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To cite this article: A G Vozmilov *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **272** 022138

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Influence of Output Parameters of a High Voltage on the Technological Characteristics of Electron-Ion Devices Technologies

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Abstract. The article considers parameters of the influence of a high voltage source (HVS), as a form of the output voltage curve and its influence on the technological parameters of the electron-ion technology (EIT) devices for various purposes, the HVS schematic solutions and their classification. A equivalent circuit a single-zone electrostatic precipitator is developed, differing from the existing ones in that the differential capacitance is moved beyond the key VD, because the volume charge can be neglected until the moment of ignition of the corona discharge when considering the corona-discharge system, i.e. for simplicity, the condition is assumed that volumetric charges are created only by corona discharge. Based on this scheme, an equivalent electrical equivalent circuit for a two-zone electrostatic precipitator was constructed. The analytical expression for calculating the electrical constructive capacity of the most commonly used in the electrostatic precipitator corona-discharge system "a number of wires - a plane," taking into account the additional electric capacity. The article presents the results of the investigation of the effect of the frequency of the output voltage of the HVS and the additional capacitance of the capacitor bank on the volt-ampere characteristic of the corona-discharge system of the electrostatic precipitator-ozonizer. The analytical expression is shown in general form, describing the volt-ampere characteristic of the electrostatic precipitator, taking into account the shape of the HVS output voltage curve. An analytical expression for determining the ozone concentration at the output of the EIT devices in the general case is also shown.

1. Introduction

At present, the devices of electron-ion technology (EIT) are increasingly used in technological processes in various industries [1, 2, 3, 4], such as air cleaning systems for air emissions (at CHP plants, chemical and metallurgical enterprises). Recently electrostatic precipitators and electrostatic precipitators-ozonizers are used for cleaning and disinfection of ventilation air in technological premises of large cattle-breeding and poultry enterprises [4].

At present, when developing EIT devices, researchers and designers consider the regime and design parameters of their operation without taking into account the influence of output parameters of HVS [1, 2, 3, 4, 5, 6, 7, 8].



When designing EIT devices for their efficient operation, it is necessary to be able to determine the main technological and electrical parameters of electrostatic precipitators, taking into account HVS. Calculation of transient processes in the HVS system - the corona-discharge system and expressions for volt-ampere characteristics (VAC) for the purpose of clarifying the operating mode and determining the corresponding requirements for HVS is possible on the basis of equivalent circuits of electrostatic precipitators.

2. Theoretical part

In [1, 2, 3, 10, 11, 12, 13, 14, 15], when examining various variants of corona-discharge systems, expressions were obtained that describe their VAC. Carrying out analysis of these dependences, we can conclude that in general form the equation of the VAC of a corona discharge can be written:

$$\begin{cases} I = GK(U - U_0)U \\ K = f(U) \end{cases} \quad (1)$$

where I - discharge current; U - effective value of the voltage of the HVS; U_0 - voltage of the beginning of the corona; G - coefficient, depending on the type of corona-discharge system (geometric coefficient); K - mobility of the ions, (m/s)/(V/m).

The mobility of ions, according to [11], can not be regarded as a constant. It depends in a certain range on the resultant field strength and, as a consequence, on the voltage applied to the corona-discharge system.

The main characteristic of the operation of electrostatic precipitators is the degree of purification and disinfection of the filtered air (gas). Analyzing the known analytical expression for the degree of purification of the electrostatic precipitator, it can be concluded that it depends on the voltage applied to the corona-discharge system:

$$\eta \sim 1 - \exp(-kU^2), \quad (2)$$

where k - coefficient of dimension, $1/V^2$. This dependence is confirmed in [7, 8, 9].

The process of corona discharge, and, consequently, all EIT devices, the function of generating ozone and ions is inherent. The most interesting is the first process, namely the process of generating ozone by EIT devices for agricultural purposes, since in agriculture there are technological processes in which ozone is used as a "working tool". On the other hand, in ventilating systems, when cleaning air and recirculation air with electrostatic precipitators, there is a restriction on the maximum concentration of ozone in purified air (maximum permissible concentration of ozone in the Russian Federation is $0.1 \mu\text{g} / \text{m}^3$, in the USA - $0.2 \mu\text{g} / \text{m}^3$) [1].

Thus there is a need to control the ozone generation EIT devices depending on the field of use, in one case, necessary to reduce the concentration of ozone, increase in the other.

