UDC 681.52:537.528:544.5
DOI https://doi.org/10.15589/znp2025.4(502).21

CONTROL OF HIGH-VOLTAGE MULTI-PULSE DISCHARGE IN AN EXOTHERMIC ENVIRONMENT

КЕРУВАННЯ ВИСОКОВОЛЬТНИМ БАГАТОІМПУЛЬСНИМ РОЗРЯДОМ В ЕКЗОТЕРМІЧНОМУ СЕРЕДОВИЩІ

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Abstract. *The aim* of the work is to analyze a high-voltage multi-pulse discharge in condensed exothermic media as a control object, determine information coordinates and initial conditions, and develop a control algorithm that ensures energy efficiency of exothermic energy conversion in the discharge channel.
Method. The assessment of the efficiency of exothermic energy conversion in the high-voltage discharge channel is carried out using the developed methodology for experimentally determining the amount of chemical energy released due to exothermic transformations, using mathematical modeling of processes in the discharge channel.
Results. A study of a high-voltage multi-pulse discharge in an exothermic environment as a control object was conducted. Rules for finding the initial conditions of the control algorithm were proposed. A correlation analysis of the relationship between electrodynamic and hydrodynamic characteristics was conducted and information coordinates were determined. A control algorithm for a high-voltage multi-pulse discharge in an exothermic environment was developed.
Scientific novelty. Based on the study of the correlation between the electrodynamic and hydrodynamic characteristics of a high-voltage discharge in an exothermic environment with controlled input of electrical energy, reliable information coordinates were determined. The control algorithm was developed using those coordinates.
Practical significance. The use of the proposed algorithm for controlling a high-voltage multi-pulse discharge in an exothermic environment will ensure an increase in the time of the exothermic reaction in a self-sustaining mode until the exothermic mixture is completely burned in each process implementation. Due to this, unproductive losses of chemical and electrical energy are reduced in each implementation while the amount of total usable energy, allocated for performing technological operations, will increase, without increasing electricity costs.
Key words: discharge-pulse technologies; high-voltage multi-pulse discharge; exothermic mixture; chemical energy; pulse current generator; control algorithm; information coordinates.

Анотація. *Метою* роботи є аналіз високовольтного багатоімпульсного розряду в конденсованих екзотермічних середовищах як об'єкта керування, визначення інформаційних координат та початкових умов, розробка алгоритму керування, що забезпечує енергетичну ефективність екзотермічного перетворення енергії в каналі розряду.
Методика. Оцінка ефективності екзотермічного перетворення енергії в каналі високовольтного розряду проводиться з використанням розробленої методики експериментального визначення кількості хімічної енергії, яка виділилась за рахунок екзотермічних перетворень, з використанням математичного моделювання процесів в каналі розряду.
Результати. Проведено дослідження високовольтного багатоімпульсного розряду в екзотермічному середовищі як об'єкта керування. Запропоновано правила знаходження початкових умов алгоритму керування. Проведено кореляційний аналіз взаємозв'язку електродинамічних і гідродинамічних характеристик і визначено інформаційні координати. Розроблено алгоритм керування високовольтним багатоімпульсним розрядом в екзотермічному середовищі.
Наукова новизна. На основі дослідження кореляційного взаємозв'язку електродинамічних і гідродинамічних характеристик високовольтного розряду в екзотермічному середовищі з керованим введенням електричної енергії визначено достовірні інформаційні координати, з використанням яких розроблено алгоритм керування.
Практична значимість. Використання запропонованого алгоритму керування високовольтним багатоімпульсним розрядом в екзотермічному середовищі забезпечить збільшення часу протікання екзотермічної реакції в самопідтримному режимі до повного згорання екзотермічної суміші при кожній реалізації процесу. За рахунок цього зменшаються непродуктивні втрати хімічної і електричної енергії при кожній реалізації і збільшить-

ся кількість виділеної сумарної енергії для виконання технологічних операцій, без збільшення витрат електроенергії.
Ключові слова: розрядно-імпульсні технології; високовольтний багатоімпульсний розряд; екзотермічна суміш; хімічна енергія; генератор імпульсних струмів; алгоритм керування; інформаційні координати.

PROBLEM STATEMENT

In technologies of discharge-pulse destruction of natural and artificial outsizes, loosening of strong bottom soils, where a long-term pressure pulse with high energy is required, high-voltage pulse electric discharge is widely used in chemically active condensed media capable of exothermic transformations in the explosive combustion mode under the influence of high temperatures and pressures created in the discharge channel. The energy released during exothermic transformations of a chemically active medium is added to the electrical energy accumulated on the plates of the capacitor bank of the energy source, as which a pulse current generator (PCG) is used. As a result, the destruction energy increases several times without increasing the accumulated electrical energy in the capacitor bank [1–4]. An important advantage of discharge-pulse technologies using a high-voltage discharge in an exothermic environment is controllability, in contrast to technologies using explosives. Therefore, the development of control systems for the high-voltage pulse discharge mode in chemically active condensed environments is an urgent task, the solution of which requires the study of the high-voltage pulse discharge in an exothermic environment as a control object, the determination of information coordinates and initial conditions, and the development of a control algorithm that ensures the efficiency of exothermic energy conversion in the discharge channel.

