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THE USE OF THE LOCATION METHOD FOR DETECTING DAMAGE TO TRANSMISSION LINES

RenatMinullin
Department of Economics and Organization of Production
Kazan State Power Engineering University, Russia

IlshatFardiev
JSC "Grid Company", Russia

ABSTRACT

A new resource-saving technology in the form of thelocation method for probing transmission lines, which allows diagnosing the condition of underground (cable) and overhead lines is described. The richest experimental material on detection of breaks and short circuits on wires of transmission lines by the location method, obtained during 20 years of research, is analyzed. The peculiarities of the procedure for the local diagnostics of cable and overhead transmission lines are considered. The methods for recognizing the reflectograms of the local probing with the indication of the type and location of the damage on the line, as well as the technique for eliminating interference, are describedıo

Keywords: Cable and Overhead Transmission Lines, Location Method, Line Faults, Short Circuits and Wire Breaks, Diagnostics, Interference.

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1. INTRODUCTION

The main requirement for determining the location of damage in electrical networks is the early restoration of power to the disconnected current collectors with the minimization oflabor, time and money expenditure for the search[1-3].

Information search which was carried out in the duration of 50 years showed that neither in Russianor abroad, the problem of operational diagnostics of the condition of the wires of power lines is not completely solved. A universal method of diagnostics, which would equally successfully detect short circuits and breaks of wires of power lines and ice deposits on them has not been found.

At Kazan State Power Engineering University (KSPEU), as a result of the research conducted in the duration of 23 years since 1995 under the leadership of professor R. Minullin, a location method has been developed and put into operation, which allows solving this problem. As a result, a new unique and multifunctional resource-saving technology with the appropriate equipment has been created, which has no world analogues[4-7].

The technology makes it possible to diagnose in real time the state of cable and overhead power lines with the voltage of 6-750 kV, thereby increasing their reliability and ensuring the uninterrupted power supply[8, 9].

The developed technology is based on the location method and allows to control cable and overhead lines along their entire length with instant detection of short-circuits and cable breaks occurring on them, indicating the type of damage and the distance to it. The technology also allows real-time monitoring of the process of dangerous ice deposits growing on the wires of overhead lines and determining the moment of necessary smelting of sediments in order to maintain the integrity of the power line wires [10].

The location method which serves as the basis for the technology is prompt (its operational speed is calculated in microseconds), remote (it's able to probe the line from one point without bypassing it), universal and multifunctional.

The location device can be connected directly to the disconnected cable lines, to theoverhead lines, it can be connected via the connection filter.

The diagnostics for the purpose of detecting damage to cable power lines using location devices (reflectometers) has been applied for a long time [1, 2]. The use of reflectometersfor the diagnosis of overhead transmission lines has no analogues in the world practice, therefore it is considered in detail in the article [4-6, 8-10].

2. THE METHODOLOGY OF THE LOCATION PROBING OF POWER TRANSMISSION LINES

During the location probing of the transmission line, a pulse signal is sent to the monitored line and the time taken to propagate it along the line in the forward and reverse directions after reflection from its wave impedance in homogeneities (hereinafter inhomogeneities) is determined. The permanent inhomogeneities are the ends of the lines, the connection points of the branches to the power lines, the ends of the branches, the places of the transposition of the wires, the couplings, the connection points of the overhead lines with the cable inserts, and if there is high-frequency processing, high-frequency protectors, etc. The resulting inhomogeneities are faults of the line in the form of breaks and short circuits of wires, insulation faults, as well as the places of unauthorized connections, etc. For location diagnostics, information about the state of the line (including the appearance of ice on the wires) is carried by the pulses reflected from any the inhomogeneity of the line that exists or has arisen on it [10].

In the case of location probing, a reflectogram of the line (see below) is reproduced on the graphic display as an image of the reflected pulses on the time axis, as a reaction of the line inhomogeneities to the probing pulse. Analyzing the trace of the line, it is possible to fix its inhomogeneities and judge whether there are any malfunctions on it or not.

Power lines always end with a load in the form of primary windings of substation transformers. In the event of an emergency, the load of the line can be a resistance equal to zero (short-circuit mode), or infinity (line break or idle), or some value different from the wave resistance (in cases of single-phase earth fault, deterioration isolation, etc.).