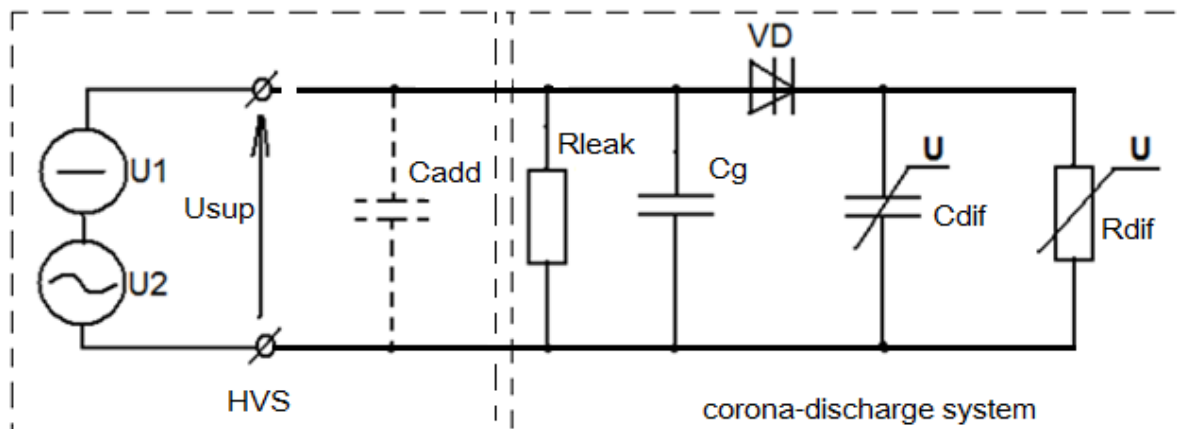
Analyzing the results of previous studies [16], we can conclude that with a negative and positive corona, the ozone concentration at the output of the EIT device will be directly proportional to the current of the corona-discharge system:

$$C_{[O_3]_{\pm}} \sim I \quad (3)$$

When describing the processes taking place in the operating system of electrostatic precipitators, an important role is played by the correct choice of an equivalent circuit. This choice is necessary when considering the requirements for a high voltage source at the stage of its calculation and design. Electrostatic precipitators are divided into two types: single-zone, in which charging and precipitation of particles occurs in one zone, and two-zone ones using both corona discharge (charging zone) and electrostatic effect (precipitation zone) [16, 17, 18].

In [19, 20, 21] equivalent circuits for single-zone electrostatic precipitators are given. Based on the analysis of these schemes and taking into account their shortcomings, we compiled an equivalent circuit for a single-zone electrostatic precipitator, which is shown in Fig. 1.

This scheme differs from the known schemes [19, 20, 21] in that instead of a diode and counter-emf, which caused unilateral conductivity of the corona discharge (unipolarity) and the initial voltage of the corona ignition, an unmanaged electronic key VD is included in the circuit. The application of the counter-emf in the replacement circuit is irrational, since it is not excluded from the substitution scheme when the corona is ignited and it turns out that the voltage on the corona-discharge system is less than the supply voltage by the amount of the counter-emf, which is incorrect. Also, the differential capacitance caused by the volumetric charge created by the ions and the charged particles is transferred for the key VD, because the volume charge can be neglected until the moment of ignition of the corona discharge when considering the corona-discharge system, i.e. for simplicity, we accept the condition that the volumetric charges are created only by corona discharge.



U_1 and U_2 - the constant and alternating component of the supply voltage U_{sup} respectively; C_{add} - additional electrical capacitance HVS, C_g and C_{dif} - geometric (structural) and differential electrical capacitances of the electrostatic precipitator, respectively; R_{leak} and R_{dif} are the resistance of the leakage current circuit and the differential resistance of the corona-discharge system, respectively.

