УДК 537.52 + 621.373 DOI: https://doi.org/10.15407/techned2018.04.037

GENERATOR OF HIGH-VOLTAGE NANOSECOND PULSES WITH REPETITION RATE MORE THAN 2000 PULSES PER SECOND FOR WATER PURIFICATION BY THE DISCHARGES IN GAS BUBBLES

N.I. Boyko*, **A.V. Makogon****
National Technical University «Kharkiv Polytechnic University»,
Kirpichova str 2, Kharkiv, 61002, Ukraine,
e-mail: qnaboyg@gmail.com; boyko@kpi.kharkov.ua

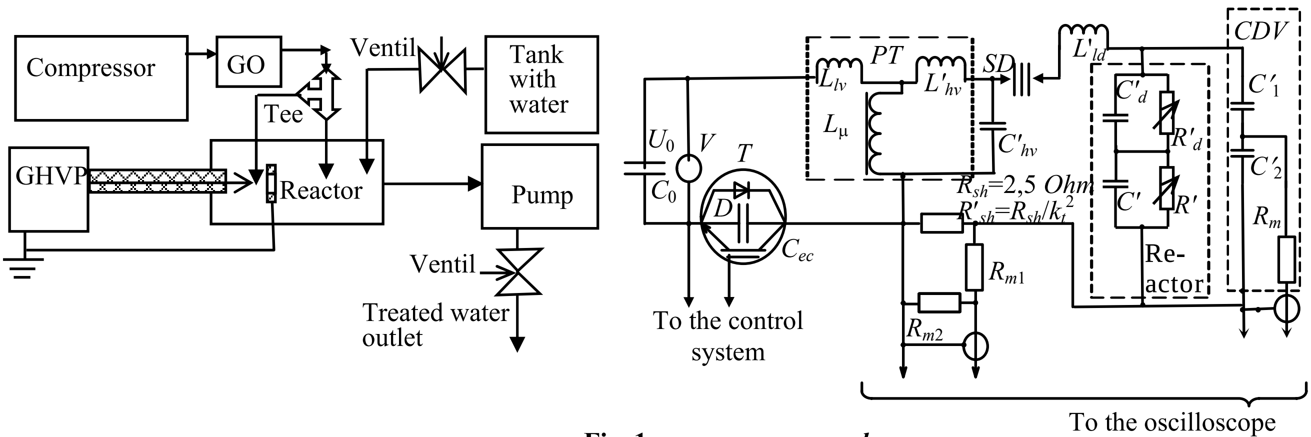
Purpose. *Purpose of this work is to create generator of high-voltage nanosecond pulses capable of operating on a load in the form of a layer of water with gas bubbles at a pulse repetition rate of more than 2000 pulses per second, and experimentally investigate with its aid the characteristics of nanosecond discharges in gas bubbles for water purification.* ***Methodology.*** *Generator of nanosecond pulses was created on the basis of the Tesla transformer scheme. We used multi-gap spark discharger to peak the front of high-voltage pulses.* ***Results.*** *Characteristics of high-voltage nanosecond discharges in gas bubbles in water are experimentally studied using a nanosecond pulse generator. These discharges allowed reducing the concentration of ammonia by 37% in a solution of ammonium nitrate in water during its purification.* ***Originality.*** *Multi-gap spark discharger provides a pulse repetition rate of more than 2000 pulse/s. Load of the generator was layer of water with gas bubbles with characteristic dimensions of 1-4 cm above it in the reactor. Voltage pulses with amplitude up to 30 kV, current pulses with amplitude of up to 35 A with characteristic durations of 60 ns and front durations of ≈10 ns are obtained in load. Shape of the pulses is close to the two-exponential waveform with superimposed oscillations.* ***Practical value.*** *Nanosecond discharges obtained experimentally in gas bubbles in water with voltage amplitude of several tens of kilovolts and the amplitude of current pulses in discharges of tens and more amperes open the prospect of purification and microbiological disinfection of water with such discharges with reduced specific energy costs in comparison with known methods.* References 9, figures 4.
Key words: generator, high - voltage nanosecond pulse, discharge into gas bubble, water purification, multi gap spark discharger, peaking capacitance, reactor.