In lines with a voltage of 35 kV and higher, in the presence of high-frequency processing, there are complex resistances: serial (connection filter) and parallel (high-frequency choke) oscillatory circuits.

3. DETECTION OF CABLE LINE FAULTS

We used the REYS-105R and REYS-205 reflectors manufactured by STELL for diagnostics of underground (cable) and overhead lines. The reflectometers generate pulses of a rectilinear positive polarity with amplitudes equal to 3.5 V and 22 V respectively, with adjustable pulse durations in the range τ = 0.007-15μs.

Usually, reflectometers are used to find faults in cable lines by identifying the damaged zone, and then - to evaluate the efficiency of burning and to diagnose the condition of the wires and cable sheath after burning it. Burning (breaking) of the cable with high voltage is used to create a current path through the fault location, then it becomes possible to determine its exact location by means of induction or acoustic methods [2].

From a large array of location measurements, as an example for analysis, the case is chosen which is the most characteristic. The probing of a 560m underground cable was carried out by pulses of duration τ equal to 0.5; 0.75; 1.0 μs (here and everywhere the pulses are counted at the beginning of the leading edge). Analyzing the shape of the pulses at points B and C on the reflectograms taken before burning the cable, we can conclude that for the given cable, based on its brand and length, the probe pulse duration is equal to 0.75 μs, since this duration creates the highest signal/noise ratio.

In order to diagnose the cable more informatively and reliably, the reflectograms should be taken by connecting the reflectometer to the line for probingin accordance with the “phase – earth (shell)” scheme (left part of Fig. 1) and the “phase – phase” diagram (right side of Fig. 1).

Before probing, the wires of the cable are disconnected from the supply buses, as well as the transformers, and are transferred to the idle mode.

Damage in the form of an interruption in the phase *B* conductor corresponds to a positive pulse on the reflectogramU_{BS} (l) in Fig. 1, *b* at point B at a distance of 350 m from the beginning of the cable during its “phase – earth (sheath)”probing. On the reflectogramsU_{AB} (l) and U_{BC} (l) in Fig. 1, *b*, obtained during the “phase – phase”probing, positive pulses at point B are also seen at a distance of 350 m from the beginning of the line, corresponding to a break in the phase *C* conductor.

On the reflectogram of U_{BS} (l) in Fig. 1, *c* for the phase *C* conductor shows that at point B at a distance of 350 m from the start of the line, instead of a positive pulse indicating a wire break, a negative pulse appeared corresponding to a short circuit between the residential phase *B* and the cable sheath after burning. Simultaneously, at the same distance from the beginning of the line at point B, a negative pulse appeared on the reflectogramU_{AS} (l), i.e. the conductor of phase *A* was burned and a short circuit was created between this conductorand the sheath. Thus, the conductor of phases *A* and *C* as a result of burning have turned out to be a short-circuited metal melt with the cable sheath and, consequently, with each other.

