The mechanism of destruction of plant rhizomes under the influence of an electric pulse discharge

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Abstract. The elimination of the harmful effects of weeds is a global challenge to the present day. The problem has become especially important from the clogging of cultivated areas with perennial rhizomatous magpies such as Humay, finger pigs. It should be noted complexity problems associated by preventing invasion harmful perennial rhizomatous weeds which is associated with versatility reproduction (reproduction seeds and rhizomes under any weather-climatic and soil conditions) lack of specific measures and means of destruction, poor quality of quarantine or failure to timely comply with measures to prevent harmful effects, high cost or increased danger of chemicals. Given the above-described circumstance in the article is discussed solution to problems of destruction perennial rhizomatous weeds using dielectric strength pulse and current with high voltage.

1. Introduction
Eliminating the harmful effects of weeds on the yield and quality of food products is an important task. Especially, because of the ill-treatment of crop areas, not timely and quality cultivation, poor quarantine not making herbicides, etc. and led to a strong growth and development of weeds.
In recent years, reduction in quality of cultivation, lack of equipment and technology in the cultivation led to sharp multiplication of weeds both in quantity and in quality with respect to the cultivated areas. Especially, the management of crop rotations and the use of various agro technical measures to destroy weeds has become the main reason for the extensive reproduction and development of perennial rhizome weeds.
Along with this, the high price, difficult accessibility, increased harm to living organisms and to humans, especially low efficiency in the destruction of perennial rhizome weeds led to a difficult closed state of the use of chemicals and herbicides.
Therefore, in order to destroy perennial rhizome weeds and prevent their invasion of cultivated areas, it was decided to look for an alternative method of weed control based on the use of high voltage electrical discharges. When using electrical methods of weed control, it is necessary to study the biological and electro physical characteristics of perennial rhizome weeds.
At the present time in our Republic among the perennial rhizomatous weeds ladies’ harm is applied by the weed humanely.

1.1. Biologic and electrical characteristics of long-term rhizomatous Humay weed
Humay, or Jones grass, Intropogen hale Pansies (L) Pers is moisture-loving, thermophile, weed plant that is demanding on fertile loose soils. On dry, compacted soils, Humay grows poorly, and does not occur at all on salt marshes. It is not resistant to drought, therefore it does not tolerate drying well. The height of
the stem reaches 2 m; the thickness is 1 cm or more. It has powerfully developed rhizomes that penetrate into the soil up to 80 cm, but the main part (90%) lies at a depth of 20 cm [1]. Humay reproduces by seeds and in a vegetative way, underground rhizome stems. The rhizomes are segmented and their internodes are thick, up to 10 cm, up to 3 cm long; scales of white, yellow and brown flowers extend from the nodes in diameter [2]. In the axils of ruder leaves, buds form in the node, from which shoots develop. Part of it turns into underground rhizomes growing in horizontal and vertical directions.

Then as a result of energy growth, the rhizomes of the first and second order themselves are processed and grown in the soil to a depth of 30-40 cm. The viability of Humay is determined by its biological characteristics - water, soluble carbohydrates and other nutrients accumulate in the roots and rhizomes, which are an energy resource in the process of adaptation to various environmental conditions. Therefore, for most agricultural pests, Humay is a source of nutrition, wireworms and larvae of various beetles live on its rhizomes, etc. Underground organs are sensitive to low temperatures, at temperatures below -15 °C they die, and aerial shoots - below 0°C.

In hot and dry weather in the sun, the rhizomes of Humay die within 5 days. The analysis of scientific and technical information in the search for the study of the biological anatomical structure of Humay did not give positive results due to the lack of any information in this direction. Therefore, we believe that it is necessary to include in the plan for further research the study of the anatomical and biological structure of Humay.

The results of the conducted anatomical and biological studies showed that the main parenchyma of the root is large - cellular and occupies a significant area in the cross section. In the crustal parenchyma, the cells are thin-walled, succulent, and unequal with numerous plants, in which they have conductive sinuses (Figure 1) [1].