Introduction. The use of pulsed electric discharges for cleaning and microbiological water disinfection is one of the most promising directions in this field [4, 6, 8, and 9]. An important goal in research in this direction is to reduce the specific energy consumption for water purification. Reduction of specific energy consumption is achieved by bubbling water with gas bubbles [5].

It is known that volumetric pulsed discharges are very promising [7]. Wherein, with the shortening of the duration of the pulses used and the transition from the microsecond to the nanosecond range, specific energy consumption for cleaning and microbiological disinfection of water decreases [6].

The purpose of this work is to create an experimental generator of high-voltage nanosecond pulses capable of operating on a load in the form of a layer of water with gas bubbles at a pulse repetition rate of more than 2000 pulses per second, and experimentally investigate with its aid the characteristics of nanosecond discharges in gas bubbles.

The features of the generator and the experimental plant as a whole. Fig.1, *a* shows a block diagram of the modernized experimental setup, and Fig. 1, *b* – the electrical circuit of the generator of high-voltage nanosecond pulses.



a **Fig. 1** *b*

ORCID: * http://orcid.org/0000-0002-1362-2867 ; ** https://orcid.org/0000-0002-3889-2601

Part of the elements of the generator and the experimental setup are described in [1]. The plant considered in [1] made it possible to obtain high-voltage pulses of microsecond duration in a load-reactor with discharges in gas bubbles. The current pulses had amplitude not exceeding 0.5 A, taking into account nanosecond bursts. The pump pumps water from the reactor at a rate of 60 l/h (Fig. 1, *a*). The pumping process can be looped. Then the pump pumps the water back to the reactor. The compressor ensures the formation of gas bubbles in the reactor at a controlled rate of 5–50 l/h. In comparison with the block diagram in [1], the block diagram in Fig. 1, *a* additionally contains an ozone generator GO, a tee and an additional hose with an atomizer at the end for bubbling with an ozone-air mixture of water in the reactor. An ozone-air mixture, which has a greater electrical strength than air, is fed through the tee into the working zone of the reactor (similar to the reactor in [1]). The use of ozone in the reactor in the form of submillimeter bubbles after the atomizer increases the degree of water purification. The concentration of ozone in the air fed to the reactor is approximately 1 g/m3. The degree of purification without ozone deteriorates by about 10%. The gas bubble (with a characteristic size (1 ÷ 4) cm) with discharges in it and a layer of water between the bases of the discharge channels in the bubble and a grounded electrode connected to one of the terminals of the high-voltage winding of the pulse transformer (*PT*) are connected in series in the reactor.

