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DISCHARGE IN GAS BUBBLES IN WATER AS A SOURCE OF AN INTENSIVE FACTORS' COMPLEX FOR WATER DISINFECTION: COMPARISON EXPERIMENTAL AND COMPUTER MODELLING RESULTS

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Computer simulation of the discharge process in an electric circuit, which contains a pulsed electric in gas bubbles in water, has been perf0rmed. The experimental oscillograms of voltage pulses are compared with the results of computer simulation of voltage pulses on the treated water layer. It is shown that the amplitudes of the voltage pulses directly on the layer of disinfected water in the reactor with a discharge in the gas bubbles are less than those measured in experiments using a capacitive voltage divider. Computer simulations have shown that the shape of the voltage on a layer of water differs significantly that at the point where it is measured by capacitive voltage. In addition, we have shown that the presence of long lines in the bit circuit of the plant must be taken into account. Given the presence of long lines in the bit circuit, the simulation results better correspond to experimental results. References 5, figures 7.
Key words: computer modelling of discharges processes, high-voltage electrical circuit, nanosecond discharge in a gas bubble, high-voltage pulse plant, pulse power, switch, disinfection of water in the stream, a reactor – a discharge unit.

Introduction. Disinfecting water treatment with pulsed electric discharges obtained using high-voltage pulse plants is one of the most promising technologies for water disinfection [1-3] in [4] an experimental plant is presented a prototype of an industrial technological plant for water disinfection by nanosecond discharges in gas bubbles. The experimental installation contains as a load the main pipeline with running water and three nozzles for supplying pulsed high voltage and air to form gas bubbles in three disinfection units of running water located at the junction of the main pipeline with nozzles. It is known that the amplitude of the pulse voltage on the decontaminated water layer plays an important role in the degree of disinfection [1, 4]. In the experiments, we used an autonomous high-speed capacitive voltage divider (CVD) [5], which was located above the nozzles. In the electrical circuit of the plant (installation) (see the scheme in [4]), the CVD is located after a group of three multi-gap multichannel sharpening switches (dischargers) connected in parallel. In the working experimental plant between the high-voltage CVD terminal and the nodes with discharges in the gas bubbles are the above-mentioned nozzles, partially filled with water (to a height of about 5-8 cm). At nanosecond fronts of pulses generated after sharpening switches (spark gaps), these sections of pipes filled with water and containing high-voltage conductors in polyethylene cast insulation are long lines with an electrical length of about 2 ns, which affect the shape and amplitude of the voltage at each node should be considered. Based on the above, computer simulation is required to determine the shape and amplitude of the pulse voltage in nodes with discharges in gas bubbles and to compare with the experimental results obtained using CVD.

The aim of the work is to calculate by computer modeling the amplitudes and shapes of voltage pulses directly on the layer of decontaminated water and to compare the calculated curves of voltage pulses with experimental ones.

We performed computer simulations using Microcap 10. Simulations were performed for two cases. For case 1, one unit was used – a reactor with discharges in gas bubbles and one multi-gap multichannel sharpening switch. For case 2, three identical units were used – reactors with discharges in gas bubbles and three multi-gap multichannel sharpening switches, electrically connected in parallel, through which the decontaminated water flows in series. The characteristic size of gas bubbles in water is 7-10 mm. The type of discharge in a gas bubble can be defined as a barrier channel discharge in a sharply inhomogeneous electric field, where treated water acts as a barrier, in which the main pulse energy is released. Fig. 1, *a* shows typical experimental oscillograms of voltage (curve *1*) and current pulses (curve *2*) for case 1, and Fig. 1, *b* shows typical experimental oscillograms of voltage (curve *1*) and current pulses (curve *2*) for case 2. The division value along the process axis for voltage oscillograms is 7.9 kV/div in Fig. 1, *a* and Fig. 1, *b*, and for current