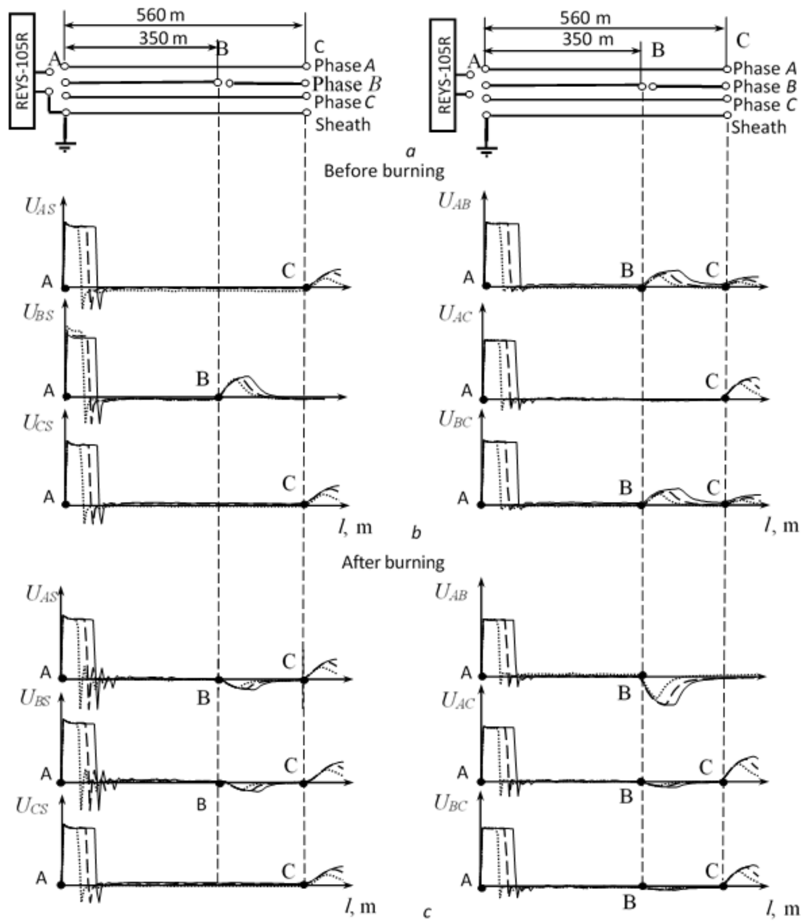


Figure 1. Identification of the results of burning a subterranean cable for various durations of the probe pulse 0.5 (·······); 0.75 (- - -); 1.0 (---) µs

[a]*a* is the connection of the reflectometer to the line wires according to the "phase-to-earth" (left column) and "phase-to-phase" (right column) schemes;

[b]*b* - reflectograms taken before burning;

[c]*c* - after burning the cable (breakage of the phase *C* conductor at point B, after burning the closure of cores of phases *A* and *B* on the cable sheath and with each other, point B - the open end of the line)

This is confirmed by probing the “phase – phase” scheme by the appearance in the place of a short circuit of a negative pulse of large amplitude at point B at a distance of 350 m from the beginning of the line on the reflectogramU_{AB} (l).

Thus, the reflectogramstaken in accordance with the “phase – earth (sheath)” and “phase – phase” schemes give a complete picture of the state of the cable conductors before and after burning. As a result, it is possible to choose the most optimal scheme for connecting the reflectometer to the cable line to obtain the maximum amplitude of the reflected local impulse.

4. DETECTION OF DAMAGE TO OVERHEAD POWER LINES

There are no descriptions of the use of reflectometers for the diagnosis of overhead power lines in the technical literature, so we carried out a series of special studies and developed a suitable methodology for using existing reflectometers for these purposes.

During the research, more than 500,000 reflectogramswere taken in laboratory and field conditions with the help of REYS-105R, REYS-205, as well as location complexes specially designed and manufactured for experimental measurements. Peculiarities of pulse reflection during locationprobing of transmission lines do not depend on the presence or absence of ahigh voltageof 50 Hz on them, as in both cases the physical principles of propagation of high-frequency signals, such as short probing pulses of reflectometers, do not change.

To the de-energized line, the reflectometer can be connected directly. To the live line, the connection of the reflectometer must be carried out through a separate high-voltage capacitor or via a coupling capacitor, which is part of the equipment of the high-frequency path of power lines with a voltage of 35 kV and higher.

When locating the power transmission lines, information about the state of the line carries pulse signals reflected from its inhomogeneities. In this case, it is necessary to take into account the attenuation of the reflected pulses caused by the line itself and its high-frequency processing elements (connection filter, high-frequency choke and high-frequency cable). Algorithms have been developed, program modules for calculation of the attenuation of signals in the high-frequency path, depending on their frequency and length of the transmission line in view of its technical parameters which allow determining the desired gain amplifier radar complex with existing transmission line parameters and a predetermined signal/noise ratio.

The transmission bandwidth of medium-length transmission lines is about 1 MHz, for short lines, this value can reach 2-3 MHz. This ensures the transmission of pulses with a duration of 0.3-1 μs. But the presence of connection filters and barrier filters in the line causes significant distortions in the shape of the reflected pulses.