![Figure 1](image)

**Figure 1.** Anatomical structure of Humay rhizome (enlarged by the Biolam microscope): a - sample section from the root collar; b - a segment of a sample of a conducting beam; s - a piece of a core sample; KP - cells of the root parenchyma; K - cells of the cortex; PP - conducting beam; CS - core cells; KZ - starchy grains; KO - sheath cells; C - ascending vessel; L - liberoform (woody parenchyma)

Under the cells of the bark is a lamellar parenchyma, which protects the rhizomes during mechanical soil cultivation. In old rhizomes (2-3 years old), the cell walls are more thickened than in young ones. For this reason, the diameter of the lumen of the vessels is much smaller. However, the thickening of the integumentary tissue in the rhizomes may indicate the adaptability of the humay weed to arid habitat conditions.

1.2. **Thermal mechanism of destruction of plant rhizomes under and pulsed action of an electric field**

Works on pulsed action on plants using short and medium pulses are carried out mainly (if not exclusively) abroad [3]. Back in the 60s of the twentieth century, it was suggested about the possibility of continuous destruction of weeds under high-voltage impulse exposure. The presence of lethal effects on various weeds and promising process have been confirmed by laboratory and field tests, by the researchers conducting e in a
number of scientific research institutes foreign countries [4-13]. However, there are opposite opinions [14]. When, during the pulse treatment of weeds (sow thistle, bent grass, etc.), only the ground mass of plants died, and the root system stimulates growth.

Taking into account such a negative conclusion, in our studies, we chose the option of electrical treatment of the rhizomes of perennial weeds (Humay) not in the soil, but after extracting from it, passing the rhizome segments through the electrode system of the moving web. This achieves a high probability of the passage of high-voltage discharge pulses through the processed objects and increases the efficiency of the process [1, 15-17].

The lethal effect of an electric pulse discharge on plants, stems, rhizomes, fibers is primarily associated with the destruction of cell structures (membranes) [3, 13, 18-20]. The destruction of the cell membrane occurs within a certain period of time, which must be less than the duration of the acting impulse [13, 21-24].

This time is expressed by the ratio:

\[ t_{pm} = \frac{M}{\sqrt{\frac{U_m}{U_{cr}}}^2 - 1} \]  

where: 

- \( M \) - coefficient determined by the properties of the membrane; 
- \( U_m \) - voltage applied to the membrane, V; 
- \( U_{cr} \) - critical voltage, V.

Analysis (1) shows that at high voltages applied to the membrane, the destruction time depends on \( U_{cr} \). A decrease in \( U_{cr} \) reduces \( t_{pm} \), therefore, reduces unproductive energy consumption. With regard to the electrical treatment of weeds, the need to choose as an initiating factor - pulsed supply (with a high voltage gradient) of high voltage current as the most technological factor - is once again confirmed.

The nonlinearity of plant resistance according to the well-known replacement scheme [25] significantly complicates the theoretical calculation of the transient characteristics. Therefore, it is necessary to experimentally establish the law of changes in the resistance of plant objects in time. Since the usual active resistance of a plant when voltage is applied changes to a certain steady-state value, which is always above the critical value.

Then the discharge of the capacitor of the high-voltage power circuit will occur in the aperiodic mode (\( R > \sqrt{L/C} \)).

The plant stem in the post-harvest period as a result of de-leafing, as well as sections of plant rhizomes in dry soil in the hot climate of Central Asia, are close in electrical characteristics to insulating materials. For this reason, for the electrical calculation in the first approximation, apparently, it is possible to use in this case the theory of the distributed model [26], especially since the electrical technology of plant processing is associated with electrical breakdown [27, 28]. The insulation breaks through in the place of the highest field strength (in the places where the plant touches the high-voltage electrode). The greater the ratio of the dielectric strength to the operating value, the electric field strength, the less likely a breakdown is isolation. Due to the statistical nature of the breakdown, it is always possible to find such a place in the insulation (a piece of rhizome, fiber), the electric strength of which would be much lower than the average value. In addition, over time, as the result of exposure to an electric field, heating and other reasons (for example, mechanical damage), weak points are formed with a low value of dielectric strength.

