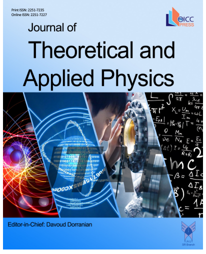

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Modeling the generator of electro-pulse discharges

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Original Research

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Abstract:

The article discusses some aspects of modeling the dynamics of high-gradient pulse processes accompanying technologies using electrical discharges in a liquid medium. Due to the presence of high pressure, these technologies are successfully used for the destruction and crushing of solid materials, the processing of mineral environments, the intensification of heat exchange processes, etc. The development of a pulse signal generator with a given frequency, taking into account the influence of environmental parameters, is an urgent technical problem. The main element of electric pulse technology is a generator for providing high discharge energy at a given frequency. A brief analysis of the block diagram of an RLC generator with pulse parameters is given. The possibility of a description of an RC generator of pulsed electric-discharge oscillations based on a system of dynamic equations is shown. Numerical solutions to the dynamic equations of the model oscillator using the MatLab package are presented, and phase portraits for various parameters are shown. The graphs of numerical calculations are in qualitative agreement with the oscillograms of pulsed current and voltage and reflect the nature of the dynamic patterns. The results obtained can be used in practice to select parameters that ensure a given operating mode of electric discharge equipment.

Keywords: Chaotic pulse generator; Electropulse discharges; System of dynamic equations; Fluctuating parameters

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1. Introduction

The study of the patterns of development of a pulsed electric discharge in an inhomogeneous liquid medium is relevant due to the widespread use of electric discharge technologies in the processing of raw materials, solid minerals, and the production of new materials [1–5]. Pulsed high-voltage electric discharge (HVED), as a process of rapid conversion of electric field energy into other types, is relevant due to its widespread use in modern industrial production technologies [6–13]. An electric discharge in dense condensed media is used as a source of pulsed high-gradient pressures, under the influence of which the processed materials are subjected to destruction, pressing, shaping, grinding, etc. Based on an equivalent circuit, a mathematical model of a HVED in a rock made of hard granite using a coaxial cylindrical electrode structure was created [6]. Relationships between factors that influence HVED, such as granite composition, electrical parameters of the circuit, distance between electrodes, and electrode shape, are obtained, and relationships between these factors are obtained. In [5], an electro-thermo-mechanical model is proposed that takes into account the influence of medium inhomogeneity on electrical breakdown. The creation of a plasma channel during rock crushing has been established. A numerical model of rock destruction under the influence of HVED pulses has been developed using a model of the random distribution of conductive particles in rock. Functional tests were carried out using deep drilling technology using HVEDs [13]. Generated by a pulsed HVEDs a plasma channel and a water shock wave are used to destroy the rock. Some works are devoted to the description of nonlinear processes accompanying the propagation of electrical discharges in water [14–18].

When using electric discharge technology to intensify heat transfer, crushing and grinding ore materials, mineral media, extracting valuable components from industrial waste, etc., it is shown that all processes are accompanied by a change in the structure of materials. Electric discharge technology is successfully used to treat liquid media in order to purify them from unwanted and often harmful impurities or to change the properties, for example, of phosphorus from phosphorus sludge, etc. [18]. It was found that the intensity of the shock wave is closely related to the power and energy dissipated in the plasma channel [19]. A longer plasma channel and faster expansion of the arc can result in higher power and energy deposited in the plasma channel, which can create a stronger shock wave.

To clarify the wide range of roles that pulse generator research plays in many systems, and to justify the importance of their development for many practically important problems, let's consider a number of examples of their creation and successful application. For example, the authors of [20] developed and created a portable high-voltage pulse generator for crushing rocks. The generating set consists of a standard set of blocks, where the high-voltage block includes a step-up transformer, a capacitive storage tank and a two-electrode gas switch. The operating parameters of the generator are given: output voltage up to 300 kV, voltage rise time $\approx$ 50 ns, current amplitude $\approx$ 6 kA with an active load of 40 Ohms and $\approx$ 20 kA in rock crushing mode.

In [21], studies were carried out on the destruction of granite by the electric pulse method using a two-electrode system. The range of changes in the interelectrode distance is $(10-300)$ mm, the energy contribution per unit length is $(3.6-100)$ J/mm. The research results showed that the efficiency of electric pulse destruction of rock increases with increasing interelectrode distance, which affects the length of the discharge channel. In [22], the processes of processing fine-grained mineral microelements are considered, and the results of comparing the influence of electrical and conventional mechanical crushing are presented.

