LIQUID RESISTORS IN ACCELERATORS OF PULSE ELECTRON BEAMS

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There are presented the characteristics of developed high-power high-voltage tight resistors based on water solutions of salts, acids and their mixtures as applied to their use in assemblies of linear induction accelerators (LIA) of high-current electron beams.

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Beginning from the 1970-s there was initiated in VNIIEF the production of generators of intense bremsstrahlung pulses on the base of high-current LIA (for example, [1]). Tight small-size but high-voltage and high-power resistors are needed for their assemblies for the following purposes, in particular: limitation of current in electric circuits; simulation of high-power loads; damping of electric oscillations and suppression of reflected pulses; prescribed distribution of electric field strength by insulators length; change of pulse voltage parameters etc.

For these purposes there were developed resistors (LR) on the base of water solutions of salts, acids and their mixtures possessing a totality of advantages as compared to other types of resistors. The advantages are as follows:

- their electric strength over the volume up to 300 kV/cm at microsecond duration;
- as compared to metals they scatter in a unit of solution mass the energy that is larger by an order;
- after breakdown the electric strength is recovered by liquid quickly;
- resistance is quickly regulated by electrolyte replacement;
- they can be of any shape;
- they possess inductance up to fractions of nH;
- they can be applied in the circuits with the frequency up to ~ 1 GHz;
- fire- and explosion-safe;
- simple in production;
- relatively cheap.

It was demonstrated that at field variation E from 1.5 to 51 kV/cm in the solutions of sulphate of copper (SC) CuSO4· 5H2O and salt NaCl the value of resistivity ρ remains constant at its variation from 40 to 104 Ω· cm and frequency of affecting voltage up to 12.5 MHz (for example, [4,5]) (as differentiated from the changes specified in [2,3]). The solutions transfer voltage pulses thorough the volume correctly if the front duration is up to 1.5 ns (what is equivalent to f ≈ 333 MHz). The electrodes of copper and stainless steel are practically neutral in the above specified electrolytes correspondingly. To provide long-term operation one should use soluble materials of OSCh or KhCh make. For SC the electrodes should be of MOOb and MOO copper makes (the content of copper should be ≥ 99.99 and 99.96 mass fractions; State Standard 859-2001). Because of the presence in natural water of different salts and dissolved gases and in tap water – iron oxides or added chlorine and fluorine water should be bi-distilled or de-ionized in columns with ion-exchange resins and qualitatively degassed.

LR possess negative temperature coefficient of resistance (TCR). It depends weakly on concentration K of the given substance in water [6]. But resistance ρ of electrolyte depends on K (g/l) [7].

At selecting polymer material for bodies its moisture permeability was taken into account as all organic materials absorb water and leak what is characterized by permeability coefficient ψ. The knowledge of ψ for different materials [8] makes it possible to determine the amount of water passed through the wall made of the given material. Finally, for LR bodies there was selected low-pressure (high density) polyethylene of make 210-15 (209-15) as it swells least of all and its $\psi = 3\cdot 10^{-9}$ g/(cm hour Torr) at 20°C, and its softening point (melting) being 124…132°C.

The first tight LR produced in 1974 (voltage up to 150 kV) to limit current to ~ 63 A in charge-discharge circuits of resistance multiplication generator (GIN) its output voltage being 500 kV and to transmit starting pulse with a front of ≥ 5ns (current ≤ 1k A) to control electrodes of trigatrons in cascades [9] are operable in any position in vessels with oil and vacuum insulation, with compressed gases. The compensation of temperature change of the solution volume is achieved by varying geometry of the polymer body of LR within the limits of its walls elastic deformation. The IK 100-0.25 (100 kV; 0.25 μF; 1.25 kJ) capacitors in each cascade were charged through LR; at self-breakdown the switch should absorb this energy of LR in aperiodic discharge at current amplitude of 63 A. The LR length *l* =13 cm and diameter d = 5 cm were prescribed by GIN composition. The internal surface at the body ends (Fig.1,a) is conical, its angle of slope being 6° to the longitudinal axis as well as the surface of the electrode 2. At the external surface of the body ends a trapezoidal thread with a 6-mm pitch is made as well as for the nut 3.4 – is an adjusting screw. After the solution is filled in a vacuum chamber to the body with the fastened on its bottom end components 2 and 3, the electrode 2 is inserted from above. The nut 3 is screwed till it touches the electrode 2 and then – with the removal to the body of electrode

2 – till the liquid displacement from the body. After that the nut was screwed till it sat to the end face of the body providing tightness of the conical joint and the increase of hydraulic pressure in liquid with simultaneous increase of d by 0.05…0.1 mm at the middle of its length. The conical shape of components 1 and 2 decreases "spreading" of polyethylene under the effect of mechanical efforts to it. Screws 4 serve to remove the electrodes 2 in the course of LR operation.

