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Investigation of the properties of electrical sources of ozonators through mathematical models

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Abstract. The study of the properties of electrical power sources of ozonators through mathematical models is crucial for satisfying sanitary-hygienic and industrial needs. Ozone is a strong oxidant with disinfectant properties, making its application widespread. However, the efficiency of its production largely depends on the quality of the ozonators' electrical power sources. In this research, we developed and utilized mathematical models aimed at determining the main electrical parameters of various types of ozonators used in ozone production. The results of the study show possibilities for enhancing the energy efficiency of ozonators and optimizing their operational parameters. Mathematical modeling serves as a significant tool for predicting the operating modes and necessary electrical power parameters of ozonators, helping to increase their overall productivity and reduce the cost of ozone production. During the analysis, we considered the stability of the electrical power sources of ozonators, their high-frequency power transmission, and the level of electrical energy consumption. Our research aimed to determine how these parameters affect the ozone production process and, considering these effects, to design and improve the electrical power sources of ozonators.

1. Introduction

The application of ozone is extensive, with its disinfecting and purifying properties playing a crucial role in air and water purification systems [1, 2]. The quality and efficiency of the electrical power sources used in industrial ozone production directly affect the productivity of these devices [3]. In this context, studying the properties of the electrical sources of ozonators through mathematical models can enhance the operational efficiency of ozone production devices.

Scientific research focuses on analyzing the working parameters of ozonators, including electrical loads, current frequency, and other critical aspects of the power source [4]. Our study is directed towards identifying how the parameters of the power sources used in ozone production affect performance. Mathematical modeling efforts demonstrate how these parameters can influence productivity under various conditions and how energy efficiency can be improved.

This article discusses the scientific and technical foundations necessary for improving the design of ozonators' power sources and optimizing their industrial application. The goal of our research is to investigate the impact of power source parameters on the productivity of ozone generators and to propose methods for designing efficient devices using this information.

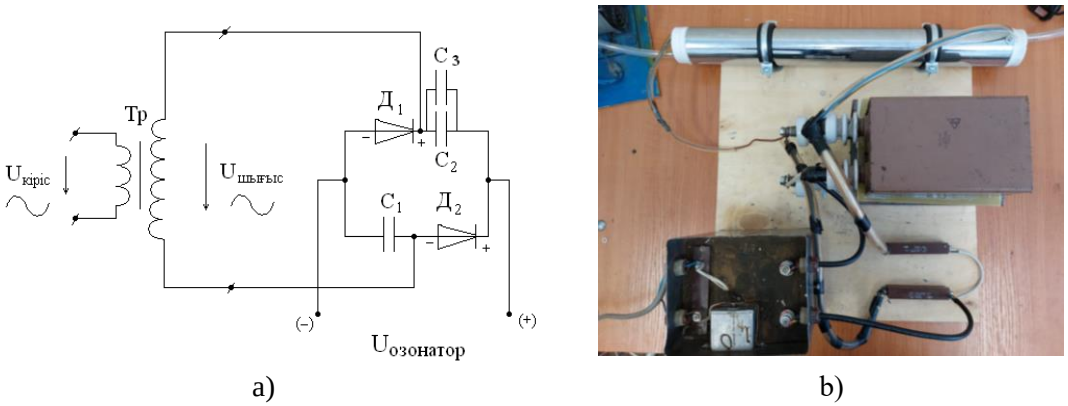
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2. Materials and methods

Materials considered in the scientific research. The need to study and develop frequency-regulated ozonation devices operating at high frequencies has emerged as a promising direction in industrial ozone production technology [5,6]. Mathematical modeling is used during the manufacturing process of ozonators. While many works have focused on modeling electromagnetic and electrochemical processes in ozonators [7, 8], developing computer models that allow studying the impact of power source parameters on the productivity of ozone generators remains a relevant issue.

