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GENERATOR ON ARCADYEV-MARX SCHEME WITH PEAKING OF THE PULSE FRONT IN ITS CASCADES FOR FOOD DISINFECTING

Purpose. To obtain experimentally that the duration of the high-voltage pulse front is less than 1.5 nanoseconds on the load of a pulse voltage generator of less than 50 ohms in the form of more than two working chambers with a water-containing product. That increases the efficiency of disinfection of treated products. Methodology. To obtain high-voltage pulses in working chambers - the generator load - the pulse generation method was used according to the Arcadyev-Marx scheme. The pulses on the load were measured with a low-ohm resistive voltage divider, transmitted over a broadband coaxial cable, and recorded using a C7-19 oscilloscope with a 5 GHz bandwidth. The working chambers were filled with water and consisted of an annular body made of PTFE 4 and metal electrodes forming the bottom and the chamber cover having flat linings of food stainless steel for contact with the food product inside the chamber. Results. The high-voltage pulses on the generator load of about 50 Ohm or less have a trapezoidal shape with a rounded apex and a base duration of no more than 80 ns. The experimentally obtained pulse amplitudes on the generator load are up to 18 kV. As the load resistance decreases, the amplitude of the pulses decreases, and the duration of the front and pulse duration in general are shortened because of the accelerated discharge of cascade capacitive storages. Originality. For the first time we have obtained experimentally on the load of the generator in the form of three parallel working chambers with water, the active resistance of each of which is less than 50 Ohm, the pulse front duration $t_f \approx 1$ ns. In addition, we have obtained experimentally a stable 9-10 channel triggering mode of the trigatron type spark gap in a five-cascade pulse voltage generator with a step-by-step peaking (exacerbation) of the pulse front in its cascades (GPVCP). Practical value. We have obtained experimentally the nanosecond pulse front duration on the GPVCP load and that opens the prospect of industrial application of such generators for microbiologically disinfecting treatment (inactivation of microorganisms in food) water-containing food products. References 6, figures 8.
Key words: **generator of pulsed voltages, peaking of the pulse front in cascades of generator, working chamber, spark gap or switch, inactivation of microorganisms in food products.**

Цель. Экспериментально получить на нагрузке генератора импульсных напряжений величиной менее 50 Ом в виде более двух рабочих камер с водосодержащим продуктом длительность фронта импульсов высокого напряжения менее 1,5 наносекунд, что повышает эффективность обеззараживания обрабатываемых продуктов. Методика. Для получения высоковольтных импульсов на рабочих камерах - нагрузке генератора применена методика генерирования импульсов по схеме Аркадьева – Маркса. Импульсы на нагрузке измерялись при помощи низкоомного резистивного делителя напряжения, передавались по широкополосному коаксиальному кабелю и регистрировались при помощи осциллографа С7-19 с полосой пропускания 5 ГГц. Рабочие камеры заполнялись водой и состояли из кольцеобразного корпуса, выполненного из фторопласта, и металлических электродов, образующих дно и крышку камеры, имеющих плоские накладки из пищевой нержавеющей стали для контакта с пищевым продуктом внутри камеры. Результаты. Высоковольтные импульсы на нагрузке генератора примерно 50 Ом и менее имеют трапециевидную форму со скругленной вершиной и длительность по основанию не более 80 нс. Экспериментально полученные амплитуды импульсов на нагрузке генератора – до 18 кВ. При уменьшении сопротивления нагрузки амплитуда импульсов уменьшается, а длительность фронта и импульсов в целом укорачивается из-за ускоренного разряда емкостных накопителей каскадов. Научная новизна. Впервые на нагрузке генератора в виде трех параллельно включенных рабочих камер с водой, активное сопротивление каждой из которых менее 50 Ом, экспериментально получена длительность фронта импульсов $t_f \approx 1$ нс. Кроме того, отлажен стабильный 9-10 канальный режим срабатывания выходного разрядника тригатронного типа в пятикаскадном генераторе импульсных напряжений с покаскадным обострением фронта импульсов (ГИНПО). Практическая значимость. Полученная экспериментально наносекундная длительность фронта импульсов на нагрузке ГИНПО открывает перспективу промышленного применения таких генераторов для микробиологически обеззараживающей обработки (инактивации микроорганизмов) водосодержащих пищевых продуктов. Библ. 6, рис. 8.
Ключевые слова: **генератор импульсных напряжений, покаскадное обострение фронта импульсов, рабочая камера, разрядник, инактивация микроорганизмов в пищевых продуктах.**

Introduction. Generators on Arcadyev-Marx are widely used in high-voltage pulse technology [1]. Due to the ability to obtain nanosecond fronts at a voltage of 100 kV and more on the load of such generators [2], repetition rates of 200 pulses per second or more, they are promising for decontaminating treatment of liquid water-containing products.

