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CRITERIA FOR PERFORMING BREAKTHROUGHS IN THE HOLES OF RADIO ELECTRONIC MEANS UNDER THE INFLUENCE OF ELECTROMAGNETIC RADIATION

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ABSTRACT

The article presents the results of a detailed description of the process of forming a high-frequency channel in the holes of case-screens of electronic means (REM), depending on the physical processes at different stages of the breakdown, taking into account the parameters of the external EMR. Analytical expressions have been obtained for the breakdown voltage and the time of formation of a high-frequency electronic channel in the holes of the case-screens. An expression describing the dynamics of the distribution of the electric voltage field during the interaction of a pulsed EMR with an ionized air media in the hole of the case-screen REM, which affects the implementation of the breakdown in the REM holes, has been obtained.

Keywords: radio electronic means, electromagnetic radiation, ultrashort pulse duration, plasma protection technologies, gaseous plasma media.

INTRODUCTION

The results of the latest achievements in the field of protecting REM from EMR have been presented in many works, including [1, 6, 9, 10, 11, 16, 18]. Many known publications have been dedicated to the traditional methods and means of protecting REM against the impact of microwave (MW) radiation [16].

At the same time, a number of works devoted to the use of radioisotope technologies, which are related to nature-like technologies in order to protect REM from the effect of powerful EMP, have appeared [12, 13, 14, 15, 17].

The nature similarity of these technologies is associated with the formation of plasma gaseous media and solid-state materials with the subsequent usage of their trailing, reflecting and absorbing properties. An example of the closing properties of the plasma gaseous media is lightning, which represents a discharge in the air, which, as a first approximation, can be considered as an analogue of creating a highly conductive channel in the holes, slots of the case-screens so as to protect against the powerful EMR by means of guaranteed breakdown and further EMR energy drainage.

METHODS

Carrying out researches on the use of the protective properties of the plasma gaseous and solid media and materials requires a detailed description of the process of formation of a high-frequency channel in the holes of the REM case-screens, depending on the physical processes that occur at different stages of the breakdown development taking into account the parameters of the external EMP, as well as determining the conditions of implementation of the breakdown by time and the value of the breakdown tension.

The aim of the work is to determine the conditions and to develop the criteria for a guaranteed breakdown during the interaction with a powerful EMR with a pre-ionized air media in the REM hole.

RESULTS

The formation of a high-conductivity channel is preconditioned by the different physical mechanisms of the appearance and loss of the charged particles. Depending on the stage of development of the discharge and the external conditions of impact (EMR parameters), one or the other of the mechanisms is decisive. In order to fully consider these physical mechanisms in the calculation of discharge implementation in the hole of the REM case-screens, as well as to determine the criteria of the breakdown, we will summarize the results of the research conducted and present them in the form of Figure-1.

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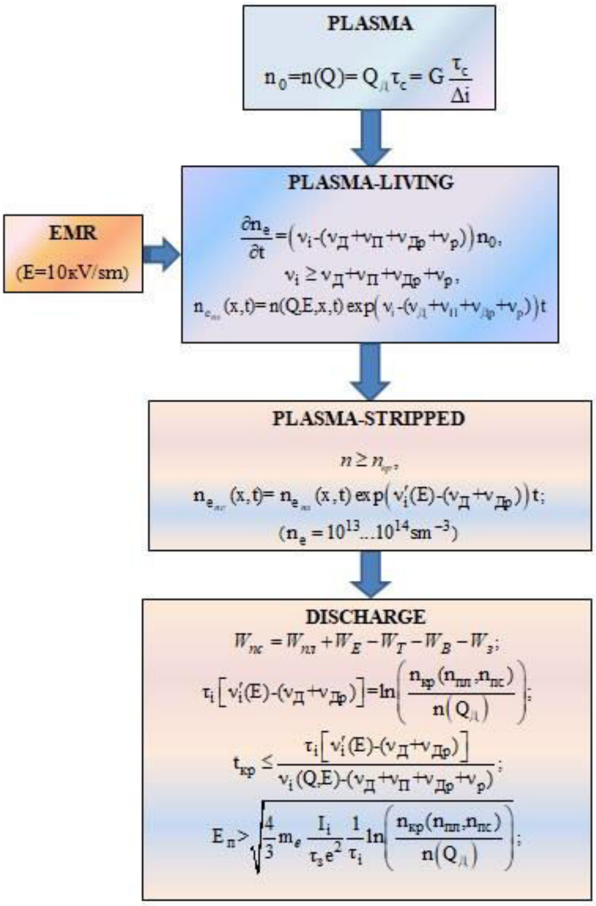

Figure-1. The block diagram of the distribution of the electron concentration at the stages of the formation of a high-frequency channel and the breakdown of the hole of the body of the screen REM.

