330 pF [3]. The resistance $R_1 = R_2 = 10$ Ohm is artificially introduced with the goal of discharge current restriction for used condensers (the admissible discharge current is 50 kA), R_3=7.68 kOhm. The nonlinear load - vacuum diode operation under explosive electron emission condition is described by a known relation [4]

$$I = 2.33 \cdot 10^{-6} U^{3/2} S/(d - vt)^2 \qquad (1)$$

where I – beam current, U – voltage on the diode, $S = \frac{\pi D^2}{4}$ – electrodes square, d – distance between the cathode and anode, t – time, v – dispersion speed of cathode plasma. The magnitude of v can be accepted

$1 \div 2 \cdot 10^6 \ \frac{\text{cm}}{\text{sec}}$. The nonlinearity of the diode is specified by the fact that at the cathode plasma ejection in the anode direction there is a modification of diode resistance. Actually also there is an anode plasma creation and movement to the cathode [4]. But in calculations this circumstance can be eliminated by introduction of a component to the cathode plasma speed.

The equivalent circuit of a MG discharge circuit working on the nonlinear element is the fifth order discharge circuit described by the fifth order nonlinear differential equations. In a general view these equations are not analytically resolved, therefore for a tentative estimation of discharge circuit parameters we shall take advantage of some simplifications.

At the beginning let's consider the MG no-load operation. The equivalent circuit in this case in view of relations between parameters of a complete equivalent circuit (Fig. 1a) can be represented in the simplified form in Fig. 2a, and in the case of the load on the nonlinear diode in Fig. 2b.

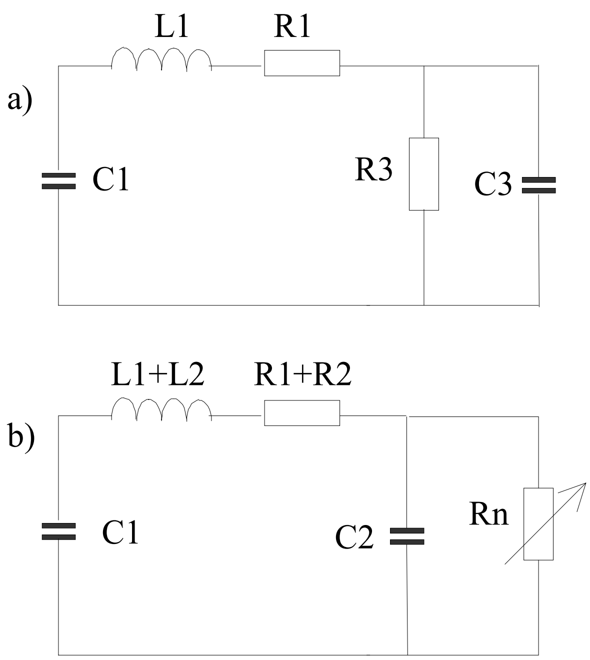


Fig. 2. MG equivalent circuit: (a) the condition of a no-load operation; (b) in the mode of operation on the nonlinear diode R_n.

In the case a) the second part of the plan the diode and connecting bus are not plugged in, therefore in the given figure the left-hand part of the complete circuit is figured only. In the case b) by virtue of the $C_3R_3 >> C_2R_n$ it is possible to eliminate the element with C_3R_3, therefore the complete circuit will accept the form shown in this figure. As follows from above reasoning the indicated approach has not lead to essential physical restrictions of real working conditions of the true circuit. Therefore below represented is the method and numerical simulation results of MG operation on a nonlinear load under pointed above assumptions.

The problem of diode voltage and current determination was solved in two stages. At the first stage the solution for circuit parameters up to the diode breakdown moment was found. In this case it was supposed $R_n = \infty$ (the diode current is equal zero) and equation for a charge q_{r1} on the condenser C_1 looks like

$$q_{r1}'' + 2\beta q_{r1}' + \omega_0^2 q_{r1} = \frac{q_{1n}}{C_2 L} \qquad (2)$$

where $\beta = \frac{R_1 + R_2}{2L}$, $\omega_0^2 = \frac{C_1 + C_2}{C_1 C_2 L}$,

