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DISTORTION OF LOCATION PULSES IN HIGH-FREQUENCY PATHS OF OVERHEAD POWER LINES

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Abstract: *The work is devoted to the features of propagation of electromagnetic signals (20–1000 kHz) along multi-wire overhead transmission lines. For monitoring the status of overhead power lines, a location method can be used. For connection to power lines, the connection equipment is used, which forms the high-frequency path of the power line, which has a limited frequency bandwidth. To select the optimal signals of location probing, it is necessary to investigate the impact of high-frequency path on the pulsed signals. This paper investigates the distortion of pulsed location signals in high-frequency paths. The influence of elements of the high-frequency path is studied using a simulation model of the high-frequency path of an overhead transmission line developed in the PSCAD software environment with subsequent experimental verification. Elements of high-frequency path of the developed simulation model are described. The influence of duration of the probe pulses on the shape and spectrum of the reflected signals is analyzed. It was established that during the passage of microsecond pulses, their differentiation occurs, the reflected signal is a combination of responses from the rising and falling edges of the probe pulse. With this in mind, criteria are proposed for optimizing the duration of the location pulses. During formation of ice deposits on the overhead lines wires, additional distortion of the pulse signals' shape occurs. Using the experimental data, the distortions of the reflected pulsed signals and their spectra are analyzed as ice deposits grow on the wires of overhead power lines. The established patterns of pulse shape distortion and the developed criteria for optimizing the pulse duration are used for location probing of overhead power lines to control ice deposits on the wires and to detect damage.*

Keywords: *overhead power line; high-frequency paths; location probing; pulse signal; shape; spectrum; duration; distortion; simulation model; ice deposits.*

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ИСКАЖЕНИЯ ЛОКАЦИОННЫХ ИМПУЛЬСОВ В ВЫСОКОЧАСТОТНОМ ТРАКТЕ ВОЗДУШНОЙ ЛИНИИ ЭЛЕКТРОПЕРЕДАЧИ

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Резюме: *Работа посвящена особенностям распространения электромагнитных сигналов (20–1000 кГц) по многопроводным воздушным линиям электропередачи. Для мониторинга состояния воздушных линий электропередачи может использоваться локационный метод. Для подключения к линиям электропередачи используется аппаратура присоединения, образующую высокочастотный тракт линии электропередачи, который имеет ограниченную частотную полосу пропускания. Для выбора оптимальных сигналов локационного зондирования необходимо исследовать влияние высокочастотного тракта на импульсные сигналы. В работе исследуются искажения импульсных локационныхсигналов в высокочастотных трактах. Влияние элементов высокочастотного тракта исследуется с помощью разработанной в программной среде PSCAD имитационной модели высокочастотного тракта воздушной линии электропередачи с последующей экспериментальной проверкой.Описываются элементы высокочастотного тракта разработанной имитационной модели. Анализируется влияние длительности зондирующих импульсов на форму и спектр отраженных сигналов.Установлено, что при прохождении микросекундных импульсов происходит их дифференцирование, отраженный сигнал является комбинацией откликов от переднего и заднего фронтов зондирующего импульса. С учетом этого предлагаются критерии оптимизации длительности локационных импульсов. При образовании гололедных отложений на проводах воздушных линий происходит дополнительное искажение формы импульсных сигналов. По экспериментальным данным анализируются искажения отраженных импульсных сигналов и их спектров при нарастании гололедных отложений на проводах воздушных линий электропередачи. Установленные закономерности искажения формы импульсов и разработанные критерии оптимизации длительности импульсов используются при локационном зондировании воздушных линий электропередачи для контроля гололедных отложений на проводах и обнаружения повреждений.*

Ключевые слова: *воздушная линия электропередачи; высокочастотный тракт; локационное зондирование; импульс; форма; спектр; длительность; искажения; имитационная модель; гололедные отложения.*

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Introduction

Overhead power lines (OHPL) are the least reliable elements of a power system, as they are long, and are exposed to atmospheric and human impacts. During their operation, dangerous impacts on their elements can appear that are not provided by the conditions of normal operation and lead to damage and, consequently, to serious accidents. In addition, in some cases the reliability of the overhead line operation is reduced due to the existing deterioration of electrical equipment. Therefore, the issues of OHPL monitoring, timely preventive control of wires condition, rapid detection and elimination of accidents consequences are urgent tasks for power engineers around the world.

According to the high voltage classes, the most massive and extended class of 110 kV brings the largest number of technological violations. A significant contribution to the accident statistics of overhead lines is made by glacial accidents occurring due to the formation of glaze deposits of excess size. For example, in the autumn-winter period of 2017-2018, the share of accidents caused by ice was about 15% of the total number of accidents[1].

Location monitoring of overhead lines

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[1] All-Russian meeting "*Results of the autumn-winter period of 2017-2018*" Ministry of Energy of the Russian Federation 2018. Available at: https://minenergo.gov.ru/node/7822 Accessed: 14 Apr 2019.

One of the promising methods for remote monitoring of the overhead power lines state is the method of location probing [1-5]. This method provides early detection of the beginning of the icing process on the wires, followed by monitoring the dynamics of the growth of ice deposits, determining the moments of the beginning and end of ice melting. In case of an accident, this method determines the distance to the place of damage.