Let us explain the breakdown development and the energy balance at the different stage of breakdown development using the presented Figure-1.

The first stage (plasmatic) is characterized by the electron concentration $n_0=n(Q)=Q_Д\tau_c=G\frac{\tau_c}{\Delta i}$. The distribution function of the electronic component for small holes is equilibrium, for large holes it is non-equilibrium.

The change in the electron concentration under the influence of the EMR in the second stage of the development of the conductive channel can be represented by the following equation:

$$\frac{\partial n_e}{\partial t}=\left(\nu_i-(\nu_Д+\nu_П+\nu_{Др}+\nu_p)\right)n_0 . \qquad (1)$$

The realization of the condition $\nu_i \ge \nu_Д+\nu_П+\nu_{Др}+\nu_p$ means the beginning of the appearance of an avalanche, the concentration of which in the general case may be represented by the expression:

$$n_{e_{пл}}(x,t)=n(Q,E_0,x,t)\exp\left(\nu_i-(\nu_Д+\nu_П+\nu_{Др}+\nu_p)\right)t . \qquad (2)$$

At this stage of formation of the high-conductivity channel and the breakdown development, the external field greatly exceeds the internal field of the plasma media. But on the verge of an avalanche-streamer these fields are leveled.

According to the results of work [18], the realization of condition (1) at atmospheric air pressure is possible when $\nu_П \approx 3\cdot10^7...2\cdot10^6 s^{-1}$, and the recombination coefficient $\alpha=(0,48...0,2)10^{-7}sm^{-3}s^{-1}$.

Under these conditions, it is necessary that the speed of the electron production is not less than $10^{12}sm^{-3}s^{-1}$ for the existence of an electronic component of the plasma media with a concentration of $n_e=10^6sm^{-3}$ at atmospheric pressure.

Ensuring of such an electron concentration is possible with the presence of an external EMR with E_0=10кV/sm, which is below the limit of the air breakdown, but is easily provided by the ionization source at the plasma stage.

Thus [17], when using α-radioactive ionization sources, the speed of the electron production $10^{12}sm^{-3}s^{-1}$ is ensured at the activity 10^{-2} …10^{-3} Ci/sm^3.

In the third stage, in order to fulfill the condition $n \ge n_{кр}$ it is necessary that the frequency of the ionization exceed the loss of electrons due to their diffusion and drift, and the reduction of the influence of EMR on ionization processes due to the dissipative processes occurring in the non-equilibrium distribution of the electronic component be taken into account:

$$n_{e_{пс}}(x,t)=n_{e_{пл}}(x,t)\exp\left(\nu_i'(E)-(\nu_Д+\nu_{Др})\right)t , \qquad (3)$$

where $\nu_i'(E)$ is the ionization frequency taking into account the EMR energy losses during the interaction with non-equilibrium plasma media.

Numerical estimations $n_{e_{пс}}(x,t)$ demonstrate that at the plasma-streamer stage, the concentration of electrons in the streamer reaches the values $n_e=10^{13}...10^{14}sm^{-3}$.

The frequencies $\nu_i'(E)$, $\nu_Д$, $\nu_{Др}$ are the function of the electron energy.

The energy balance equation at the plasma-streamer stage of the breakdown development will look as follows:

$$W_{пс}=W_{пл}+W_E-W_T-W_B-W_з , \qquad (4)$$

where

$W_{пл}$ - energy of the plasma-avalanche stage;
W_E - addition of energy from the external field;
W_T - thermal energy losses;
W_B - energy losses due to radiation;
$W_з$ - energy losses due to collisions.