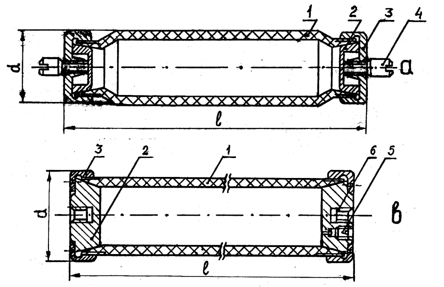

Fig.1. LR structure: a – for GIN of LIA-10; b – for GIN with the increased capacity of capacitors

Before the LR assemblage the surfaces of bodies and components that will be in contact with the solution were degreased with benzine "Kalosha" and /or Freon, rinsed in solutions of caustic soda, calcinated soda and trinatrium phosphate and then - several times in distilled or bi-distilled water. Quite useful was washing of components in ultrasonic bath.

The assembled LRs were placed to a refrigerator at +1°C for 5 hours. If tightness is not provided, air was sucked to the solution. For higher guarantee LR were often placed in the chamber with exhaustion of ~ $1.5\cdot 10^4$ Pa. If the tightness was not provided the electrolyte was sucked through it to the chamber and being evaporated it left a visible layer of salt.

The testing of LR consisted in conducting current through LR within 0.5 minute with 1.5 minute periodicity what simulated the passage through them of charge q=0.125°C equal to the charge of all capacitors in GIN cascades per one cycle of its switching. At resistance R=1.6 kΩ there was provided ~ $5\cdot 10^3$ operations with no noticeable change of LR condition. Within one cycle of q charge passage there was absorbed in LR the energy $W \approx 0.4$ J what increased the temperature of solution by $\Delta T \approx 0.239 W/V \approx 0.77\cdot 10^{-3}$°C and solution volume V – by $\Delta V \approx \beta\cdot V\cdot \Delta T \approx 2\cdot 10^{-5}$ cm^3 ($\beta \approx 3\cdot 10^{-4}$/°C – temperature coefficient of water volume change). The performed later testing of all LR in insulated with oil GIN under conditions close to real operation conditions at GIN start up each 2-3 minutes confirmed these results.

Beginning from 1978 there appeared the necessity in LR of higher power for GIN with increased capacity in each cascade [10]. LR presented in Fig.1,a were taken as a base of the above LR but with increased external diameter of the body (up to 52 mm) simplified end parts of body 1 and usual metric thread with a pitch of 2 mm (Fig.1,b). A larger step between capacitors in cascades made it possible to increase the length *l* up to 18 cm; moreover, there was decreased the length of components 2 and 3. As a result, the volume of solution in LR constituted 244 cm^3 and became larger by a factor of 1.45. In the electrode 2 there was made a hole tightened by the screw 5, and the hole 6 to fasten LR.

These LR turned out to be simpler in production and operation. Thus, they are still applied today in GIN complexes (72 units) of LIA-30 accelerator put into operation in 1988, GIN (18 units) of LIA-10M (1994) [1] and other facilities.

The solution of the problem of reducing the rate of bubble formation in the solution because of moisture permeability of walls was found in LR design with the increased thickness of the wall of body 1 and gas-vapor cavity in one or both electrodes 2 and 4 (Fig.2). The surface of this cavity walls are shaped in such a way that they form a somewhat water seal and gas from the cavity can not get to liquid at any position of LR in space, while gas leave the solution for the cavity [5]. The cavity is filled with the solution through a hole in the electrode 4 closed by the screw 9. Level 10 of electrolyte surface is set so that it is higher than the face of the tube 5 at any position of LR thus forming a water seal. The size of the vessel with gas is higher (larger) than level 10 and the height of solution above the tube 5 face is determined reasoning by operation conditions. When the seals are in both electrodes gas can get to the electrode cavity almost at any position of LR in space, except horizontal one.

Under tests the charge up to 0.4°C was passed through LR at 100 kV. The ultimate applied pulse (~ 1 μs) voltage constituted 270 kV.

