Improving the energy performance of ozone generators used in agricultural ecology

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Abstract. In order to improve the energy characteristics for low-power ozone generators, it is proposed to use a continuous discharge burning mode. It is due to a significant phase shift between the currents and voltages on the ozone generator. Conditions for conducting the continuous discharge mode were identified.

1. Introduction
The ozonation technique is used to solve the environmental problems of large industrial regions: disinfection of drinking water, air and wastewater treatment. Numerous studies are underway to increase the productivity of ozone generators and improve the operational performance of ozonation stations. They are devoted to questions of increasing the frequency supply, improving the design of the electrode system and the search for other effective methods for producing ozone [1, 2]. However, ozonation stations are high-tech, energy-intensive and expensive systems. Therefore, their direct use in solving local problems of rural ecology does not seem technically and economically feasible. Systematic research is carried out concerning the use of ozone in the water supply of rural settlements, air purification of poultry facilities, effluent neutralization from livestock farms (during epizootic diseases) and others [3-9].

2. Materials and methods
Low-power, technologically sophisticated, compact ozonation plants are used. The main element of these installations is the ozone generator, where due to small, low-cost scientific and technical decisions; their energy performance can be significantly improved. The classical theory of the ozone generator as an electric apparatus is given in the work of Yu.V. Filippov [10]. He determined the laws of changes in current and voltage on the elements of the ozone generator, and also built the corresponding graphs of their changes in time (figure 1).
Figure 1. Schedule changes in current, network voltage, barrier and gap (according to Yu.V. Filippov).

Here, in the initial period (interval 0-ωt0), as the voltage of the network increases, the voltage of the barrier and the discharge space increase. During the discharge period (interval ωt0 - ωt1), when $U_n$ reaches the value of the discharge burning voltage in the air gap, an air gap breakdown and a current surge occur. Further, the magnitude of the current is determined only by the rate of change of voltage on the dielectric barrier of the ozone generator. The voltage at the discharge gap remains unchanged, which is explained by the nonlinearity of the resistance of the discharge gap, which changes so that the burning voltage of the discharge remains unchanged, but changes its sign in different half-periods of the mains voltage. In the non-discharge period (interval ωt1 - ωt2), the discharge in the ozone generator stops when the maximum voltage of the network is reached (point ωt1). The current is equal to zero. Further, the mains voltage decreases, respectively, the voltage across the dielectric barriers and the discharge zone decreases. When the ozone generator is an active capacitive load, the current flow time increases due to the EMF of the transformer winding self-induction.

Provided that the full period is constant, this leads to a decrease in the non-discharge period. A further increase in the overall inductance should further lengthen the discharge period and reduce the non-discharge one. The feasibility of changes in the supply circuit of the ozone generator to improve the shape of the current curve by introducing additional inductance is described in the work of S.E. Nevsky [11]. It is proposed to use a resonant mode of operation.

Seeing the need for the ozone generator-transformer system to work in resonance mode in order to obtain a continuous discharge mode. An increase in inductance in the power circuit of the ozone generator leads to a resonant mode. In this case, a discharge occurs at the moment when a certain voltage on the barrier and breakdown of the air gap are reached.

$$U = U_m \sin \omega t_1 = U_n + U_\delta$$

In voltage resonance mode $U_n = U_\delta$ that is why

$$U_m \sin \omega t_1 = 2U$$

Hence
\[ \omega t_1 = \arcsin \frac{2U_n}{U_m} \]

Given the invariance of the gap voltage during the discharge period, the moment of extinction of the discharge in the ozone generator can be determined from the condition.

\[ \omega t_2 = \pi - \omega t_1 \]

In resonance mode, the current amplitude increases with

\[ I_m = \frac{U}{\sqrt{R^2 + (X_L - X_C)^2}} \quad I_m^1 = \frac{U}{R^1} \]

where \( R \) - total resistance of the gap and the secondary transformer winding; \( R^1 \) - the same with the additional inductance.