ANALYSIS OF LATEST RESEARCH AND PUBLICATIONS

Previous studies have shown that the use of high-voltage pulse discharge in an exothermic environment allows expanding the scope of application of pulsed material processing technologies. This is due to the fact that with identical characteristics of pulse current generators used in pulse discharge technologies as an energy source, when using a discharge in chemically active condensed environments capable of exothermic transformations, the amplitude and duration of the generated pressure pulse increase. In [5], pressure profiles, obtained taking into account the emission caused by the reaction of exothermic mixtures, are analyzed.

Ensuring energy efficiency is important in the technological use of a discharge in an exothermic environment. In [6, 7], a single-pulse mode of energy input into the discharge channel is investigated, in which the combustion reaction of the exothermic mixture stops within several tens of microseconds, which leads to incomplete combustion of exothermic mixtures and loss of potential chemical energy. This causes insufficient efficiency of single-pulse energy input due to the short duration of the pressure pulse generated by a high-voltage discharge.

Analysis of the results of the study of the introduction of electrical energy into the spark discharge channel in condensed environments [8–10] showed that on the basis of multi-circuit pulse current generators it is possible to form pressure pulses with several consecutive pulsations, the number of which is equal to the number of pulsations of electric power. Each pulse provides an increase in the amplitude and duration of the pressure pulse. The analyzed literary sources reasonably show the advantages of multi-pulse energy input into the discharge channel.

The conducted analysis of references shows that the issue of controlling the supply of consecutive discharge pulses to ensure the efficiency of exothermic transformations during each implementation of a high-voltage multi-pulse discharge in an exothermic environment remains open.

PURPOSE OF THE RESEARCH

The purpose of the study is to analyze a high-voltage multi-pulse discharge in condensed exothermic environments as a control object, determine information coordinates and initial conditions, and develop a control algorithm that ensures the energy efficiency of exothermic energy conversion in the discharge channel.

To achieve this goal, the following tasks were performed:

– the influence of the modes of controlled input of electrical energy into the discharge channel on the efficiency of exothermic energy conversion was investigated in order to determine the initial conditions of the control algorithm;

– the relationship between the electrodynamic and hydrodynamic characteristics of the discharge with the controlled input of electrical energy was investigated in order to determine reliable information coordinates;

– a control algorithm for the high-voltage multi-pulse discharge mode in condensed exothermic environments was developed, which allows to ensure the specified technological modes and maximum efficiency of exothermic energy conversion for each discharge implementation.

MAIN SECTION

The purpose of controlling the process of high-voltage pulse discharge in condensed exothermic media is to ensure maximum efficiency of exothermic energy conversion at each implementation, which determines the efficiency of the technological action on the processing objects. The efficiency of exothermic energy conversion is ensured by the complete combustion of the mass of the exothermic mixture M. With complete combustion, the amount of chemical energy released is close to the potential energy of the exothermic mixture. However, with uncontrolled single-pulse energy input into the discharge channel, only about 20 % of the total amount of exothermic mixture, introduced into the discharge gap, reacts. The main reason for this is the termination of the self-sustaining exothermic reaction, due to a dramatic decrease in pressure in the discharge channel from hundreds of MPa to less than $P_{\min}$ = 23 MPa, which is equal to the minimum pressure level required for the self-sustaining exothermic reaction to occur.

In order to increase the efficiency of chemical energy release, it is necessary to maintain the pressure level in the discharge channel higher than the minimum for a longer time. A method is proposed to increase the efficiency of exothermic transformations at each discharge realization, which is based on the sequential portionwise introduction of electrical energy into the discharge channel according to a given algorithm, with current indirect (mediated) control of the pressure level in the discharge channel in order to prevent the extinction of the self-sustaining exothermic reaction. The implementation of this method requires the development of an appropriate algorithm for controlling the process of introducing electrical energy into the discharge channel.

With controlled multi-pulse introduction of electrical energy into the discharge channel, it is necessary to determine the initial distribution of electrical energy between pulses, which ensures the maximum specific energy efficiency of the exothermic transformation. An objective criterion for the efficiency of releasing potential chemical energy of an exothermic mixture can be the value $\mu = \Delta W_x/M$ – specific energy efficiency of exothermic transformation, J/kg: The total energy W_t required to perform the specified technological operations consists of the electrical energy introduced by successive pulses $W_\tau = W_1 + W_2 + \ldots + W_i$ and the thermal chemical energy ΔW_x released during oxidation of the exothermic mixture. Studies have been conducted on the influence of the pulse energy ratio on the efficiency of releasing potential chemical energy of an exothermic mixture and the dependences $\mu = f(W_\tau/W_i)$ were obtained, which have maxima, which allows us to determine the optimal ratios W_τ/W_i [11].