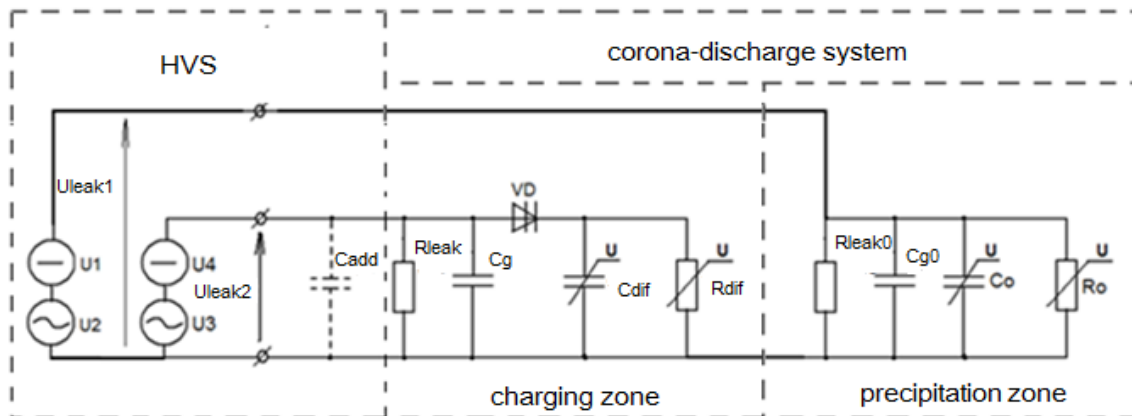
Figure 1. Equivalent circuit single-zone electrostatic precipitator.

This equivalent circuit takes into account all the features of single-zone electrostatic precipitator, such as structural (R_{leak} and C_g) and features of the corona discharge itself (VD, C_{dif} and R_{dif}). The role of the idealized unmanaged electronic key (dinistor) VD is that it opens when a certain voltage level is reached - the voltage of the crown ignition and in the future has a conductivity equal to ∞ . Thus, the condition for the operability of the substitution circuit is that before reaching the ignition voltage of the crown, $C_{dif} = 0$, and R_{dif} is large, but less than ∞ , ie:

$$\lim_{U \rightarrow U_0-} R_{dif} \rightarrow \infty \quad (4)$$

Based on the scheme shown in Figure 1, an equivalent circuit for a two-zone electrostatic precipitator was constructed, which is shown in Figure 2.

The above scheme takes into account the variant of separate feeding of the charging zone and the precipitation zone of the electrostatic precipitator. The differential electric capacitance C_0 is caused by the volumetric charge created by charged particles that have fallen into the precipitation zone from the charging zone. The nonlinear resistance R_0 is due to the deposition of charged particles on the precipitation electrodes and its nonlinearity is caused in the general case by the inhomogeneity of the concentration of the incoming charged particles during the operation of the electrostatic precipitator, the dustiness of the environment under real conditions is not a constant value and depends on many factors.



R_{leak0} and R_0 - resistance of leakage currents in the precipitation zone and nonlinear resistance, respectively; C_{g0} and C_0 are the geometric and differential capacitance of the precipitation zone, respectively.

Figure 2. Electrical schematic diagram of the replacement of a two-zone electrostatic precipitator.

Resistance to leakage currents and geometric (structural) electrical capacity of the corona-discharge system depend on the design of the electrostatic precipitator and the insulation materials used. If the value of the resistance to leakage currents can be determined with sufficient accuracy only with electrical tests of a specific design of the electrostatic precipitator, the value of the geometric capacity can be analytically calculated with sufficient accuracy by considering the concrete design of the corona-discharge system. The value of the geometric capacity can be calculated from the expressions given in [22].

We obtained an analytical expression for calculating the electrical constructive capacity of the most commonly used in the electrostatic precipitators of the agricultural system for the corona-discharge system "a number of wires-a plane" with allowance for the additional electric capacity:

$$C = \frac{n2\pi\epsilon\epsilon_0 l N}{\ln\left(\frac{P \sum_{k=1}^n \sqrt{4h^2 + a^2(k-1)^2}}{r \cdot a(k-1) \cdot (k-1)!}\right)} + C_{add} \quad (5)$$

where n - number of corona electrodes; l - length of the corona electrode, m; h - distance between the corona electrode - plane, m; a - distance between the corona electrodes, m; r - radius of the corona electrode, m; N - number of planes; S_{add} is the value of the additional electric capacity, according to the equivalent circuits for the replacement of electrostatic precipitators. The number of planes $N = 1$ for the system "row of wires - plane" and $N = 2$ for the system "a series of wires between two planes".