Figure 1 shows a diagram of connection of location equipment to an overhead power line at the Kutlu-Bukash substation (SS) using a coupling capacitor (CC) and a connection filter (CF). To prevent shunting of substation buses, a high-frequency stopper (HFS) is used, which together with the overhead lines form a high-frequency (HF) overhead line path. A connection filter FPM-6400 (passband of 51–1000 kHz) with a coupling capacitor SMP-110√3-6400 and a supression filter VZ-630-0.5 (suppression band is 160–1000 kHz) are installed on this overhead line.

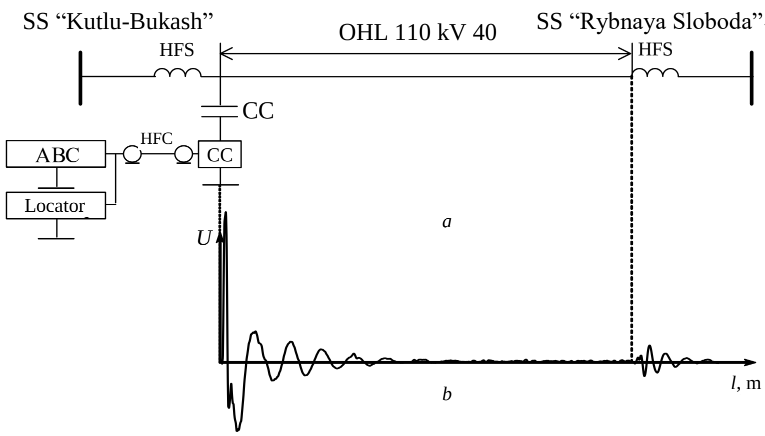


Fig. 1. Connection diagram of the location device to the wires of the 110 kV “Kutlu-Bukash – Rybnaya Sloboda” OHPL (a), reference reflectogram (b)

The transmitter of the location device emits a probe pulse to the overhead power line, which after reflection from the inhomogeneities of the wave resistance of the overhead line (for example, the line end, branch, damage) is received by the receiver of the location device. In this case, the propagation time and amplitude of the reflected pulse characterize this inhomogeneity and the propagation conditions of pulse in the line.

Most commonly, a location device works in parallel with technological high-frequency communication equipment, which imposes a number of requirements on the mutual compatibility of equipment [6], and on the methods used to extract location signals among technological RF communication signals [7]. The existing simulation models of overhead power lines either do not take into account the influence of the connection equipment [8, 9], or describe the line wires using a phase-independent frequency model [10], and this is a reason why there is a discrepancy between the model and experimental results.

Simulation model of an overhead power line

To study the features of distribution of location signals along the HF paths of the overhead lines, a simulation model was developed in the PSCAD software environment. The model of the HF path of the overhead line includes: multi-wire lines near the earth surface (phase wires and ground wearers of the overhead line); connection devices consisting of connection filters with coupling capacitors, HF cables; processing devices, consisting of high-frequency stoppers - separation circuits, which are a particular case of separation filters; high-voltage equipment of substations, located behind the high-frequency stopper (it is presented by an equivalent active resistance and capacity).

The RF path circuit starts with a pulse generator and ends with a "connection device", simulated by a 75 Ohm load. Consider the process of setting the parameters of the elements of the RF path.

1. The pulse generator is a standard component from the PSCAD component library and allows one to get a pulse of a given duration and amplitude. The following basic parameters are set for the generator: the start time of the pulse generation, duration, pulse amplitude and output resistance. The probe pulse duration of location probing can be set in the range from 1 to 200 μs, the pulse repetition period is from 0.1 to 100 ms. The pulse generator is connected directly to the HF cable. An oscilloscope is connected to the same point, which enables recording probe and reflected signals with a given time step, and this is a way to measure the reflectogram.

2. The connection device consists of a high-frequency cable (HFC), a connection filter and a coupling capacitor. The RC-75 high-frequency coaxial cable is a standard component from the cable library. The main parameters specified for this component are: cable length, radius of the current-carrying core, radius of the insulating layer, radius of the protective coat, specific resistance of the core, specific resistance of the ground, frequency range. The high-frequency cable is connected to the connection filter (Fig. 2).

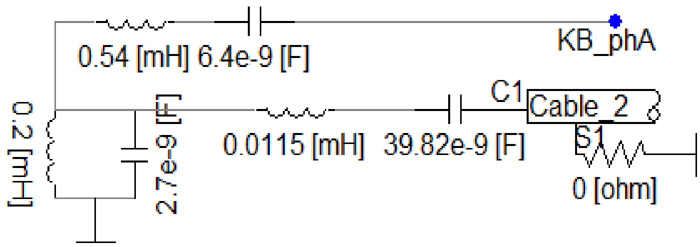


Fig. 2. Wiring diagram of the RF cable to the connection filter

The connection filter performs the following functions: compensates the reactance of the coupling capacitor at operating frequencies; grounds the lower lining of the coupling capacitor at a frequency of 50 Hz; serves as a matching element between the RF cable and the linear path. FPM-6400 connection filter is installed at the 110 kV overhead line "Kutlu-Bukash – Rybnaya Sloboda". The coupling capacitor SMP-110 is represented by a capacity of 6400 pF.