The processing of products by pulsed electric fields (PEF) with nanosecond fronts makes it possible to conserve the initial quality of food products with the use of traditional thermal methods while reducing the specific energy consumption for inactivating microorganisms in them [3, 4]. In the PEF method, or a complex of high-voltage impulse actions (CHIA), short electric pulses are used, which can be obtained with the help of Arcadyev-Marx generators. Decontamination treatment is carried out in working chambers with a processed product, which is a load for generators of high-voltage pulses. The typical duration of pulses of strong pulsed electric field strength in working chambers can vary from 50 ns to 1 μs, the amplitude ranges from 5 kV/cm to 200 kV/cm without breakdowns. Several working chambers with a water-containing product connected to the generator output are a low-impedance load for the generator, which can not exceed 50 Ω and can lead to undesired elongation of the

voltage pulse front. In [5], a method for treating liquids and flowing products in several working chambers is proposed, which makes it possible to avoid undesirable extension of the front due to the use of impulse frontizers. The Arcadyev-Marx pulse voltage generators in the regime of the step-by-step aggravation of the pulse front (GPVCP) make it possible in practice to solve the problem of undesirable elongation of the front. In this paper, an experimental check of the operation of the GPVCP on a load of not more than 50 Ω in the form of three working chambers with water, connected in parallel, without extension of the front of the pulses on the load, was carried out.

The goal of the work is to experimentally obtain on a generator load of less than 50 Ω in the form of more than two working chambers with a water-containing product, the duration of the high-voltage pulse front less than 1.5 nanoseconds, which increases the efficiency of disinfection of the processed products.

Experimental installation. The installation circuit is shown in Fig. 1.
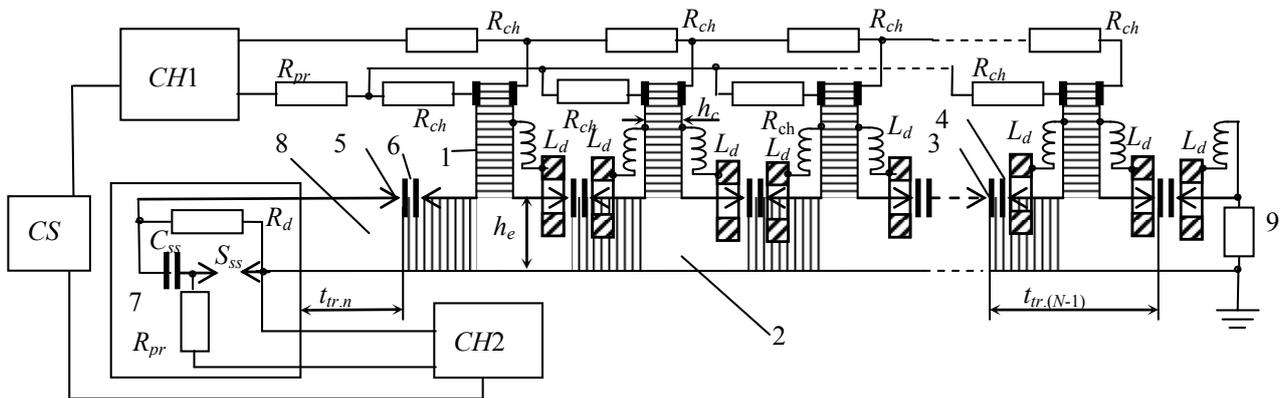
Fig. 1. Circuit of installation with generator of pulse voltages with a step-like peaking of the pulse front