One of the significant phenomena of the corona discharge is the intermittent nature of the corona discharge. It consists in locking the corona under the action of a space charge and is expressed in the impulse of the discharge current. This effect, according to [23, 10, 11], directly depends on the voltage applied to the corona-discharge system and, as a consequence, on the shape of the curve of this voltage. The greater the voltage applied to the discharge gap, the sooner the corona locking process is performed and the more, therefore, the frequency of the current pulses. The presence of negative ions at a certain distance from the cathode-the corona electrode, according to the Poisson equation and the laws of motion of charged particles in a gas, limits the density of the discharge current [11]. The pulse repetition rate is due to the time of scattering of the space charge formed near the corona electrode. In order to create a new pulse, it is not necessary for the ions to reach the anode - a precipitation electrode, it is sufficient that they move back to a relatively small distance from the region of corona formation [10, 11].

Thus, the corona point is a source (generator) of high-frequency current pulses, and the sum of these currents will be the resultant current of the corona-discharge system. The effect of locking the corona discharge depends on the voltage applied to the corona-discharge system and increases with the growth of the latter [10, 11]. Consequently, we can conclude that the current of the corona-discharge system depends on the volume charge density at the corona point, which is a function of the electric field strength, and, consequently, on the acting voltage applied to it.

Most EIT devices are powered by rectified voltage, i.e. unipolar pulsating voltage; voltage, the shape of the curve of which has ups and downs (front and rear pulsation front). Thus, it can be concluded on the basis of studies [23, 10, 11] that during the decline of the supply voltage (the rear ripple front), the effect of locking the corona discharge is likely to increase due to a drop in the emission of electrons from the corona electrode and a large charge density around it from previously produced ionization. In other words, each subsequent pulse of the discharge at the point of corona will be locked by the previous one. the mobility of charged dust particles is less than the electron mobility [10, 16, 24], then they do not have time to move away from the corona point for some distance to form a new corona pulse and this pulse occurs later, i.e. the duty cycle of current pulses increases at the corona points and the resultant current value decreases.

From this, it can be concluded that the longer the voltage drop time (the longer the back edge of the ripple), the lower the resulting current at the same operating voltage.

All EIT devices are active-capacitive system, which means that the rear ripple front will always be longer than the front one, i.e. the voltage drop time will always be longer than its rise time to the amplitude value ($t_{U\downarrow} > t_{U\uparrow}$). It is the change in the ripple decay time that allows you to change the time for locking the corona discharge.

The shape of the voltage curve is estimated from two known coefficients:

- the coefficient of voltage ripple - the value equal to the ratio of the largest value of the variable component of the pulsating voltage to its constant component

$$K_p = \frac{U_{m-}}{U_{=}} \quad , \quad (6)$$

- coefficient of amplitude of the AC voltage curve - a value equal to the ratio of the maximum value in the module over the period of the voltage value to the effective value of the periodic voltage

$$K = \frac{U_m}{U_v} \quad (7)$$

These coefficients, assuming the condition that $U = \approx U_e$ can be related by the following relation

$$K_A \approx K_p + 1 \quad (8)$$

Consequently

$$U_v = \frac{U_m}{K_p + 1} \quad (9)$$

In turn, the pulsation coefficient has a dependence on the repetition rate

$$K_p = \frac{1}{2mf\tau} \quad (10)$$

where m - index of the rectification of the rectification circuit; f - frequency pulsations repetition Hz.

According to the substitution scheme (Fig. 2), the following system of equations

$$\begin{aligned}
 U_v &= \frac{U_m}{(1/2\pi f C R) + 1}; \\
 R &= \frac{R_{dif} \cdot R_{leak}}{R_{dif} + R_{leak}}; \\
 C &= C_{add} + C_{go} + C_{dif}
 \end{aligned}
 \tag{11}$$

It is seen from (11) that for $U_m = \text{const}$, the value of the acting voltage (U_e) will vary, so as the total electric capacity of the system, frequency or co-electrical capacitance and frequency increases, the value of the acting voltage increases. It should also be noted that the same value of the actual voltage with an unchanged value of the pulsation amplitude can be obtained for different values of the total electrical capacitance of the system and the repetition rate of pulsations. It can be concluded that due to the change in the additional capacity and the repetition rate, the value of the acting voltage and current will change, with the help of which, according to the dependencies (1), (2), (3), and (11) of the circuits in Figures 1, 2 and the effect of locking the corona discharge, it is possible to control the parameters of the corona-discharge system and, as a consequence, the technological parameters of the whole EIT devices as a whole. Thus, to optimize the operation mode of the EIT devices for agricultural purposes in specific technological processes.

