

Theoretical basis for the movement of a pulsed current discharge through a plant organism

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Abstract. The article presents the current state of the problem of contamination of cultivated areas with weeds. A tribute to the analysis of scientific and technical information on weed control, their advantages and disadvantages are described. Theoretically substantiated processes are the destructive effects of electric discharges of current on plant tissue.

I. Introduction

A huge number of weeds grow on the sown areas of agricultural crops along with useful plants. As a rule, due to good vegetation and a strongly developed root system, weeds grow early, take a large amount of mineral resources and thereby deplete the soil composition, which replenishment requires additional expenses of mineral fertilizers, labor, time and financial costs. The next negative side of weeds is that all pathogens during hibernation find refuge in their rhizomes and plant debris. Therefore, when calculating the degree of harmfulness of weeds, it would be desirable to include crop losses associated with diseases that develop at an early stage in weeds. To prevent the invasion of weeds and reduce the harmfulness of weeds, various technological measures are proposed that should counter the aggravation of the problem [1, 2, 3, 4, 5].

To destroy weeds, methods such as manual weeding, agrotechnical, mechanical, chemical, fire, solarization - plastic mulching (soil warming), strict observance of quarantine measures, biological and electrical are used.

The study and analysis of scientific and technical sources made it possible to assess the advantages and disadvantages of the above methods. For example, when using manual weeding, the best successful results are achieved. However, its application requires a huge amount of human labor, time and money, which are unreasonable in the conditions of self-sufficiency and cost accounting.

Agrotechnical measures cover crop rotation in crops such as cotton, autumn wheat and short-term fodder plants. This approach in agriculture eliminates the break of vegetation, i.e. maximum use of sown areas provides an opportunity for the development of new species of one and perennial weeds. This approach contributes to the growth and development of unwanted plants and weeds.

The use of various mechanical devices and tools in the fight against weeds is also ineffective because of the correspondence of the reproduction and distribution of root residues that develop exclusively from rhizomes of perennial rhizome weeds and weed seeds in general. In some cases, mechanical measures (plowing, loosening the soil, cultivation) create favorable conditions for planting weed seeds in the intermediate growing season.

The chemical method, based on the use of various pesticides, accompanies the ability to accumulate chemical compounds and harmful substances in the composition of the soil and plant tissues. Accumulated pesticides in soil and plants can be transmitted through food products, which lead to very dangerous consequences.

The use of infected products with strong toxins causes allergic, chronic and incurable diseases in living organisms. Therefore, for environmental and ethical reasons, the chemical method is considered inappropriate.

The most modern and effective method of controlling weeds is currently considered the struggle with the use of various biological preparations and insects. However, the lack of research and the selectivity of living beings do not allow the widespread use of the biological method [4, 5, 6, 7, 8].

The analysis of scientific and technical information indicates that the application of the above methods is a resourceful and financial expansive, either during the application or subsequently.

To date, various electrical methods have been proposed and tested to control weeds, in which current (constant, alternating) and voltage (low, high) and frequency (industrial, low, high) are considered action parameters. Experimental and serial electrical installations with various damage factors have been developed.

To determine the damaging parameters, high efficiency of fatal outcomes of plant tissues after processing with high-voltage variations of sugar is required, which saves energy, resources and time, requiring theoretical research and justification.

2. Methods

Analysis of studies of the effects of electrical impulse discharges on living plant organisms.

As known [1, 2, 9, 10, 11, 12, 13] the electric spark of a current pulse is a multifactor working body in which energy is released in a short period of time (pulse mode), which causes the appearance of a high temperature of the spark discharge channel, a high density of electric current, ionization processes, electric and magnetic fields, optical radiation, etc. Isolation of one-factor action on plant tissue is quite difficult, but with some certainty it can be argued [6, 7, 9, 14, 15] that when discharged without overlapping plant tissue on the surface, the plant is damaged by conduction currents, shock waves and is due to electro biological and structural changes in the plant tissue.

