ЕНЕРГОЗБЕРЕЖЕННЯ ТА ЕНЕРГОЕФЕКТИВНІСТЬ

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FORMING THE CURRENT OF UNDERGROUND METAL PIPELINES BY THE HIGH-FREQUENCY COMPONENTS OF CATHODIC STATIONS OUTPUT SIGNAL

Introduction. The overwhelming majority of underground metal pipelines in Ukraine consists of metallic underground pipelines. Cathodic protection of underground pipelines from electrochemical corrosion provides the integrity of pipelines and minimizes current draining from the pipeline to the surrounding soil. Minimization the drainage currents is provided by methods of active and passive protection. Active protection methods include formation of protective potential the cathodic protection stations (CPS) for underground pipelines, which prevents currents draining from the pipeline to the ground. Forming protective potential requires additional electric energy consumption and anode material, which affects the process increasing the cost of transportation of raw materials (natural gas). Reduction of energy consumption of electrochemical corrosion protection in combination with providing high quality parameters of the CPS is an urgent problem addressing several objectives. One way to improve the overall energy efficiency of the electrical system of electrochemical protection from corrosion of underground metal pipelines is to use CPS with improved power and weight-to-dimensions ratio.

The analysis of publications shows that rapid development of semiconductor technology provides plenty industrial circuit solutions that provide reduction in size while improving adjusting characteristics of the CPS [1,2]. Current methodology for the calculation of electrochemical protection is based on the assumption that the electrochemical system "soil - SSI - underground metal pipeline - electrified railway line" includes direct currents (voltages) or AC currents at industrial frequency of 50 Hz. [3, 4, 6]. At the same time, active use of controlled current sources in semiconductor circuitry (voltage), changes the characteristics of the structure of current field in the soil. The process of forming the protective potential on the underground metal object which contain new elements that change the nature of the potential change in length of the pipeline [6].

Main part. Stations of cathodic protection, as active elements of corrosion protection of underground metal pipes, creating potential of the metal pipe by imposing the rectified voltage with amplitude that depends on the given current level. Usually, the voltage varies within range from 5.0 to 45 V. Recently most applied became CPSs with high-frequency electrical power converters (Fig. 1).

Waveforms of power switches that commute to section of high-current transformer, depend on the switching control laws, as well as preferred type of modulation. Voltage form in this type of CPS undergoes several transformations from rectifying stage at the input to the output of the inverter.

In terms of energy efficiency (minimizing energy loss in the switching range) rectangular pulses are most viable (Fig. 2). But in case of pure ohmic load, the output signal comprises low-amplitude oscillations. The value of the protective potential of underground pipeline varies with time (Fig. 1-3). Uneven value of potential of underground metal pipeline over time detriments the corrosion protection quality. This phenomenon further intensifies given the natural unevenness of capacity building along of pipeline.

In the case of continuous current (the load inductance is sufficient to support current in intervals of negative voltage), medium voltage depends from the switching angle of power transistors ofthe controlled rectifier. This dependence is described by the expression:

$$U_{load} = \frac{2U_m}{\pi}\cos(\alpha), \tag{1}$$

where U_m - the voltage at the input of the controlled rectifier; α - control angle.

Rectified Voltage curves contain a range of higher harmonics. For example, spectral composition (Fig. 4) of rectangular signal (Fig. 1) contains high components. This complicates the process of forming the protective potential.