In Fig. 1 pre-charged to voltage U_{main} sections of the power line and capacitive storages are shaded; N is the number of cascades; 1 – capacitive storage of a cascade with capacitance C_{st}, which can be a long line with distributed parameters; 2 – power line – broadband homogeneous long line with distributed parameters with distance he between direct and reverse current conductors with wave impedance z_e; 3 – cascade discharger; 4 – capacitance (C_{gap}) between the discharge gap electrodes 3; 5 – starting discharger of the GPVCP; 6 – capacitance ($C_{gap.o}$) between the discharge gap electrodes 5; 7 – starting system (device); 8 – long transmission line with wave impedance $Z_n = Z_e$ between the device 7 and the starting discharger 5; 9 – load with impedance Z_{load}; $t_{tr.n}$ and $t_{tr.k}$ are the times of the electromagnetic wave traveling along the line 8 and between two adjacent cascade dischargers, respectively; k is the number of the cascade ($k = 1, 2,…, N$); h_c is the length of the discontinuity in the live current conductor, into which (discontinuity) the capacitive storage of the k-th cascade is connected. $R_{pr}=1$ MΩ, $R_{ch}=3.2$ kΩ, $R_d=1440$ Ω, $L_d≈0.5$ μH.

Both CH1 and CH2 chargers are assembled according to the Cockcroft multiplication scheme [6] and are powered by step-up transformers fed with an adjustable AC voltage from the CS control system. Starting device 7 contains a ceramic capacitor K15-10 with of 10 nF (C_{ss}) and a two-electrode spark gap S_{ss}, triggered by overvoltage (for self-breakdown).

In GPVCP, on which experiments were conducted, there are 5 cascades. Capacitive storage of cascades $C_{st} = 3×10^{-9}$ F are made in the form of low-resistance strip lines (which can be considered as flat capacitors when

charged) from foil-coated glass-fiber laminate, 0.45 m in height and width of coatings, and with dielectric thickness $h_c = 5$ mm.

The power line of this GPVCP is made in the form of a real strip line with a distance between the forward and reverse current conductor h_e=50 mm [2]. The return current line is a brass sheet 1 m long, 0.4 m wide, 1 mm thick. It has a sheet of plexiglass 8 mm thick. The remaining space between the forward and reverse conductor is filled with air at atmospheric pressure.

The general view of a five-cascade pulse voltage generator with a step-like exacerbation of the front of the generated pulses, on which experiments are performed, is shown in Fig. 2.

Dischargers of cascades are of trigatron type with air filling at atmospheric pressure. Each of the two electrodes of the discharger is made in the form of a metal plate fixed to a plexiglass support, 5 mm thick, in which 10 holes are made at equal distances from each other. In these holes are inserted 10 needle electrodes connected in a short time with the corresponding capacitive storage plate of the GPVCP cascade and through the inductance $L_d≈0.5$ μH – with the plate.

Inter-electrode gaps in the dischargers are regulated along the length. Such a design of the dischargers provides a uniform electric field in them when the GPVCP cascades are charged and the field is sharply unhomogeneous during discharge. Therefore, when the GPVCP is discharged, spark channels are formed only between the corresponding two needle electrodes located on the same axis. In each of the cascade dischargers can be formed in the discharge from 1 to 10 sparks.

Fig. 2. General view of the GPVCP

The load 9 (Fig. 1) during the experiments was varied: it was carried out in the form of 10 resistors TBO-10 with nominal resistance of 560 Ω each (measured value of resistance was from 580 to 630 Ω), in the form of one working chamber with water, three working chambers with water. Load resistors and working chambers were connected to the corresponding tip electrodes of the 10-channel output gap of the GPVCP.

The experimental setup works as follows. With the help of the *SC* control system, capacitive storage of the GPVCP cascades is charged through *CH*1, and then the capacitive storage C_{ss} of the starting system is charged through *CH*2 before the S_{ss} self-breakdown. The charge level is controlled by kilovoltmeters C-196.

Pre-capacitive storage 1 of cascades of the generator are charged to the voltage U_{main} (Fig. 1). In general, charging can be either rectified voltage or an impulse voltage. After preliminary charging, the only discharger on which there is no «on standby» voltage U_{main} is the spark gap at the output of the GPVCP, it is also the discharger of the last *N*-th cascade. After charging the cascade from the start device 7 to the start-up discharger 5, a voltage pulse with an amplitude U_{ivp} is provided along the line 8 on the generator, providing the time of its switching $t_{sw.0}$ and the duration of the front $t_{f.0}$ of the generated pulse by a shorter time $2t_{tr.0}$ of the double path of the electromagnetic wave between the starting discharger of the first cascade. The dischargers of the GPVCP are triggered sequentially, starting from the starting one, triggered by the control pulse from the start-up system, and ending with the output discharger with the shortest switching time.