Studies have shown that the optimal signal for locationprobing of a transmission line is a rectangular pulse, the duration of which is selected within 0.5-4 μs, depending on the length of the transmission line and the amplitude-frequency characteristics of its high-frequency processing elements (band transmittance).

Power lines of 6-10 kV voltage are part of the distribution networks and usually have a tree-like configuration with numerous branches [10].

The linear configuration occurs only in certain sections of such lines [10].

In Fig. 2, as an example, the results of probing an overhead line with a voltage of 10 kV with a linear configuration (feeder No. 23 of the “Airport” substation), where *a* is the scheme for connecting the REYS-105R reflectometer to the line; *b* and*c* are the reflectograms in case of a break and short circuit of the wires at the end of the line, respectively. The length of the de-energized line is 8,890 m, the wire mark is AS-70. The reflectometer was connected to two phase conductors of the line (“phase – phase” circuit), with the probing pulse amplitude U = 3.5 V, pulse duration τ = 0.5 μs. As seen in Fig. 2, with a wire break (idling), the reflected pulse has a positive polarity, and in the case of a short circuit it has a negative pulse, the pulses are well distinguished.

The line of the simplest configuration shown in Fig. 2, can be loaded on the transformer winding, which for high-frequency pulses of 0.5 μs duration (the required bandwidth Δf = 2 000 kHz) is a large inductive resistance. At the same time, a near-idle mode appears in the line. The reflected pulse, in this case, retains its polarity and has almost the same amplitude as in the case of a wire break (Fig. 2, *b*).

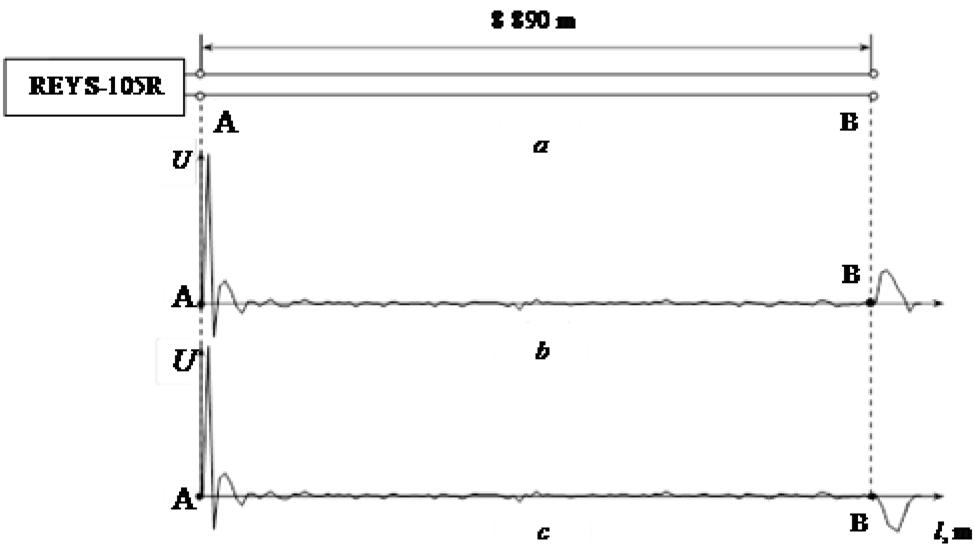


Figure 2. Results of probing of an overhead line of 10 kV with a length of 8,890 m, a pulse with a duration of 0.5 μs,

[a]*a* is the circuit for connecting the reflectometer to the line;

[b]*b* - reflectogram with a break at the end of the line;

[c]*c* - short-circuit reflectogram at the end of the line

The reactions of inhomogeneities of real lines with a tree-like configuration were investigated on the operating lines of 10 kV voltage of the distribution networks of Prigorodny Distribution Zone ofVolga Electric Networks (OJSC “Grid Company”, Tatarstan). The REYS-105R reflectometer was connected to a line that was in the de-energized state during the investigation, according to the “phase – phase” scheme.

When probing lines with a tree-like configuration,on the reflectograms, there are pulses that are reflected once and repeatedly from the connection points of the branches, their ends, the cable inserts, the couplings and other line inhomogeneities. The procedure for isolating impulses corresponding to the damage that has arisen among this mass of constantly existing reflected pulses is a very difficult task. But it can be solved by using thedifference method, in which the original reflectogram, taken at its nominal state, is subtracted from the current reflectogram taken when the line is damaged.