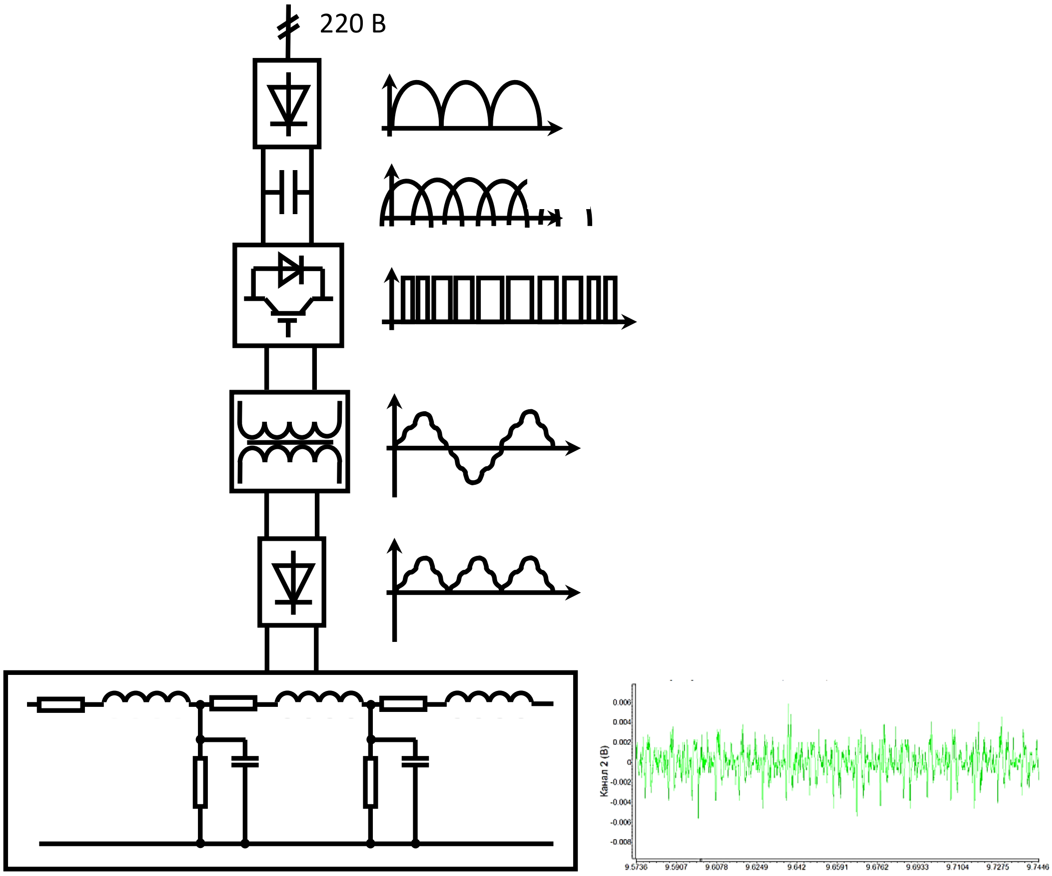

Fig. 1 The scheme of station cathodic protection

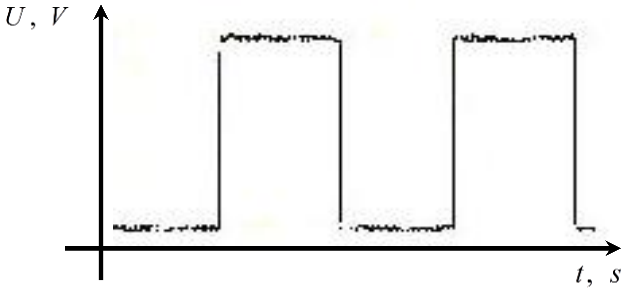

Fig. 2 Rectangular impulse of power transistor provided purely resistive load

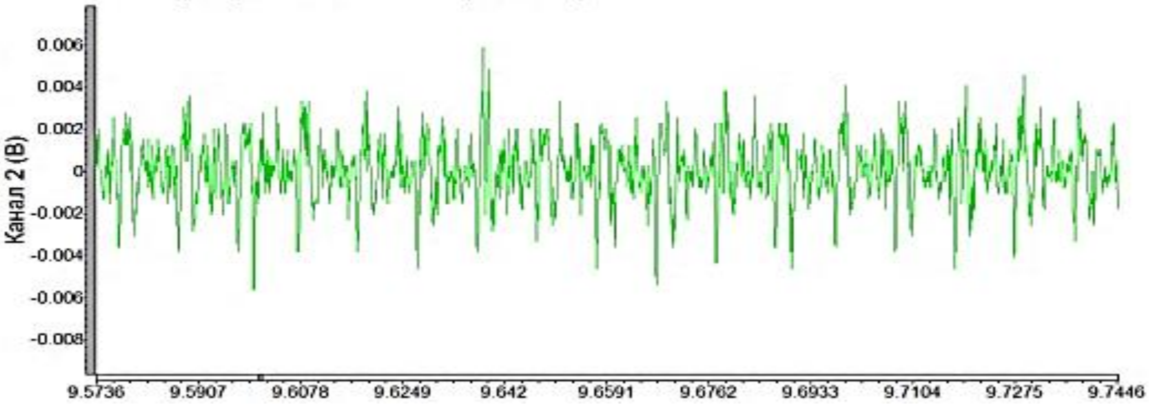

Fig. 3 Protective potential of underground pipeline

Fig. 4 Rectangular signal spectrum

Voltage switching processes in the cathodic protection stations provide much more complex waveforms of their output signals (Fig. 5, 6).