For GIN there was developed an LR common for all stages [11]. This made it possible to increase at the previous overall dimensions the length of the column between cascades, to decrease electric field in the solution and its temperature, to charge capacitor in cascades more uniformly. Between the electrode ends there are arranged regularly by the solution column length the copper electrodes in the form of flat discs (they are four in number for a 5-stages GIN) that possess holes and are fastened with dowels through the body walls. Such LRs were applied in GIN with two parallel charge-discharge circuits of voltage multiplication. Thus, 4 units were installed in each of them. Two of them had an overall length equal to 95.8, while the two others – 98.3 cm. In each cycle of GIN operation the pulse voltage up to 500 kV was applied to LR.

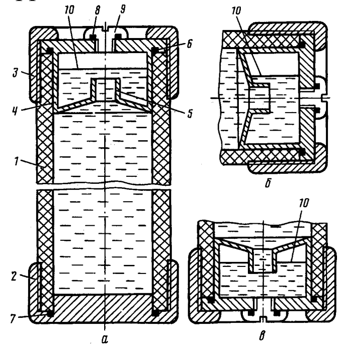

Fig. 2. Resistor with water seal in the electrode cavity arranged with the seal at the top (a); at the bottom (b) and in horizontal position (c); 3 – nut; 6-8 – gaskets

To reduce the effect of bubble to electric strength the LRs were fastened in GIN at a slope of ~5°. Above is arranged an anode in which a layer of H_2SO_4 of higher density is formed at charging what assists in uniform concentration of electrolyte by the length of its column.

To transfer pulses with nanosecond fronts in LR there must be provided uniform current density over the cross-section of the solution at any moment of pulse time what is achieved on condition that $r < \delta/5$, where r – radius of electrolyte column, δ – thickness of skin-layer in it at which boundary the current density falls by e ≈ 2.71 times; $\delta \approx 50.3 \cdot 10^2 \rho^{0.5} f^{-0.5}$ (cm), where f – frequency (Hz) equivalent to front or pulse duration depending. This formula is obtained for metal conductor; thus, thus the evaluations of δ by it in water solutions with "low conductivity" and at a large value of water permittivity ($\varepsilon \approx 80$) are not quite correct. It was found in paper [12] that for water electrolytes this formula can be applied if $f\rho << 1.43 \cdot 10^7$ Hz·Ω·cm. In another ultimate case $f\rho >> 1.43 \cdot 10^7$ the value ε of the solution should be taken into account, thus, $\delta \approx 34 \cdot 10^7 \rho^{0.5} \varepsilon^{-0.5} f^1$ (cm).

To measure volt-ampere characteristics of blocks of LIA-30 accelerator [1] at simulation of the effect of cathode electrode (external diameter ≤ 94 cm) with up to 300 kA current through it and tubular beam of electrons with the current up to 200 kA there was developed and used a load simulator (LS) made of a large number of LR (up to 62 units) [12]. To elaborate injector and diode blocks of LIA-30 as to electric strength there are applied 250 kV LR with glass bodies [5] that were regularly installed (being 384 in number) by the circumference 1276 mm in diameter between the electrodes of accelerating tube.

To measure parameters of pulses with the amplitude up to 2.1 MV was developed a divider based on arms of LR [12]. Effective damping in the amplitude line of spreading in reverse direction pulses of voltage was provided by a special LR [14] while the increase of GIN operation accuracy is achieved by applying resistive-capacitor elements with the changing in time value of constant time [15].

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ЖИДКОСТНЫЕ РЕЗИСТОРЫ В УСКОРИТЕЛЯХ ИМПУЛЬСНЫХ ПУЧКОВ ЭЛЕКТРОНОВ

А.И. Герасимов

Приведены характеристики разработанных мощных высоковольтных герметичных резисторов на основе водных растворов солей, кислот и их смесей применительно к использованию в узлах линейных индукционных ускорителей сильноточных пучков электронов.

РІДИННІ РЕЗИСТОРИ В ПРИСКОРЮВАЧАХ ІМПУЛЬСНИХ ПУЧКІВ ЕЛЕКТРОНІВ

А.І. Герасімов

Наведено характеристики розроблених потужних високовольтних герметичних резисторів на основі водяних розчинів солей, кислот і їхніх сумішей стосовно до використання у вузлах лінійних індукційних прискорювачів потужнострумових пучків електронів.