Given the aforesaid, the expression for the condition of the breakdown in the REM hole under the influence of EMR will look like:

$$\tau_i\left[\nu_i'(E)-(\nu_Д+\nu_{Др})\right]=\ln\left(\frac{n_{кр}(n_{пл},n_{пс})}{n(Q_Д)}\right). \tag{5}$$

Accordingly, we shall write the expression for the time of formation of a high-frequency electronic channel:

$$t_{кр}\le\frac{\tau_i\left[\nu_i'(E)-(\nu_Д+\nu_{Др})\right]}{\nu_i(Q,E)-(\nu_Д+\nu_П+\nu_{Др}+\nu_р)}. \tag{6}$$

From (5) and taking into account the electron energy under the influence of EMR $-W_e=\frac{e^2}{2m_e}\frac{E^2}{\nu_{me}^2}$ we obtain the expression for the breakdown voltage:

$$E_п>\sqrt{\frac{4}{3}m_e\frac{I_i}{\tau_з e^2}\frac{1}{\tau_i}\ln\left(\frac{n_{кр}(n_{пл},n_{пс})}{n(Q_Д)}\right)}. \tag{7}$$

The breakdown criterion has been determined from the energy balance equation according to (4) and the particle balance (1) and (5).

The ratios (3, 5-6) include the parameter of electric voltage, which is variable due to the collective processes occurring in the ionized media of the REM hole under the influence of EMR. Thus, there is a need to identify the distribution of the electric voltage field in the interaction of EMR with the ionized air in the hole of the REM case-screen.

The process of EMP interaction with the ionized air media in the holes of the REM case-screens is described by the kinetic equation in case of large holes and quasi-equilibrium particle distribution:

$$\left.\frac{\partial f}{\partial t}\right|_з=\frac{f_0(v)-f_1(r,v,t)}{\tau}=\frac{f_0-f_1(r,v,t)}{\tau}, \tag{8}$$

where τ is the characteristic time of collisions.

In cases of small holes and non-equilibrium distribution of the electronic component, it is advisable to use the kinetic equation of the following kind:

$$\frac{\partial f(p,t)}{\partial t}+\mathrm{div}(\vec{j}_i)=\psi(p,f(p,t)). \tag{9}$$

The equations (8) and (9) should be supplemented with the Maxwell equations which relate the charge density ρ and stream i, as well as the electric $\mathbf{E}$ and magnetic $\mathbf{B}$ fields:

$$\begin{cases}\mathrm{rot}\mathbf{B}=\frac{4\pi}{c}\mathbf{j}+\frac{1}{c}\frac{\partial\mathbf{E}}{\partial t}\\ \mathrm{rot}\mathbf{E}=-\frac{1}{c}\frac{\partial\mathbf{B}}{\partial t}\\ \mathrm{div}\mathbf{E}=4\pi\rho\\ \mathrm{div}\mathbf{B}=0\end{cases} \tag{10}$$

The functions of distribution of the charged particles found by the solution of kinetic equations (8), (9) allow to determine all macroscopic parameters of the air media in holes, slots, cable channels of the REM case-screens, or in the waveguide antenna inputs of the receiving paths of the apparatus, and, first of all, permeability and conductivity of the ionized air media. On this basis, in order to determine the impact of EMP on REM, the system of equations (10) should be presented in the following form:

$$\begin{cases}\nabla\bar{k}\varepsilon_0\mathbf{E}=0;\\ \nabla\mu\mu_0\mathbf{H}=0;\\ \nabla\mathbf{E}=-\mu\mu_0\frac{\partial\mathbf{H}}{\partial t};\\ \nabla\mathbf{H}=-\bar{k}\varepsilon_0\frac{\partial\mathbf{E}}{\partial t},\end{cases} \tag{11}$$

where $\bar{k}$ is the vector wave number;
ε_0, μ_0 - dielectric and magnetic permeabilities of the vacuum;
μ - relative magnetic permeability.

From the system of equations (11) we obtain a wave equation with respect to the electric field strength $\mathbf{E}$:

$$\nabla\times\nabla\times\mathbf{E}=\nabla(\nabla,\mathbf{E})-\nabla^2\mathbf{E}=-\frac{\bar{k}\mu_0}{c^2}\frac{\partial^2\mathbf{E}}{\partial t^2}. \tag{12}$$

A similar equation can be written with respect to the magnetic field strength $\mathbf{H}$:

$$\nabla\times\nabla\times\mathbf{H}=-\frac{\mu\varepsilon_0}{c^2}\frac{\partial^2\mathbf{H}}{\partial t^2}. \tag{13}$$