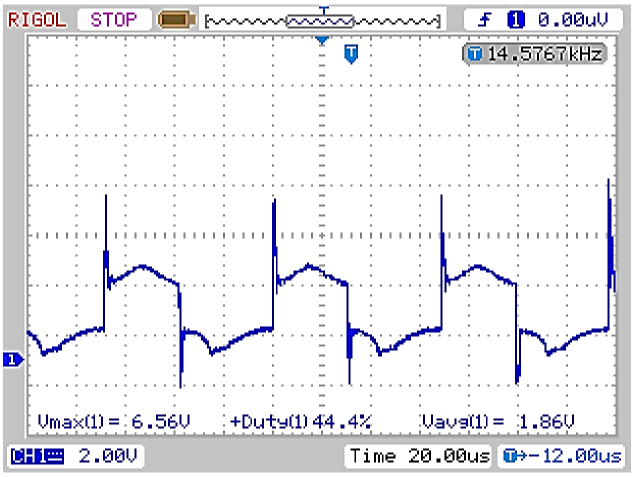

Fig. 5 Switching processes in power CPS switches

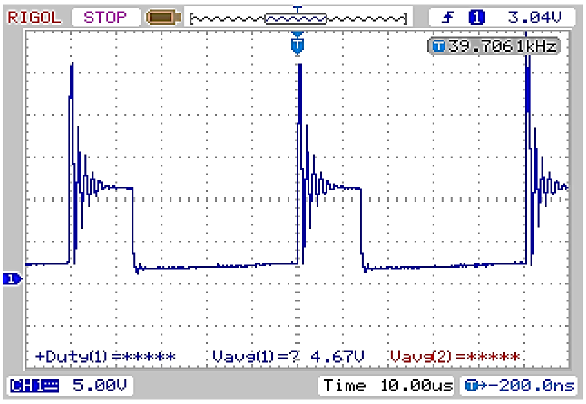

Fig. 6 The switching processes in the power switches of the CPS which is connected to the pipeline with improved insulation

Similar transients occur when using one-port PWM with symmetric control (Fig. 6). It forms output voltage that varies according to the expression:

$$U_{load} = \frac{1}{T}\int_{0}^{\gamma T}\frac{U_d}{2}dt - \frac{1}{T}\int_{\gamma T}^{T}\frac{U_d}{2}dt = (2\gamma - 1)\frac{U_d}{2} \qquad (2)$$

where - U_d - - the converter voltage, γ - the relative duration of the first state of keys switching, T - switching interval.

Transient processes that occur during the operation of station at underground metal pipe contain significant overshoot with oscillations. This not only causes considerable deviation of the protective potential of underground metal pipeline (Fig. 3), but also leads to changes in its stable distribution:

$$\frac{\frac{1}{2\pi h_{\mathrm{t}} r_{\mathrm{t}} \sigma_t}\sqrt{\frac{\omega\mu\sigma_t}{2}}h_{\mathrm{t}}\sqrt{\frac{\omega\mu\sigma_t}{2}}\;\frac{sh2sh2\sqrt{\frac{\omega\mu\sigma_t}{2}}h_{\mathrm{t}}+sin\,2\sqrt{\frac{\omega\mu\sigma_t}{2}}h_{\mathrm{t}}}{ch2\sqrt{\frac{\omega\mu\sigma_t}{2}}h_{\mathrm{t}}-cos\,2\sqrt{\frac{\omega\mu\sigma_t}{2}}h_{\mathrm{t}}}+4.9\cdot10^{-5}+}{R_{\mathrm{t}}^{\mathrm{iz}}+\frac{1}{\sigma\pi}ln\frac{1.12}{\sqrt{\frac{\omega\mu\sigma_t}{2}}\sqrt{r_{\mathrm{t}}H}}}$$