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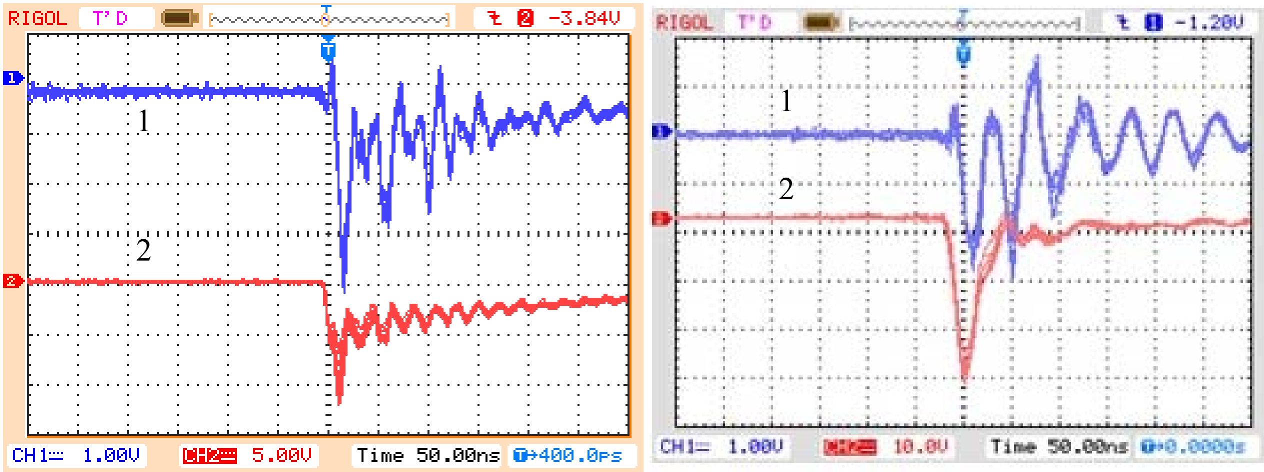
waveforms is 11.7 A/div in Fig. 1, *a* and 23.4 A/div in Fig. 1, *b*. The division price along the time axis in fig. 1 is 50 ns/div. We considered the degree of coincidence of the shape of the voltage pulses, simulated and obtained experimentally, as a criterion for the correspondence of the results of computer simulation with experimental results for determining voltage pulses in the same place in the electrical circuit.



a ***b***

Fig. 1

Electrical circuit for computer simulation. Fig. 2 shows the calculation scheme for computer simulation in Microcap 10 for case 1. The voltage source is the one of DC voltage of 5 units (for example, 5 tens of kilovolts) with an internal resistance *R*1=1 Ohm. This voltage source is connected to the rest of the circuit by means of the *SW*1 switch charging the initially uncharged capacitive storage C3=200 pF, which is the (modeling) storage capacity of our experimental setup (plant), reduced to the high-voltage winding of the pulse transformer. The high-voltage pulse transformer in the scheme (Fig. 2) is represented by the magnetizing inductance *L*1=300 μH and the leakage inductance *L*2=500 nH. The high-voltage capacitance *C*5=150 pF is charged through a volt pulse transformer from the storage capacitance *C*3 and discharges the load part of the circuit after turning on *SW*3, which has a parasitic capacitance *C*10, assumed to be high-voltage equal to C10=1 pF. The load part of the circuit consists of forward and reverse conductors with inductances: *L*4, *L*3, *L*7 - for the direct conductor; *L*5, *L*6 - for the return conductor. Between the forward and reverse wires there are capacitances *C*7, *C*9, *C*8. In the gap between the forward and reverse wires, a long line *T*1 is included, 2 ns long with a wave impedance *Z*0=150 Ohm. The gas bubble with a discharge in it (in the load part of the circuit) is represented by *SW*2 with a parasitic capacitance size of *C*6. The active resistance *R*3 of the discharge channels in the gas bubble is taken equal to *R*3=35 Ohm.. The actual load of the entire installation in the form of a layer of water in the diagram is represented by active resistance *R*2 = 1000 Ohm and capacitance *C*4 = 50 pF connected in parallel.