3. The processing device consists of VZ-630 high-frequency stopper. The stopper is cut into the line working wire between the connection point of the coupling capacitor and the substation buses. In this range, it is possible to form the following tuner configurations: single-frequency, double-frequency, single-frequency blunt, double-frequency blunt, broadband. The diagram of VZ-630 stopper is shown in Fig. 3.

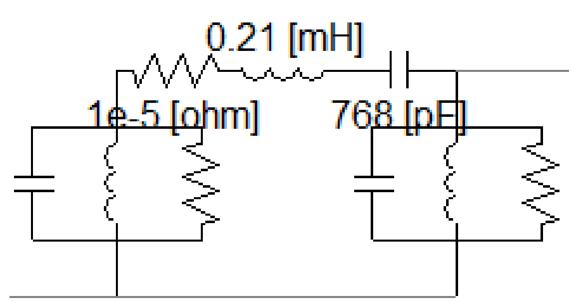


Fig. 3. Electrical circuit of the high-frequency stopper.

4. The linear RF path is formed by the OHPL phase wires and ground wearers, if the overhead line is double-circuit, then the phase wires of the second circuit are also taken into account. Power line wires are presented in the form of a coaxial cable with a zero thickness of the insulating layer and a protective coat, although the PSCAD software environment has standard libraries for Tline overhead lines. This choice of model is due to the fact that in this model it is possible to set the core cross section of the steel-aluminum wire. The 110 kV overhead line “Kutlu-Bukash – Rybnaya Sloboda” in the model is represented by the Line09 element (Figs. 4, 5). The terminal ends of the three phase wires and ground wearers at the substations “Kutlu-Bukash” and “Rybnaya Sloboda” are designated as C1, C2, C3 and C4. The ends of the ground wearers C4 are low-resistance grounded.

The main parameters specified for this component are: the overhead line length, the location of the wires in vertical and horizontal directions relative to the ground, the steel core radius, the aluminum coil radius, the insulating layer radius, the wire resistivity, the ground resistivity, the frequency range.

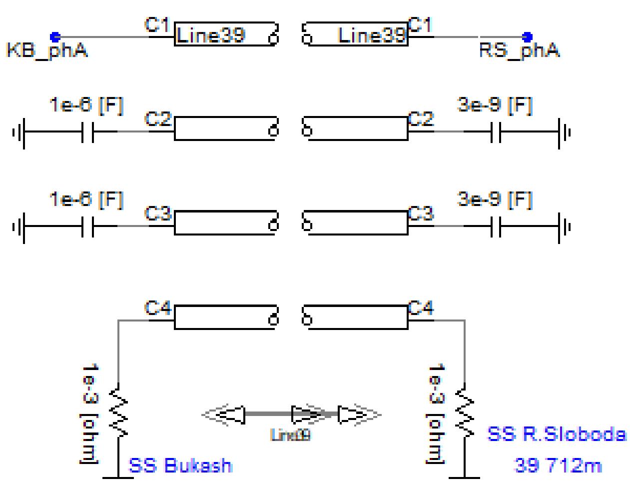


Fig. 4. Elements of the model of the 110 kV overhead power line.

5. The input resistance of the substation at the ends of the HF path, at the places of HF bypass and at the taps is set by the equivalent capacitance, the value of which is determined in accordance with the recommendations set out in the Methodological guidelines for calculating the parameters and choosing high-frequency path circuits for 35-750 kV AC power lines (Standard of PJSC FGC UES STO 56947007-33.060.40.052-2010. - Access mode: http://www.fskees.ru/upload/docs/sto_56947007-33.060.40.05.05-2010_red.pdf. (Access date 12/20/2018).).

Simulation procedure

In the developed model of the 110 kV “Kutlu-Bukash – Rybnaya Sloboda” overhead line, the optimal parameters of the probe pulse were determined by simulation. The expected shape of the received reflected pulses was obtained upon reflection from the end of HF path to supply the highest amount of probe pulse energy to the HF path and optimization the measurement results processing. In addition, this model allows one to simulate the detection of damage on the overhead power lines wires using the location method [11].

The results of calculating the pulse shapes and the corresponding frequency spectra during the passage of a rectangular pulse of 2 μs duration through the HF elements of the “Kutlu-Bukash-Rybnaya Sloboda” overhead line are shown in Fig. 6.