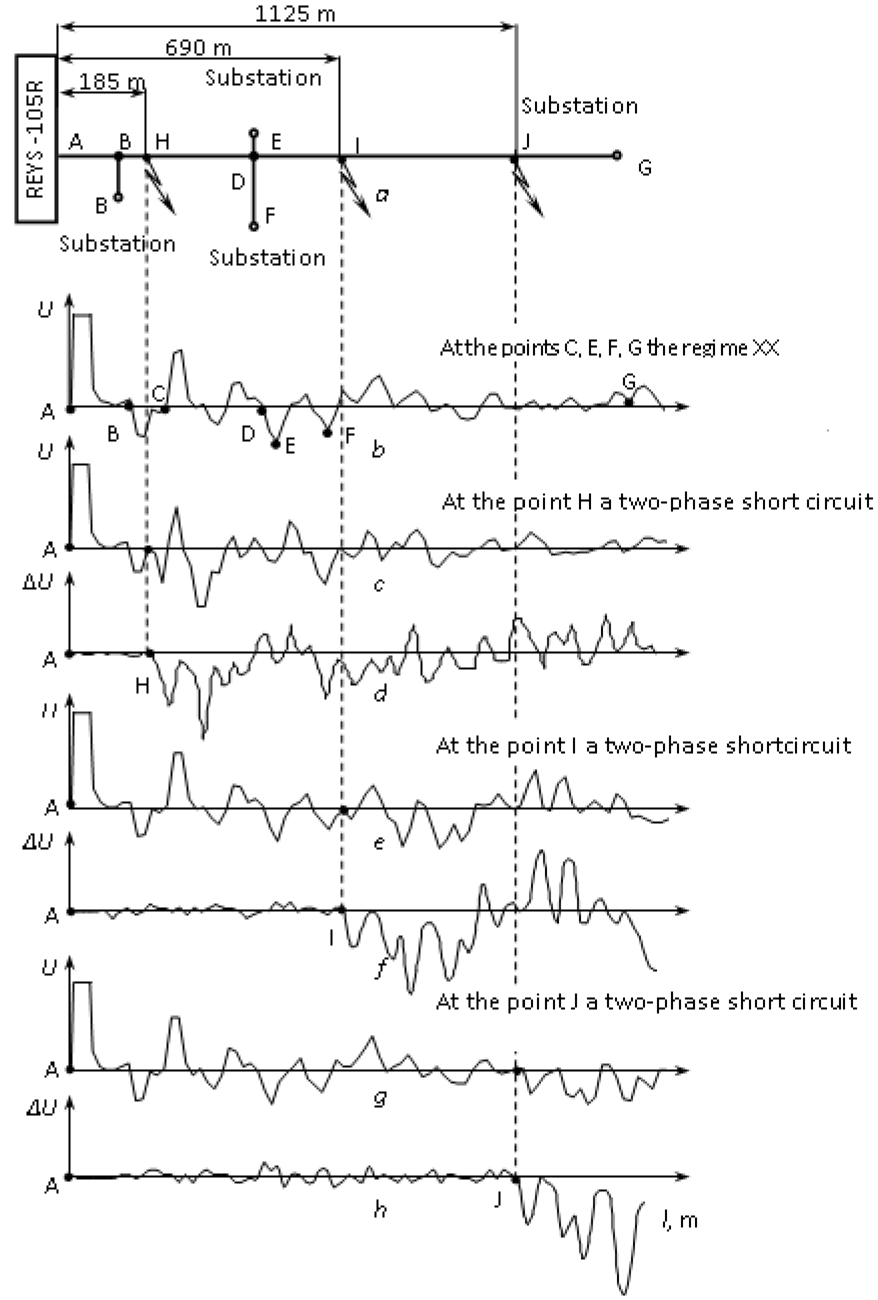


Figure 3. Determination of the location of two-phase short-circuiting by the difference method on the 10 kV overhead line with a length of 1 425