Research on electromagnetic and physicochemical processes based on mathematical models was conducted at the Department of Electronics, Telecommunications, and Space Technologies at K.I. Satpaev Kazakh National Technical Research University, taking place within the electrical engineering complex [9], which includes a primary power source, three-phase rectifier, electrical filter, resonant inverter, energy circulation channel, high-voltage transformer, and the cascaded connection of the "ETRO-02" ozone generator based on electrical discharge [10, 11].

Methods used in scientific research. For modeling, MATLAB and its Simulink module are used, which enable the analytical and numerical examination of electromagnetic and physicochemical process dynamics. During modeling, we create subsystems that represent the working principles of the high-voltage transformer and the ozone generator. The electrical layout (a) and the general appearance (b) of the generator in the ozonator are shown in figure 1 below. Additionally, blocks for measuring active and reactive power are used to evaluate various aspects of the ozonator's operating modes.



a) b)

Figure 1. The electrical layout (a) and the general appearance (b) of the generator in the ozonator.

Our methodology is aimed at maximizing energy efficiency and enhancing productivity in ozone production. Through experimental work and numerical modeling conducted during this methodological process, we gain a deeper understanding of the properties of the electrical power sources of ozonators based on the accumulated data. The results of the modeling allow us to determine how the parameters of the electrical power sources affect productivity in ozone production and to apply this in optimizing ozone production processes in industrial environments.

3. Results and discussion

The computer model of the complex, created within the MATLAB integrated package environment, is aimed at optimizing electromagnetic modes and determining the installed powers of the ozonator electrical equipment (figure 2), consisting of a high-voltage transformer, ozone generator subsystem, and mathematical blocks from the Simulink library. In the subsystem (figure 3), the Active & Reactive Power block measures the active power used in the discharge chamber of the ozone generator.

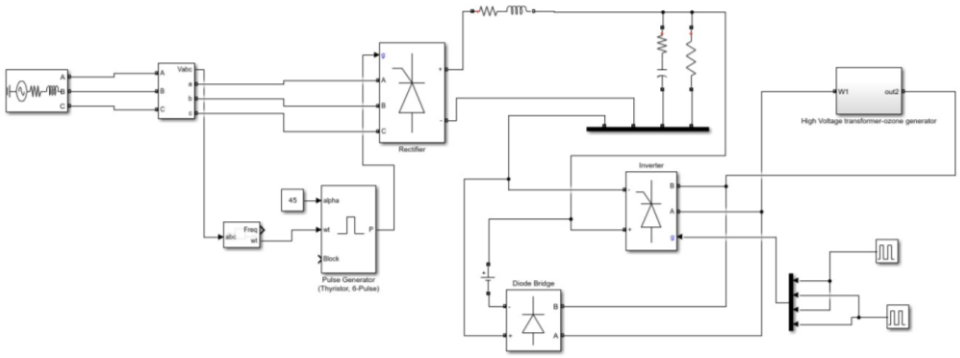


Figure 2. Structural layout of the simulation mathematical model of electromagnetic processes in ozonators.