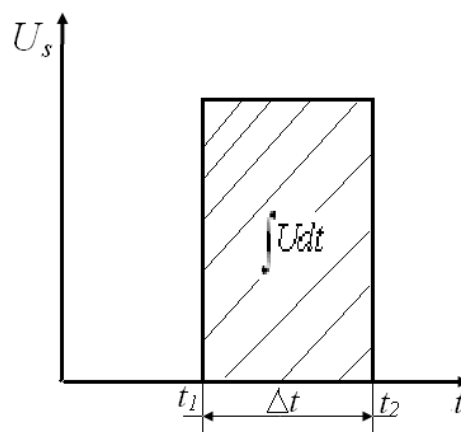


Figure 1. The dependence of the voltage (U_s) on the duration of the discharge (t)

In general, plant tissue and its cell can be represented as an electrolyte surrounded by a semipermeable membrane [4, 5, 7, 15]. When an external electric field is applied to such a solution, dissociation of electrolyte ions is observed, which accumulate on the outer and inner sides of the cell (the membrane can be considered as a dielectric spacer between capacitor plates).

For the most part, stimulation is produced by a voltage pulse, the simplest form of which is a rectangular pulse (Figure 1).

The magnitude of the voltage pulse (or voltage peak) can be determined by the expression (3.1.):

$$\int_{t_1}^{t_2} U dt = U_s \cdot (t_2 - t_1) = U_s \Delta t, \quad (1)$$

This voltage surge causes a current surge in the excitable system $\int_{t_1}^{t_2} I dt$.

When the impedance of the system is neglected, the reactive component of the tissue impedance is negligible, the current shock will also be rectangular:

$$\int_{t_1}^{t_2} I dt = I \cdot \Delta t, \quad (2)$$

The irritation energy received from the rectangular pulse will be equal to:

$$U \cdot I \cdot \Delta t, \quad (3)$$

Assuming a voltage drop U_s on the biological system is always the same, then for the characterization of irritation it is enough to know the product $I \cdot \Delta t$. Therefore, instead of the energy of threshold stimulation in electrophysiology, it characterizes threshold irritation by the magnitude of the current.

With a constant voltage drop, the product $I_s \cdot \Delta t$ should also be constant if I_s there is that current at which excitation occurs.

$$I_s \cdot \Delta t = const, \quad (4)$$

Thus, the threshold current changes with the duration of the stimulation, which with a longer duration of the stimulation will require a lower threshold current to cause excitation. In electrophysiology, this dependence is represented by the curve "current - duration" (Figure 2). There is a certain minimum for the current value, below which the current pulse; whatever its duration, can no longer cause excitement. This minimum current is called a reobase. The current-duration curve approaches it asymptotically.

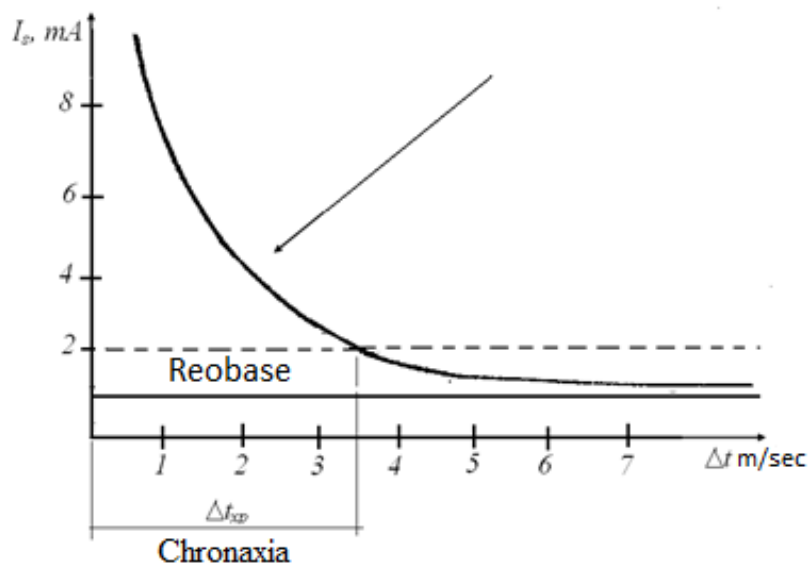


Figure 2. The dependence of the current value (I_s) on the duration of irritation (Δt)

For practical purposes, it is sufficient to determine the rheobase at a pulse duration of 1000 m/s. Denoting the reobase by Rh , the equation for $I_s \cdot \Delta t = const$ will be rewritten in the form:

$$(I_s - Rh) \cdot \Delta t = const, \quad (5)$$

where Rh is the current corresponding to the reobase.