The authors of this article previously conducted experiments to determine the optimal parameters of an electric-pulse installation for effective crushing and grinding of samples of mineral ores from the largest deposits of Kazakhstan [23]. Electric pulse processing of ore was carried out under various parameters: the number of discharge pulses varied from $N = 50$, 750, 1000 and 1250, the discharge energy per unit length W (from 65 to 200 J), the interelectrode gap on the switching device ($l = 8$, 10, 12 and 14 mm) and with capacitor bank capacities $C = 0.25$; 0.5; 075 μF. As a result of the experiments, the optimal capacitance values of the capacitor bank, from the point of view of efficiency, were determined to be values 0.5 μF. Electric pulse processing technology made it possible to grind natural ore to fractions with a given degree of dispersion. In addition, it has been shown that electric pulse processing of ore at the beneficiation stage can significantly increase the copper content in the studied samples.

Article [24] discusses methods of crushing and grinding copper ore using an electric pulse installation, the operation of which was carried out by direct discharge of a capacitor bank onto an electrode system in a liquid. The operating parameters were maintained as follows: operating voltage (30–50) kV, frequency (1–10) Hz, pulse energy (100–1000) J, pulse rise time (1.5–2.0) μs. Processing in the specified range made it possible to obtain up to 36% of the mass of the crushed product with a fraction diameter of up to 1 mm. As can be seen from a brief review of examples of the use of electric discharge technology in practice, the range of parameters of electric pulse action varies depending on the object of treatment (minerals, granite, coal, ore, etc.). But technology to create of high values of electrical parameters that allow the discharge to be carried out with an almost instantaneous release of large energy amounts, is the same. The formation of streamers of electric discharges in a liquid has stochastic character and proceeds in a very short period of time. Research confirms that the dynamics of rapidly changing processes accompanying a HVED in a continuous medium cannot be described on the basis of the classical apparatus of differential equations [25–28]. For example, based on a stochastically deterministic approach to describing the dynamics of growth of the discharge structure and the operation of a high-voltage generator, the patterns of development of a single electric discharge in a condensed dielectric were modeled [27]. It's means, a nonlinear fractal model of dielectric destruction was developed. Let's consider the possibility of creating a dynamic model of a generator of electric pulse discharges in a liquid medium.

2. Problem statement. Initial data

Any complex non-stationary object can be considered, at least to a certain approximation, as a dynamic system. Abstracting from the specific physical nature of an object, it can also be considered as a dynamic system. Then it is possible to define a set of quantities that are classified by algorithms as variables and characterize the system state so that their values at any subsequent point in time receive their initial set according to a simplified rule, the so-called "evolution operator" [26]. An electro-hydro-pulse installation with discharge initiation by spontaneous breakdown of the formation of an air gap in a sequential operating mode can be implemented as a nonlinear dynamic self-oscillating system, causing a generator of chaotic pulses with inertial nonlinearity [27, 28].

To effectively use underwater HVEDs, it is necessary, first of all, to study the mechanism of their formation in inhomogeneous liquid media. Based on this, it is important to develop and create installations that allow, due to the effects of electric discharges in a liquid medium, to change the characteristics and structure of various materials and substances [29–32]. The results of computer and physical modeling of discharge processes in pulsed plasma ignition systems of a new type for gas turbine engines with a controlled switching spark gap are presented in [31]. The main element of this technology is generators (step-up transformers) to obtain the necessary energy, the implementation of which requires large financial costs. Therefore, the development and creation of a chaotic pulse model generator with inertial nonlinearity for underwater electrical installations is an urgent technical problem.

The prerequisites that allow electric discharge devices to be classified as stochastic signal generators with inertial nonlinearity are the following factors:

- the discharge circuit during the breakdown of the air forming gap is, in essence, an oscillatory circuit;
- the presence of a delay at the stage of discharge formation, moreover, the delay time has a statistical spread;
- studies of breakdown in water and aqueous electrolytes, based on direct photographing of processes, make it possible to identify the beginning of the leader stage with the formation of a luminous spot at the electrode and to distinguish the complex structure of randomly located leaders in the form of self-luminous and non-luminous branches;
- the effect of the duration of the discharge delay time on the amplitude of the current pulse, and, accordingly, the pressure at the front of the shock wave;
- the relationship of mass transfer processes occurring in a multiphase medium in the interelectrode gap during the discharge, to the breakdown of the air gap of the forming spark gap and to the values of the initial parameters of subsequent electric discharge pulses;
- the presence of a feedback of mass transfer processes occurring in the interelectrode gap during the discharge on the breakdown of the air gap of the forming spark gap, and, consequently, on the parameters of the subsequent electric discharge pulse.