3. Results and discussion

The results of the investigation of the effect of the frequency of the output voltage of the HVS and the additional capacitance of the capacitor battery on the volt-ampere characteristics of the corona-discharge system of the electrostatic precipitator-ozonizer, its cleaning efficiency and ozone-current characteristics are shown in Figures 3,4,5,6.

An analysis of the results obtained in Figure 3 shows that with an increase in the frequency or a decrease in the ripple coefficient, the volt-ampere characteristic shifts to a region of high voltage. When an additional electric capacitance is introduced into the output stage, the shape of the output voltage becomes closer to the constant voltage, which also leads to a shift of the volt-ampere characteristic to the region of high voltages. These dependences reflect the influence of the form of the output voltage of the HVS on the VAC of the EIT device. This allows to obtain the same current of the corona-discharge system at high values of the applied voltage applied to the corona-discharge system and, as a result, to increase the corona discharge power.

The analysis of the data in Figure 4 shows how the type of the output voltage of the HVS changes with the maximum ripple coefficient at a repetition rate of 50 Hz without connecting additional capacitors and with a minimum coefficient at the repetition rate of 200 Hz with a maximum capacity of 3760 pF in the output stage of the HVS.

On the basis of the results obtained, it can be concluded that expression (1) is valid only for a "constant current source". In general, taking into account the effect of pulsations on the parameters of the output voltage of the HVS, the expression describing the volt-ampere characteristic of the electrostatic precipitator can be written in the form

$$\begin{aligned}
 I &= G K K_U (U - U_0) U; \\
 K &= f(U); \\
 K_U &= f(U(t)) .
 \end{aligned}
 \tag{12}$$

where K_U – coefficient depending on the shape of the EIT supply voltage device.