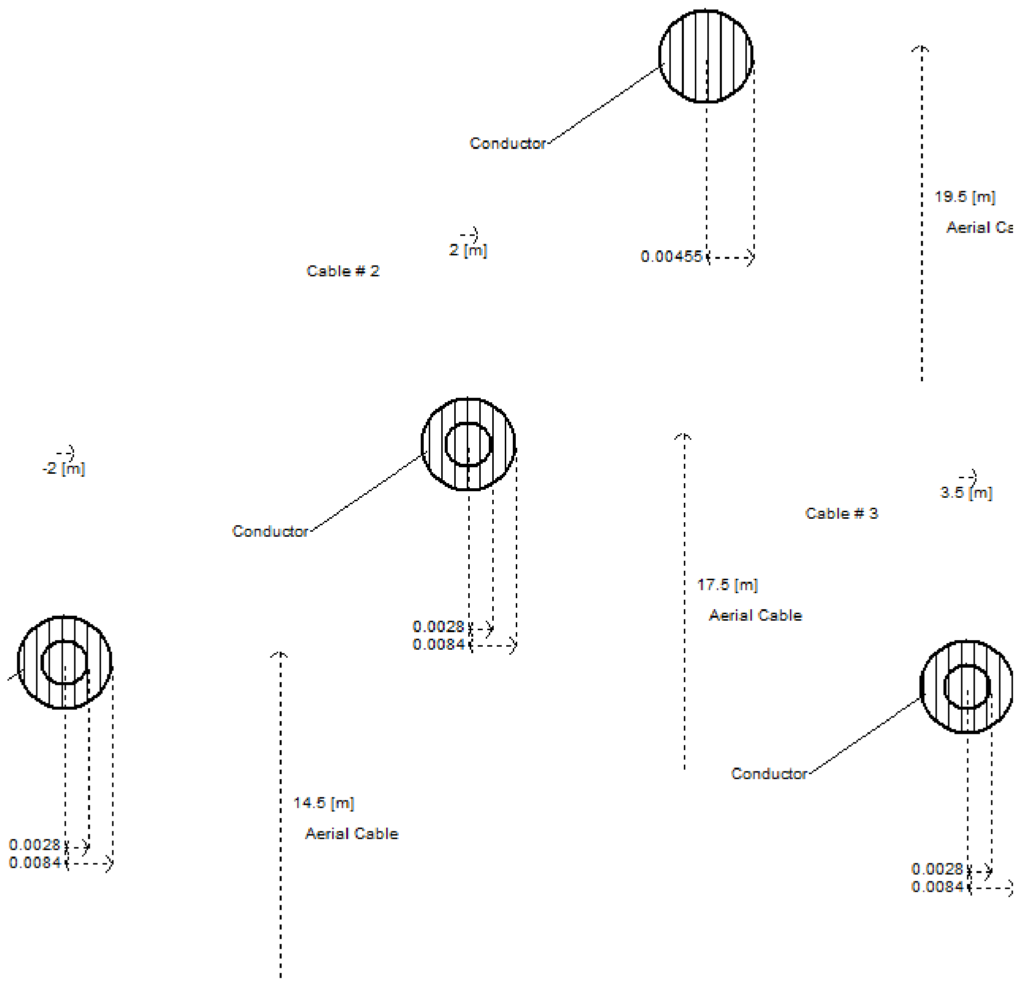


Fig. 5 The layout of the 110 kV overhead power line wires relative to the earth

The rectangular pulse (Fig. 6, a) after passing through the high-frequency cable remains practically unchanged: there is a slight increase in the duration of the fronts (Fig. 6, b). After passing through the connection filter, the pulse turns into a response (Fig. 6, c), which is approximately similar to one and a half period of a sinusoidal signal of approximately 15 μs. In this case, the constant component disappears, since the signal passes through the coupling capacitor, and the amplitudes of the low-frequency components (harmonics) sharply decrease, the maximum of the spectrum is in the region of 120 kHz.

After the pulse signal passes through the connection filter, damped oscillations appear (Fig. 6, c), as was indicated above. The HF stopper partially shunts these oscillations (Fig. 6d) and their amplitude decreases. Under the influence of HF trap, a maximum of the spectrum appears in the region of 60 kHz, due to the occurrence of “ringing effect” of the HF stopper. After the signal passes through the line wires, the maximum of the spectrum appears in the region of 140 kHz, and a pulse delay of 135 μs appears, which is determined by the covered distance of 40 km. When the pulse passes back and forth twice (Fig. 6, f), a delay of 270 μs appears, and the signal amplitude decreases by about 10 times. The amplitude of the reflected signal (marked by a solid oval in Fig. 6, f) becomes comparable with the amplitude of the “ringing" (marked by a dashed oval in Fig. 6, f) of the stopper.