If space dispersion is disregarded, then the expression (12) will look like:

$$\nabla^2 \mathbf{E} = \frac{\bar{k}\mu_0}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2}. \quad (14)$$

Assuming that the spatial distribution of the electric voltage field in the interaction of EMR with the ionized air media in the hole of the REM case-screens is constant, the three-dimensional problem can be reduced to the two-dimensional one, which makes it possible to go to a system of cylindrical coordinates. Then, without taking into account the influence of the magnetic field, we will rewrite the equation (14) in the following way:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \mathbf{E}}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 \mathbf{E}}{\partial \theta^2}-\frac{k}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2}=0. \quad (15)$$

The distribution of the electric voltage vector of the EMR radio pulse at the boundary of the air-ionized media of the hole will be presented as follows:

$$\mathbf{E}\left(r=a,\theta\in(-\theta;\theta)\right)=E_0\sin(\omega_0 t)\exp\left(-\frac{t-T}{T}\right)^2 G\exp\left(-\frac{\theta_0^2}{\theta^2}\right), \quad (16)$$

where $G\exp\left(-\frac{\theta_0^2}{\theta^2}\right)$ is the EMR intensity distribution function at the plasma boundary;

θ_0 is the maximum irradiation angle of the ionized air in the hole.

The solution of the equation (15) lies in the following expression:

$$E(r,\theta,t)=\frac{1}{\sqrt{2\pi}}\sum_{i=1}^{N}e^{j\omega_i t}\sum_{k=1}^{M}\left(\begin{array}{l}\frac{\cos k\theta}{2\pi}\int_{-\pi}^{\pi}E_0(\omega,\theta)\cos k\theta d\theta+\\+\frac{\sin k\theta}{2\pi}\int_{-\pi}^{\pi}E_0(\omega,\theta)\sin k\theta d\theta\end{array}\right)\frac{L_n(r)}{L_n(m)}, \quad (17)$$

where

$$L_n(r)=Y_n\left(\frac{r\omega}{c}\right)-\frac{1}{c^2}\left(J_n\left(\frac{r\omega}{c}\right)+\frac{\left(Z_n\left(\frac{a\omega}{c}\right)+Y_n\left(\frac{a\omega}{c}\right)\right)}{N_n\left(\frac{a\omega}{c}\right)}N_n\left(\frac{r\omega}{c}\right)+Z_n\left(\frac{r\omega}{c}\right)\right),$$

N - the number of harmonics which describe the envelope function of wave packets reflected from the ionized media;

M - the number of additions to the row that describe the function with the required accuracy;

J_n - Bessel function of the first kind by the index n;

N_n - Neumann function by the index n.

The $E_0(\omega,\theta)$ function under the integral (17) determines the boundary conditions of the problem of determining the distribution of the electric voltage field in the interaction of pulsed EMR with the ionized air media in the hole of the REM case-screen:

$$E_0(\theta,\omega)=\frac{1}{\sqrt{2\pi}}\int_0^{\tau}e^{-j\omega t}E_{max}\exp\left(-\frac{t^2}{2a^2}\right)\sin(\omega t)\exp\left(-\frac{\theta_0^2}{\theta^2}\right)dt. \quad (18)$$

The $Z_n\left(\frac{r\omega}{c}\right)$ function is determined by solving the non-uniform Bessel equation for $L_n\left(r/c\right)$, which is determined by the plasma frequency parameter, in which the concentration of charged particles is considering losses.

The expression (18) is a model for the distribution of the electric voltage field in the interaction of pulse EMR with the ionized air media in the hole of the REM case-screen.

CONCLUSIONS

The conditions of realization of the guaranteed breakdown in the REM holes with the interaction of the powerful EMR with the pre-ionized air media have been determined. The criteria have been developed and analytical expressions for the time of formation of a high-frequency electronic channel and the breakdown voltage have been obtained. The equation for describing the dynamics of the spatial-temporal distribution of the microwave pulse voltage in the ionized air media of the hole of the REM case-screen have been obtained, taking into account kinetic processes in the ionized air media, in particular taking into account the impact of charged particle losses on the formation of a high-frequency channel.

DISCUSSIONS

The peculiarity of the equation is that determining the distribution of the microwave pulse voltage in the ionized air media in the hole does not require a numerical solution of the Maxwell equation system and is based on the use of the parameters found from the solution of the wave equation.

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