In Fig. 1, *b* capacitance C_0 = 4230 μF (9 capacitors TAMICON 470 μF, 450 V in parallel) is charged from the mains (220 V, 50 Hz) through the diode bridge (in Fig. 1, *b* is not shown) to the voltage U_0. V is a voltmeter. The switch is a transistor switch *T*, consisting of four parallel-connected IGBT-type transistors, type IRG4PH50UD. The energy is switched on when the transistors in the *T* key are closed. The duration of the open state of the *T* key is 110 μs. D - built-in into transistors of IGBT-key reverse diodes; $C_{ec}\geq 1$ nF - capacitance "emitter-collector" of IGBT-key, $C'_d<C_{ec}<<C_0$; R'_{sh} - reduced resistance of the measuring shunt in high-voltage circuit of the generator; R_{m1}=300 Ohm, R_{m2}=60 Ohm - matching shunt resistance, R_{sh}=2.5 Ohm; C'_1, C'_2 are the reduced capacitances of the high-voltage and low-voltage arms of the capacitive voltage divider *CDV* (real capacitances $C_1\approx 2.7\times 10^{-12}$F, C_2 = 20.4×10^{-9} F, division coefficient $k_d\approx 7650$) with matching resistance R_m=50 Ohm. In the electrical circuit of the reactor, C_d, R_d are the capacitance and nonlinear active resistance of the discharge gap (DG) in the gas bubble, and *C*, *R* is the capacitance and nonlinear resistance of the water layer between the discharge gap and the low-voltage (earthed) electrode (C'_d, R'_d, C', R' are the values of these quantities reduced to the primary winding of *PT*). *IT* on a magnetic circuit made of steel tape (80 μm tape thickness) is represented by the magnetization inductance $L\mu$ and inductances L_{lv}, $L'hv$ are the primary leakage inductance and the reduced leakage inductance of the secondary winding *PT*. The coefficient of *PT* transformation is k_t = 30. In the primary winding of the *PT* w_1 = 10 turns, in the secondary winding w_2 = 300 turns. In contrast to [1], the circuit in Fig. 1b does not contain a current-limiting resistor. The initial value of the gap h in the gas bubble between the tip high-voltage electrode inside the bubble and the surface of the gas bubble in water is h≈7 mm. During the purging process, the shape of the gas bubbles changes, causing a change in the value of h. The inductance L_{ld} of the load-discharge circuit is $L_{ld}\approx 0.5$ μH.

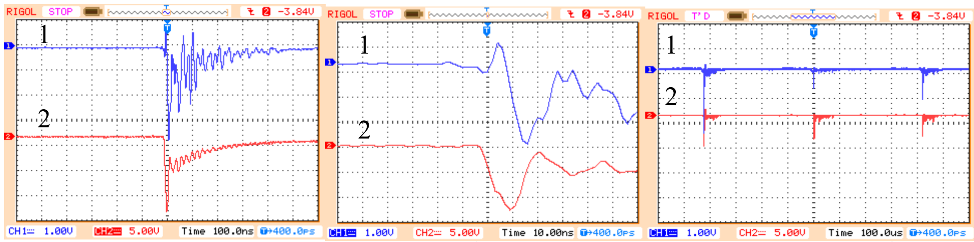
To significantly increase the amplitude of the current and voltage pulses in the generator's reactor and to reduce the specific energy consumption during water purification, the peaking capacitance C'_{hv}, and the multi-gap spark discharger *SD* (Fig. 1, *b*) are introduced into the generator. The capacitance C'_{hv}=150 pF was collected from six capacitors of KVI-2 with a capacity of 100 pF each, designed for a voltage of 20 kV. Capacitance C'_{hv} are three parallel chains of two capacitors KVI-2, connected in series. C_d capacitance of DG is the capacitance between the tip high-voltage electrode inside the bubble and the interface of the gas bubble and water ($C_d\leq 10^{-12}$ F). Resistance R_d of DG before the start of the discharge exceeds 1 MOhm, therefore all voltage with C'_{hv} is applied to the series-connected discharger *SD* and DG. After the discharge starts, the R_d decreases in the DG, and in the case of a discharge transition into the channel stage of the spark discharge, it (R_d) can be significantly less than 1 Ohm. However, in the presence of a sufficiently thick (several cm) of water layer between the base of the discharge channel and the low-voltage electrode, this does not occur, and it can be assumed that R_d) decreases to ~ 100 Ohms.