Chronaxia is understood to mean the shortest duration (Δt_{xp}) that a pulse of a current doubled in comparison with a reobase must have in order to cause excitation.

The minimum irritation energy $Q_{min}^{irritation}$ can be calculated using the expression:

$$Q_{min}^{irritation} = U_s Rh \cdot \Delta t_{xp}, \quad (6)$$

If two electrodes are attached to the outer surface of the cell (for example, to the shell of the axial cylinder of the fiber-rhizome of the plant), then excitation occurs under the cathode. If the stimulation energy reaches a threshold value, then a local reaction will be observed, but the propagation of excitation does not occur, since this energy is insufficient to transfer the excitation to the neighboring region.

A further increase in the energy of stimulation leads to pervasive excitation. It should be noted that a sharp boundary between local and propagating excitation cannot be established. Following the spreading excitation with a further increase in energy, a “breakdown” of the membranes occurs, accompanied by changes in the cellular structure. Breakdown occurs at a certain current strength.

These are the main stages of exposure of a living plant tissue to an electric field: local and pervasive cell excitation, breakdown of membrane structures with the formation of plasmolysis, and cell death.

When a cell absorbs energy after reaching the threshold of irritation, in accordance with the Joule – Lenz law, it heats up and dies at a certain temperature (plasmolysis temperature). Cell death is accompanied by a loss of ability to retain moisture in vacuoles, coagulation of membrane proteins and cytoplasm.

Let us dwell on these stages in more detail, in order to obtain the main regime characteristics of the electro-technological process of processing plant rhizomes. Apparently, the approach to solving these stages will be different.

In [16, 17, 18, 19], an important, from the point of view of the technological process, thermo selective effect of an electric current on cellular tissues is considered, based on the characteristics of the conductive properties of cells. It was found that selectivity increases with increasing current through the tissue and a decrease in the time of its exposure, which is also consistent with the current-duration dependence described above. With an increase in the energy input rate, the temperature difference between the membrane and the cytoplasm increases (in a short time the membrane does not have time to transfer heat to the cytoplasm). It is an increase in the voltage gradient that is accompanied by an increase in the gradient through biomass and the time of plasmolysis is reduced. This, in turn, is possible only with a pulsed technological process, and vice versa, a decrease in the voltage gradient leads to a decrease in the current through the tissue. Therefore, plasmolysis time and energy consumption increase, since not only the membrane structure is heated, but also the contents of the cell along with vacuolar moisture. There is an unnecessary waste of energy.

Taking a number of assumptions regarding the size and weight of a plant cell, its heat capacity and plasmolysis temperature (65^0), you can find the amount of energy going to its destruction. As calculations show, electroplasmolysis of one cell requires an average $(1,1 \cdot 5) \cdot 10^{-10}$ J.

The amount of energy used to destroy cells of 1 kg of plant mass can be estimated by the formula (3.7)

$$A_{RC} = \frac{A_{cells} \cdot M}{\eta}, \quad (7)$$

where A_{cell} - is the energy of electroplasmolysis of one cell, J ;

M - is the number of cells in 1 kg of plant mass;

η - is the efficiency of the ratio of the energy absorbed by the cells to all the energy supplied to the mass.

With an increase in the rate of energy input (electrokinetic phenomena predominate, leading to the death of the cell and the exit of moisture due to damage to the membrane) and the magnitude of the current, an electrosomatic push of the cell contents is also possible.

Thus, to reduce the energy costs of processing plants, it is advantageous to directly destroy the cell membranes in comparison with their destruction due to indirect heating. A sharp increase in the electric field is needed, which is possible only in a pulsed mode. A prerequisite is the presence of a non-linear section in the current-voltage characteristics (CVC) of the cell membranes [16, 18].