Due to the dynamic nature of chaotic regimes and their sensitivity to small disturbances, they allow effective control through externally controlled influences. The purpose of such an influence may be to implement a periodic regime in the system instead of chaos or falling into a given region of phase space. This idea, originally put forward by a group of American researchers from the University of Maryland (Ott, Gredogi, and Yorke, 1990), seems very promising and fruitful in terms of application. In radio engineering and electronics, a number of applications are known where generators of noise-like oscillations are needed, which can be played by various devices operating in the dynamic chaos mode. Basically, in electric pulse installations, various current pulse generators are used, designed to generate repeatedly repeated current pulses that reproduce the electrohydraulic effect. However, the efficiency of these devices does not exceed 30% since the process has not been studied. It has been shown that electric pulse processing of ore at the beneficiation stage can significantly increase the content of copper and other valuable components in the studied samples. At the same time, neither in Kazakhstan nor abroad, the industrial use of electric pulse installations has not yet become widespread, since specific requirements for the generator parameters. One of the main reasons holding back the development of electric discharge technologies is the imperfection of electrical equipment.

3. A chaotic pulse generator with inertial nonlinearity

The description of the classical model of a chaotic pulse generator, in particular the generalized equations of generators with 1.5 degrees of freedom, is given in [17, 18, 27]. A block diagram of a radio engineering device and a system of equations are presented, the solution of which describes self-oscillations arising in the generator. It is shown that this division of self-oscillating systems does not reflect fundamental differences in the mechanisms of the development of strange attractors [27]. The authors proposed a modified generator with an inertial nonlinearity that creates stochastic oscillations with a corresponding strange attractor in a three-dimensional phase space. Let us use the developed oscillator circuit, which is an RLC oscillator with fluctuating parameters consisting of a selective element, an amplifier in the feedback circuit, and an amplifier in the nonlinear converter circuit (Fig. 1).

We adapt this generator to calculate the parameters of the modified equivalent circuit of the generator of electric discharge pulses. In the weakly inertial mode of operation of the generator, the feedback nonlinearity can be described through the behavior of the nonlinear converter and can be considered constant, or the parameter has been set to zero. In [20], a system of equations was derived and presented that describes the operation of such a generator. Let us give an example of the derivation of this system of equations. The equation for the current in the generator circuit is presented in the form

$$\frac{di}{dt}=\frac{R}{L}i+\frac{1}{LC}\int(i-M\frac{dGi}{dt})dt=0, \tag{1}$$

where: L is inductance; R - resistance; C - circuit capacity; M - mutual inductance; G - steepness of the amplifier in the feedback circuit; t - time.

Accepting the following conditions and notation condition

$$i=x, \quad \omega_0^2=\frac{1}{LC} \quad \text{and} \quad \dot{V}=-\gamma V+\gamma\phi(x), \tag{2}$$

We obtain

$$\ddot{x}+\frac{R}{L}\dot{x}+\omega_0^2M(\dot{G}x+G\dot{x})=0, \;\; G=G_0-G_1x^2-bV \tag{3}$$

where: V is the voltage at the output of the inertial converter; G_0, G, γ, b - parameters; $\phi(x)$ - non-linear function describing the operation of a non-linear converter.

Introducing the following notation:

$$\mu=M\omega_0^2G_0-\frac{R}{L}, \;\; \beta=M\omega_0^2b, \;\; \delta=M\omega_0^2G_1$$

from Equation 3 it follows

$$\ddot{x}+\frac{R}{L}\dot{x}+\omega_0^2x-M\omega_0^2(G_0-G_1x^2-bV)\dot{x}-M\omega_0^2$$
$$(-2G_1x\dot{x}-bV)x=0.$$

or

$$\ddot{x}+(\beta V-\mu)\dot{x}+\omega_0^2x+3\delta x^2\dot{x}+\beta\dot{V}x=0,$$

and there is:

$$dotx=(\mu-\beta V)x+y-\delta x^3 \tag{4}$$

where $y=-\omega_0^2x$.

Let's transform into a system of equations:

$$\begin{cases} \frac{dx}{\omega_0dt}=\left(\frac{\mu}{\omega_0}-\frac{\beta V}{\omega_0}\right)x+\frac{y}{\omega_0}-\frac{\delta}{\omega_0}x^3 \\ \frac{d(\frac{y}{\omega_0})}{\omega_0dt}=-x \\ \frac{d(\frac{\beta V}{\omega_0})}{\omega_0dt}=\frac{y}{\omega_0}\frac{\beta V}{\omega_0}+\frac{y}{\omega_0}\frac{\beta}{\omega_0}\phi(x). \end{cases} \tag{5}$$

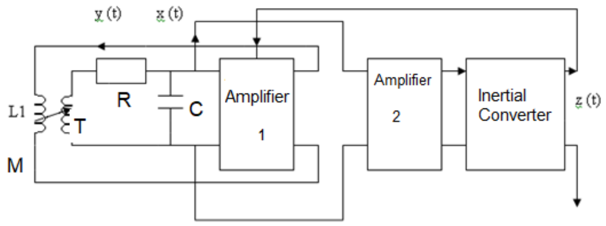

Figure 1. Scheme of the RLC generator.