The nanosecond pulse fronts on the load-reactor in the form of a layer of water under a gas bubble are provided by discharger (*SD*). And short duration of current and voltage pulses of the order of 100 ns in the load is provided by choosing a small value (150 pF) C'_{hv}. Overall dimensions of *SD* are: length including terminals − 200 mm, width − 150 mm, height − 50 mm. The discharger *SD* is made taking into account the recommendations [2] on the development [3]. The photos of the multi-gap discharger *SD* are shown in Fig. 2 (Fig. 2, *a* shows the ratio of the length, width and height of the arrester, Fig. 2, *b* illustrates the regular work of SD in multi-channel mode). The inter-electrode gaps in *SD* are ~ 1 mm each. We used 5 gaps. The electric field in each gap is quasi-uniform. At a pulse repetition rate of more than 2000 pulses/s without the use of blowing, the electrodes of the multi-gap *SD* discharger overheated, the multi-channel spark discharge in each gap was converted into a single-channel arc discharge, and the electrical strength of the gaps after each discharge was not restored. The discharger (or switch) was short-circuited. Heating of the multi-gap discharger *SD* in the process of work was eliminated by blowing it with a fan. In this case, the electrical strength of its gaps after each discharge was completely restored.

a **Fig. 2** ***b***

Experimental results. Fig. 3 shows the oscillograms of the voltage pulses (curves *1*) and current (curves *2*) obtained as a result of the investigation of the processes in the circuit (Fig. 1, *b*). The amplitude of the voltage reaches 30 kV and the current amplitude reaches 35 A. The value of the division along the process axis for the voltage oscillograms is 7.9 kV/div, and for the oscillograms of the current is 11.7 A/div. Fig. 3, *a* shows oscillograms of nanosecond pulses.

The price of the division along the time axis is 100 ns/div. The oscillograms show that the duration of the t_p pulses in terms of the amplitude decay level in e≈2.72 times can be taken to be approximately t_p≈60 ns. The form close to the decaying exponential with superimposed oscillations is determined by the discharge contour C_{hv} – *SD* – L_{ld}- (R_d in parallel with C_d) - (*R* in parallel with *C*) -R_{sh}-C_{hv}. The presence of superimposed oscillations is explained by the presence of the vibrational contour C_{hv} - L_{ld} - *C*. The current in the discharge circuit creates a reserve of energy in L_{ld}. This energy then additionally charges *C*. Since $C << C_{hv}$, in so far as the voltage amplitude in *C* can in the limit reach twice the amplitude value on C_{hv}, at which *SD* breaks. Fig. 3, *b* shows the oscillograms of nanosecond pulse fronts (10 ns/div is on the time axis). The duration of the pulse fronts is t_f≈(10 ÷ 12) ns. The used digital oscilloscope RIGOL DS1102E has a bandwidth of 100 MHz and can introduce distortions into the measurements. The oscillograms in Fig. 3c in a time scale of 100 µs/div allow us to determine the pulse repetition rate f_{rpt}. Fig. 3, *c* show that the repetition period is T_{rpt}=420 µs. Hence repetition rate is f_{rpt}≈2381 pulses/s.



a ***b*** ***c*** **Fig. 3**

Fig. 4 shows the glow in the DG (gas bubbles), caused by the obtained nanosecond pulses. It is much brighter than the glow obtained with the help of microsecond pulses in [1] with the amplitude of voltage pulses at DG 8 kV, the amplitude of current pulses 0.2 A and f_{rpt}≈6250 pulses/s.

The possibility of using the obtained nanosecond pulses in the reactor (Fig. 1) for water purification was tested on a solution of ammonium nitrate NH_4NO_3 in water. The aim was to reduce the amount of ammonia in said solution. A similar goal was also in [9], where a solution of NH_4Cl - ammonium chloride was used. In [9], a 35% decrease in the ammonium concentration was achieved by treating the NH_4Cl solution in water for 20 min with pulses of 200 ns duration, voltage amplitude of 30-40 kV, a repetition rate of 1000 pulses per second, pulse energy of 0.25 Joules. The initial concentration of ammonium ions was about 300 mg/l. A solution of NH_4Cl in water was sprayed over the electrode system in the form of falling drops with a diameter of 0.1-1.0 mm, forming a mixture with atmospheric air. This mixture was treated with electrical discharges in the electrode system.