At the same time, there is an increase in the voltage drop across the barrier and the gap

\[ \frac{U}{U_{\delta-n}} = \frac{I_Z}{I_{\delta-n}} = \frac{R}{x_{\delta-n}} \quad (2) \]

However, the barrier is a glass dielectric whose strength is limited by the ultimate breakdown voltage. Therefore, for the normal operation of ozone generators in resonance mode, the following is required:

\[ U_{m,\delta} \geq U_{\delta} = U \frac{x_{\delta}}{R} \quad (3) \]

where \( U_{m,\delta} \) - barrier breakdown voltage

However, considering \( x_{\delta} > R \) it can be argued that in the resonant mode, breakdown of dielectrics is not excluded.

To obtain a continuous discharge, it is necessary that when the discharge current is extinguished, a voltage higher than the discharge burning voltage is applied to the ozone generator.

\[ \text{Figure 2. Continuous burning of a discharge in an ozone generator.} \]
Obviously, this is only possible with a significant phase shift between the current and the applied voltage. In this mode, the current curve $\phi$ anticipates the voltage curve by an angle, so when the discharge current decreases to zero, the voltage necessary for burning the discharge is already applied to the gap. The inductance of the secondary transformer winding contributes to the maintenance of the discharge current. To obtain the required phase shift, it is necessary, according to the vector diagram (figure 2), to change the inductance or capacitance of the circuit. In this case, the shear angle satisfying the condition of discharge continuity is determined from the following considerations. For instant reignition of the discharge when the current passes through zero and the capacitive nature of the current, it is necessary to observe the limit condition:

$$U_m \sin(-\phi) \geq |U_n|$$

where $U_m \sin(-\phi)$ - source voltage, application to the ozone generator.

Taking into account the oddness of the sinusoidal function, is obtained:

$$-U_m \sin(\phi) \geq |U_n|$$

Considering that $\sin \phi = \sqrt{1 - \cos^2 \phi}$

$$\cos \phi \leq \sqrt{1 - \left(\frac{U_n}{U_m}\right)^2}$$

From the obtained condition it follows that the determining parameter of the regime of continuity of combustion of the discharge is the ratio $\frac{U_n}{U_m}$ which can be determined from the current-voltage characteristics of the ozone generator. The theoretical results obtained are confirmed by the oscillograms of the operation of the ozone generator in the mode with non-current pauses and the continuous discharge mode.

Frequency analysis showed that in the second variant, the distortion coefficient of the current curve increases

$$\nu_2 = 0.98 > \nu_1 = 0.82$$

This contributes to an increase in the power factor of the ozone generator.

$$\chi = \nu_1 \cos \phi$$

where $\nu_1 = \frac{I_1}{\sqrt{I_1^2 + I_3^2 + I_5^2 + I_7^2}}$ distortion factor

The limit value for the distortion coefficient $\nu = 1$ should therefore be remembered that an excessive increase $\chi$ in the shear angle can lead to a decrease due to a sharp decrease $\cos \phi$.

The estimation of the ozone generator productivity by ozone output showed that, provided that the discharge is continuously burning, the ozone output increases by 30-40%. Thus, for example, in the normal mode at a voltage of 11.8 kV and an air flow rate of 6 l/min, the ozone concentration at the outlet was 3.6 mg/l. In continuous combustion mode, the ozone output increased to 4.8 mg/l.
3. Conclusions
The features of the operation of electric ozone generators are considered. It was established that to improve the energy characteristics of ozone generators, it is necessary to introduce additional changes in the supply circuit of the ozone generator. The analysis shows that for this it is necessary to change to increase the inductance or reduce the circuit capacity.

Conditions are given for the implementation of a continuous discharge burning mode, where the determining parameter is the ratio of the gap voltage to the maximum voltage. Using the continuous burning mode of the discharge can increase the output of ozone up to 30-40%.

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