The non-linear section of the current-voltage characteristic with increasing voltage ends with a sharp increase in current and destruction of the membrane.

In fundamental works on biophysics [16, 20, 21, 22, 23, 24] and original [3, 8, 17, 25, 26, 27, 28] the applicability (in a first approximation) of the distributed model for describing the processes of signal (impulse) propagation along the nerve fiber, muscle tissue, and symplast of a higher plant is shown. The main difference between the distributed models used to describe the processes of signal propagation through the plant's conducting system is the heterogeneity of the symplast. The symplast of a higher plant (the provider's system) is not only structurally heterogeneous - branching, diameter changes, but also functionally heterogeneous. Different levels of metabolism of different parts of the symplast serve as a source of different membrane potentials in these areas and the difference in electrical potentials between them. For the mathematical analysis of processes in the conducting system of plants (also called rhizomes), knowledge of their electrical passive and active characteristics is necessary. Passive electrical characteristics include: constant length of the symplast, specific capacitance and resistance of the membrane, internal and external resistance of the medium; to active characteristics - a set of data on the excitation signal (action): amplitude, front slope, propagation speed, duration, etc.

2.1. Justification of the functional model of the rhizome with a conductive core: Resistance and capacity of a cylindrical fiber (rhizome)

Considering the electromagnetic processes propagating along the stems (like cable and two-wire electric lines), it must be borne in mind that the electric and magnetic fields (components of the pulse) are distributed along the entire length of the line. The conversion of electromagnetic energy into heat also occurs along the entire length of the line (stem), i.e. the stem is a chain with distributed parameters called primary and per unit length. Therefore, it is necessary to introduce these unit parameters: resistivity along the stem and specific capacity. The processes occurring in such lines are described by well-known telegraph equations.

The inherent property of a material to resist electric current is described by its resistivity R_i , which is expressed in ohms/cm. It can be represented as resistance between opposite faces of a cube with a rib length of 1 cm made of this material. For an inhomogeneous medium, such a cube should be a small, volume element: in this case, R_i is equal to the resistance between the faces times the length of the rib in cm.

In principle, R_i is a differential quantity and, in the general case, a function of coordinates. For an arbitrary conducting body, the macroscopic resistance can be determined by integrating R_i .

To describe a homogeneous cylindrical structure, one can choose an indicator such as axial resistance per unit length (i.e., Ohm / cm). According to a formula known from the theory of electricity, the resistance per unit length is equal to the specific resistance divided by the cross-sectional area.

Therefore, if r_i is the resistance per unit length and α - is the radius of the cylinder, then:

$$r_i = \frac{R_i}{(\pi \cdot \alpha^2)}, \text{ (Ohm/cm)}, \quad (8)$$

Let us agree that lowercase letters will denote quantities reduced to a unit of length. Then C_i is the membrane capacity per unit length, and r_m is the membrane leakage resistance multiplied by the

length. If R_m is the specific resistance of the membrane ($\text{Ohm} \cdot \text{cm}^2$), and S_t is its specific capacity ($\mu\text{F}/\text{cm}^2$), then:

$$r_i = \frac{R_m}{2 \cdot \pi \cdot \alpha}, \quad (9)$$

where - is the leakage resistance of the "cm²" of the membrane, its dimension is consistent with a decrease in the total resistance of the membrane with an increase in area in accordance with the parallel inclusion of resistance; C_m - the capacity of "cm²" of the membrane, and it increases with increasing area.

For Axon Kalmar fiber - $C_m \approx 1 \mu\text{F} / \text{cm}^2$; $R_m = 10000 \text{ m}/\text{cm}^2$.

3. Results and Discussions

3.1. Designing an electrical model of plant tissue

Based on the idea taken from the theory of electric circuits, it is possible to develop a model of a single fiber, rhizome. If we make a reasonable assumption about the axial symmetry of the rhizome (i.e., $d/d\theta = 0$), then the model in principle becomes one-dimensional. It can be assumed that in the excised rhizome (fiber) in the intracellular (as well as extracellular) region, the current caused by external action has an axial direction. Then the equivalent electrical circuit of a plant segment (rhizome), reflecting its distributed properties, is (Figure 3).