To simplify the writing of the resulting system of equations, the following notation were introduced

$$\begin{aligned}&\tau=\omega_0 t,\ \ m=\frac{\mu}{\omega_0}=M\omega_0 G_0-\frac{R}{L\omega_0},\\&d=\frac{\delta}{\omega_0}=M\omega_0 G_1,\ \ g=\frac{y}{\omega_0}\end{aligned}\tag{6}$$

and

$$x=x,\ \ Y=\frac{y}{\omega_0},\ \ Z=\frac{\beta V}{\omega_0}=M\omega_0 bV,\ \ \phi(x)=M\omega_0 b\phi(x).\tag{7}$$

Assuming $\phi(x)=g\varphi(x)x^2$, we obtain for derivatives with respect to τ:

$$\begin{cases}\dot{X}=(m-Z)X+\frac{Y}{K}(m,g,\tau)-dX^3\\ \dot{Y}=-X\\ \dot{Z}=g(\varphi(X)X^2-Z)\end{cases}\qquad \varphi(x)=\begin{cases}1,x>0\\0,x\le 0.\end{cases}\tag{8}$$

As a result of the transformations carried out, a system of applicable ones was obtained, which include solutions for various values, allowing the parameters of the model to take into account the dynamics of significant fast-changing technological processes.

4. RC - electric discharge generator with fluctuation parameters

The system of Equations 8 was derived for the RLC generator. Let us consider the possibility of describing an RC electric discharge generator with fluctuating parameters (Fig. 2) based on a similar system of equations. Let us derive a system of equations for the RC chain. Kirchhoff's law for a point is written as follows:

$$i=i_1+i_2=i_1+\frac{u_2}{R_n}.\tag{9}$$

For contours I, II, III:

$$\text{I. } iR_3+\int\frac{i_2}{C_p}dt+u_2=u_1\tag{10}$$

$$\text{II. } -\int\frac{i_1}{C}dt+\int\frac{i_2}{C_p}dt+i_2R_\Pi=0,\tag{11}$$

$$\text{III. } -\int\frac{i_1}{C}dt+\int\frac{i_2}{C_p}dt+u_2=0\tag{12}$$

where $u_1=f(u_2)$, and $f(u_2)$ is the amplifier function. Differentiating with respect to time the first Equation 12 and taking into account 11 we obtain

$$\frac{i_1}{C}-\frac{i_2}{C_\Pi}=\dot{u}_2\tag{13}$$

$$i_1=\frac{C}{C_p}i_2+C\dot{u}_2,\ \ i_2=\frac{u_2}{R_\Pi},\ \ i=\frac{C}{C_p}i_2+C\dot{u}_2+i_2,$$

$$i=\frac{C}{C_pR_\Pi}u_2+\frac{1}{R_\Pi}u_2+C\dot{u}_2$$

For circuit I:

$$\begin{aligned}&\frac{CR_3}{C_pR_\Pi}u_2+\frac{R_3}{R_\Pi}u_2+R_3C\dot{u}_2+\int\frac{u_2}{C_pR_\Pi}dt+u_2=u_1,\\&u_1=f(u_2)\end{aligned}\tag{14}$$

By differentiating 14 we get

$$\begin{aligned}&\frac{CR_3}{C_pR_\Pi}\dot{u}_2+\frac{R_3}{R_\Pi}\dot{u}_2+R_3C\ddot{u}_2+\frac{1}{C_pR_\Pi}u_2+\dot{u}_2=u_1,\\&\dot{u}_1=\frac{df(u_2)}{dt}\end{aligned}\tag{15}$$

Let introduce the notation $\omega_0=1/(CR_3)$, $\omega=1/(C_pR_3)$, and divide 15 by R_3C

$$\begin{aligned}&\ddot{u}_2+\left(\frac{1}{C_pR_\Pi}+\rightleftarrows\frac{1}{CR_\Pi}+\frac{1}{CR_3}\right)\dot{u}_2+\\&\qquad\frac{1}{CR_3C_pR_\Pi}u_2-\frac{1}{R_3C}\frac{df(u_2)}{dt}=0\\&\ddot{u}_2+(\omega+\omega_0+\frac{1}{CR_\Pi})\dot{u}_2+\omega_0\omega u_2-\omega_0\frac{df(u_2)}{dt}=0\\&\ddot{u}_2+\acute{\omega}\dot{u}_2+\omega_0\omega u_2-\omega_0\frac{df(u_2)}{dt}=0\end{aligned}\tag{16}$$