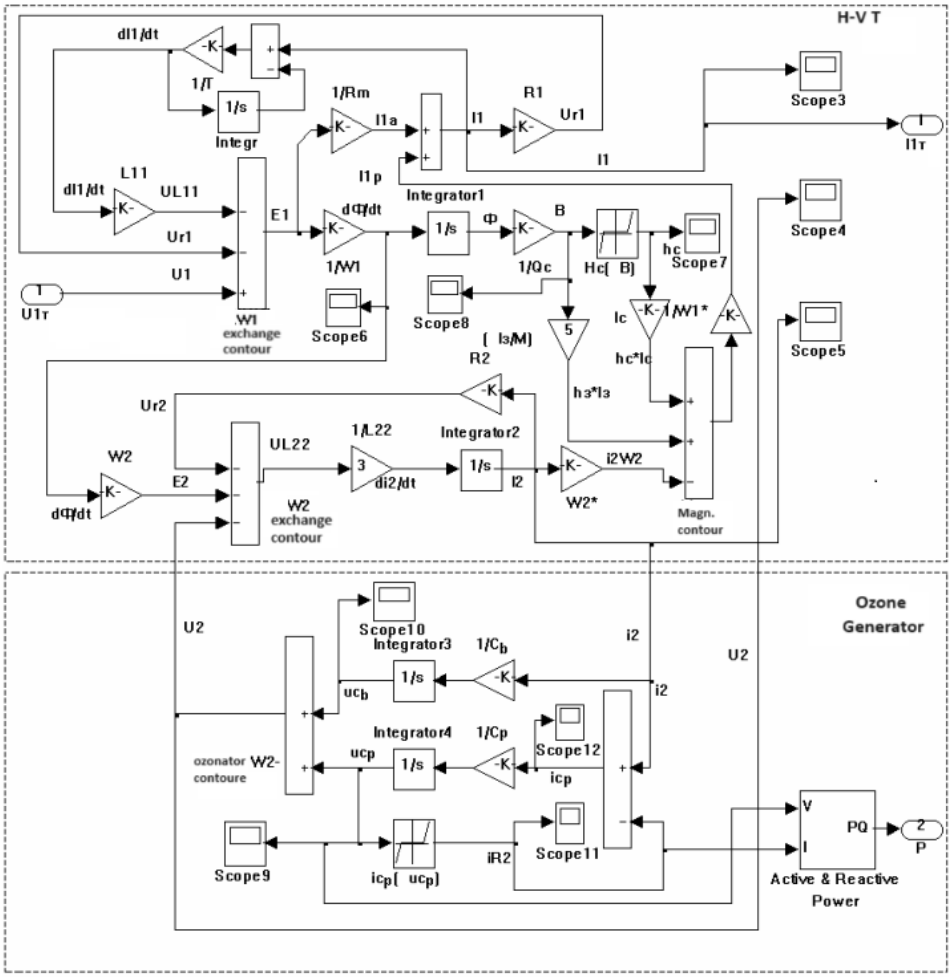


Figure 3. Simulation model of the internal system of the ETRO-02 high-voltage ozone generator.

The computer model enables the study of the impact of the energy recovery level in the power source on the integral characteristics of the ozonator, as proposed in the electrical layout [12]. Some research

works [13, 21] indicate the development of the modeling system, distinguished by the inclusion of a regulated constant voltage source between the output (-) of the "diode bridge" block and the input (+) of the "inverter" block. By changing the voltage, the reactive energy between the filter and the ozone generator is altered.

The results of the modeling are shown in figure 4. The initial two graphs display the electromotive force and voltage diagrams in the high-voltage coil of the transformer. The difference between them is explained as the commutation inductance is constructively the transformer's leakage inductance, causing the electromotive force to have a nearly rectangular shape, while the voltage appears in a peaked form. The subsequent graphs show the voltage division between the barrier capacitance (Cb) and the gap distance (Cr). Because Cb ≥ Cr, the gap distance charges faster (Cr), reaching the necessary UR value to initiate discharge. Subsequently, a breakdown occurs in the gap distance, and the capacitance discharge (Cr) is shunted with a voltage equal to the electromotive force. The high-voltage transformer continues the capacitance charging along the capacitance (E) contour. After the capacitance (Cb) is charged, its voltage (due to the energy stored in the inductance) exceeds the total voltage across the gap distance and the secondary coil of the high-voltage transformer. Then, the capacitance discharges through the gap distance, transformer, diode bridge, and DC through the filter capacitance. This process also facilitates ozone synthesis. Thus, by altering the DC voltage, the productivity of the ozone generator can be regulated [22, 23]. The subsequent graphs show the temporal diagrams of currents between the gap distance and discharge interval (figures 4 and 5). The current graph peaks twice within a half-cycle, corresponding to the energy recovery in the ozone generator. The productivity of the ozone generator is regulated by changing the output voltage of the rectifier in the constant current series or by introducing breaks in the duty cycle of the inverter, and at the same time setting the required frequency [14, 15].