An increase in the contact surface of the electrodes with the insulating layer also leads to an increase in weak points according to the laws of mathematical statistics.
2. Experiment and Methods

2.1. Assessment of the electric field strength and potential in the insulating rod (rhizome)

Experimental measurements of the resistivity, volumetric and surface resistance [1] of treated Humay rhizomes, amounting to tens and hundreds of km, allow, in the first approximation, to consider them as insulating rods (rhizomes). Knowing or setting the space charge density in the insulator rod is parabolic \((\rho = \alpha \cdot r^2)\) or exponential, \((\rho = \rho_0 \cdot e^{\alpha r})\).

Let us estimate the magnitude of the tension and potential at specific points of the insulating rod, for example, at the origin coinciding with the origin.

The field strength is found by the Gauss theorem [25]:

\[
E = \begin{cases} 
\frac{a \cdot r^3}{4 \epsilon_0} \cdot \frac{r}{r} & \text{at } r \leq R \\
0 & \text{at } r \geq R
\end{cases}
\]

For a rod of length \(l=0.1\) m and the radius \(R = 0.01\) m at \(\rho = \alpha \cdot r^2\) (where \(\alpha = 2\) - positive permanently I \((\text{kl/m}^{-5})\); \(r\) - Current radius (m), calculations give:

\[
E(0;0;0) = 0 \quad E(0;0;0.005) = \frac{a \cdot r^3}{4 \cdot \epsilon_0} = 0.7 \times 10^4 \text{ V/m};
\]

\[
E(0;0;0.001) = \frac{a \cdot R^3}{4 \cdot \epsilon_0} = 0.7 \times 10^4 \text{ V/m};
\]

\[
E(0;0;0.02) = \left(\frac{a \cdot R^3}{4 \cdot \epsilon_0}\right) \times \frac{R}{0.1} = \frac{5.6 \times 10^4 \cdot 0.01}{0.2} = 2.8 \times 10^5 \text{ V/m};
\]

The value of the potential at the origin can be found from the integral expression in which the integration is carried out over the volume of the rod:

\[
\varphi(0,0,0) = \frac{1}{4 \cdot \pi \cdot \epsilon_0} \int \frac{\rho \cdot \left(\frac{r}{r}\right) \cdot dV'}{r},
\]

It is convenient to integrate in a cylindrical coordinate system. That breaking cross-sectional view of the cylinder on the ring area \(2 \cdot \pi \cdot r \cdot dr\), and the cylinder length - at \(dx\) segments represent:

\[
\sqrt{r^2 + x^2}; \quad dV = 2 \cdot \pi \cdot r \cdot dr \cdot dx,
\]

Then

\[
\varphi(0) = \frac{2 \cdot \pi \cdot a}{4 \cdot \pi \cdot \epsilon_0} \int_0^r \frac{r^3 \cdot dr}{\sqrt{x^2 + r^2}} = \frac{a}{\epsilon_0} \int_0^r \ln \frac{l + \sqrt{4r^2 + l^2}}{-l + \sqrt{4r^2 + l^2}} \cdot dr,
\]

\(\varphi(0)\)
When \( \frac{l}{2r} \geq 50 \) it is possible to expand under the integral expression in a series of powers of the ratio \( \frac{2r}{l} \).

Restricting to the first two terms of the expansion, we find:

\[
\phi(0) = \frac{a \cdot R^4}{\varepsilon_0} \int_0^{2r} \left( \ln \frac{l}{r} + \frac{r^2}{l^2} \right) \cdot dr = \frac{a \cdot R^4}{\varepsilon_0} \left[ \frac{1}{16} \ln \frac{l}{R} + \frac{R^2}{6l^2} + \ldots \right] \approx \frac{a \cdot R^4}{16 \cdot \varepsilon_0} \left[ 1 + 4 \ln \frac{l}{R} \right].
\]  

(6)

Substituting the numerical values from the experimental conditions, we find \( \phi(0,0,0) \approx 2350 \text{ V} \), with \( a = 5 \text{ cells/m}^5 \); \( \phi(0.0,0) \approx 5978 \text{ V} \); which is in good agreement with the electric fields used in the technological process.