$q_{r1}(t=0) = q_{1n} = C_1 U_0$, U_0 is the initial voltage on the condenser C_2. Solution (2) in view of starting conditions for $q_{r1}'(t=0) = 0$ looks like

$$q_{r1}(t) = \frac{q_{1n}}{\omega_0^2 C_2 L}\left(1 + \frac{e^{-\beta t}}{\omega}(\omega_0^2 C_2 L - 1)(\omega\cos\omega t + \beta\sin\omega t)\right), \qquad (3)$$

where $\omega^2 = \omega_0^2 - \beta^2$. At the second stage at reaching on the condenser C_2 the breakdown voltage U_B it was supposed that the diode current flows past under the law (1). In this case the set of equations describing the process of a condenser charge evolution looks like

$$\begin{aligned} &q_1'' + 2\beta q_1' + \frac{1}{C_1 L} q_1 = \frac{1}{C_2 L} q_2, \\ &q_1' + q_2' = -\frac{2.33 \cdot 10^{-6} q_2^{3/2} S}{C_2^{3/2}(d - vt)^2} \end{aligned} \qquad (4)$$

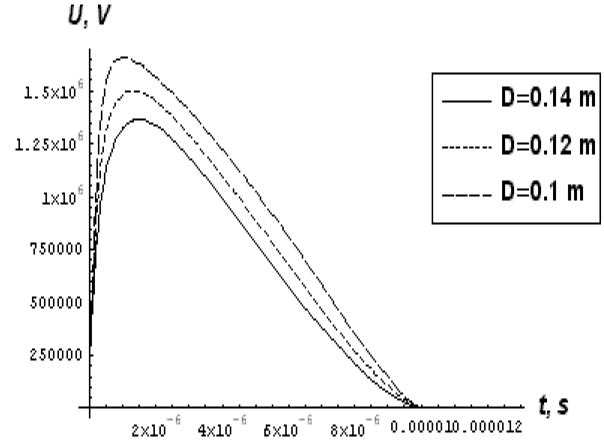
Thus the entry conditions for (4) were determined from (3) by the determination of an breakdown instant t_B in view of a charge conservation law

$$q_{r2}(t_B) = q_{1n} - q_{r1}(t_B) = C_2 U_B .$$

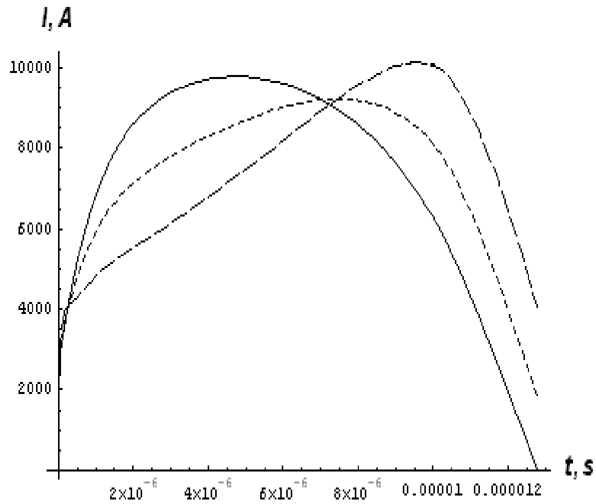
Thus

$$q_1(t=0) = q_{1r}(t_B),\ q_1'(t=0) = q_{r1}'(t_B),$$
$$q_2(t=0) = q_{r2}(t_B),\ q_2'(t=0) = q_{r2}'(t_B).$$

The set of equations (4) was solved by the numerical methods. The outcomes of calculations are represented in Fig. 3.



a)



b)

Fig. 3. Dependence a) voltage and b) current intensity of the nonlinear diode from time at such parameters: $D = 0.14$ *m*; 0.12 *m*; 0.1 *m* , *(* $v = 10^4$ *m/s,* $U_0 = 2\cdot10^6$ *V,* $U_B = 2\cdot10^5$ *V,* $C_1 = 0.04\cdot10^{-6}$ *F,* $C_2 = 300\cdot10^{-12}$ *F,* $L = L_1 + L_2 = 150\cdot10^{-6}$ *H,* $R_1 + R_2 = 20$ *Om,* $d = 0.1$ *m).*

The dependencies obtained are interpreted from general reasons of the MG operation and diode behavior described by the ‘three second’ law. At the greater cathode sectional area the greater current flows through the diode that leads to decrease its resistance and diminution of a discharge time MG on the load. To voltage pulse ending practically all the energy stored in the generator will be released on the load. The diameter diode increase leads to resistance decrease. Thus to the moment of the diode voltage pulse ending caused by the switching of an accelerating gap by plasma, by means of current feature analyses (the current prolongs to increase) it is possible to conclude, that the further MG energy liberation will occur in a short circuit mode. Thus our numerical simulation results allow to receive beam optimum parameters at fixed parameters of MG by means of the diode geometrical characteristic variation.

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