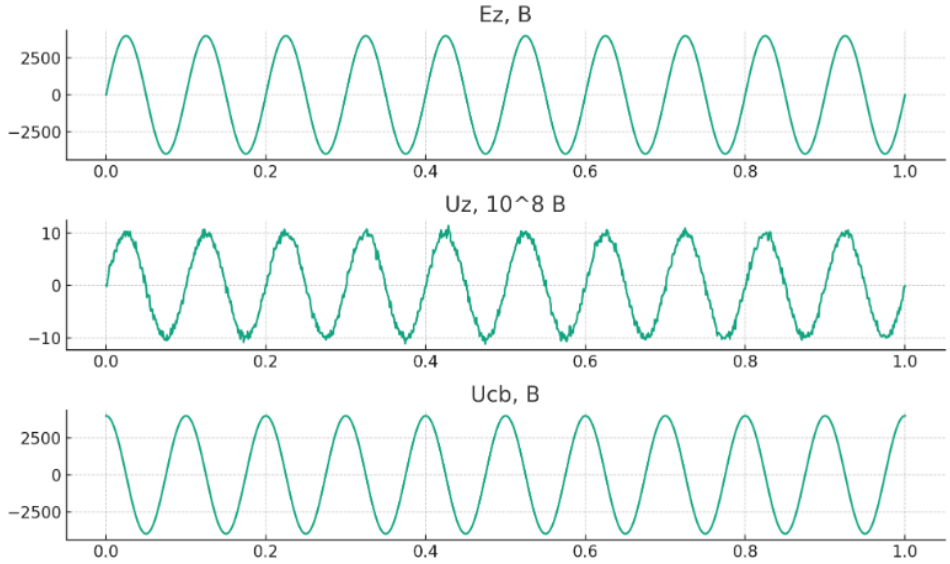


Figure 4. Sinusoidal waveforms for Ez, Uz, and Ucb over time.

This figure 4 displays three separate sinusoidal waveforms plotted over time, each marked with different variables. Each graph represents a waveform corresponding to different physical quantities (electrical field, high voltage, and indicated by Ucb) over a specific time interval. The axes and functions represented in these graphs are as follows:

1. Top graph: This is a graph of Ez, representing the electromotive force, i.e., the voltage of the electromagnetic field. The graph shows a high-amplitude sinusoidal waveform with maximum and minimum values approximately between +2500 and -2500 V/m along the axes.

2. Middle graph: This is a graph for Uz, scaled by 10−8 B, indicating that the voltage magnitude is proportional to magnetic induction. The scaling factor of 10-8 is used to adjust the measurement units. This graph has much smaller amplitude oscillations compared to the previous graph, with maximum and minimum values approximately between +10 and -10.
3. Bottom graph: This graph is for Ucb voltage, where 'cb' is an index for a specific physical quantity. The shape and amplitude of this graph are similar to the top graph, also having maximum and minimum values around +2500 and -2500 V/m.