We represent the amplifier function in the form

$$f(u_2)=ku_2,\ \ k=k_0-k_1u_2^2-bV,\tag{17}$$

where, k is the slope of the amplifier; k_0, k_1, b - are its parameters; V - voltage at the output of the inertial converter, which is determined from the equation

$$\dot{V}=-\gamma V+\gamma\phi(x),\tag{18}$$

here $\phi(x)$ - non-linear function describing the operation of a non-linear converter.
Then

$$\frac{df(u_2)}{dt}=(k_0-k_1u_2^2-bV)\dot{u}_2+(-2k_1u_2\dot{u}_2-b\dot{V})u_2.$$

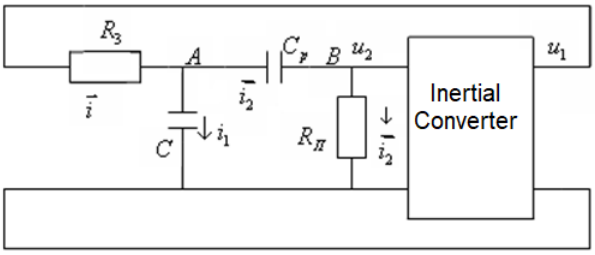

Figure 2. Scheme of an RC-electric discharge generator.

We introduce the notation $x = u_2$. Then, combining Equations 16-18, we obtain

$$\ddot{x} + \acute{\omega}\dot{x} - \omega_0(k_0 - k_1x^2 - bV)\dot{x} + \omega_0\omega x - \omega_0(-2kx\dot{x} - bV)x = 0$$

$$\ddot{x} + \left(\frac{\acute{\omega}}{\omega_0} - k_0 + bV\right)\omega_0\dot{x} + \omega_0\omega x + 3\omega_0k_1x^2\dot{x} + \omega_0bVx = 0 \tag{19}$$

Let's replace

$$y = -\omega_0\omega x; \quad m = -\frac{\omega}{\omega_0} + k_0; \quad d = k_1,$$

After integration and change of variables, we have

$$\dot{x} + (m - bV)\omega_0x - y + \omega_0dx^3 = 0$$

$$\left\{\begin{array}{c} \frac{dx}{\omega_0dt} = (m - bV)x + \frac{y}{\omega_0} - dx^3 \\ \frac{d(\frac{y}{\omega_0})}{\omega_0dt} = -x \\ \frac{d(bV)}{\omega_0dt} = -\frac{y}{\omega_0}bV + \frac{y}{\omega_0}\varphi(x) \end{array}\right\} \tag{20}$$

If accept $X = x$, $Y = y/\omega_0$, $Z = bV$, $g = y/\omega_0$, $r = \omega_0t$, we obtain

$$\begin{cases} \dot{x} = (m - z)x + \frac{y}{k(m,g,r)} - dx^3; \\ \dot{y} = -x; \\ \dot{z} = g(\varphi(x)x^2 - z), \end{cases} \qquad J(x) = \begin{cases} 1, x > 0 \\ 0, x \leq 0. \end{cases} \tag{21}$$

Here $J(x)$ is the Heaviside function.

The real generator and the oscillatory circuit have an inertial nonlinearity, and the range of values of the inertia parameter g is limited to a certain interval, the values of the parameters themselves fluctuate. The original system is converted to this form to take into account the nonlinearity. Thus, Equations 8 or 21 have almost the same form and describe the operation of an RC-EG generator with fluctuating parameters.

For $g > 1$, the parameter b can be taken equal to 0, however, in order to obtain an adjustable form of the intermittent signal, we introduce a new parameter μ - the coefficient that regulates the value of Z (μ - is the gain); g is the ratio of the frequency of the nonlinear receiver and the oscillatory circuit, and $g > 1$.Then the system of equations takes the form:

$$\begin{cases} \dot{x} = (m - \mu.z).x + \frac{y}{k(t)}; \\ \dot{y} = -x; \\ \dot{z} = g(J(x).x^2 - z), \end{cases} \qquad J(x) = \begin{cases} 1, x > 0 \\ 0, x < 0, \end{cases} \tag{22}$$

where $k(t) = 1 + D\cos\omega t$.
Then we get

$$\begin{cases} \dot{x} = (m - \mu.z).x + \frac{y}{(1+D\cos(x))}; \\ \dot{y} = -x; \dot{z} = g(J(x).x^2 - z), \end{cases} \tag{23}$$

A feature of system 23 is that instead of the parameter $k(t)$, a function is introduced that describes the dynamics of the pulsed current in the form of an explicit cosine dependence [10, 14]. This dependence can be interpreted as a mode of pulsed voltage supply from the generator. The resulting system of equations is called dynamic. To verify the resulting system of equations, we numerically solve system 23 and construct time sweeps of the electrical parameters of the model circuit, which can then be compared with experimental data.