Using the optimal ratios W_τ/W_1, $W_2, \ldots, W_i$, we determine the required voltage U_1, $U_2, \ldots, U_i$ on the capacitors of a multi-circuit pulse current generator (PCG), which have a constant capacitance, from the ratios:

$$W_\tau = \frac{W_t - \Delta W_x}{\eta}; \quad W_\tau = W_1 + W_2 + \ldots + W_i; \quad W_i = \frac{C_i U_i^2}{2}. \quad (1)$$

The determined voltage values U_i are used as the initial conditions of the control algorithm.

The next stage is the development of a control algorithm for the signal to turn on the next discharge circuit to increase the time of the exothermic reaction in the self-sustaining mode. The next discharge circuit should be turned on at the moment when the pressure in the discharge channel reaches the maximum permissible minimum value for this exothermic mixture. It is impossible to set the time of the second pulse in advance due to the stochasticity of the processes in the discharge channel. It is important to use a reliable information coordinate for indirect (mediated) estimation of the pressure in the discharge channel $P(t)$. The pressure in the discharge channel has a significant statistical spread and is operationally undefined, and therefore cannot be used as an information coordinate in the control system. In this regard, studies were conducted to establish operationally determined information coordinates that can be an indirect estimate of the pressure in the discharge channel. Such quantities include breakdown voltage $U(t)$, discharge current $I(t)$, electric power $N(t)$. Electrodynamic and hydrodynamic processes in the discharge channel are stochastic in nature. There are a number of studies that show that these characteristics obey the normal distribution law [12]. In order to establish the relationship between the electrodynamic $U(t)$, $I(t)$, $N(t)$ and hydrodynamic $P(t)$ characteristics, their correlation analysis was conducted. Since the studied quantities are distributed normally, the linear Pearson correlation coefficient r, which is used to estimate the linear relationship, and the coefficient of determination $R = r^2$, which characterizes the density of the relationship, were used to conduct the correlation analysis. The most dense informational connection (R = 0.9368) is observed between $P(t)$ and $N(t)$. Thus, as an informational coordinate that indirectly determines the pressure in the discharge channel, the operationally determined value of the electric power $N(t) = U(t) \cdot I(t)$ can be used. The current value of $P(t)$, corresponding to the measured value $N(t) = U(t) \cdot I(t)$, can be quickly determined by the expressions describing the processes in the discharge channel:

$$\frac{1}{\gamma - 1} \cdot \frac{d(P \cdot \pi \cdot a^2)}{dt} + P \cdot \frac{d(\pi \cdot a^2)}{dt} = \frac{N}{l}, \quad (2)$$

$$P = \frac{\rho}{2 \cdot \pi} \cdot \frac{d^2(\pi \cdot a^2)}{dt^2} \cdot \ln\left(\frac{l}{a}\right) - \frac{\rho}{8 \cdot \pi \cdot (\pi \cdot a^2)} \cdot \left(\frac{d(\pi \cdot a^2)}{dt}\right)^2, \quad (3)$$

where P is the pressure in the discharge channel, a is the radius of the discharge channel, l is the length of the discharge gap, γ is the effective adiabatic index, ρ is the density of the medium.

Using $N(t) = U(t) \cdot I(t)$ as an information coordinate will allow us to estimate the pressure in the discharge channel $P(t)$ with sufficient accuracy for timely supply of a control signal to turn on the next discharge circuit of the pulse current generator.

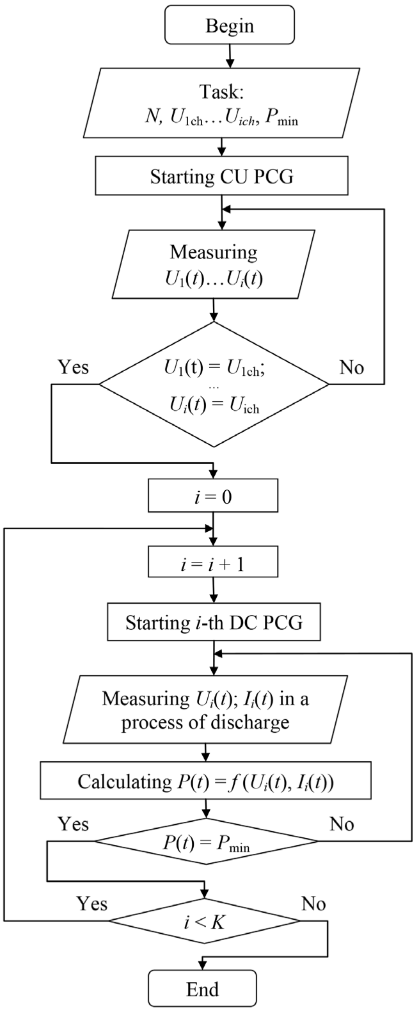

Fig. 1. Control algorithm

The automatic software control system implements the control algorithm for a multi-circuit pulse current generator, ensuring the supply of a control signal to turn on the next discharge circuit at the moment when the pressure in the discharge channel $P(t)$ reaches the minimum allowed value (Fig. 1).