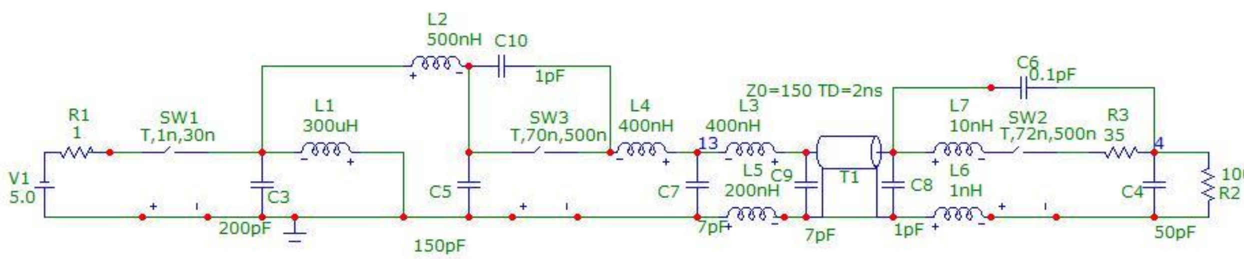


Fig. 2

Simulation results and their comparison with experimental results. Fig. 3 and Fig. 4 show the results of computer simulation for this case, taking into account the presence of a long line (electrical length 2 ns) filled with water (Fig. 3) and without taking into account the presence of such a line (Fig. 4). From Fig. 3 and Fig. 4 it follows that the calculated voltage pulse curve between nodes 13, to which the high-voltage output of the capacitive voltage divider is connected in the experiments, and grounded terminal, taking into account the presence of a long line in the circuit in Fig. 2, is much closer to the experimental voltage pulse curve in Fig. 1, *a* than the long line is not taken into account.