5. Discussion of results

5.1 Numerical modeling of the generator parameters

The system of Equations 23 is numerically investigated by the 4th-order Runge-Kutt method using the standard procedure ode45 of the Matlab package. The integration step in the main calculations was taken to be equal to $\delta = 10^{-3}$. Previously, in the "work" block, the calculated functions were described, then the initial data and constants were entered. Then, referring to the Runge-Kutt calculation program, the commands for constructing dependency graphs and phase portraits are written. As a result of calculations,

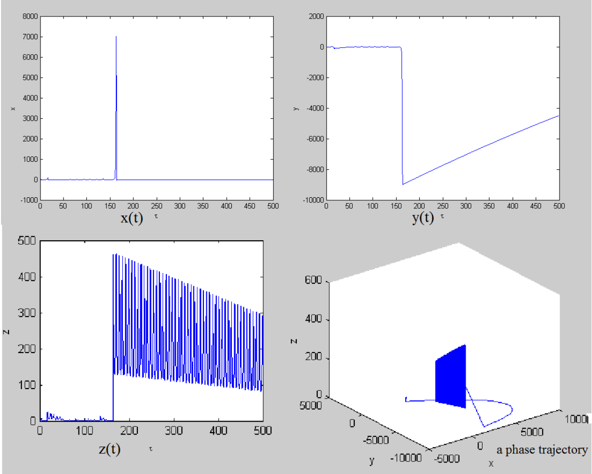

Figure 3. Solutions of the system of dynamic Equations (23) and phase trajectory, $D = 0.95$.

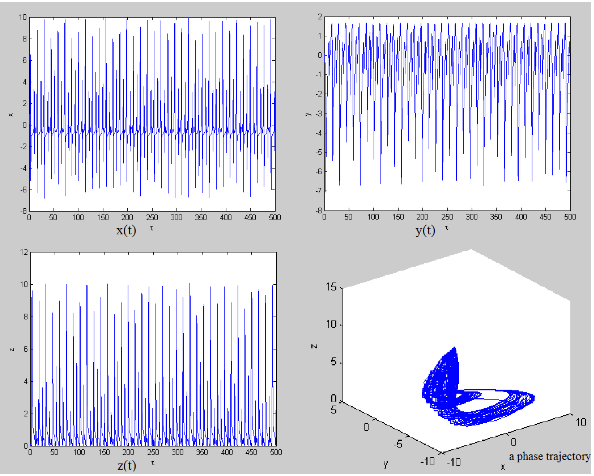

Figure 4. Solutions of the system of dynamic Equations (23) and phase trajectory, $D = 0.75$.

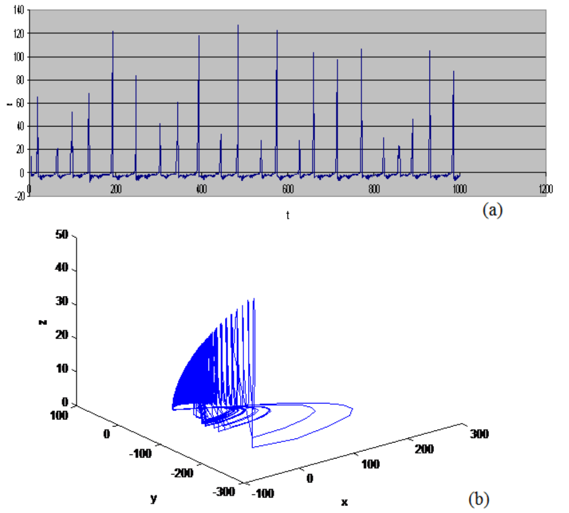

Figure 5. Calculated graph of the current (a) and phase trajectory (b) of the system (23) with the parameters: $D = 0.9$, $\mu = 3.0$, $m = 2.3$, $g = 3.0$.

solutions of dynamic Equations 23 and phase portraits were obtained for various initial electrical parameters of the circuit (Fig. 3, 4).

Figures 5-6 show examples of calculation results, which are time sweeps of the calculated impulse current signals and their phase portraits for various parameters of the proposed model.