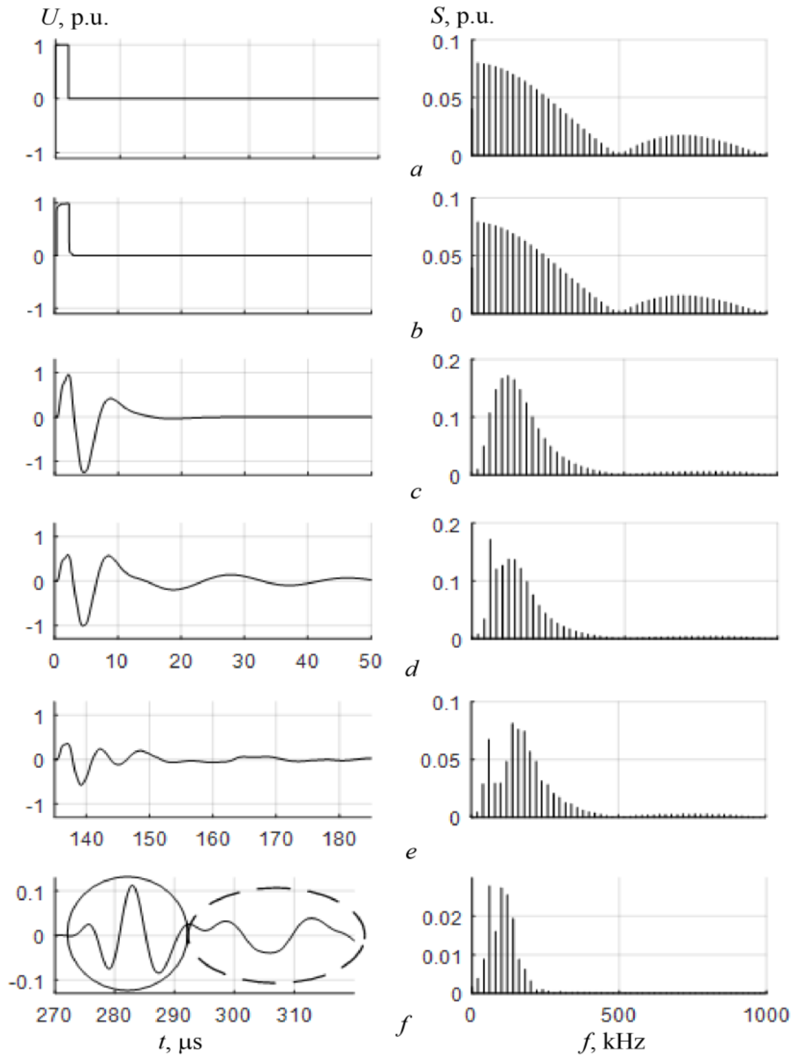


Fig. 6. Changes in the shape of the location signal (a) of a 2 μs duration (left column) and its spectrum (right column) after passing through the elements of the HF path: b - HFC; c - HFC and CF; g - HFC, CF and HFS; d - after passing the HF path (HFC, CF, HFS and line wires) in one direction; e - after two-fold passing the HF path back and forth; the solid oval marks the reflected signal, and the dashed line indicates the "ringing" of the HFS

Distortion of various-duration pulses

The pulse energy is determined by its amplitude and duration. In the simulation model, studies were conducted of the passage of rectangular pulses with a duration of 2–12 μs through the 40 km long HF path of the "Kutlu-Bukash – Rybnaya Sloboda" overhead line (Fig. 7).

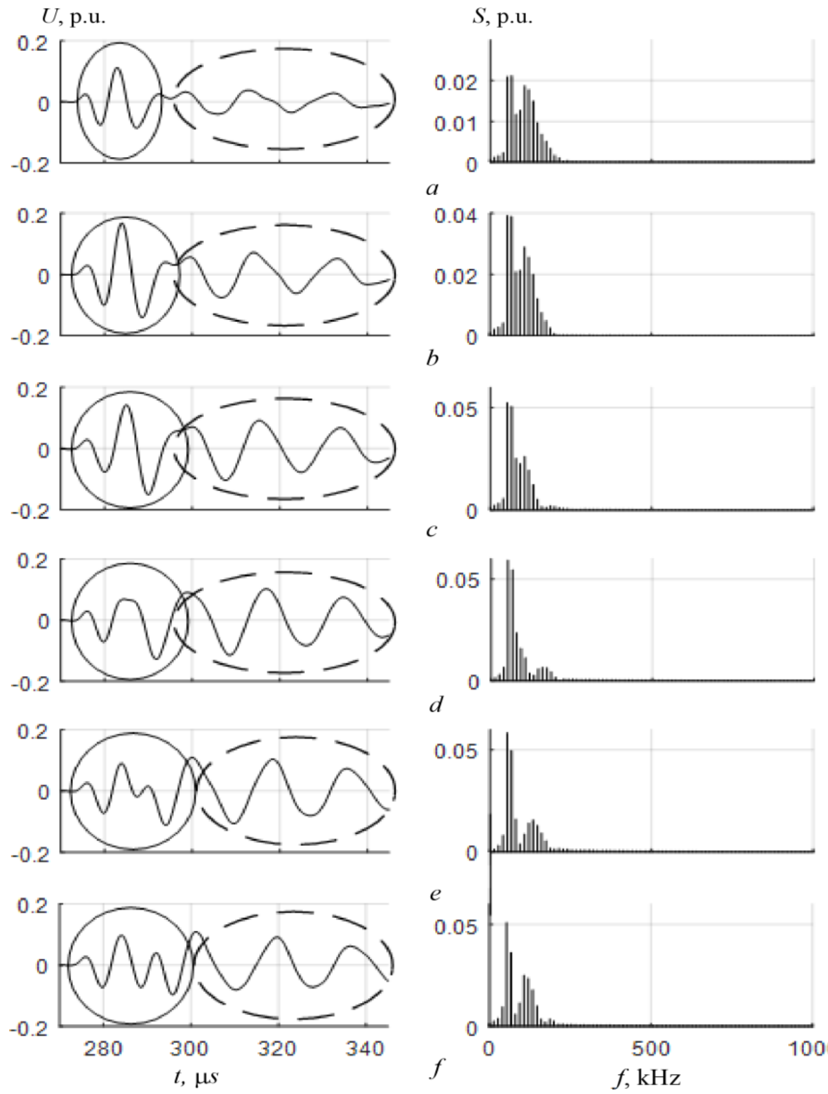


Fig. 7. Changes in the shape of location signals (left column) with durations of 2 (a), 4 (b), 6 (c), 8 (d), 10 (d), 12 µs (f) in the HF path of the 110 kV "Kutlu-Bukash – Rybnaya Sloboda" OHPL and their spectra (right column); the solid oval marks the reflected signal, and the dashed line indicates the "ringing" of the HFS

When changing the duration of the probe pulse, the shape of the reflected pulses changes. At the minimum studied pulse duration $\tau = 2$ µs, the amplitude of the reflected pulse does not have time to reach its possible maximum (Fig. 7, a), in contrast to pulses with long durations (Fig. 7, b-c).