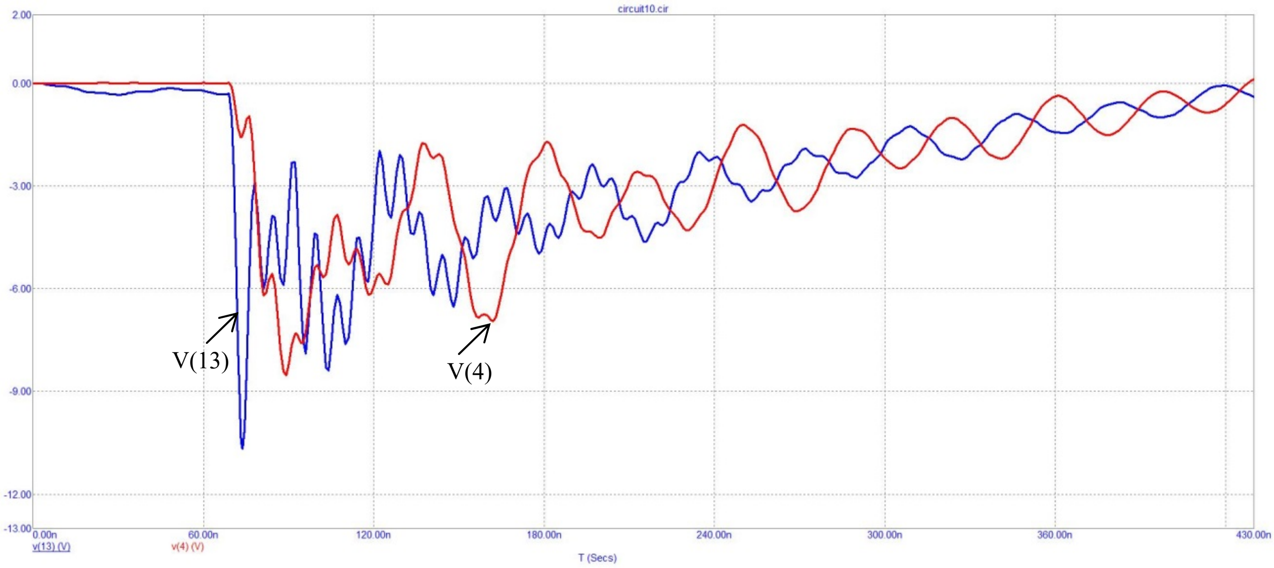


Fig. 3

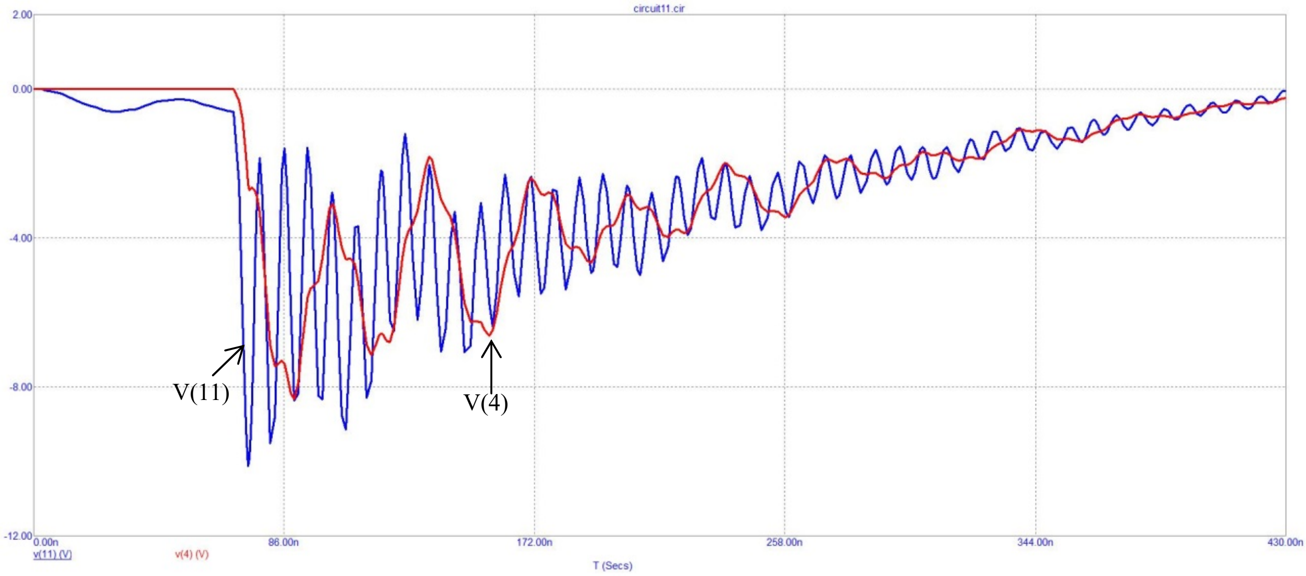


Fig. 4

In the case without taking into account the presence of a long line in the circuit in Fig. 4, the node (point) with a high potential, to which the capacitive voltage divider was connected in the experiments, has number 11, and not 13, as in the case, taking into account the presence of a long line (see Fig. 3). Accordingly, the curves of the calculated voltage pulses in Fig. 3 and in Fig. 4 are marked $V(13)$ and $V(11)$. On fig. 3 and fig. 4 and further in fig. 6 and fig. 7, the abscissa shows time in nanoseconds. The division price along the abscissa axes in fig. 3 and fig. 4 60 ns/div. The ordinates in these figures (Fig. 3, 4, 6, 7) show the voltage in tens of kilovolts. The division price is 10 kV/div.

The digital oscilloscope ***RIGOL DS1102E***, which we used in the experiments, has a bandwidth of 100 MHz, so it cannot transmit high-frequency oscillations with a characteristic frequency of about or more than 100 MHz without significant distortion. He smoothes and integrates these oscillations.

It should be noted that the moment of switching on (the beginning of switching) of switching dischargers in the calculating schemes significantly affects the development of the transient process in the discharge circuit.

Calculated curves of voltage impulses (in reactors directly on the water layer) between the discharge in the gas bubble and a metal lead with some inductance ($L5+L6$ in Fig. 2) in Fig. 3 and Fig. 4 are $V(4)$ curves. Number 4 in the diagram in Fig. 2 shows the point with the highest potential (in absolute value) on the layer of disinfected water. From an electrical point of view, this layer is considered as a parallel connection of capacitance $C4$ and active resistance $R2$. The calculation results show that the voltage pulses $V(4)$ on the water layer in the reactors differ significantly from the calculation results $V(13)$ in Fig. 3 and experiments (see oscillograms in Fig. 1) to determine the volt-second characteristics of voltage pulses between point 13 (to which the high-voltage output of the capacitive voltage divider is connected) in the circuit (Fig. 2) and ground. On Fig. 4, the role of $V(13)$ is played by $V(11)$, since if the long line is not taken into account in the scheme of Fig. 2 high-voltage terminals of capacitances $C9$ and $C8$ are short-circuited and the numbering of some nodes is changed. Node 13 acquires the number 11. It can be seen that the superimposed high-frequency oscillations, if the long line is taken into account in the calculations, do not penetrate into the layer of disinfected water. If a long line is not taken into account, high-frequency oscillations penetrate into the treated water layer. In reality, a long line in the electrical circuit exists during nanosecond discharges. A common feature for the cases of taking into account and not taking into account a long line is that the voltage amplitude $V(4)$ is noticeably smaller than the voltage amplitude $V(13)$ or $V(11)$, but noticeably larger than the voltage amplitude of the power supply $V(1)$.