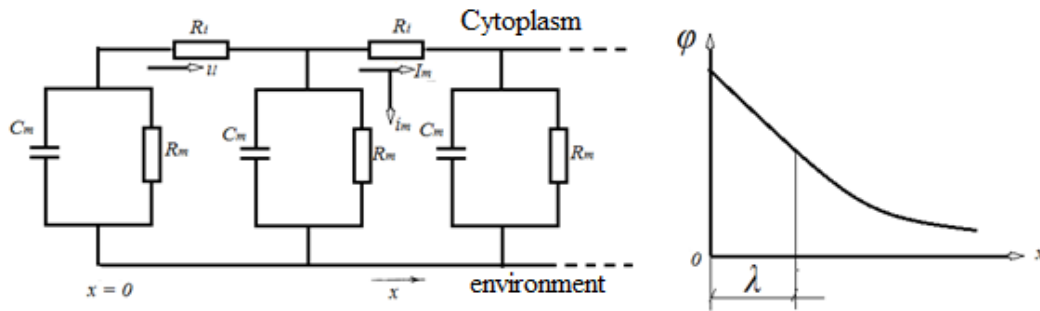


Figure 3. An equivalent electrical circuit of a segment of a rhizome (fiber), reflecting the cable properties - a and the distribution of potential along the rhizome - b, with current injection at the point $x = 0$, λ is a constant of length; R_m and C_m — cytoplasmic resistance; i_l is the longitudinal current; i_m is the membrane current

The potential distribution along the rhizome (fiber) under conditions when the membrane is not excited is determined by the strength of the longitudinal current in the cytoplasm. According to Ohm's law, the longitudinal current (i_l) is proportional to the conductivity of the cytoplasm (axoplasm) section and the voltage drop in this section:

$$i_l = -\frac{1}{r_i} \cdot \frac{d\phi}{dx}, \quad (10)$$

With increasing distance x , the longitudinal current decreases due to leakage into the external environment; this part is membrane current. Since the current through the membrane i_m is equal to the decrease in the longitudinal current in the section dx , we can write:

$$i_m = -\frac{di_l}{dx} = \left(\frac{1}{r_i}\right) \cdot \frac{d^2\phi}{dx} = \frac{1}{r_i} \cdot \frac{d^2V_m\phi}{dx^2}, \quad (11)$$

On the other hand, according to Ohm's law, the membrane current is $i_m = \frac{\varphi}{r_m}$,

where φ is the potential difference at a distance x from the point of application φ_0 .

$$\text{As a result, we get: } \left(\frac{r_m}{r_i}\right) \cdot \frac{d^2\varphi}{dx^2} = \varphi \text{ или } \left(\frac{r_m}{r_i}\right) \cdot \frac{d^2V_m}{dx^2} = V_m, \quad (12)$$

where $\lambda^2 = \frac{r_m}{r_i}$ - constant length.

Denote by $\tau = r_m \cdot C_m$ the time constant of the cell. Both parameters λ and τ are important in the theory of conductors. Under stationary conditions, λ is the distance at which the voltage V_m (or current) changes by "e" times. For spherical cells, τ is equal to the time during which the transitional response of the cell to a stepwise current pulse reaches a value that differs from its stationary level by a factor of 1/e. Often these parameters are accessible to direct measurement and have a very definite physical meaning. Therefore, they are suitable for quantitative description purposes. The transition from $r_i R_i$ gives:

$$\lambda^2 = \left[\frac{R_m / 2 \cdot \pi \cdot d}{R_i / \pi \cdot \alpha^2} \right]^{1/2} = \left[\frac{\alpha \cdot R_m}{2 \cdot R_i} \right]^{1/2}, \quad (13)$$

Where α - radius of the rhizome (fiber).