[a]*a* is the line diagram;

[b]*b* - reflectogram of the line in the initial state;

[c]*c* - areflectogram of the line with a two-phase short circuit at a distance of 185 m;

[d]*d* is the difference between the reflectograms*b* and*c*;

[e]*e* - a reflectogram of the line with a two-phase short circuit at a distance of 690 m;

[f]*f* is the difference between the reflectograms*e* and *b*;

[g]*g* - a reflectogram of the line for a two-phase short circuit at a distance of125 m;

[h]*h* is the difference between the reflectograms g and b

The method of application of the difference method is illustrated by the analysis procedure of the reflectograms shown in Fig. 3. Locationprobing was carried out according to the "phase – phase" scheme on the 10 kV line (feeder No. 12 of the "Airport" substation) with a length of 1 425 m with pulses of 0.25 μs duration. Two-phase closures on the main line were alternately created at distances of 185, 690 and 1 125 m, as shown in Fig. 3, *a*.

According to the changes in the reflectograms*U* (*l*) in Fig. 3, c, e, g, which were taken at closures from the line beginning at distances *l* equal to 185, 690 and1 125 m, respectively, it is very difficult to establish the place of closure. But if we subtract the reference trace *U* (*l*) from Fig. 3b, then on the difference reflectograms Δ*U* (*l*) in Fig. 3, *d*, *f*, *h* the closures are clearly distinguished by the instant of the onset of the first outburst of the negative polarity of the fluctuating signal of large amplitude. Locations of closure are denoted by points H, I, and J. Their locations on the reflectors coincide with the places of short circuits that were created artificially on the air feeder № 12 of the substation"Airport".

In the same way, it is possible to determine, the locations of the breaks that have arisen on the power lines.

Power lines with a voltage of 35 kV and above usually have high-frequencyprocessing and a simpler linear configuration compared to 6-10 kV lines. Therefore, their reflectograms are much simpler in structure and are much easier to decipher, since they do not have multiple reflected and re-reflected pulses from branches attached to the main line.

Locationprobing of high-voltage lines can be carried out without disconnecting them from the supply buses and feeding the probe pulse into the line through the high-frequency cable (HC), the connection filter (CF)and the coupling capacitor (CC)in the presence of a high-frequency choke (HFC), as shown in Fig. 4.

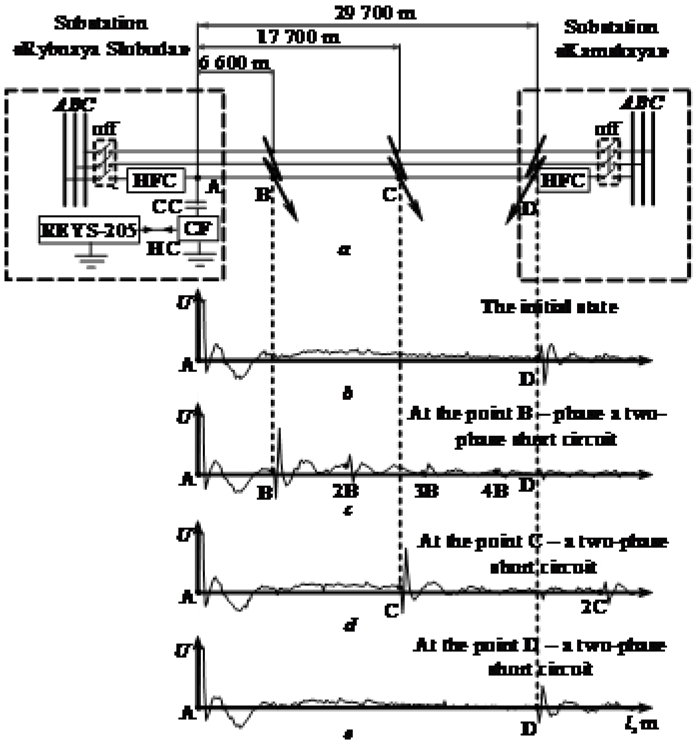


Figure 4 Determination of the location of two-phase short circuits by logical analysis on the 110 kV overhead line with a length of 29,700 m

[a] *a* is the line diagram;

[b] *b* - reflectogram of the line in the initial state;

[c] *c*, *d*, *e* - reflectograms for a two-phase short circuit at distances of 6 600, 17 700, 29 700 m from the beginning of the line, respectively

As shown by numerous studies, the features of the reflection of the location signals on the operating lines of 35, 110, 220 and 330 kV are approximately the same. Therefore, as an example, the reflectograms of an operating line with a voltage of 110 kV are considered.