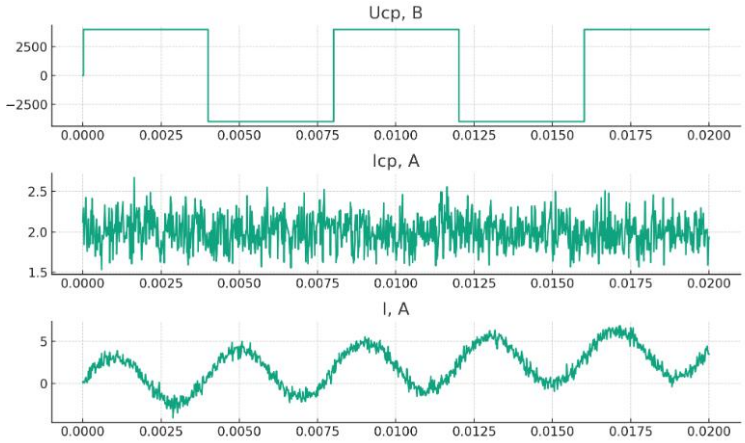
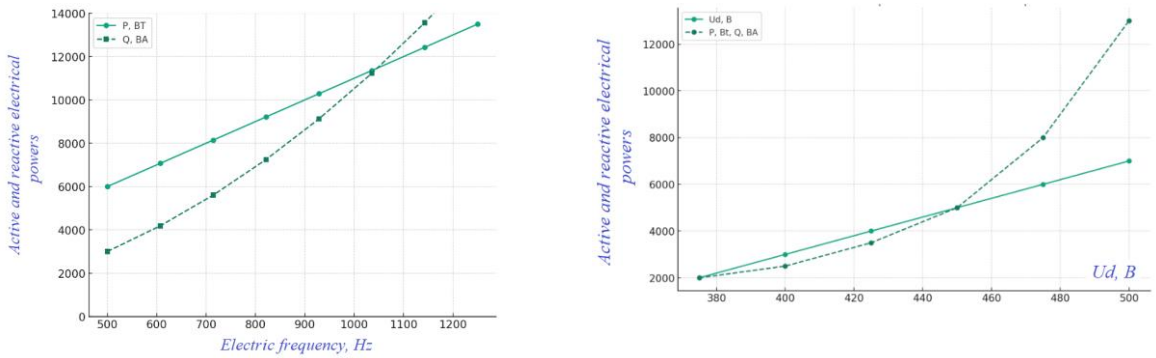


Figure 5. Changes in electrical signals over time.

This figure 5 displays three different electrical signals plotted over a specific time interval. Each graph is marked with different variables and units, indicating the type of signal displayed:

1. "Ucp, V" represents the average voltage arriving at the electrodes in the ozonator (it appears as a square wave);
2. "Icp, A" shows the average current passing through the electrodes in the ozonator (it resembles a noisy constant signal or a very low-frequency signal with noise);
3. "I, A" represents the varying current passing through the electrodes in the ozonator (depicted as a noisy sinusoidal signal in the figure).

Figure 6 below shows the characteristics of frequency (a) and amplitude (b) regulation.



a) b)

Figure 6. Adjustment characteristics: ○ active power; □ reactive power.

Modeling enables the selection of semiconductors and electromagnetic elements, capacitors, and also the identification of steady-state electrical regimes during the design process. The model depicted in figure 2 is designed for studying the processes in ozonators with an open-loop automatic control system. Consequently, the calculations for the ozonator are conducted with a certain degree of indeterminacy, as the models do not possess nodes that generate information about the productivity of the ozone generator. The desired operating mode of the ozonator is one in which the electrical regime and the productivity of the ozonator are optimized simultaneously. To this end, control blocks in industrial ozonators are incorporated with a sensor for measuring ozone generator productivity, which measures ozone concentration and generates a feedback signal to the control system. Publication [12, 24] reports on a developed complex model that includes a mathematical block with an output signal proportional to the productivity of the ozone generator. It not only analyzes the electrical modes of the system but also accounts for the physicochemical processes occurring in the discharge chamber of the ozone generator. The new quality of the mathematical model was achieved by incorporating a "Sensor" subsystem into the structural diagram of the Simulink model, which encompasses the mathematical characterization of the kinetics of the physicochemical processes in the discharge chamber of the ozone generator. The model illustrates the relationship between the electrical energy applied to the ozone generator per unit volume of initial gas and the productivity of the ozonator, which is given by the following analytical formula [8]:

$$x = \frac{k_0 \cdot \alpha}{k_0 + k_{1,T1} e^{\frac{E}{R}\frac{T_2 - T_1}{T_2 \cdot T_1}}} \cdot \left[1 - \exp\left(-\frac{P}{V} \cdot \left(k_0 + k_{1,T1} e^{\frac{E}{R}\frac{T_2 - T_1}{T_2 \cdot T_1}}\right)\right)\right] \quad (1)$$

Here, P is the active power of the discharge, measured in watts; V is the volumetric flow rate of the gas, measured in liters per hour; α is the empirical constant for ozone formation; T_1 is the temperature of the liquid cooling the electrodes (20°C); T_2 is the temperature of the gas in the reaction zone; k_1, T_1 is the ozone decomposition constant at 20°C; E = 2100 kcal/mol is the activation energy of the ozone decomposition reaction; R = 1180 is the Reynolds number.