According to fig. 7, the probe pulse, when passing through the HF tract, "differentiates", as shown in Fig. 6. In this case, the pulses turn into responses in the form of several periods of sinusoidal oscillation. In addition, damped oscillations ("ringing") are superimposed on the reflected signals, marked by dashed ovals in Fig. 7(a–e), which are caused by a high-frequency stopper, as was shown in Fig. 6.

With an increase in the pulse duration of more than 6 µs, the amplitude of the reflected signals decreases (marked by solid ovals in Fig. 7), which is caused by the fact that the responses from the falling and rising edges of the probe pulse begin to diverge in time, turning into separate responses.

Thus, pulses with τ = 2–6 μs, having the largest amplitude of the negative burst, are optimal for high-voltage lines with a length of 40 km, which makes it easier to separate them from the noise constantly present in the high-frequency path of power lines. An increase in the pulse duration from 2 μs to 8 μs causes an increase in the amplitude of the "ringing" of the airspace, with a further increase in the pulse duration, the amplitude of the "ringing" practically does not change.

Moreover, the correlation coefficients of the reflected signals obtained experimentally and during simulation for the durations of the probe pulses of 2-12 μs are at least 0.9, which confirms the adequacy of the developed simulation model.

To study the responses from the falling and rising edges of the pulse, model studies of passage of pulses with a duration of more than 200 μs were performed (Fig. 8). For such duration of the probe pulse, the response from the falling edge comes after the oscillatory processes caused by the leading edge of the pulse have completely decayed.

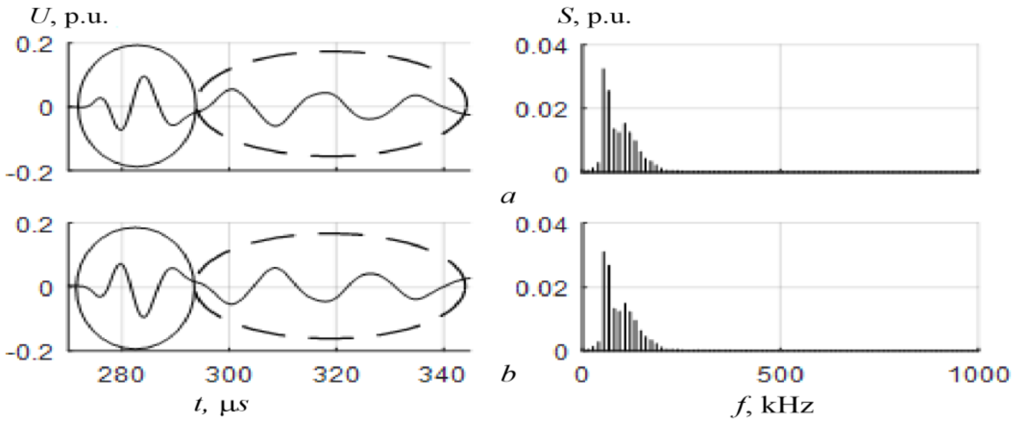


Fig. 8. Responses to the rising (a) and falling (b) edges of the probe pulse with a duration of 200 μs in the HF path of the 110 kV "Kutlu-Bukash – Rybnaya Sloboda" OHPL (left column) and their spectra (right column); the solid oval marks the reflected signal, and the dashed line indicates the "ringing" of the HFS

As it is seen from fig. 8, the reflections of the rising and falling edges of the probe pulse differ only in polarity, while their spectra also completely coincide. In this regard, by varying the pulse duration, it becomes possible to suppress the HFS "ringing" or to increase the amplitude of the reflected signal to a maximum.

Figure 9 shows the reflected signals for pulse durations of 4.8 μs and 17.6 μs. In the first case, due to the superposition of the reflection from the rising and falling edges, an almost twofold increase in the reflected signal amplitude is achieved (see Fig. 8). In the second case due to the mixing of reflections from the fronts for the period of "ringing" oscillations (17.6 μs) the "ringing" from the rising edge is compensated by "ringing" from the falling edge, while the reflected signal separates the reflections from the rising and falling edges of the probe pulse.

Investigations were carried out on the existing 110 kV "Kutlu-Bukash – Rybnaya Sloboda" OHPL of 40 km length. A comparison of the results of model calculations with experimental data shows that the main patterns of transformation of the reflected pulses' shape with a change in its duration coincide. The response from the rising edge of the signal pulse stably maintains its position on the time axis of the reflectorgam. Moreover, it is practically independent of the duration of the probe pulse. The reflected pulse with its short duration is the sum of two responses from the rising and falling edges. With increased pulse duration, these responses diverge in time and are not summed. Therefore, a subsequent increase in the pulse duration does not lead to an increase in the amplitude of the reflected signal, but can be used to suppress the "ringing" of the HF line path.