Fig. 4

We achieved a 37% reduction in NH_3 - ammonia concentration (from 57 mg / l to 35.7 mg / l) by treating NH_4NO_3 in water with discharges in gas bubbles in this solution for *t*=18 min with pulses of duration t_p≈60 ns, with an average amplitude of voltage pulses *U*≈30 kV, average amplitude of current pulses *I*≈25 A, repetition rate f_{rpt}≈2381 pulses/s. The volume V_0 of treated water was V_0=1.2 liters. In this case, the energy in the pulse can be estimated as $W_p ≈ 0.5*U*I*t_p = 0.5*30000*25*6*10^{-8}$ J=$22.5*10^{-3}$ J=22.5 mJ. The specific energy costs W_s were $W_s = W_p*f_{rpt}*t/V_0 ≈ 48215.25$ kJ/m^3≈13.4 kWh/m^3. Estimated efficiency of the developed generator is 75%.

Conclusions. Generator of high-voltage nanosecond pulses was created. With its help in gas bubbles 1-4 cm in size, nanosecond discharges are obtained in water. The repetition rate of discharges reached 2500 pulse/s at the amplitude of the voltage pulses at the reactor 30 kV and the amplitude of current pulses in the discharge circuit up to 35 A. Nanosecond pulse fronts in the reactor are formed by a compact multi-gap spark spark gap. A nanosecond discharge in a gas bubble with breakdown voltages of about 20 kV, a sharply nonuniform field in a discharge gap of about 7 mm, is the source of high-intensity factors (active microparticles and broadband radiation) for water purification. The possibility of purifying water containing ammonium nitrate NH_4NO_3 from ammonia is shown. A decrease in the concentration of ammonia (NH3) by 37% was achieved. To reduce specific energy consumption and increase the degree of water purification by discharges in gas bubbles, further studies are needed in it.

1. Boyko N.I., Makogon A.V. Experimental Plant for Water Purification with the Help of Discharges in Gas Bubbles. *Tekhnichna elektrodynamika*. 2017. № 5. Pp. 89 – 95. DOI**:** https://doi.org/10.15407/techned2017.05.089 (Rus)

2. Boyko N.I. Scientific bases for the creation of electric technological plants for high-voltage pulsed effects: The author's abstract of the dissertation … doctor of technical sciences: 05.09.13. NTU KhPI. Kharkiv, 2003. 38 p. (Ukr)

3. Evdoshenko L.S. Improvement of high-voltage spark dischargers with alternating electric strength for electric technological plants: The author's abstract of the dissertation … candidate of technical sciences: 05.09.13. NTU KhPI. Kharkiv, 2013. 21 p. (Ukr)

4. Foster J., Sommers Bradley S., Gucker S. N., Blankson I. M., and Adamovsky G. Perspectives on the Interaction of Plasmas with Liquid Water for Water Purification. *IEEE Transactions on Plasma Science*. 2012. Vol. 40. No 5. Pp. 1311–1323.

5. Gershman S., Mozgina O., Belkind A., Becker K., and Kunhardt E. Pulsed Electrical Discharge in Bubbled Water. *Contributions to Plasma Physics*. 2007. Vol. 46. No. 1-2. Pp. 1–7. DOI: https://doi.org/ 10.1002/ctpp.200710002

6. Hazmi A., Desmiarti Reni W., Eka P. & Darwison. Removal of Microorganisms in Drinking Water using a Pulsed High Voltage. *J. Eng. Technol. Sci.* 2013. Vol. 45. No. 1. Pp. 1–8.

7. Kebriaei M., Ketabi A. and Niasar Abolfazl H. Pulsed Corona Discharge, a New and Effective Technique for Water and Air Treatment. *Biological Forum*. 2015. No. **7**(1). Pp. 1686-1692.

8. Malik Muhammad A., Ghaffar A. and Malik Salman A. Water purification by electrical discharges. *Plasma Sources Sci. Technol*. 2001. No. 10. Pp. 82–91.