$$\frac{i\left(\frac{1}{2\pi h_{\mathrm{t}} r_{\mathrm{t}} \sigma_t}\sqrt{\frac{\omega\mu\sigma_t}{2}}h_{\mathrm{t}}\;\frac{sh2sh2\sqrt{\frac{\omega\mu\sigma_t}{2}}h_{\mathrm{t}}-sin\,2\sqrt{\frac{\omega\mu\sigma_t}{2}}h_{\mathrm{t}}}{ch2\sqrt{\frac{\omega\mu\sigma_t}{2}}h_{\mathrm{t}}-cos\,2\sqrt{\frac{\omega\mu\sigma_t}{2}}h_{\mathrm{t}}}+6.3\cdot10^{-5}\,ln\frac{93}{\sqrt{\sigma_{\mathrm{t}}t_{\mathrm{t}}}}\right)}{R_{\mathrm{t}}^{\mathrm{iz}}+\frac{1}{\sigma\pi}ln\frac{1.12}{\sqrt{\frac{\omega\mu\sigma_t}{2}}\sqrt{r_{\mathrm{t}}H}}} \tag{3}$$

where $\sigma_{\mathrm{p}}-$ specific conductivity rails; r_{t} - the radius of the tube; $\mu-$ the permeability of underground metal pipeline; h_{t} - Thickness of the pipeline, ω - the frequency.

Propagation constant of the pipeline is an important characteristic of underground metal structures for the organization of protective measures to minimize current draining of the pipeline to the ground. Consider underground metal pipeline as electrical system with distributed parameters [2]. This assumption allows to take into account the frequency spectrum of the signal supplied to the pipeline, considering the effect of other signals to the process forming the protective capacity and the sequence of signals with exponential fronts (Fig. 7).

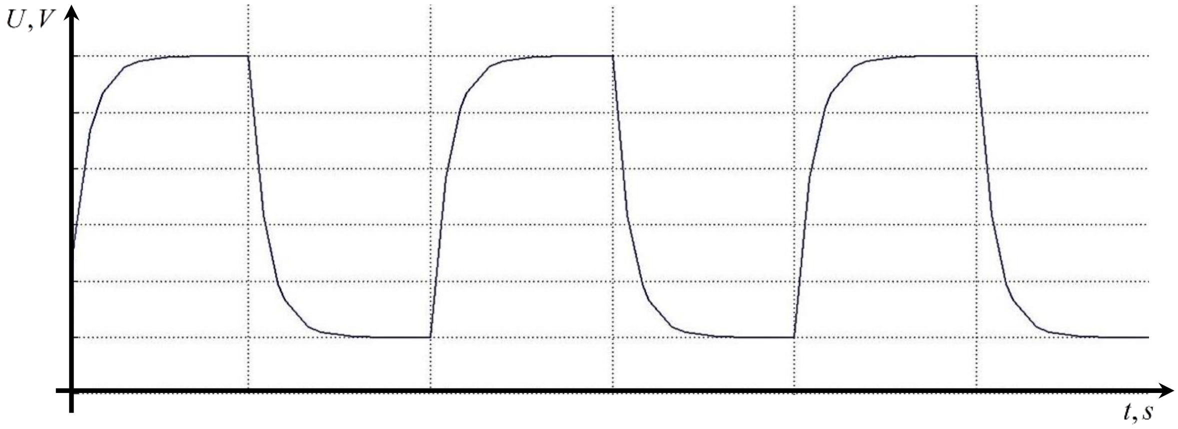

Fig. 7 The sequence of signals with exponential fronts

It is known that function with non-sinusoidal periodic signal can be represented by the infinite sum of basic trigonometric functions with amplitude A_k :

$$U(t)=\frac{a_0}{2}+\sum_{k=1}^{\infty}A_k\cos(k\omega_1 t-\varphi_k)=\frac{a_0}{2}+\sum_{k=1}^{\infty}(a_k\cos(k\omega_1 t)+b_k\sin(k\omega_1 t)), \tag{4}$$

where $A_k=\sqrt{a_k^2+b_k^2}$ - amplitude, $a_0=\frac{2}{T}\int_{-T/2}^{T/2}U(t)dt$; $a_k=\frac{2}{T}\int_{-T/2}^{T/2}U(t)\cos(k\omega_1 t)dt$; $b_k=\frac{2}{T}\int_{-T/2}^{T/2}U(t)\sin(k\omega_1 t)dt$;

$\varphi_k=arctg\frac{b_k}{a_k}$ - phase shift.