3. Results and Discussion

3.1. Calculation of thermal processes during electrical pulse processing of weed rhizomes

Taking into account the layered structure of humai rhizomes (similar to the structure of a distributed model), it is advisable to estimate the limiting voltage of thermal breakdown, since there is a significant heating of the areas of the punctured rhizome (stem). The released heat heats up the insulating layer, heat losses increase with increasing temperature.

The thermal instability of the insulating layer can be estimated based on the fact that the heat flow \( W \) is always equal to the product temperature \( T^0 \) on the thermal resistance \( R_{\text{is warm}} \). The resistance of the discharge channel at the moment of maximum current strength is determined by the expression [26]:

\[
R_{\text{min}} = \frac{2 \cdot k \cdot l}{C \cdot U_0^2} \cdot e^{\frac{U_0 \cdot \tau_{\text{max}}}{R}}.
\]  

(7)

where: \( k \) and \( \alpha \) - constants (\( k = 0.2 \cdot 10^{-2} \text{ V} \cdot \text{s/cm}; \alpha = 2.3 \cdot 10^{-5} \text{ s}^{-1} \))

\( l \) is the distance between the electrodes, m;
\( C \) is the capacity of the charging capacitor, (F);
\( U_0 \) - capacitor charge voltage, (B);
\( \tau_{\text{max}} \) - exposure duration, (s).

\( R_{\text{min}} \) - usually constitutes a fraction of Ohm at the time of discharge. Heat is generated in the insulating layer (dielectric):

\[
W_g = \omega \cdot C \cdot U_0^2 \cdot \tau g \delta_0.
\]  

(8)

where \( \tau g \delta_0 \) - in the simplest case, does not depend on either the electric field strength or the temperature at different points of the insulating (dielectric) layer.

The general equation of the thermal state is stated:

\[
W_k + W_g = \frac{t_0 \delta}{R_{\text{ner}0}} \cdot \tau g \delta_0,
\]  

(9)

where:

\[
W_k = \frac{I^2 \rho_0 \delta}{S} (1 + at_{\text{inal}}) = \frac{I^2 R_{\text{min}}}{l} (1 + at_{\text{inal}}),
\]  

(10)

where \( I \) is the current flowing through the rhizome, A;
\( S \) — section of the discharge channel, \( \text{m}^2 \);
and - the temperature of the discharge channel coefficient \( 1/\text{C} \).
\( t_{\text{inal}} \) - temperature difference between the discharge channel and the environment, \( ^\circ \text{C} \);
\( t_{\text{vol}} \) - excess of the rhizome surface temperature over the environment \( (\text{C}) \);
\( R_{\text{heat}0} \) - thermal resistance of the environment, deg.-cm/W;
\( R_{\text{min}} \) - is the resistance of the discharge channel according to the formula (7).
For an approximate calculation of the dielectric loss in the insulating layer, in the simplest case, it is necessary to calculate some average value of the temperature \( t_{at} \) and substitute it in (10).

So, for the logarithmic temperature distribution in the insulating layer, \( t_{at} \) can be obtained from the obvious equality:

\[
t_{at} = \frac{1}{R - r} \int_r^R t_x \cdot dx + t_{vol},
\]

where,

\[
t_x = \frac{t_{isual} - t_{vol}}{\ln N} \left( \ln R - \ln x \right), \quad N \frac{R}{r},
\]

Integrating (11) from \( R \) to \( r \), we get:

\[
\frac{t_{at} - t_{vol}}{t_{isual} - t_{vol}} = \frac{1}{\ln N} - \frac{1}{N - 1} = K,
\]

Thus, the average heating of the insulating layer is determined by the heating of the plasma channel and the geometric dimensions (stem) of the rhizome (\( N \)).