9. Nazarenko O.B, Shubin E.G. Investigation of Electric Discharge Treatment of Water for Ammonium Nitrogen Removal. Environmental Physics Conference, Alexandria, Egypt, 18-22 Feb. 2006. Pp. 85–90.

УДК 537.52 + 621.373

ГЕНЕРАТОР ВЫСОКОВОЛЬТНЫХ НАНОСЕКУНДНЫХ ИМПУЛЬСОВ С ЧАСТОТОЙ СЛЕДОВАНИЯ БОЛЕЕ 2000 ИМПУЛЬСОВ В СЕКУНДУ ДЛЯ ОЧИСТКИ ВОДЫ ПРИ ПОМОЩИ РАЗРЯДОВ В ГАЗОВЫХ ПУЗЫРЯХ

Н.И. Бойко, докт.техн.наук, **А.В. Макогон**
Национальный технический университет «Харьковский политехнический институт»,
ул. Кирпичева, 2, Харьков, 61002, Украина,
e-mail: qnaboyg@gmail.com; boyko@kpi.kharkov.ua

Экспериментально исследованы характеристики высоковольтных наносекундных разрядов в газовых пузырях в воде при помощи созданного генератора наносекундных импульсов. Он создан на основе схемы трансформатора Тесла. Для обострения фронта высоковольтных импульсов использован многозазорный искровой разрядник, обеспечивающий частоту следования импульсов более 2000 имп./с. Нагрузкой генератора являлся слой воды с газовыми пузырями с характерными размерами 1-4 см над ним в реакторе. В нагрузке получены импульсы напряжения с амплитудой до 30 кВ, импульсы тока с амплитудой до 35 А с длительностью 60 нс, длительностью фронтов ≈10 нс. Форма импульсов близка к двухэкспоненциальной с наложенными колебаниями. Указанные разряды позволили уменьшить концентрацию аммиака на 37% в растворе нитрата аммония в воде. Библ. 10, рис. 4.

Ключевые слова: генератор, высоковольтный наносекундный импульс, разряд в газовом пузыре, очистка воды, многозазорный искровой разрядник, обостряющая емкость, реактор.

ГЕНЕРАТОР ВИСОКОВОЛЬТНИХ НАНОСЕКУНДНИХ ІМПУЛЬСІВ З ЧАСТОТОЮ ПРОХОДЖЕННЯ БІЛЬШЕ 2000 ІМПУЛЬСІВ ЗА СЕКУНДУ ДЛЯ ОЧИЩЕННЯ ВОДИ ЗА ДОПОМОГОЮ РОЗРЯДІВ У ГАЗОВИХ БУЛЬКАХ

М.І. Бойко, докт.техн.наук, **А.В. Макогон**
Національний технічний університет «Харківський політехнічний інститут»,
вул. Кирпичова, 2, Харків, 61002, Україна.
e-mail: qnaboyg@gmail.com; boyko@kpi.kharkov.ua

Експериментально досліджено характеристики наносекундних розрядів у газових бульках у воді за допомогою створеного генератора наносекундних импульсів. Він створений на основі схеми трансформатора Тесла. Для загострення фронту високовольтних імпульсів використано багатозазорний іскровий розрядник, що забезпечує частоту проходження імпульсів більше 2000 імп./с. Навантаженням генератора був шар води з газовими бульками з характерними розмірами 1-4 см над ним в реакторі. У навантаженні одержано імпульси напруги з амплітудою до 30 кВ, імпульси струму з амплітудою до 35 А з тривалістю 60 нс, тривалістю фронтів ≈10 нс. Форма імпульсів близька до двоекспоненціальної з накладеними коливаннями. Вказані розряди дозволили зменшити концентрацію аміаку на 37% у розчині нітрату амонія у воді. Бібл. 10, рис. 4.

Ключові слова: генератор, високовольтний наносекундний імпульс, розряд у газовій бульці, очищення води, багатозазорний іскровий розрядник, загострююча ємність, реактор.

Надійшла 05.03.2018
Остаточний варіант 28.03.2018