By solving a homogeneous equation [6]:

$$\lambda^2 \cdot \frac{d^2 \cdot V_m}{dz^2} \cdot V_m = 0$$

we receive the formula below:

$$V_m(x) = A \cdot e^{-\frac{x}{\lambda}} + B e^{\frac{x}{\lambda}}$$

Here the constants A and B are found from the boundary conditions of Table 1.

Table 1. Indicators of boundary conditions

	Permanent	A	B
X	0	C	0
X	0	0	C

The equation can be written in a compact form:

$$V_m(x) = C \cdot e^{-\frac{x}{\lambda}}, \quad (14)$$

C is determined from the boundary conditions.

The stationary solution has the form:

$$V_m = -\frac{r_e \cdot \lambda \cdot I_0}{2} \cdot e^{-\frac{x}{\lambda}}, \quad (15)$$

where r_0 is the resistance of the extracellular medium per unit length; I_0 is the total applied stimulation current (injection).

Details of the output are omitted here. It should only be noted that current is supplied from an electrode located near the rhizome (fiber) at the point $x = 0$. All assumptions of the model with a

conductive core are satisfied. The current flows along the rhizome (fiber) and it can be represented by an idealized source, which is described by a spatial delta - function:

$$i_p = I_0 \cdot \delta(x), \quad (16)$$

Where $\delta(x)$ - delta is the Kronecker function. By definition, represents $\delta(x) = 0$ at $x \neq 0$; $\delta(x) = \infty$, $\int \delta(x) dx = 1$

I_0 is the total current applied to the rhizome (fiber).

If we introduce a source in the form of a delta function into the equation of a distributed model, then it has the form:

$$\frac{d^2 V_m}{dx^2} - \frac{dV_m}{dT} - V_m = r_e \cdot \lambda^2 \cdot I_0 \cdot \delta(x), \quad (17)$$

where X and T are normalized spatial and temporal variables:

$$X = \frac{x}{\lambda}; \quad T = \frac{t}{\tau}, \quad (18)$$

The current jump at the origin is taken into account by introducing a boundary current at $X = 0$. In fact, a homogeneous equation without the right-hand side is considered. I_0 stimulation current (injection) can be supplied inside or outside the cell. In the equation on the right side, the index changes with resistance r (r_i or r_e). This equation is solved rather complicated with the help of Laplace transforms (relative to T). The Laplace transform from dV_m/dT is equal to:

$$S \bar{V}_m - V_m(0, x), \quad (19)$$

where the bar above denotes the Laplace transform. In this case, the response of the passive model to the pulse current applied at $t \geq 0$ is described by the equation:

$$\frac{d^2 \bar{V}_m}{dx^2} - (S+1) \cdot \bar{V}_m = 0, \quad (20)$$

The advantage of using the Laplace transforms is that the partial differential equation with respect to X and T can be transformed into an ordinary differential equation containing only X .

The solution to the last equation has the form:

$$\bar{V}_m = A_{\exp} [-X \cdot (S+1)^{1/2}] + B_{\exp} X \cdot (S+1)^{1/2}, \quad (21)$$

Consideration of boundary conditions (intermediate operations omitted) leads to the answer:

$$\bar{V}_m = \frac{I_0 \cdot r_i \cdot \lambda}{2 \cdot S \cdot (S+1)^{1/2}} \cdot \exp[-X \cdot (S+1)^{1/2}], \quad x > 0, \quad (22)$$

The desired solution is found by performing the inverse transform from the last equation. The easiest way to do this is by looking at the Laplace transform table, we get:

$$V_m(X, T) = \frac{I_0 r_i \lambda}{4} \cdot \left\{ e^{-x} \left[1 - \operatorname{erf} \left(\frac{x}{2\sqrt{T}} - \sqrt{T} \right) \right] - e^x \left[1 - \operatorname{erf} \left(\frac{x}{2\sqrt{T}} + \sqrt{T} \right) \right] \right\}, \quad (23)$$

Here erf is the error probability integral or error function, defined as:

$$\operatorname{erf}(y) = \frac{2}{\sqrt{\pi}} \int_0^y e^{-z^2} \cdot dz; \quad \operatorname{erf}(\infty) = 1; \quad \operatorname{erf}(-\infty) = -1$$