Fig. 4 shows the results of detection of two-phase short circuits on the line with a voltage of 110 kV “Rybnaya Sloboda-Kamskaya” with a length of 29,700 m with high-frequency processing devices (connection filter FPM-6 400, SMP-110 / √3-6 400 coupling capacitor, high-frequency choke VZ 630) on both its ends. The probing was carried out with the help of the REYS-205 reflectometer with pulses of duration $\tau = 2$ μs on the de-energized line in the “phase – ground” scheme via the phase *A* wire. The connection of the reflectometer to the line is shown in Fig. 4, a.

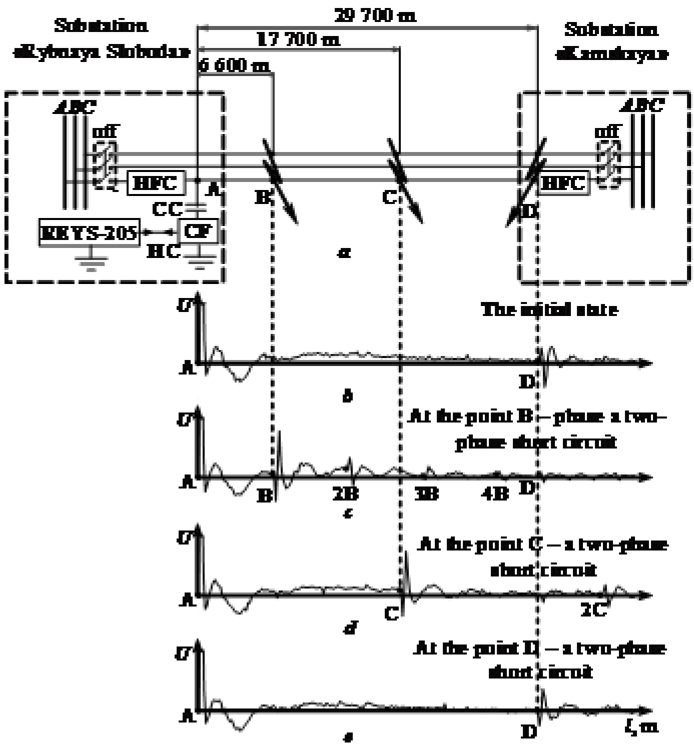
On the initial (standard) reflectogram*U* (*l*)(Fig. 4, *b*), a probing pulse is seen with accompanying signal oscillations due to the narrow band of the high-frequency tract of the transmission line and the positive pulse reflected from the high-frequency choke at the end of the line at the point D (also with signal vibrations), which is detected absolutely unambiguously.

On the reflectogram*U* (*l*) (Fig. 4, c), obtained with a two-phase short-circuit of the 110 kV line at a distance of 6,600 m from its origin, a negative reflected pulse with amplitude fluctuations is seen at point B, and pulses reflected several times are seen at points 2B, 3B, 4B.

On the reflectograms*U* (*l*) in Fig. 4, *d* and Fig. 4, *e*, obtained with two-phase closures on the 110 kV line at distances of 17,700 m and 29,700 m from the start of the line, respectively, the same regularities in the reflection of pulses are observed, as when closing at a distance of 6,600 m.

The study on the detection of cases of single-phase ground-faults and cases of wire breaks on the existing lines of distribution networks and main power transmission lines by locationprobing was carried out. In all cases, the reflected location pulses are clearly and reliably identified.