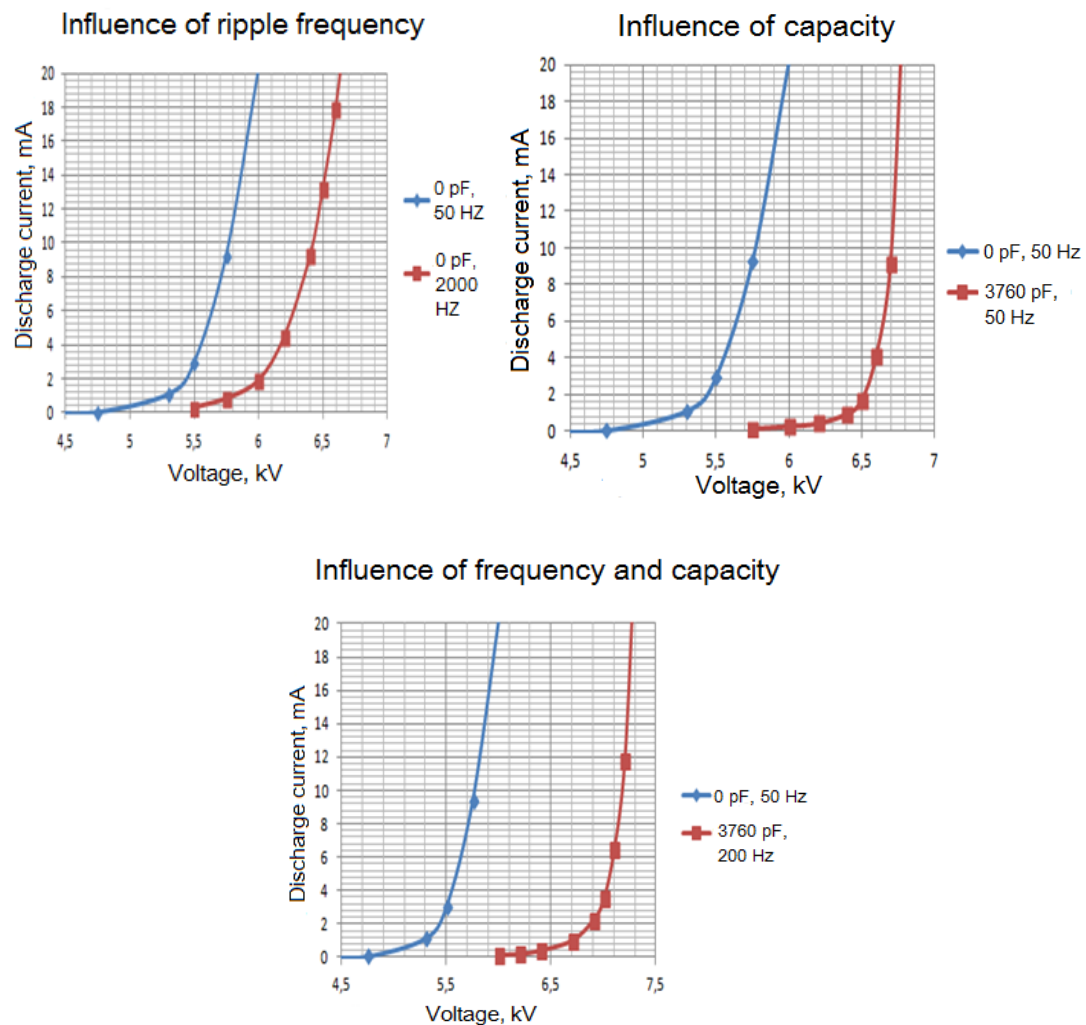


Figure 3. VAC of an electrostatic precipitator-ozonizer for various values of the frequency and ripple of the output voltage of the HVS.

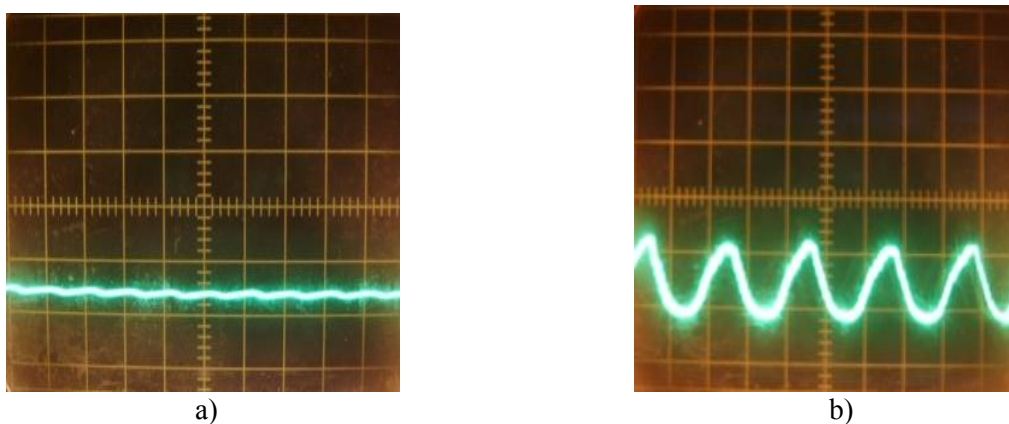


Figure 4. Oscillograms of the output voltage of the HVS: a) 0 pF 50Hz; b) 3760 pF 200 Hz. Scale $Y = 5\text{V/cm}$; $X = 5\text{ ms/cm}$; $K_{DIV} = 758$