Let us denote by:

\[
m = \frac{t_{at}}{t_{vol}} = \frac{K \left( W_k + W_0 \right) S_{isual}}{W_k + W_g} S_0,
\]

where \( W_k \) - heat, divisible in the discharge channel;
\( W_g \) - dielectric losses;
\( S_{isual} \) - thermal resistance of the insulating layer;
\( S_0 = R_{heat,0} \) - equivalent thermal resistance of the environment.

Typically, \( K \) is in the range from 0.4 to 0.5. Considering only dielectric losses, it is possible to obtain for the critical temperature of heat transfer from the surface of the dielectric cylinder (intermediate operations are omitted):

\[
t_{cr} = \frac{1}{a \cdot m} + \Delta t,
\]

where \( \Delta t \) is the excess of the ambient temperature over the temperature corresponding to \( tg(\delta) \).

For a plasma channel, approximately \( a \approx 0.05 \). On the other hand, in the general case, we have:

\[
W_g = \frac{t_{cr} - \Delta t}{R_{heat,0}} = \frac{t_{cr} - \Delta t}{S_0},
\]

since \( R_{heat,0} = S_0 \)

Therefore,

\[
W_g = \omega \cdot C \cdot tg(\delta) \cdot U_{cr}^2 = \frac{t_{cr} - \Delta t}{2,72 \cdot R_{heat,0}},
\]

From here we find the value of the thermal breakdown of the insulating layer (humay rhizomes) of interest to us:
\[ U_{cr} = \frac{t_{cr} - \Delta t}{\sqrt{2.72 \cdot R_{heat.0} \cdot \omega \cdot C \cdot \text{tg} \delta_0}}, \]  
(18)

We make it clear to them that \( R_{heat.0} \) - cooling of the heated dielectric rod (rhizomes) - occurs in the air exclusively due to convection. Warm of howling field around the rod practically absent, so we introduce the concept of equivalent thermal resistance, in this case surround the segments of Humay:

\[ R_{heat.0} = \frac{1}{\pi \cdot D_{st} \cdot h} = S_0, \]  
(19)

Where \( D_{st} \) is the diameter of the rod;

\( h \) - is a constant (a coefficient numerically equal to the amount of heat given off by 1 cm\(^2\) of the outer surface of the rod at a temperature difference between it and the surrounding air of 1 °C, W/deg.cm\(^2\)), has a value of the order \( 10^{-3} \div 10^{-2} \).

Calculations for this coefficient give the expression

\[ h = a^4 \sqrt{\frac{W}{D}} \]; where \( a = 2.7 \cdot 10^{-3} \),

(20)

To simplify the expression for \( U_{cr} \), we use only the value of \( h \) itself. Then finally for \( U_{cr} \) we get:

\[ U_{cr} = \frac{D_{st} \cdot h}{\sqrt{5.54 \cdot a \cdot m \cdot f \cdot C \cdot \text{tg} \delta_0}}, \]  
(21)

where \( f \) - is the frequency of the fundamental harmonic of the voltage pulse acting on the processed sections of humai rhizomes.

The value is determined on a basis of spectral analysis, affecting pulse trains, \( f = 450 \) Hz.

It can be argued that the obtained expression for the thermal breakdown \( U_{br} \) adequate to the known coefficient of viability \( K_0 \) of the plant, since physically these values are equally related to structural cellular changes in the stems of rhizomes of perennial weeds (RPW). Indeed, an increase in the current through the sample with an increase in \( U_{slave} \) is accompanied by an increase in \( \text{tg} \delta \) and average temperature \( m \) of the treated RPW and ends with cell death and \( K_0 \rightarrow 1 \).