The phase wire break in the form of a reaction of the existing 110 kV Bugulma-110-Biryuchevka line 8,000 m in length (Fig. 5, *a*) is illustrated by a reflectogram taken with the help of the REYS-205 reflectometer. At the end of the line in Fig. 5, *b*, a positive pulse reflected from the high-frequency choke is observed. Phase A wire breakage occurred at a distance of 11,600 at point B. On the reflectogram in Fig. 5,c at the breakpoint B a positive surge of the reflected signal with subsequent damped oscillations appeared. Such a reaction is usually characteristic of idling. The signal reflected from the end of the line at point D is absent in this case since the energy of the probing pulse is completely reflected from the place of the break, but at the same time at 2B there is a pulse reflected twice.



x

Figure 5. Determination of the place of a wire break at the line 110 kV "Bugulma-110-Biryuchevka" with a length of 18 000 m

[a] *a* is the line diagram;

[b] *b* – reflectogram of the line in the initial state;

[c] *c* is the reflectogram of the line when the wire of phase *A* breaks off at a distance of 11 600 m from the beginning of the line

The cycle of experiments was devoted to the studyof the detection of irregularities in electro lines in the form of unauthorized branches, contaminated insulators, ice formations, cable inserts. It is established that the pulses reflected from these inhomogeneities during the location probing are clearly and unambiguously recognized on the reflectograms and enable it for the distance to be measured.

So, numerous measurements show the efficiency and reliability of the location method for detecting damage of various types on wires and cables of active power transmission lines with a voltage of 6-220 kV.

5. CONCLUSION

Location complexes allow:

- to detect line faults in the form of breaks and short circuits of wires, in the form of single-phase faults on the ground, indicating the type of damage and the distance to it;
- to determine the presence of a metal short circuit on the power line wires when the recloser is activated;
- to detect cable inserts on overhead power lines and couplings on underground power lines measuring the distance to them;
- to detect unauthorized connections to power line wires made in order to steal electricity;

- to perform the role of security alarm when the power lines are stolen with an indication of the distance to the place of theft.

Keeping the above-mentioned in mind:

1. the probing pulse signal simultaneously performs the functions of the sensor and the carrier of information on the state of the wires of overhead lines, therefore there is no need to install separate sensors on the wires of the transmission lines and telemechanical equipment for transmitting the readings of the sensors to the control room;
2. control of the overhead line over the entire length and not just one span is provided;
3. with one location device, control of all overhead lines departing from the substation is ensured;
4. during the installation of the location device, there is no need for interference with the design of the transmission line;
5. smaller, simpler and cheaper equipment is used, which is installed in the heated production room of the substation, which increases its reliability and facilitates its operation while eliminating the threat of vandalism on transmission lines;
6. installation in the workplace and the commissioning of the location probing equipment takes only a couple of minutesminutes if the transmission line has high-frequency processing.

Locationprobing can be carried out on live lines, on disconnected lines, as well as on ground wires. Due to the presence of its own generator of probing pulses, the location device functions steadily when the power supply to the power line is accidentally cut off, which the relay protection and automation systems are not capable of.

The signals of the locationprobing do not affect the operation of relay protection equipment, emergency automatics, telemechanics and communications. At the same time, with a certain digital processing, these signals cease to be a hindrance to the signals of the locationprobing.

So, since 2009,location complexes for diagnosing the condition of the wires of 110-330 kV overhead power transmission lines have been developed and put into operation at 4 substations in Russia: in Tatarstan (2 complexes), Bashkortostan and North Caucasus. The complexes function successfully in 24-hour automatic mode and allow reliable monitoring of the condition of the wires[10, 11].

In 2012, the staff of KSPEU together with the employees of Open Joint-Stock Company Scientific-Production Association “Radioelectronics”named after V. Shimko” by the order ofPublic Joint-Stock Company“Federal Grid Company of the Unified Energy System”manufactured and tested a prototype of an automatic system for monitoring the condition of power transmission lines in the 16-channel version[12-14].

In 2017, KSPEU employees together with the employees ofLimited Liability Company “Promenergo” under the Federal Target Program of the Ministry of Education and Science of the Russian Federation began to develop a pilot sample of a multifunctional location complex for monitoring overhead power lines with the location of damage to the wires and the detection of ice on them.

The made layout of the location complex successfully functions at the Bugulma-110 substation (Tatarstan). In the future, it is planned to replicate the location complexes ordered by energy companies.

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