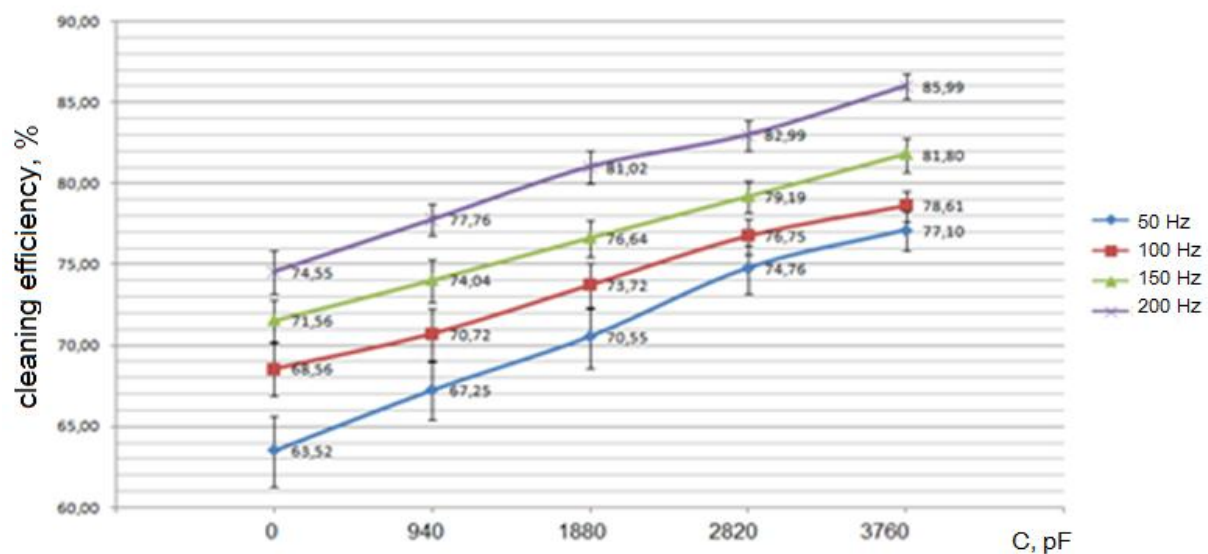


Figure 5. Dependence of the degree of air purification on the magnitude and frequency of the ripple of the output voltage HVS (air flow through the electrostatic precipitator is 3 m/s, the ambient air temperature is 22 °C, the relative humidity of the ambient air is 64%, the particle size is 0.5 μm).

The analysis of the results in Fig. 5 shows that when the ripple coefficient decreases or when the ripple frequency increases, the degree of purification increases. Thus, when a maximum capacity of 3760 pF is introduced into the system, i.e. at the maximum reduction of the output voltage HVS at the maximum pulse repetition frequency of 200 Hz, the increase in the purification rate was 22.5% compared to the system without the inclusion of additional capacitors with a repetition rate of 50 Hz.

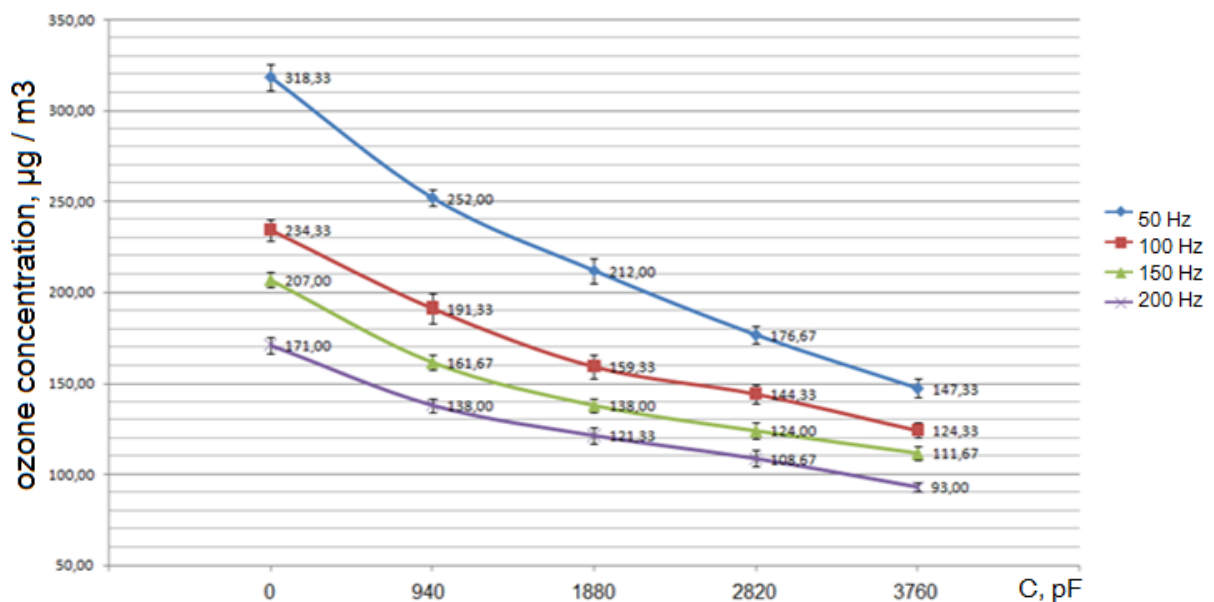


Figure 6. Dependence of the ozone concentration at the output of the electrostatic precipitator-ozonizer on the value and frequency of the output voltage HVS pulsations (the airflow through the electrostatic precipitator is 3 m/s, the ambient air temperature is 22 °C, the relative humidity of the ambient air is 64%, the particle size is 0,5 μm).