Fig. 5 shows the calculating (design) scheme for computer simulation in Microcap 10 for case 2. The difference between this scheme and the scheme in Fig. 2 is that the values of a number of circuit elements have been changed: $C7=C9=10$ pF, long line impedance $Z0=50$ Ohm, $R3=12$ Ohm, $R2=333$ Ohm, $C4=50$ pF. For the scheme in Fig. 2 these values are: $C7=C9=7$ pF, long line wave resistance $Z0=150$ Ohm, $R3=35$ Ohm, $R2=1000$ Ohm, $C4=150$ pF. $C7$ and $C9$ model capacitances between conductors supplying voltage pulses to nodes with discharges in gas bubbles (up to a long line $T1$). The wave resistance of the long line $Z0$ in case 1 is 150 Ohm, and in case 2 it is 50 Ohm insofar as for a single long line $Z0 \approx 377d/(b\sqrt{\varepsilon})$ Ohm $\approx$ 377 3cm/(0.84cm$\sqrt{81}$)=377 3.6/9$\approx$150 Ohm. Here d is the characteristic distance between the direct and return conductors of the long line $T1$ filled with water with a relative permittivity $\varepsilon=81$, b is the characteristic transverse size of the conductor of the long line. For case 2, the long line $T1$ is a total long line, consisting of three identical single long lines with a wave resistance of 150 Ohm each, connected in parallel. $R3$ is the resulting active resistance of the gas bubble discharge channel(s) in one reactor ($R3=35$ Ohm) for case 1 or in three reactors connected in parallel for case 2 ($R3=12$ Ohm). $R2$, $C4$ are, respectively, the active resistance and capacitance of the water layer between the gas bubble with the discharge and the return metal conductor with inductance $L5=200$ nH. In case 1, $R2=1000$ Ohm, $C4=50$ pF is accepted. Accordingly, for case 2, when three such water layers are electrically connected in parallel, $R2=333$ Ohm, $C4=150$ pF.

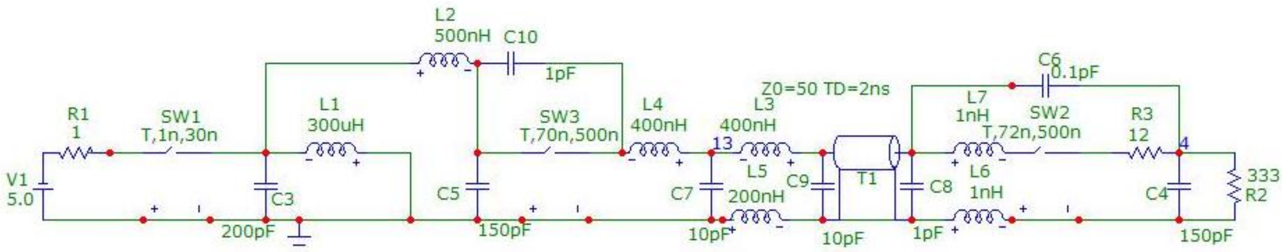


Fig. 5

Fig. 6 and Fig. 7 show the results of computer simulation for this case, taking into account the presence of a long line (electrical length 2 ns) filled with water (Fig. 6) and without taking into account the presence of such a line (Fig. 7). The division price along the abscissa in Fig. 6 is 86 ns/div, and it is 100 ns/div in Fig. 7. The values plotted along the axes in these figures are described above. From Fig. 6 and Fig. 7 it follows that the calculated voltage pulse curve between node 13 and ground, taking into account the presence of a long line in the circuit in Fig. 6 is much closer to the experimental voltage pulse curve in Fig. 1*b* than without taking into account the presence of a long line.