The beginning of the fall of the impulse voltage on the load of the GPVCP generator immediately after the voltage rise on it to the value A_N [2]:

$$A_N = \left(NU_{main} + 2U_{ivp}\right)\frac{Z_{load}}{Z_{load} + Z_e}, \quad (1)$$

or

$$A_N = 2A_{N-1}\frac{Z_{load}}{Z_{load} + Z_e}, \quad (2)$$

where Z_{load} is the load impedance ensured by the fact that possible reflections from the trigger device 7, which can lead to a slow increase in the voltage amplitude on the load up to $2 \times A_N$, are compensated by the discharge of the cascade capacitors, and also because the start device is separated from the GPVCP proper by the transmission line 8 with the corresponding time The path of an electromagnetic wave along it. Number of cascades in this GPVCP *N* = 5.

In according with (1) at U_{main}=6 kV, U_{ivp}=12 kV, Z_{load} = 50 Ω, Z_e=50 Ω A_N=(5×6+2×12)×50/(50+50)= = 27 kV.

Results of investigations. Investigation of the pulse characteristics at different loads of the GPVCP was carried out using a low-resistance resistive voltage divider connected to the load of the generator, a recording C7-19 oscilloscope with 5 GHz bandwidth and a broadband coaxial cable with Z_c 50 Ω impedance connecting the shielded low-voltage divider arm to the input of oscilloscope through an attenuator of 20 dB. The oscilloscope was located in the measuring cabin, which protects it from electromagnetic interference.

Resistance of high-voltage divider arm R_1 = 560 Ω – one of the load resistors TBO-10 in the GPVCP, the resistance of the low-voltage arm R_2 = 3 Ω is collected from the parallel-connected resistors TBO-0,5 (Fig. 3). The low-voltage divider arm and the matching resistor R_3= 50 Ω are located in a shielding metal case of a cylindrical shape with a flange connected shortly with the generator's return current. The cable is connected to the low-voltage divider arm using a coaxial connector.
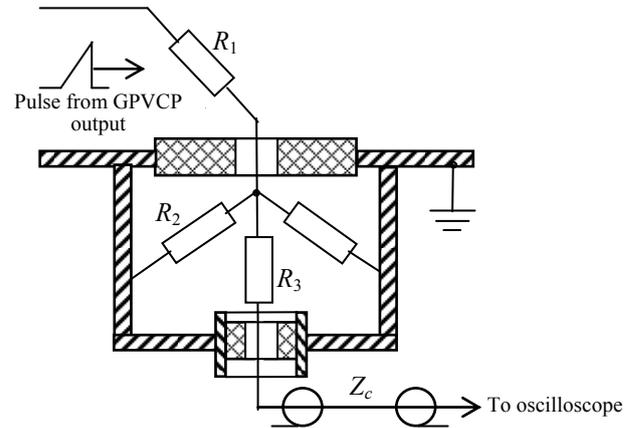
Fig. 3. Circuit of the resistive divider on the GPVCP output

Taking into account the fact that the input impedance of the oscilloscope C7-19 is 50 Ω, the divider division factor K_d = $[(R_1+R_2)/R_2] \times (R_3+Z_c)/Z_c$ = = [(560+3)/3]×(50+50)/50 ≈ 375 (Ω). Between the input of the oscilloscope C7-19 and the end of the cable with the connector, an attenuator 20 dB was inserted, which attenuates the incoming signal by a cable 10 times.

Therefore, the total division factor $K_{d\ total}$≈3750. The sensitivity of the oscilloscope CS7-19 is 1.6 V/div = = 1.6 V/cm.