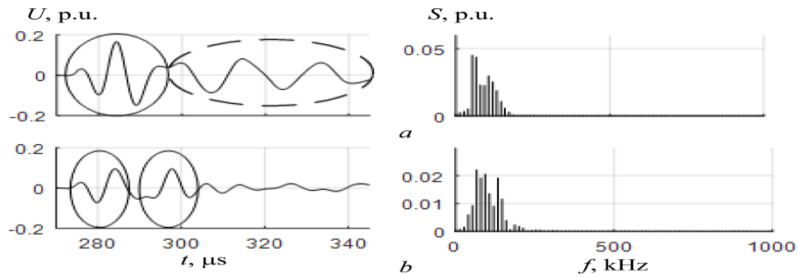


Fig. 9. Reflected signals (left column) at optimal probe pulse durations of 4.8 μs (a) and 17.6 μs (b) in the HF path of the 110 kV "Kutlu-Bukash – Rybnaya Sloboda" OHPL and their spectra (right column); the solid oval marks the reflected signal, and the dashed line indicates the "ringing" of the HFS

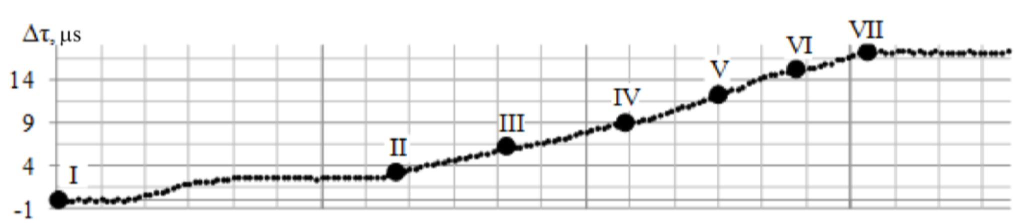
Distortion of reflected signals when ice deposits appear

When ice deposits appear on the wires, the conditions of signal propagation along the HF paths of the overhead lines change: the propagation speed of electromagnetic waves decreases, causing a delay Δτ of the location signals, and additional attenuation Δα appears due to dielectric losses in ice.

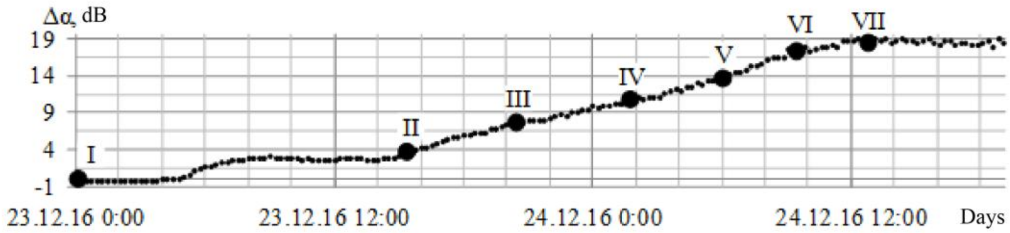
Figure 10 shows the change dynamics of delay Δτ and attenuation Δα of the reflected location signals in the HF path of the 110 kV "Kutlu-Bukash – Rybnaya Sloboda" OHPL for December 23-24, 2016. During this period, intense icing occurred on the wires of overhead power transmission lines. The growth of icy deposits continued around 30 hours; by 1 p.m. on December 24, the maximum thickness of ice deposits was about 8 mm. Deposits remained on the wires until 9 a.m. on December 25, after which their sizes began to decrease naturally, and in a week, the wire line was completely cleared of ice.

Sections of seven reflectograms for the period of December 23-24, 2016 were analyzed to study changes in the shape of location pulses during icing. The reflectogram measuring times are marked with bold dots I – VII in Fig. 10.

Fig. 11 shows sections of reflectograms of HF path of the 110 kV "Kutlu-Bukash – Rybnaya Sloboda" OHPL. To illustrate the changes in the reflected pulses, the intervals Δt_i indicate the positions of the reflected signals peaks relative to 260 μs (the beginning of the time window for searching of the reflected signal in the reflectogram of this overhead line). In this case, the signal delay $\Delta\tau_i$ is connected with the interval Δti via relation $\Delta\tau_i = \Delta t_i - \Delta t_1$.



a)



b

Fig. 10. Dynamics of changes in delay Δτ (a) and attenuation Δα (b) of the reflected location signals in the HF path of the 110 kV “Kutlu-Bukash – Rybnaya Sloboda” OHPL for December 23–24, 2016

Fig. 11 shows a decrease in the amplitude of the reflected signal both on reflectograms and on their spectra. Initially, the spectrum of the reflected signal is concentrated in the frequency range 50–150 kHz with a maximum at a frequency of 90 kHz. With the formation of ice deposits, the duration of the reflected signals increases and the maximum of the spectrum of the reflected signal shifts to lower frequencies by 70–80 kHz, this is due to the fact that the components of the signal at higher frequencies decay faster than the signal components at low frequencies [12].

Also, a tendency toward an increase in the reflected signals delay as ice builds up on the wires is observed in Fig. 11. In the absence of ice deposits on the wires, the time of location pulse propagation (Fig. 11, a) is approximately 270 μs, and it gradually increases as ice builds up, and reaches 287 μs (Fig. 11, g).