Based on the calculation results, the limits of variation of the parameters of the system of Equations 23 are determined. In calculations at $D = 0.8$, the parameters varied within the limits $\mu = 3.0 \div 5.0$, $m = 2.1 \div 2.5$, $g = 2.0 \div 5.0$. The compiled program allows you to change all four parameters included in the system of dynamic equations.

5.2 Results of electric discharge pulses oscillography

In experiments, pulse processes in multiphase media were implemented by the organization of rapidly changing processes that accompany HVEDs in an inhomogeneous liquid medium. As such a medium, aqueous solutions of minerals, coals, etc. were used, which were subjected to electrohydraulic treatment at various parameters of the discharge circuit. The development of the discharge structure in the dielectric and the work of the pulse voltage generator are modeled on the basis of the equivalent circuit of the oscillatory circuit, which contains capacity C, resistance R, and inductance L (Fig. 7).

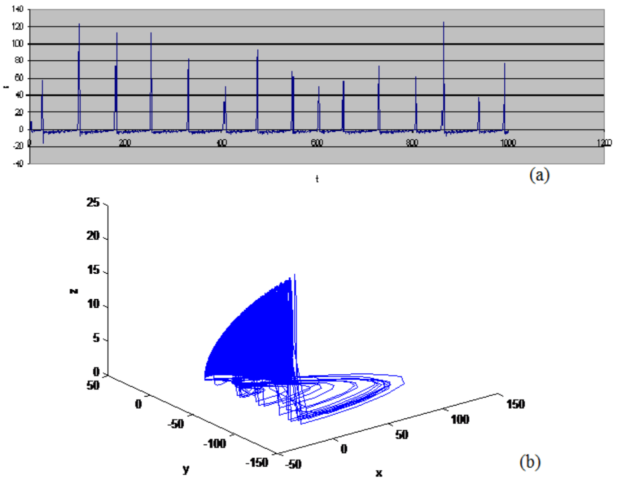

Figure 6. Calculated graph of the current (a) and phase trajectory (b) of the system (23) with the parameters: $D = 0.75$, $\mu = 5.0$, $m = 2.3$, $g = 4.0$.

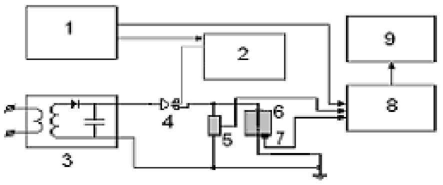

Figure 7. Circuit of the high-voltage test desk for pressure measurement: 1- delayed-pulse oscillator, 2- firing block, 3- surge current generator and energy storage, 4- cell-type tube, 5- potential divider, 6- useful capacity, 7- pulse pressure transducer, 8- oscillograph PCS-500, 9- computer.

For the registration of the pressure pulse of a blast wave in a working cavity, the pressure meter has been established.

Measurements were carried out at the following parameters of the discharge circuit: voltage $U = (2.5 \div 5.0)$ kV, storage capacity $C = (0.10 \div 0.25)$ mkF; interelectrode distance $l = (0.5 \div 12)$ mm; discharge-repetition frequency $n = (1.5 \div 2.0)$ Hz. The accuracy of pulsed current and voltage measurements is equal to $3-5\%$. The experiments were carried out using the automation system of an electronic oscilloscope. The resolution of the time base is 100 points per 5 s; the current step is 32 points per 15 mV. A digital storage oscilloscope allows you to see the time base of pulsed signals on a computer monitor, and is used as a spectrum analyzer [18].

The PCLab 2000 software allows you to measure the magnitude of signals using special vertical markers. Using horizontal markers, it is possible to measure the duration

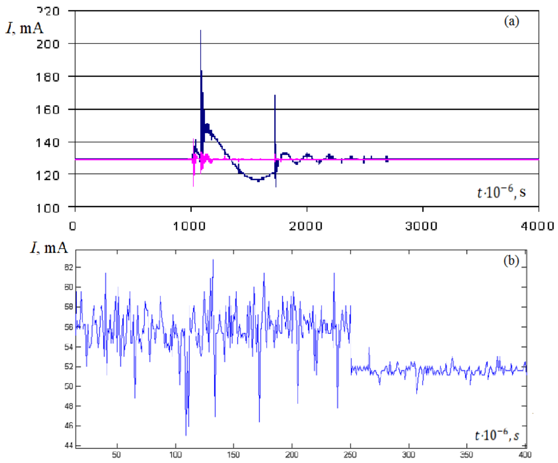

Figure 8. Current oscillograms: (a) single impulses; (b) under repeated electrodigit influences.