The output multichannel discharger of the GPVCP at the amplitude of the charging voltage of the high-voltage capacitive storage of the control system, which exceeds twice the amplitude of the charging voltage of the main storages of the GPVCP cascades, stably operates in the 9-10 channel mode (10 is the maximum possible number of discharge channels in the discharger). This mode when the GPVCP operates on a resistive load in the form of ten TBO-10 resistors with a nominal resistance 560 Ω each is illustrated in Fig. 4. After the formation of ten channels in the output discharger, all ten load resistors are connected in parallel.
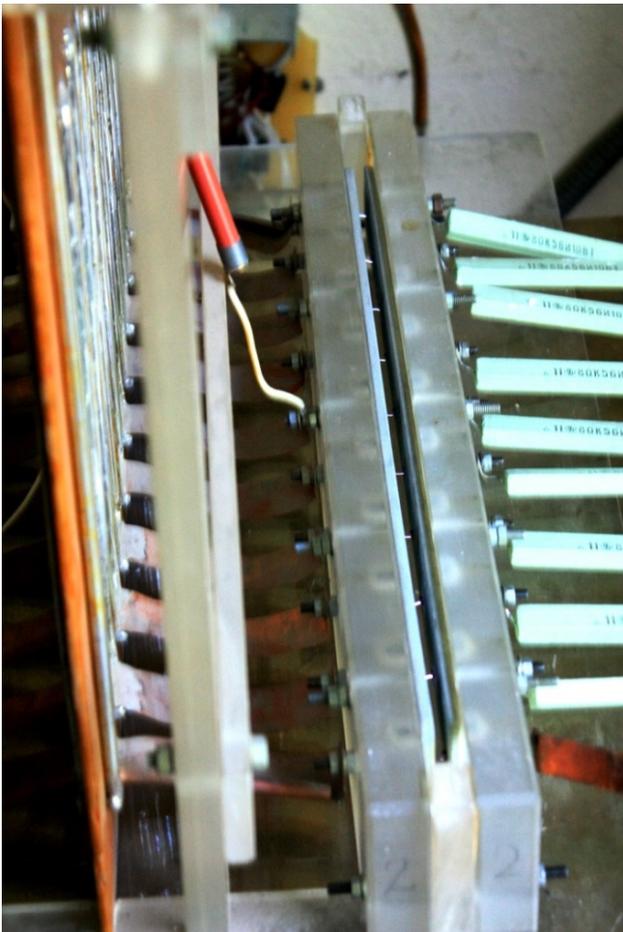
Fig. 4. Photo of the multichannel spark discharge in the GPVCP output

We note that the brightness of the discharge channels is approximately the same, which indicates that the current is uniformly distributed over the discharge channels. Oscillograms of pulses with nanosecond fronts on the GPVCP load in the form of TBO-10 resistors, one working chamber, and three working chambers are obtained. The shape of the pulses on the load is close to trapezoidal, which is illustrated in Fig. 5.

From the oscillograms in Fig. 5 it can be seen that the pulse front contains two parts: the first (initial) steep part and the second (closer to the top) more sloping. This indicates that in the GPVCP spark gap in this particular regime, there is not a complete, partial exacerbation of the front of the pulses being formed. Because of the presence of the sloping part, the total duration of the front of the t_f pulses is approximately $t_f \approx 20$ ns. The gently sloping part of the pulse front also occurs due to reflections of electromagnetic waves caused by the triggering of dischargers, from various inhomogeneities in the GPVCP power line and in the launch system. The pulse duration along the base is approximately 80 ns, the amplitude is 18 kV. This is 1.5 times less than the calculated amplitude given above.

The smaller values of the experimentally obtained amplitude, in comparison with the calculated amplitude, are explained by the lengthening of the front due to its incomplete aggravation by cascade dischargers, inadequate matching of the wave resistance of the

