Detection of Ice on Wires of Overhead Transmission Lines by Reflectometry Method

Minullin Renat, Kasimov Vasil, Filimonova Tamara

Kazan State Power Engineering University (KSPEU), 51, Krasnoselskay str., 420066, Kazan, Russian Federation, minullin@mail.ru

Abstract: one of the methods for early detection of ice deposits on high voltage overhead power transmission lines is the reflectometry method, which has been developed in the Kazan State Power Engineering University for more than 15 years. The method, technology and equipment of reflectometry sensing of overhead power transmission lines are described in this paper. The results of comparing experimental data of ice detecting by reflectometry method and by method of weight sensors are reported. Is shown that reflectometry method can reliably monitor in real time the dynamics of icing on wires, allows clearly identifying the starting time of ice melting, which is necessary to prevent wire breakage on power lines and it allows monitor ice melting process.

Keywords: overhead power transmission lines, ice deposits on wires, ice detection, reflectometer, technology, advantage of reflectometry detection of ice.

1 Introduction

Currently, there are two ways of ice detection on wires of overhead power transmission lines (OTL):

1) Forecasting the probability of icing on basis of meteorological data of environment around the wire, taking into account the technical parameters of OTL.

2) Immediate control of icing with sensors and ice detection devices.

Ice forecasting based on meteorological environmental data, is used in many countries where icing on OTL is an urgent issue to mitigate or avoid its impact on effectiveness of these lines.

Formation of ice on wires on OTL depends on the climatic region and is subject to certain meteorological laws: depends on the humidity and ambient air temperature, wind conditions. Formation of ice also depends on wire diameter, suspension height, mounting inflexibility, twists on wire, current flowing through the load.

Unfortunately, the forecast data may not be specifying indications at the beginning and the ending of ice melting, formed on the wires of OTL.

Now a days immediate control of icing on OTL is being performed by two methods: method of weight sensors and reflectometry method.

The method of weight sensors is based on comparing the weight of the wires in a passage in absence and presence of ice deposits. The value of wire tension is determined by ice load, wind, as well as ambient temperature. Assessment of the stress state of the wire and comparing it with the maximum permissible value, are carried out with weight sensors. The sensors detect the weight of glaze deposits close to one pillar, their data is transmitted to the receiving station using means of remote control.

Reflectometry detection method of ice on wires of OTL is an alternative method of weight sensors. The method is being developed in the KSPEU over 15 years since 1998 [1-7].

Formation of ice on wires represents as impure dielectric, reducing the speed v of spreading signal along the line causes additional attenuation α due to dielectric losses of electromagnetic wave energy that is consumed in heating of ice layer coating. Reflectometry method allows to determine the occurrence of icing on a OTL by comparing the propagation time τ of the reflected signals and their amplitudes U in presence and in absence of ice formation.

To probe line with reflectometer, which is a simplified diagram of the connection to the line is shown in Figure 1, *a* totality of the reflected pulses forms a trace. The appearance of ice deposits on line causes a change in trace. If, from the standard (reference) trace (Figure 1, *b* – green line) to deduct the current trace (Figure 1, *b* – blue line), the difference changes are reliably detected by the appearance of a signal corresponding to the end of the line (Figure 1, *b* – red line). The more the characteristic impedance of the line will change under the influence of thickness of ice deposits due to changes of dielectric constant between the wires of the line, the more will be the difference between the traces, the more will decrease pulse amplitude ΔU and will increase pulse delay $\Delta\tau$ (Figure 1, *b*).

In presence of ice deposits the amplitude U and delays $\Delta\tau$ change synchronously, as shown in Figure 2 (marked by dashed ovals). Using two criteria's U (or ΔU) and $\Delta\tau$ increase the reliability and accuracy of ice detection on wires of OTL.

Hardware-software complex of ice monitoring system consists of the following components: 1) reflectometry sensing device; 2) commutation device; 3) industrial computer; 4) central server.

Commutation device is designed to connect output/input of reflectometer with one of 16 wires of OTL of substation.