This is confirmed by anatomical studies of pulsed-treated RPW segments [1]. Therefore:

\[ K_0 = \gamma \cdot U = \frac{\gamma \cdot F}{\sqrt{\text{tg} \delta \cdot m}}; \]  
(22)

where \( F \) - is determined outside the expression \( U_{slave} \) RPW parameters, power supply circuit and a processing mode, \( F = 500 + 800 \); \( \gamma \) - coefficient of proportionality, \( 10^2 \div 10^3 \) 1/V.

To check the reliability of equation (21), we plot a graph of the theoretical relationship between the electrical coefficient of viability (\( K_0 \)) and voltage (\( U \)) (curves 1.3), which, when compared with the experimental ones (curves 2.4.), Graphically indicate the adequacy of this expression (Figure 2).

The graph shows that as a result of the electrical impulse effect on the tissues of humai rhizomes at voltages from 3000 to 9000 V with a capacitor capacitance \( C=0.5 \cdot 10^{-9} \) F and \( C=1.0 \cdot 10^{-9} \) F, practical measurements confirm the theoretical indicators. This means that after the electric pulse treatment in the plant tissue, there is a sharp drop in electrical resistance. This phenomenon can be explained by the fact that the destruction of the outer membranes of cells, the destruction of intercellular channels, a decrease
in turgor pressure and a disorder of the life cycle occur in the plant tissue. When Ko tends to mark 1, this means that the necrosis of plant tissues is not reversible. Along the curve of the graph, it can be observed that after processing the plant material at a voltage from \( U = 5000 \) to \( U = 7000 \) V, capacitance of the capacitor \( C=1.0 \cdot 10^{-9} \) F, we reach the values of \( Ko = 2.5 \) to \( Ko = 2 \). Comparison of the indicators of Co can be seen that the values fall by 2 or more times.

\[ \text{Figure 2. Dependence of the electrical coefficient of viability (necrosis, } K_{\text{necrotic}} \text{) on the pulse voltage (} U, \text{ V): 1-3-curves based on theoretical calculations; 2-4-curves for triple on the basis of practical measurements.} \]

It is possible to estimate the permissible load current based on the same basic equation (11):

\[ W_k + W_s = \frac{f_{\omega}}{S_0}, \quad (23) \]

The influence of dielectric losses released in each elementary volume of the insulating layer can be estimated as follows.

The amount of heat released due to dielectric losses in an elementary layer of radius \( r \) and thickness \( \Delta r \) will be expressed by the approximate equation:

\[ \Delta W_k = \omega \cdot C \cdot \tan(\Delta U)^2, \quad (24) \]

where the layer capacity:

\[ \Delta C = \frac{\varepsilon}{1.8 \cdot 10^{12}} \cdot \frac{r_s}{\Delta r}, \]

and the voltage drop is not mute:

\[ \Delta U \approx E_s \cdot \Delta r = \frac{U \cdot \Delta r}{r_s \cdot \ln \frac{R}{r}}, \quad (25) \]

Then
\[ \Delta W_x = 2\pi \cdot \frac{f \cdot \varepsilon \cdot \tan \delta \cdot U^2 \cdot \Delta r}{1,8 \cdot 10^{12} \left( \ln \frac{R}{r} \right)^2 \cdot r} = 2\pi \gamma_{equ} \frac{U^2}{\left( \ln \frac{R}{r} \right)^2} \cdot \Delta r; \]  

(26)

where the equivalent conductivity of the dielectric at alternating current:

\[ \gamma_{equ} = \frac{f \cdot \varepsilon \cdot \tan \delta}{1,8 \cdot 10^{12} \cdot r} \quad (1/\text{Om*sm}); \]  

(27)

On the other hand, the presentation of the heat flux through an elementary annular layer: with the thickness \( dr \) will be equal to the change in its temperature \( d\theta \) divided by the thermal resistance of the layer, i.e.

\[ d \left( \frac{d\theta}{\sigma_{insul} \cdot dr} \right) dW_x = 2\pi \cdot \gamma_{equ} \cdot \frac{U^2}{\left( \ln \frac{R}{r} \right)^2} \cdot \frac{dr}{r_x}, \]  

(28)

where \( \sigma_{insul} \) is the thermal resistance of the insulating layer, deg·cm/W.