GPVCP power line with its resistive load, resulting from this undesirable voltage reflections in the GPVCP and a fairly rapid discharge of capacitive storage devices GPVCP.
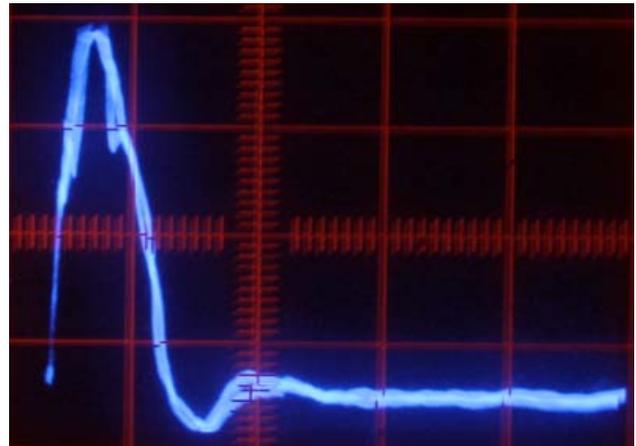
Fig. 5. Oscillograms (two oscillograms are superimposed) of the voltage pulses on the load in the form of 10 TBO-10 resistors 560 Ω: the division by the time axis is 100 ns/div, in the process axis 6 kV/div

The oscillogram in Fig. 6 illustrates the shape of the voltage on the load in the form of one working chamber and five TBO-10 resistors at 560 Ω.

From the oscillogram in Fig. 6 it follows that the pulse front duration is approximately 2.5 ns, and the amplitude is 12 kV. The amplitude decreased due to the fact that the load became more low-impedance after connecting the working chamber with water (see also formula (1)). The ring-shaped body of the working chamber is made of PTFE, and the metal electrodes forming the bottom and the chamber cover have flat linings of food grade stainless steel for contact with the food product inside the chamber.

The working volume of the working chamber filled with water has a disk shape with diameter $D = 90$ mm and height $h = 15$ mm. With a specific volume resistivity of water $\rho = 10 \Omega \times$ m, the active resistance R_w of water in the working chamber is $R_w = \rho h/(\pi D^2/4) = = 10 \times 0.015/(3.14 \times 0.09^2/4) \approx 23.6 \ \Omega$.
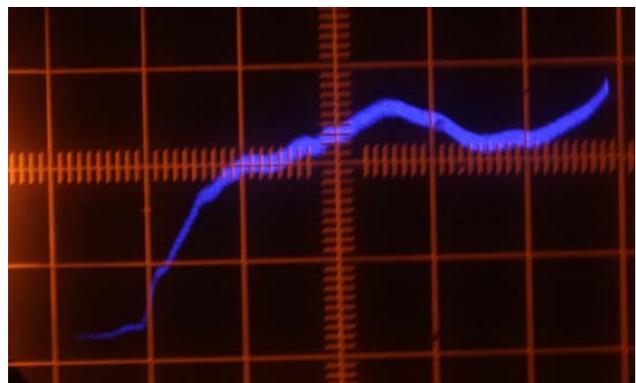
Fig. 6. Oscillogram of the front part of the voltage pulse on the load of the GPVCP in the form of one working chamber, connected in parallel with five load resistors TBO-10; the division by the time axis is 2.5 ns/div, in the process axis – 6 kV/div

In connection with the decrease in the load resistance capacitive cascade storages began to discharge faster, which in turn led to a decrease in the amplitude. At the same time, the contribution of the non-rapid part to the pulse front time on the load decreased significantly, and the front was shortened to ≈2.5 ns.