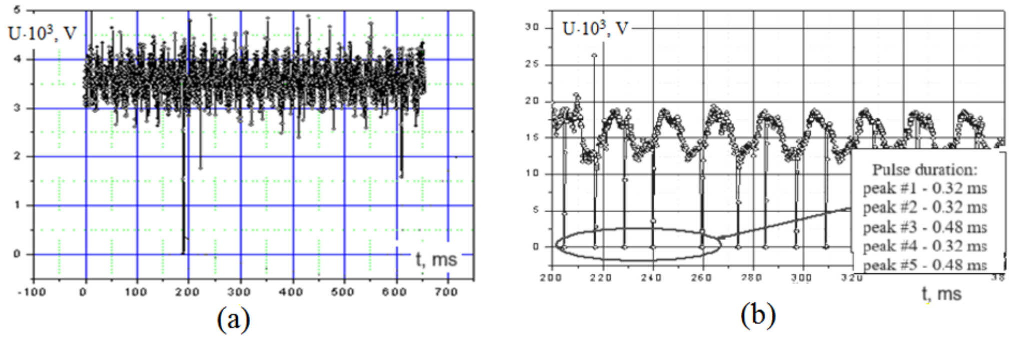

Figure 9. Oscillogram of the impulse voltage at: (a) $C = 0.25\ \mu$F, $l = 1.5$ mm; (b) $C = 0.10\ \mu$F, $l = 1.0$ mm.

of a signal. An automatic digital oscilloscope determines the frequency. In experiments, the measuring technique of current pulses of duration $0.32 - 0.64$ ms by means of a digital oscilloscope (Velleman PCS-500) has been developed. The software PC Lab-2000 has allowed us to observe single impulses and discharge current oscillograms (Fig. 8).

It's possible to view signals with repetitive, stable peaks at various frequencies. In Fig. 9, example of oscillograms of impulse voltage are given. Oscillogram in Fig. 9 was obtained at a low pulse frequency, which can ensure that the pulse peaks were recorded. The voltage and current of the discharge channel during electrical breakdown of the liquid were recorded using a pulse voltage divider (division ratio 1:100) and a coaxial current shunt. Discharge duration measurements were carried out with the following parameters: $C = (0.10 \div 1.0)$ mkF; distance $l = (1.0 \div 5)$ mm; $U = (1.0 \div 5.0)$ kV.

In Figure 9, four pulse peaks can be distinguished, which have durations of 0.48 ms and 0.64 ms, with the difference in measured durations being 0.16 ms. The duration of peaks located outside the graph area can be 0.32 ms, 0.48 ms, 0.64ms. On the oscillogram of the pulsed current, the peaks alternate ap-periodically, regardless of the chosen values of the variable parameters of the discharge circuit. It can be seen that the time duration of the pulses under different experimental conditions are the same. However, it is impossible to compare one peak with another measured with other parameters based on the time of appearance. In order to determine general statistical patterns of signals, an analysis of experimental data obtained with various processing modes was carried out, which shows a wide variety of pulse signals with sometimes repeating pulse shapes. It's established that the highest peak corresponds to the voltage of discards. And created by the shock wave the pressure is recorded by the piezometric sensor immediately after the electric discharge in the liquid.

6. Conclusion

Practice shows that electrohydraulic installations using pulse signal generators are convenient from a technical point of view for implementing various technological processes with rapidly changing high-gradient parameters. The formation of streamers of electrical discharges in a liquid occurs very quickly and is stochastic in nature. This fact does not allow us to model such rapidly changing processes based on solving systems of classical differential equations. Therefore, the simulation was carried out on the basis of a stochastically deterministic approach to describing the dynamics of the growth of the discharge structure and the operation of the high-voltage generator. It was previously shown that stochastic oscillations with a corresponding strange attractor in three-dimensional phase space can be obtained using a modified RLC oscillator with inertial nonlinearity. The article presents a comparative analysis of the results of numerical calculations and presents experimental data. The calculation results are in satisfactory agreement with the experimentally obtained oscillograms of the pulsed current and qualitatively convey the nature of the dynamic patterns. It should be noted that such a representation of the pulse parameters as a nonlinear dynamic self-oscillating system with the properties of a chaotic pulse generator with inertial nonlinearity has not yet been discovered among published works.

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Ethical approval
This manuscript does not report on or involve the use of any animal or human data or tissue. So the ethical approval is not applicable.

Author contribution statement
Saule E. Sakipova and Aya Edris developed the generator models, analyzed measurements and calculations data. Bekbolat R. Nussupbekov and Ulan B. Nussupbekov developed schemes, carried out experimental tests, formulated conclusions. Didar A. Ospanova and Raikhan S. Turlybekova calculated numerical experiments in the MatLab package and processing results.

Data Availability Statement
All data generated or analyzed during the reported research are presented in the article.

Conflict of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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