The signal for the "Sensor" subsystem comes from the Active & Reactive Power measurement block in the submodel of the "high-voltage ozone generator" (figure 3). Additionally, the subsystem receives signals described in the analytical formula. Thus, in the mathematical model of the ozonator's electromagnetic and physicochemical processes, the model of electromagnetic processes in the ozonator is integrated, which includes channels for regulated energy return, and the model of physicochemical transformations in the ozone generator. Computer modeling helps to depict the dependencies of the relative individual productivity of the ozone generator on the capacitor and inductance, as well as the optimal ratios of the frequency filter, shown in figure 7. Creating this model opens up possibilities for mathematically modeling processes in ozonators equipped with closed-loop automatic control systems.

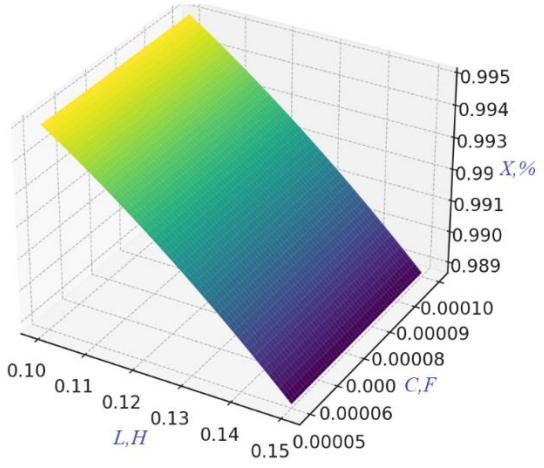


Figure 7. Dependency of individual productivity on the frequency filter parameters of the "Frequency Converter - Ozone Generator" complex.

The conformity of the created schematic model is confirmed by testing experimental models of ozonators with capacities of 10 – 27 kW and frequencies of 500 Hz and 13 kHz. Computer modeling has enabled the creation of a database used in designing the ETRO-01 and ETRO-02 series ozonators [12,16]. Their power consumption ranges from 5 to 10 kW, with frequencies between 500 Hz and 13 kHz. The ozonators operate based on an unregulated energy return scheme.

The practical significance of this research work is based on the process of oxidizing and decontaminating harmful compounds such as microorganisms and heavy metals [18, 25] in both underground and surface water compositions, using ozone and UV radiation [17, 26].

4. Conclusion

This scientific research involves the study of the properties of the electrical power sources of the ETRO-01 and ETRO-02 ozonators through mathematical modeling. Ozone is a strong oxidizer and disinfecting agent, and while its application is extensive, the efficiency of its production heavily depends on the quality of the ozonators' electrical power sources. We have developed and utilized mathematical models to determine the main electrical parameters of various types of ozonators used in ozone production. Additionally, special attention was given to improving the accuracy of digital spectral correlation in the automatic control process of ozonators—particularly to methods of interferometric direction finding for reconstructing analytical signals to process incomplete spectral data [19, 20].

Our analysis has identified opportunities to enhance the energy efficiency of ozonators and optimize their operational parameters. Mathematical modeling serves as a critical tool for predicting the operating modes of ozonators, aiding in improving their overall productivity and reducing the cost of ozone production.

The scientific article utilizes computer modeling with MATLAB and Simulink to explore how the parameters of the electrical power sources of ozonators affect the ozone production process and considers the design and refinement of these power sources. These studies are expected to deepen understanding of the properties of the power sources of ozonators and determine how they impact the productivity of ozone production.

We have developed a model that opens up possibilities for mathematically modeling processes in ozonators equipped with closed-loop automatic control systems and have created a database to identify the life zones of steady electrical regimes. The article also considers the improved design of the electrical power sources of ozonators.

The content of the scientific article highlights the significance of research in innovative methods and technical solutions in ozone production, aimed at improving productivity and reducing production costs.

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