The calculation results show that the voltage pulses $V(4)$ on the water layer in the reactors differ significantly from the calculation results $V(13)$ in Fig. 6 and experiments (see oscillograms in Fig. 1) to determine the volt-second characteristics of voltage pulses between point 13 in the circuit (Fig. 2) and the ground. On Fig. 7, the role of $V(13)$ is played by $V(11)$, since if the long line is not taken into account in the scheme of Fig. 2, the high-voltage terminals of the capacitances *C*9 and *C*8 are short-circuited (as in the case 1 considered) and the numbering of some nodes is changed.

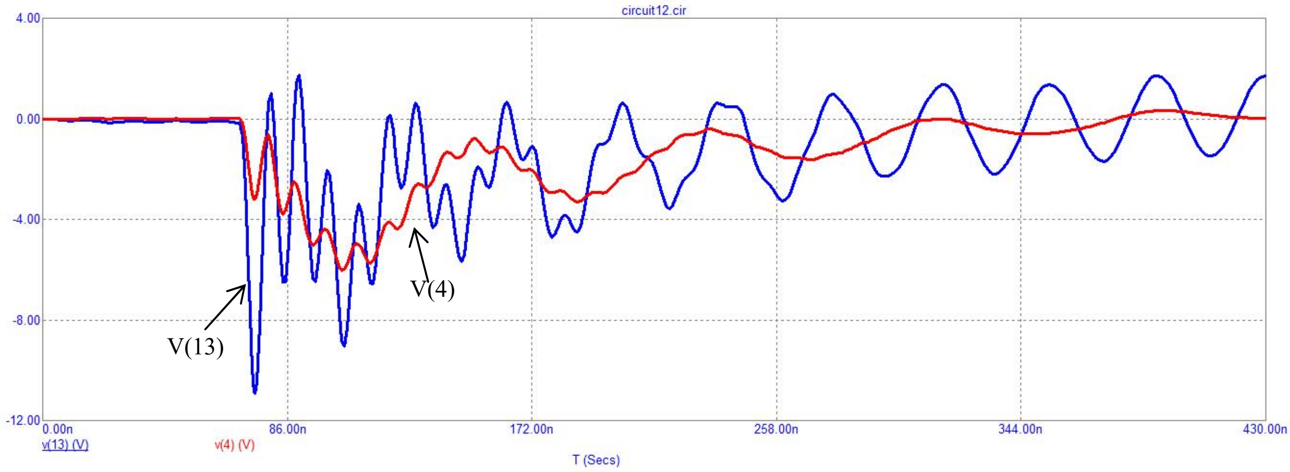


Fig. 6

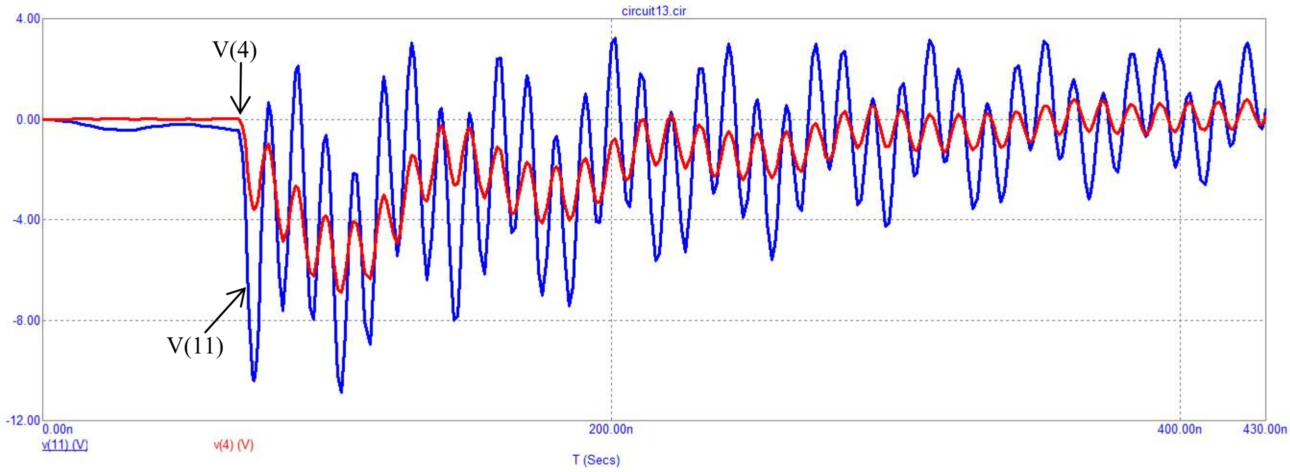


Fig. 7

Node 13 acquires the number 11. It can be seen that the superimposed high-frequency oscillations, if the long line is taken into account in the calculations, weakly penetrate into the layer of disinfected water. If a long line is not taken into account, the penetration of high-frequency oscillations into the treated water layer is significant. In reality, a long line in the electrical circuit exists during nanosecond discharges. Common for the cases of taking into account and not taking into account a long line is that the voltage amplitude *V*(4) is less than the voltage amplitude *V*(13) or *V*(11) and is approximately equal to the voltage amplitude of the power supply *V*(1). In case 1, the voltage pulse curves *V*(4) and *V*(13) with superimposed oscillations have a clearly aperiodic shape (see Fig. 3 and Fig. 4) with steeper fronts than in case 2 (see Fig. 6 and Fig. 7). In case 2, the voltage pulse curves *V*(4) and *V*(13) with superimposed oscillations approach the oscillatory form in shape. This is explained by a significant decrease in the active resistance of the discharge circuit in case 2.

The simulation results show that the voltage shape on the layer of disinfected water differs significantly from that at the place where it is measured by a capacitive voltage divider, the presence of a long line (long lines) in the discharge circuit should be taken into account, the moments of switching on switching dischargers significantly affect the simulation results (calculations).). When the presence of a long line (long lines) in the discharge circuit is taken into account, the simulation results are more consistent with our experimental results.