The result obtained is valid for an infinite model when current (I_0) is introduced into the intracellular space (r_i) at the point $X = 0$ and describes the behavior of the membrane at $X = 0$. In the resulting solution, we can go to the absolute values of X and T .

$$V_m(x,t) = \frac{I_0 r_i \lambda}{4} \cdot \left\{ e^{-\frac{[x]}{\lambda}} \left[1 - \operatorname{erf} \left(\frac{[x]}{2\lambda} \left[\frac{\tau}{t} \right]^{1/2} - \left[\frac{t}{\tau} \right]^{1/2} \right) \right] - e^{-\frac{[x]}{\lambda}} \left[1 - \operatorname{erf}(\dots) \right] \right\}, \quad (24)$$

Based on this decision, it can be argued:

- the current I_0 introduced into the rhizome (fiber) clearly affects the potential $V_m(x, t)$ and this influence strongly depends on X . The largest change in V_m in the same application of current I_0 with an increase in X causes a decrease in exponentially V_m ;
- current I_0 causes hyperpolarization of the rhizome membrane (fiber), which can be predicted if we consider the voltage drop $I_0 R_m$ on the membrane resistance;
- λ is a quantitative measure of the distance from the source over which the disturbance V_m extends;
- at $t > \tau$, those for a spatial picture approaching a stationary state, $V_m(x)$ tends to be true: exponential of X . The leakage resistance for membranes is responsible for this continuous decrease in V_m with increasing X ;
- the time effect depends on τ . At $t > \tau$, the response of a distributed model (rhizome or fiber) quickly approaches a stationary state. The presence of a capacitance C_m to achieve a stationary state requires a certain time, a measure of which is $\tau = r_m \cdot C_m$. Only at $x = \lambda$ is the constant τ equal to the usual value obtained for exponential growth.

Answers to many questions about the electrical properties of stems, rhizomes (fibers) can be found in terms of ideas about input resistance (impedance). It is possible to analyze the effects arising from the fact that the distributed model has a finite rather than infinite length. This analysis is performed by comparing the input impedance for cases of finite and infinite lengths.

The input impedance z_0 is defined as the ratio:

$$z = \frac{V_m}{I_i}, \quad (25)$$

where I_i is the longitudinal (intracellular) current (and not the input current. I_0)

In contrast to the traditional use of Ohm's law, the voltage V_m is related to the longitudinal current.

Using equation (3.25) for a distributed model (conductor) of infinite length (the solution is not considered here) gives a simple result:

$$z_0 = (r_i \cdot r_m)^{1/2}, \quad (26)$$

The input impedance for an infinitely long model is equal to the square root of the product of the membrane and intracellular resistances (in relation to the rhizome, fiber, etc.).

3.2. Rhizomes, fiber of a distributed model of finite length

Considering the input impedance z_{bx} of a distributed model of arbitrary length L ending with an element with arbitrary impedance z_L , of interest is the special case of rhizomes (fibers) of length L with a short circuit ($z_L = 0$). This is due to the fact that the degree of coincidence is a quantitative measure of the degree to which the final length of the distributed model approaches the input characteristics of this model of infinite length. Results have a wide range of applications.

Let $X = L$ end with the load impedance z_L . At point $X = 0$, the input voltage $V_m = V_0$ is applied to the input. For $X > 0$, the equations of the distributed model in a uniform form have the well-known (12) form:

$$\lambda^2 \cdot \frac{d^2 V_m}{dx^2} - V_m = 0$$

Its solution is expression (13). The relationship of V_m and I_i , also found from the equations distributed model has the form:

$$\frac{d V_m}{d x} = -r_i \cdot I_i, \quad (27)$$

Substitution of (3.13.) Into (3.27) and the solution with respect to I_i gives:

$$I_{i(x)} = \frac{1}{z_0} \cdot \left[A \cdot e^{-\frac{x}{\lambda}} - B \cdot e^{\frac{x}{\lambda}} \right], \quad (28)$$

where, $z_0 = (r_m \cdot r_i)^{1/2}$.