First integration in the range of \( r \) to \( r_x \) yields

\[ \frac{d\theta}{dr} \bigg|_{2\pi \cdot r_x} \sigma_{insul} = 2\pi \cdot \gamma_{equ} \cdot \frac{U^2}{\left( \ln \frac{R}{r} \right)^2} \cdot \ln \frac{r}{r_x} + C, \]  

(29)

Moreover:

\[ W_x = \frac{2\pi \cdot \gamma_{equ} \cdot U^2}{\ln \frac{R}{r}}. \]

Then the differential equation will be written:

\[ d\theta = \frac{\sigma_{insul}}{2\pi} \left\{ \frac{W_x}{\ln \frac{R}{r_x}} \left( \ln \frac{r}{r_x} \right) \frac{dr}{r_x} + C \cdot \frac{dr}{r_x} \right\}, \]  

(30)

Integrating again by \( r_x \) to \( R \), we obtain the magnitude of the heating current heat transmission channel allocated to the discharge channel and an insulating dielectric layer:

\[ \theta_x - \theta_0 = \frac{\sigma_{insul}}{2\pi} \left\{ \frac{W_x}{2 \ln \frac{R}{r_x}} \cdot \left( \ln \frac{R}{r_x} \right) \cdot \ln \frac{R r_x}{r_x^2} + W_r \cdot \ln \frac{R}{r_x} \right\}, \]  

(31)
So obviously, that the constant $C$ is equal to the $W_{the k}$.

The general expression for the temperature at any point of the insulating layer for the steady-state thermal regime can be written as:

$$\theta_r = \frac{W_s \sigma_{\text{final}}}{4\pi \ln R} \cdot \left( \ln \frac{R_{r_k}}{r_k} \right) + \frac{W_s \sigma_{\text{final}}}{2\pi} \cdot \ln \frac{R_{r_k}}{r_k} + \left( W_s + W_g \right) S_0 + \theta_0,$$

(32)

Substituting the value of $W_g$ at $n = 1$, we get:

$$\frac{I_{vol}}{S_0} = I^2 \cdot R_{\min} + \frac{2 \cdot \pi \cdot \gamma \cdot U^2}{\ln R/r} \cdot e^{m \alpha},$$

(33)

We can assume:

$$I_{at} = I_{vol} \cdot m,$$

(34)

The value of $m$ can be judged by the expression (16). Then, substituting this value in (33) and solving it with respect to the current, we obtain the following expression for the permissible load current of the insulating rod (humay segments), taking into account the temperature dependence of dielectric losses in the insulation:

$$I_{perm} = \sqrt{\frac{1}{R_{\min}}} \cdot \sqrt{\frac{I_{vol}}{S_0} \cdot \frac{2 \pi \gamma_{\text{final}} \cdot U^2}{\ln R/r} \cdot e^{m \alpha}},$$

(35)

Where, $R_{\min}$ determined from the expression (7), and $S_0$ (21).

Thus, the obtained expressions for the thermal breakdown of the insulating layer (Humay rhizomes) according to expression (20) and the permissible load current according to (35) make it possible to theoretically estimate their values for known (experimentally measured) specific parameters of the stem samples (sections of Humay rhizomes). The calculations are in quite satisfactory agreement with the experimental results.

4. Conclusions

1. The results of theoretical research and practical measurements are evidence of the irreversible process of necrosis of plant tissues after electric pulse treatment.
2. The suitability of the equation for determining the coefficient of viability can be used in theoretical calculations, which is confirmed by the results of practically x values.
3. The theoretical estimate of the potential at the point of application of the operating voltage allows one to determine the optimal parameters of electrical processing, which is consistent with the experimental conditions.
4. Based on the calculation of thermal processes in the dielectric segments of plant rhizomes, an expression was obtained to assess the potential of their thermal breakdown, depending on the physical parameters and processing mode, as well as an expression for assessing the permissible load current in a stationary mode.

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