The maximum changes in delay and attenuation for Fig. 11, g were 17 μs and 19 dB. In this case, the amplitude of the reflected signals decreased from approximately 2 V to 0.15 V. Table 1 shows the attenuation and delay of signals for these seven reflectograms.

Table 1

Changes in attenuation and delay of location signals with ice growing

Measurement No.	I	II	III	IV	V	VI	VII
Date,	23.12.2016			24.12.2016			
time	00:30	15:30	20:45	01:50	06:00	9:50	13:00
Delay Δτ, μs	0	3	6	9	12	15	17
Attenuation Δα, dB	0	4	8	11	14	17	19

The maximum dimensions (wall thickness) of the ice clutch, according to calculations, amounted to about 8 mm, such deposits are not able to cause wire breakage. Therefore, the removal of ice deposits in this case was not performed, and they disappeared naturally in the next 6-7 days.

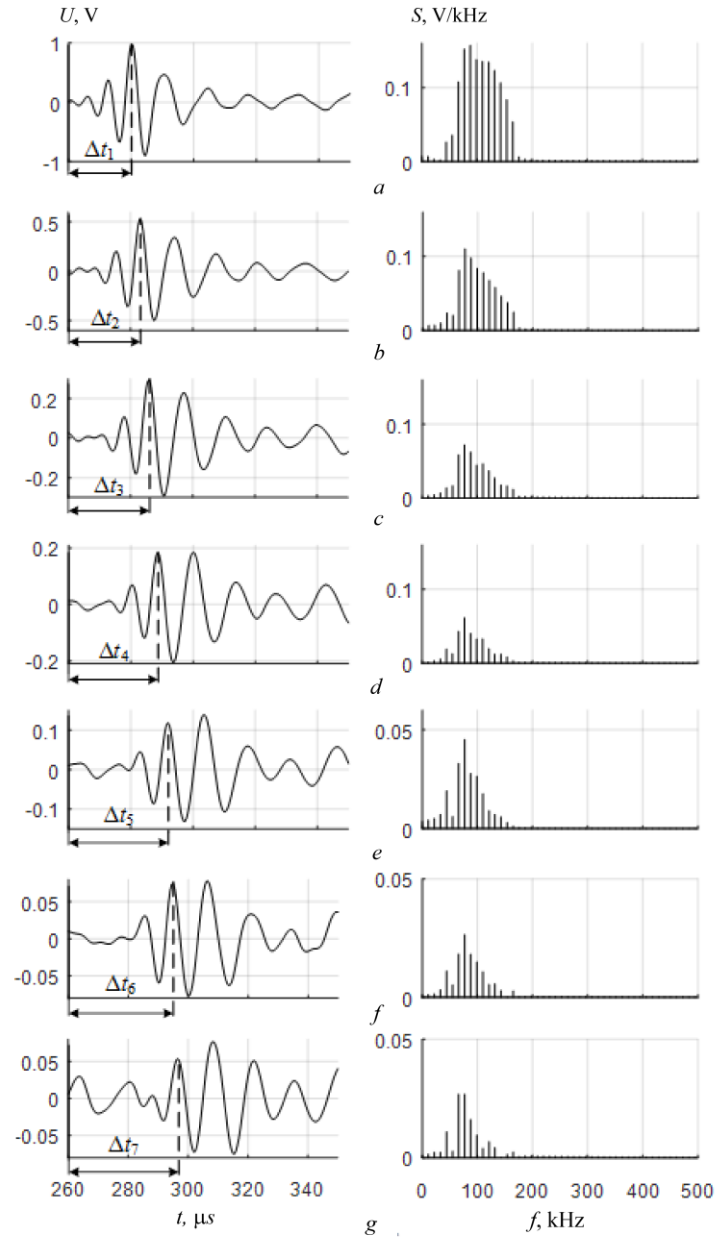


Fig. 11. Changes in reflected location signals in the HF path of the 110 kV “Kutlu-Bukash – Rybnaya Sloboda” OHPL (left column) and their spectra (right column) for the period from December 23–24, 2016 when ice is formed on the wires (moments of reflectogram measurement a-g are marked with points I – VII in Fig. 10)

Conclusions

The changes of location signal shapes during the passage of the elements of the high-frequency path were studied using a simulation model. The developed simulation model for the propagation of broadband probe pulses through narrow-band HF paths of OHPL makes it possible to determine the distortion of location pulses depending on their shape and duration. Elements of high-frequency path make a filtering impact on the broadband location signal. As a result, in this example the spectrum width of the reflected location signal is narrowed significantly from 1000 kHz to 200 kHz.

Analysis of the passage of pulses of different durations showed that the optimal pulse duration can be selected based on two criteria: minimizing the oscillatory processes caused by the high-frequency stopper, or maximizing the amplitude of the reflected location signal. The probe pulses durations will be determined either by the period of the oscillatory process caused by high-frequency stopper or by the half-period of the center frequency of the reflected location signal.

Analysis of changes in the parameters of reflected location pulses during ice formation showed that ice deposits cause a decrease in the propagation speed of location signals, which leads to a delay in reflected signals, in addition, ice causes significant attenuation of location signals, while the high-frequency components decay faster, which leads to a gradual shift of central frequency of the reflected location signals spectrum to the low-frequency region.

The research results are used to optimize the parameters of the probe pulse signals of the location software and hardware complex.

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