Analysis of the characteristics (Figure 6) shows that with a decrease in the ripple ratio of the output voltage of the HVS and an increase in the frequency of these pulsations, the ozone concentration at the output of the electrostatic precipitator-ozonizer decreases with a fixed corona discharge current of 10 mA. Thus, the ozone concentration at the output of the EIT device is not a function of the mean current of the corona-discharge system. In the case of a unipolar pulsating voltage, using expression (3), with $K = \text{const}$, we can write:

$$\begin{cases} \frac{dC_{[O_3] \pm}}{dt} = K_{\pm} \cdot \frac{dI}{dt} = K_{\pm} \cdot \frac{dI(U)}{dU} \cdot \frac{dU(t)}{dt} = K_{\pm} GK(2U - U_0) \cdot \frac{dU(t)}{dt} \\ I = f(U(t)) \\ I = GK(U - U_0)U \end{cases} \quad (13)$$

where - K_{\pm} ion mobility with positive and negative corona, respectively, (m/s)/(V/m).

It is seen from (13) that the ozone concentration will be constant at the output of the EIT device at $\frac{dU(t)}{dt} = 0$. Therefore, the expression (3) is valid only for a specific VAC EIT device and can not be applied generally. The concentration of ozone at the output of the EIT device in the general case is determined by the expression:

$$\begin{cases} C_{[O_3] \pm} = K_{\pm} GK K_U (U - U_0)U = K_{\pm} K_U I \\ K = f(U) \\ K_U = f(U(t)) \end{cases} \quad (14)$$

Expression (14) takes into account the influence of the shape of the supply voltage curve and, therefore, can be applied to any of the family of volt-ampere characteristic curves of the EIT device. This dependence will allow more accurate and correct calculation of the ozone concentration at the output of the EIT devices.

The main share of EIT devices is made by electrostatic precipitators, ozonizers and electrostatic precipitator-ozonizers - devices with high energy consumption, the high-voltage part of the HVS is built on the principle of full-wave rectification and smoothing of the sinusoidal voltage. With this type of supply voltage and the HVS device, the only VAC of the agricultural EIT devices, at which $K_U = 1$, is the "natural VAC of the EIT device" (rectified current with a ripple content of no more than 10% of the actual value). Any other volt-ampere characteristic of the EIT devices obtained under other parameters supplying the corona-discharge voltage system will be considered artificial.

The natural volt-ampere characteristic of the EIT device, according to the theoretical assumptions and results of experimental studies, will be shifted to the maximum of voltage. This operating mode corresponds to the operation mode of electrostatic precipitators, since for a given volt-ampere characteristic, it is possible to obtain a larger value of the acting voltage at a lower current and, as a consequence of (2), the maximum degree of air purification. At the same time, the coefficient depending on the shape of the EUT supply voltage (K_U) will be in the interval:

$$0 < K_U \leq 1 \quad (15)$$

The mode of operation of ozonizers, according to the dependence (14), requires the provision of the maximum possible current of the corona-discharge system. For these EIT devices, the optimal mode will be the work on the "artificial volt-ampere characteristic", shifted to lower voltages. With this volt-ampere characteristic, the maximum current of the corona-discharge system can be obtained at lower values of the voltage supplying the EIT device.

4. Conclusions

1) Changing the shape of the output voltage curve HVS has a significant effect on the operating mode of the EIT device. With a decrease in the ripple coefficient, i.e. when the shape of the HVS voltage curve approaches the DC voltage:

- there is a shift of the volt-ampere characteristic to the region of high voltages;
- the degree of cleaning of the electrostatic precipitator increases;
- the concentration of ozone at its output is reduced.

2) With a decrease in the ripple coefficient:

- there is a shift of the volt-ampere characteristic to the region of lower voltages;
- the degree of cleaning of the electrostatic precipitator decreases;
- the concentration of ozone at its output increases.

3) The classical equation of the volt-ampere characteristic of a corona discharge (1) is valid only when the corona-discharge system is supplied with a DC voltage. The obtained volt-ampere characteristic equation (12) takes into account the influence of the shape of the supply voltage curve of the EIT device.

4) The concentration of ozone at the output of the EIT device is not a function of the mean current of the corona-discharge system. It is necessary to take into account the influence of the shape of the supply voltage curve.

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