At the point $x = 0$ have $z_{bx} = \frac{V(0)}{I(0)}$ so from (12) and (28) for z_{bx} we get:

$$z_{bx} = z_0 \left[\frac{A+B}{A-B} \right], \quad (29)$$

In order to avoid infinite potential growth for a distributed model of infinite length $B = 0$, then

$$z_{bx} = z_0.$$

For a distributed model of finite length and with an arbitrary load at the end, finding the input impedance requires the definition of A and B. This definition is facilitated by introducing a factor containing the terminal impedance and known as the reflection coefficient.

At the point $X=L$ $z_L = \frac{V_m(L)}{I_i(L)}$. Then, dividing (12) by (28), we obtain:

$$z_L = z_0 \left[\frac{A \cdot e^{-\frac{L}{\lambda}} + B \cdot e^{\frac{L}{\lambda}}}{A \cdot e^{-\frac{L}{\lambda}} - B \cdot e^{\frac{L}{\lambda}}} \right], \quad (30)$$

Define the "reflection coefficient" "G" as follows:

$$G = \frac{z_L + z_0}{z_L - z_0}, \quad (31)$$

Substituting (3.30.) Into (3.31.) And, accordingly, simplifications give:

$$G = \frac{A \cdot e^{-\frac{L}{\lambda}}}{B \cdot e^{\frac{L}{\lambda}}}, \quad (32)$$

$$z_L = z_0 \left[\frac{\Gamma + 1}{\Gamma - 1} \right], \quad (33)$$

When $z_L = z_0$ the final load is equivalent to a model of infinite length, and reflection is absent ($G = \infty$). If, $G = \pm 1 \cdot (z_L = \infty, 0)$ then the end of the distributed rhizome model introduces maximum

heterogeneity (everything is reflected). In this regard, there is a similarity in mathematical formulas for the propagation of electromagnetic waves in a common model and biological fibers, although the physical situation is different.

Finally, substituting (3.32) into (3.29.) Gives an expression for through G:

$$z_{bx} = z_0 \left[\frac{G \cdot e^{\frac{2L}{\lambda}} + 1}{G \cdot e^{\frac{2L}{\lambda}} - 1} \right], \quad (34)$$

For a distributed model (fiber) of finite length ending in an open circuit (and $G = 1$), we obtain:

$$z_{bx} = z_0 \left[\frac{-e^{\frac{2L}{\lambda}} + 1}{e^{\frac{2L}{\lambda}} - 1} \right] = z \cdot \operatorname{cth} \left[\frac{L}{\lambda} \right], \quad (35)$$

Numerical calculations using this expression for the normalized input impedance (Table 2) for different lengths of the distributed model (fiber) show that very short segments of the distributed model ($L < \lambda$) differ significantly from the infinite distributed model.

Table 2. Numerical normalized impedance values

L/λ	0,1	0,5	1	2	3
z_{bx} / z_0	10,0	2,16	1,31	1,04	1,01

At $L \geq \lambda$ from the input side of the final distributed model (fiber, rhizome) it becomes indistinguishable from the infinite, especially when $L \geq 2\lambda$ the difference is not more than 1%.

As noted in the analysis to this section, a consideration of the propagation of excitation along rhizomes (fibers) based on the theory of a distributed model allows us to identify different processes. Nature allows understanding the conductive properties of biological objects. In this regard, this part of the problem is of more academic interest, although the passive and active characteristics of the plant conducting system are experimentally measured. The plant system is necessarily preceded by the final technological act of rhizome treatment.

4. Conclusions

1. Theoretically substantiated for the electro technological processes of processing rhizomes of perennial weeds, a pulsed treatment mode with a high potential gradient. The equations of the electric model of rhizomes (segments of gum) and their solutions show the conditions for the propagation of electrical excitation along the rhizome and achieve a stationary state.

It should be noted that these processes precede the final, technological act of processing rhizomes.

2. A theoretical assessment of the potential at the point of application of the operating voltage. The results are in good agreement with the experimental conditions.

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