Using the Euler expressions we get:

$$U(t)=\frac{a_0}{2}+\sum_{k=1}^{\infty}\left(a_k\frac{e^{jk\omega_1 t}+e^{-jk\omega_1 t}}{2}-jb_k\frac{e^{jk\omega_1 t}+e^{-jk\omega_1 t}}{2}\right). \tag{5}$$

From (5) we get direct expressions (6) and reverse expressions (7) for Fourier transform:

$$C_k=\frac{1}{T}\int_{-T/2}^{T/2}U(t)e^{-jk\omega_1 t}dt, \tag{6}$$

where C_k - periodic signal range.

$$U(t)=\sum_{k=-\infty}^{\infty}C_k e^{jk\omega_1 t}. \tag{7}$$

The spectrum of the signal from the exponential fronts (Figure 8) differs from that ofrectangular signal spectrum (Fig. 4). Obviously, reducing the steepness of fronts, we narrow the frequency spectrum of the signal. This creates the potential for pipeline protection. Note the low-frequency component of the signal (Fig. 8). In the case of pipelines and medium-pressure pipelines, which have a significant extent, this lead to additional fluctuations of protective potential.

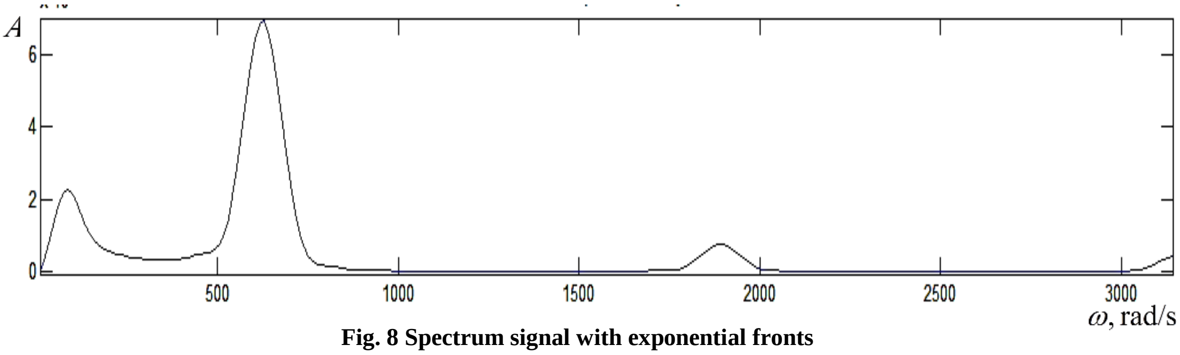

Fig. 8 Spectrum signal with exponential fronts

Signal frequency spectrum from the exponential fronts also contain high-frequency component with a frequency of 300 Hz. Wide frequency spectrum makes it necessary to recalculate the cathodic protection system parameters.

Circuit solutions with power elements and trapezoidal signal control are well known [5] (Fig. 9). In this case, the spectral characteristics of the signal has different composition, with which the present frequency of the low-frequency range of 300 Hz (Fig. 10). Thus, different composition of the frequency spectrum that is inherent in the most common types of control signals transistors, supersedes the values of sustainable distribution pipeline with respect to the case where the electrical system "underground metal pipe - soil - CPS" exists alternating signal frequency of 50 Hz.

The value α_t also affects the diameter of the pipeline caused by the influence of the skin effect (3). For small diameter pipes, up to 0.5 m., For frequencies above 50 Hz. there is another dependent α_t on the frequency and the diameter of the pipeline (Fig. 11). Pipelines with a diameter of 0.5 m. The most common are low-pressure gas pipelines, which are often under the influence of currents wander through locations in industrial zones and urban locations electrified rail transport network.