Conclusions. 1. The voltage pulse amplitudes directly on the layer of disinfected water in the reactor with a discharge in gas bubbles are less than those measured in experiments using a capacitive voltage divider.

2. The shape of the voltage on the layer of disinfected water differs significantly from that at the place of its measurement by a capacitive voltage divider.

3. The presence of a long line (long lines) in the discharge circuit should be taken into account. When the presence of a long line (long lines) in the discharge circuit is taken into account, the simulation results are more consistent with our experimental results.

4. The moments of switching on switching dischargers significantly affect the results of modeling (calculations).

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РОЗРЯД У ГАЗОВИХ БУЛЬКАХ У ВОДІ ЯК ДЖЕРЕЛО КОМПЛЕКСУ ІНТЕНСИВНИХ ФАКТОРІВ ДЛЯ ЗНЕЗАРАЖЕННЯ ВОДИ: ПОРІВНЯННЯ ЕКСПЕРИМЕНТАЛЬНИХ РЕЗУЛЬТАТІВ З РЕЗУЛЬТАТАМИ КОМП'ЮТЕРНОГО МОДЕЛЮВАННЯ

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Проведено комп'ютерне моделювання розрядного процесу в електричному колі, яке містить імпульсний електричний розряд у газових бульках у воді. Проведено порівняння експериментальних осцилограм імпульсів напруги з результатами комп'ютерного моделювання імпульсів напруги на оброблюваному шарі води. Показано, що амплітуди імпульсів напруги безпосередньо на шарі знезаражуваної води в реакторі з розрядом в газових бульках менше, ніж виміряні в експериментах за допомогою ємнісного дільника напруги. Комп'ютерне моделювання показало, що форма напруги на шарі води суттєво відрізняється від такої у місці вимірювання її ємнісним дільником напруги. Крім того, показано, що треба враховувати наявність довгих ліній в розрядному колі установки. При урахуванні наявності довгих ліній в розрядному колі результати моделювання краще відповідають одержаним нами експериментальним результатам. Бібл. 5, рис. 7.

Ключові слова: комп'ютерне моделювання розрядних процесів, високовольтне електричне коло, наносекундний розряд в газовій бульці, високовольтна імпульсна установка, імпульсна потужність, розрядник, знезараження води у потоці, реактор – розрядний вузол.

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