The task is entered into the control system from a database that stores the results of previously conducted experimental studies and calculations that determine the required energies of successive discharge pulses $W_1 + W_2 +\ldots + W_i$, which ensure maximum efficiency of chemical energy release. The value of the limiting pressure value in the discharge channel P_{min}, which is necessary to maintain the flow of the exothermic reaction in a self-sustaining mode, is determined by the composition and mass of the exothermic mixture selected based on the given technological mode. The values of the charging voltage $U_1, U_2, \ldots, U_i$ on the capacitive energy storage devices, which correspond to the values of the electrical energy of the discharge pulses $W_1 + W_2 + \ldots + W_i$, necessary to ensure maximum efficiency of potential chemical energy release, are determined from the relations (1). The determined values are set as the initial conditions of the control algorithm ($U_{1ch}, U_{2ch}, \ldots, U_{ich}$ i P_{min}). The initial conditions also include the number of active PCG discharge circuits K, required for complete combustion of the exothermic mixture.

After setting the initial conditions, a signal is received to turn on the charging unit (CU) of the PCG for charging capacitive energy storage devices ($C_1, C_2, \ldots, C_i$). During the charging process, the current voltage values $U_1(t), U_2(t), \ldots, U_i(t)$ on the capacitive storage devices are measured by voltage sensors. Information signals from the sensors are sent to the automatic control system, where the current voltage values are compared with the set values $U_{1ch}, U_{2ch}, \ldots, U_{ich}$. At the moment when the voltages on the capacitors reach the set values, a signal is received from the automatic control system to turn on the first discharge circuit (DC) of the pulse current generator and the first discharge pulse is sent to the electrodes. The process of high-voltage electrochemical explosion of the exothermic mixture in the reaction chamber begins. During the implementation of the first discharge pulse, the voltage $U_1(t)$ is measured by a voltage sensor and the discharge current $I_1(t)$ by a current sensor that is inductively connected to the first discharge circuit. The values of the voltage $U_1(t)$ and the discharge current $I_1(t)$ are transmitted to the control system. In the control system, the current pressure value in the discharge channel of the first high-voltage discharge pulse $P(t)$ is calculated using expressions (2, 3). A pre-formed database can also be used to determine the pressure based on electrodynamic characteristics. The current pressure value in the discharge channel $P(t)$ is compared with the specified minimum limit value P_{min}, necessary to maintain the flow of the exothermic reaction in the self-sustaining mode. When the current pressure value reaches the limit value $P(t) = P_{min}$, the automatic control system sends a signal to turn on the next DC PCG. The electrodes are supplied with the next discharge pulse, which increases the pressure in the reaction chamber and ensures the further course of the exothermic reaction in a self-sustaining mode. Further cycles continue until the complete combustion of the exothermic mixture after the discharge of all K capacitors.

CONCLUSIONS

The rules for determining the initial conditions of the discharge mode control algorithm are proposed, which ensure the maximum efficiency of exothermic transformations, based on the use of the dependence of the specific energy efficiency of the potential chemical energy release of the exothermic mixture on the distribution of the total electrical energy between successive discharge pulses.

A correlation analysis of the relationship between the current pressure in the discharge channel and the electrical parameters of the discharge, which characterize the mode of electrical energy input, was carried out. According to its results, it is proposed to use the operationally determined electrical characteristics of the discharge $U(t)$, $I(t)$, $N(t)$ as information coordinates that indirectly determine the pressure in the discharge channel.

A control algorithm for a high-voltage multi-pulse discharge in an exothermic environment was developed, which allows avoiding the extinction of the exothermic reaction when the pressure is randomly reduced to the maximum permissible minimum value due to the stochasticity of the process. The use of the proposed control algorithm will ensure an increase in the time of the exothermic reaction in a self-sustaining mode until the exothermic mixture is completely burned in each process implementation. This will reduce losses of chemical and electrical energy in each implementation and increase the amount of total energy allocated for performing technological operations, without increasing electricity costs.

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Дата надходження статті до редакції: 16.11.2025
Дата затвердження статті до друку: 04.12.2025
Опубліковано: 30.12.2025