It should be noted that the considered spectrum idealized signals that do not contain complex transition component (Fig. 5.6) which also complicates the structure of the frequency spectrum. Constant distribution of pipeline affects the determination of total current and current draining of underground pipeline. Since the greatest impact on changing the frequency is observed in small diameter pipes (Fig. 11), which is characteristic of the distribution network, we shall consider the impact of the rail network on the current distribution of underground metal pipelines. With the current definition of draining current from rail track and full-contact current complete of rail network, field, that is created is defined as [7]:

$$E_x^{ext}=\frac{-1}{2\pi\sigma}\frac{\partial}{\partial x}\int_{-\infty}^{\infty}j_r(\zeta)\frac{d\zeta}{\sqrt{(x-\zeta)^2+y^2}}-\frac{i\omega\mu}{4\pi}\int_{-\infty}^{\infty}I_0(\zeta)\left(\frac{1}{\sqrt{(x-\zeta)^2+y^2}}-\frac{1}{\sqrt{(x-\zeta)^2+y_1^{\,2}}}\right)d\zeta, \tag{8}$$

where $y_1^2 = y_2 - \frac{2i}{\gamma^2}$; $\gamma_t = \sqrt{\frac{\omega\mu\sigma_t}{2}}$ - absorption in the material of the conductor (pipeline).

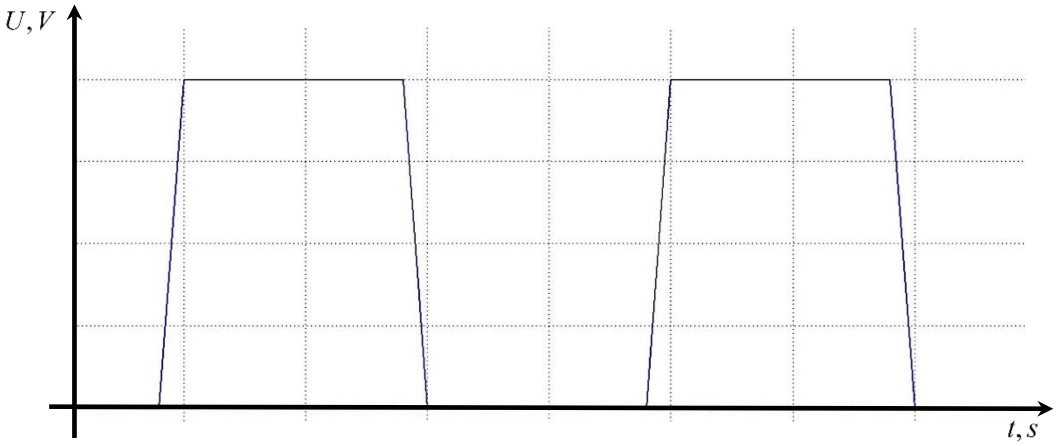

Fig. 9 Trapezoid signal

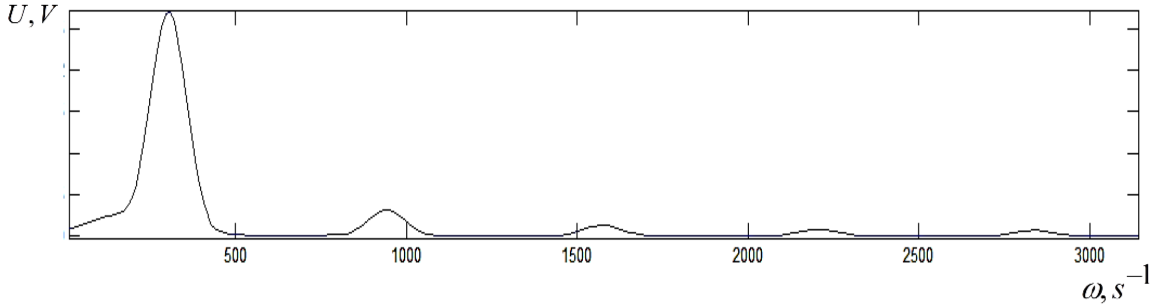

Fig. 10 Frequency spectrum of trapezoidal signal

The electric field E_x^{ext} is external to the underground pipeline and makes it the following distribution of current:

$$I_t = I_t''(x) - \alpha_t I_t(x) = -\frac{E_x^{ext}(x)}{R_{trans}^t} \qquad (9)$$

where R_{trans}^t - transition resistance pipeline.