When three working chambers are connected as a load (see Fig. 7), the voltage amplitude on them becomes even smaller (see Fig. 8) than on one working chamber.
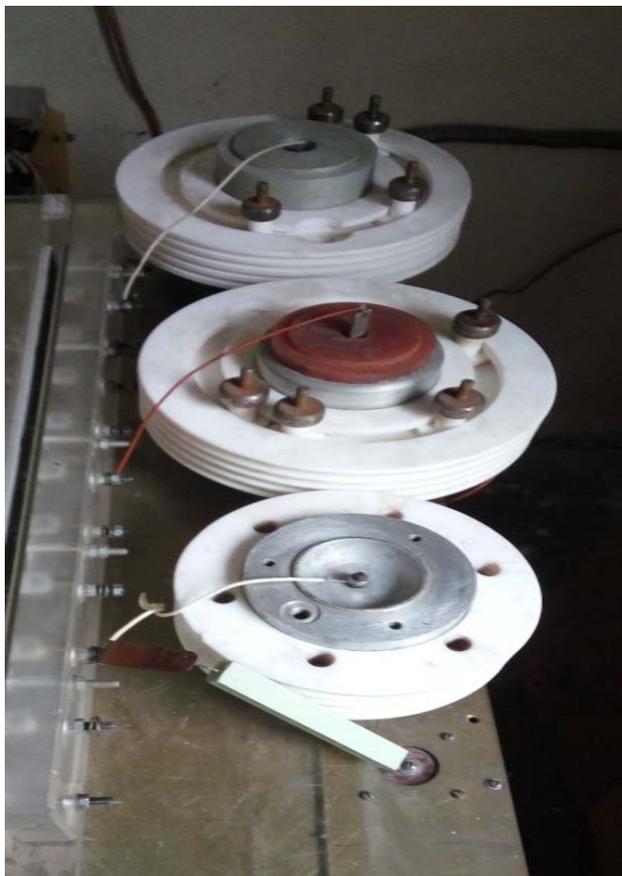
Fig. 7. GPVCP load as three working chambers with water
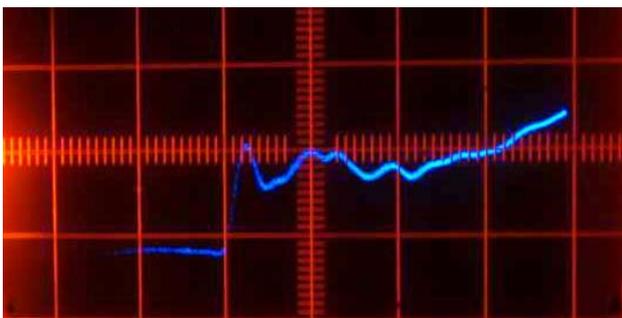
Fig. 8. Oscillogram of the front part of the voltage pulse on the load of the GPVCP in the form of three working chambers connected in parallel with each other and with a load resistor TBO-10; the division by time axis is 2.5 ns/div, in the process axis – 6 kV/div

From the oscillogram in Fig. 8 it follows that the duration of the pulse front on the load is about 1 ns, and the amplitude is about 8 kV.

To increase the intensity of the pulsed electric field in the working chambers and the voltage on them without extending the front of the pulses, it is necessary to increase the charging voltages of the capacitive storage devices from the charging devices CH1 and CH2, thus increasing the gaps in the GPVCP dischargers accordingly.

The possibility shown experimentally (see Fig. 8) of obtaining in several working chambers, connected in parallel, the voltages, and consequently also the strengths of the pulsed electric field with a record short front (about 1 ns), opens up the prospect of reducing the specific energy consumption for microbiologically disinfecting treatment of water-containing food products, increasing the shelf life of these products without impairing their consumer value. And, consequently, the prospect of industrial application of GPVCP.

Conclusions.

1. A method is proposed for shortening the front of pulses in working chambers for inactivating microorganisms processing food products by using pulse-voltage generators in accordance with the Arcadyev-Marx scheme in the regime of a step-by-step exacerbation of the pulse front.

2. The front of duration t_f ≈1 ns of pulses on the GPVCP load in the form of three parallel working chambers with water, the active resistance of each of which is less than 50 Ω was experimentally obtained. Such a short duration of the pulse front confirms that generators - GPVCP are promising for microbiologically disinfecting treatment of water-containing food products (inactivation of microorganisms in products).

3. The stable 9-10 channel mode of the output of the five-cascade generator – GPVCP – is debugged.

4. The pulses on the load are measured with a low-resistance resistive voltage divider, as a transmission line a broadband coaxial cable is used, connected to a recording device - an oscilloscope C7-19 with bandwidth of 5 GHz.

5. Working chambers made in the form of an annular body made of fluoroplastic and metal electrodes forming the bottom and the chamber cover having flat linings of food stainless steel for contact with the food product inside the working volume are used. The chambers were filled with water.

6. High-voltage pulses on the GPVCP load of about 50 Ω or less have a trapezoidal shape with base duration of no more than 80 ns, experimentally obtained pulse amplitudes on the load – up to 18 kV. As the load resistance decreases, the amplitude of the pulses decreases, and the duration of the front and pulses is generally shortened. The shortening of the front occurs as a result of the fact that the sloping (slow) part of the pulse front, which is due to reflections of electromagnetic waves caused by the operation of the dischargers, from various inhomogeneities in the GPVCP power line and in the launch system, is removed partially or fully by an accelerated discharge of capacitive cascade storages to a load with reduced resistance.

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