The solution of equation (9) is

$$I_t(x) = \frac{1}{2\alpha_t R_{trans}^t} \int_{-\infty}^{\infty} e^{-\alpha_t |x-t|} E_x^{ext}(t) dt \qquad (10)$$

Taking into account (8.9) we obtain the expression for determining the current at full current rail lines and draining current of rails:

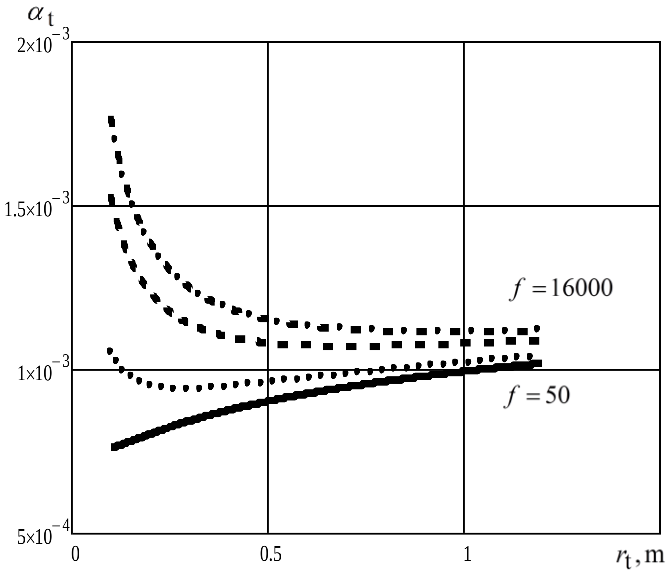

Fig. 11 Dependence constant distribution of pipeline from its radius

$$I_t(x) = -\frac{1}{4\pi\sigma\alpha_t R_{trans}^t}\left(\int\limits_{-\infty}^{\infty} e^{-\alpha_t|x-t|}dt\frac{\partial}{\partial t}\int\limits_{-\infty}^{\infty} j_r(\zeta)\frac{d\zeta}{\sqrt{(t-\zeta)^2+y^2}} + \right.$$
$$\left. + i\gamma_t^2\int\limits_{-\infty}^{\infty} e^{-\alpha_t|x-t|}dt\int\limits_{-\infty}^{\infty} I_0(\zeta)\left(\frac{d\zeta}{\sqrt{(t-\zeta)^2+y^2}} - \frac{1}{\sqrt{(t-\zeta)^2+y_1^2}}\right)d\zeta\right) \quad (11)$$

More compact and easy to use form of the expression (11) we obtain by replacing $\zeta = \tau + t$ the changing order of integration:

$$I_t = -\frac{1}{4\pi\sigma\alpha_t R_{trans}^t}\left(\int\limits_{-\infty}^{\infty}\frac{f(\tau)d\tau}{\sqrt{\tau^2+y^2}} + i\gamma^2\int\limits_{-\infty}^{\infty}F(\tau)\left(\frac{1}{\sqrt{\tau^2+y^2}} - \frac{1}{\sqrt{\tau^2+y_1^2}}\right)d\tau\right) \quad (12)$$

where $f(\tau) = \int\limits_{-\infty}^{\infty}\frac{\partial j_r(\tau+t)}{\partial t}e^{-\alpha_t|x-t|}dt$; $F(\tau) = \int\limits_{-\infty}^{\infty}I_0(t+\tau)e^{-\alpha_t|x-t|}dt$.

From the expression (12) shows that using (3), based on dependencies (Fig. 8,10,11) by forming an appropriate control law power transistors of CPS, provided corresponding value of current pipeline. The currents also include draining components of underground metal pipeline, which is an important characteristic of criterial as protection against galvanic corrosion.

Conclusions

It is obvious that it is appropriate to use control signals applied for control of power transistors, which, although not rational in terms of power switching processes, minimizes high-frequency component in signals form the protective potential of underground metal pipe. Minimizing the current draining of the pipeline can be provided by changing of the control law power transistors of CPS. This improves the quality of protection of metal pipelines from electrochemical corrosion.

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