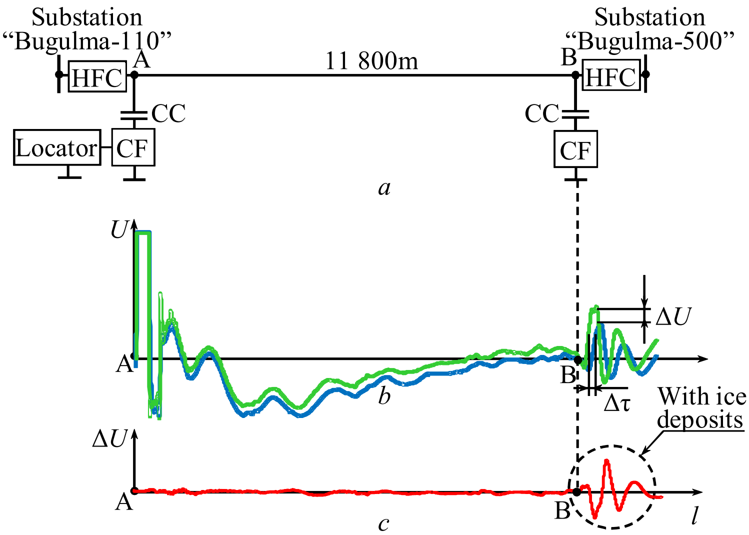

Figure 1

Detection of ice on OTL 110 kV "Bugulma-110–Bugulma-500": *a* – line diagram; *b* – trace of line without ice (green line) and in presence of ice (blue line); *c* – difference (red line) line traces without ice and in the presence of ice with fluctuations in the signal at point B due to the presence of ice deposits (HFC – high-frequency choke, CC – coupling capacitor; CF – connection filter, locator - reflectometer)

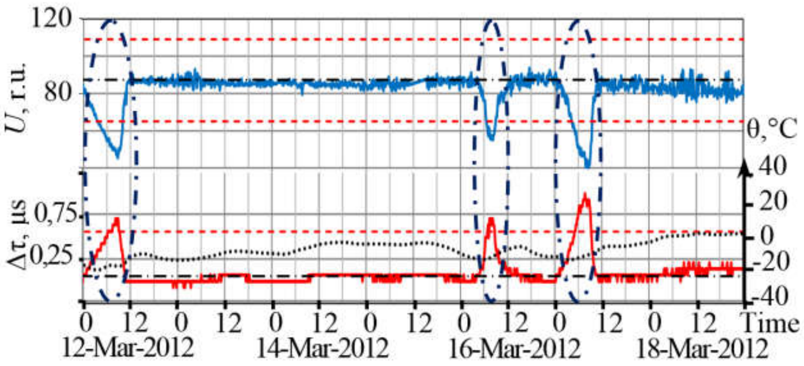

Figure 2

Daily bases change of amplitude *U* (top) and the delay Δτ (lower graph) of the reflected pulses of 110 kV OTL "K Bukash-R Sloboda"; ovals designated registration of ice formations [12.03-18.03.2012]

The computer along with wireless modem and interface control the operation of reflectometer, transmit data to the central server, and form the operator interface.

The central server performs as an archiver.

Reflectometry sensing technology of ice deposits formation for OTL is developed. It includes the following steps:

1. Trial traces are taken and digitally precessed to extract the desired signal from noise in control line.

2. By using impulse reflectometer length of line is determined. Attenuation in line is calculated to determine the amplitude of sensing source impulse.

Reference trace is measured and saved in memory.

3. Interfering condition of controlled line is studied in detail.

4. Sensing mode is defined; parameters of sensing impulse are set.

5. Taste traces are taken and sensing modes are adjusted to optimize them.

6. The value of delay $\Delta\tau$ obtained by measuring and reducing the impulse amplitude ΔU are used to recalculate the thickness of ice deposits. If the line consists of several areas then weight and thickness of the ice are calculated for each of them separately.

7. The calculated values of ice deposits are transferred to control room of power distribution company where these are displayed in user friendly format. In case of detecting ice deposits which can cause accident in OTL, melting decisions is taken.

Recently, employees of KSPEU designed and manufactured a small series of reflectometry system for sensing OTL, which are being successfully used to control icing on existing OTL. In 2012, employees of KSPEU together with employees of OJSC “Scientific-industrial enterprise “Radioelektronika” named after V.I. Shimko” by the order from JSC “Federal Grid Company of Unified Energy System” designed, manufactured and tested a prototype of an autonomous and automatic ice monitoring system with 16 channels (Figure 3).

Control of icing on OTL has been carrying out since 2009 in lines of 35-110 kV substation "Bugulma-110" (the Volga region), on lines of 110 kV substation “K Bukash” (Volga region), and from 2013 on lines of 110 kV substation “Shkapovo” (Ural) and on the lines of 330 kV substation “Baksan” (North Caucasus). The complex operates continuously in an automatic sensing mode and transmits data every 30 (60) minutes to the control center of KSPEU. Ice deposit data transmitted to control room, providing a user-friendly interface to monitor the dynamics of icing and melting of ice on wires of OTL.

Currently in substation “Bugulma-110” reflectometry system is serving 7 OTL, out of then six are of 110 kV and one in of 35 kV. A schematic arrangement of controlled power transmission lines in relation with substation “Bugulma-110” is shown in Figure 4.

Figure 3

Reflectometry system for ice detection on overhead power transmission lines with 16 channels

Figure 4

A schematic arrangement of seven OTL of substation "Bugulma-110" controlled by reflectometry system

Examples of multi-channel sensing results in substation “Bugulma-110” for the period November-December 2014 with measurements of specific values δτ are shown in Figure 5.

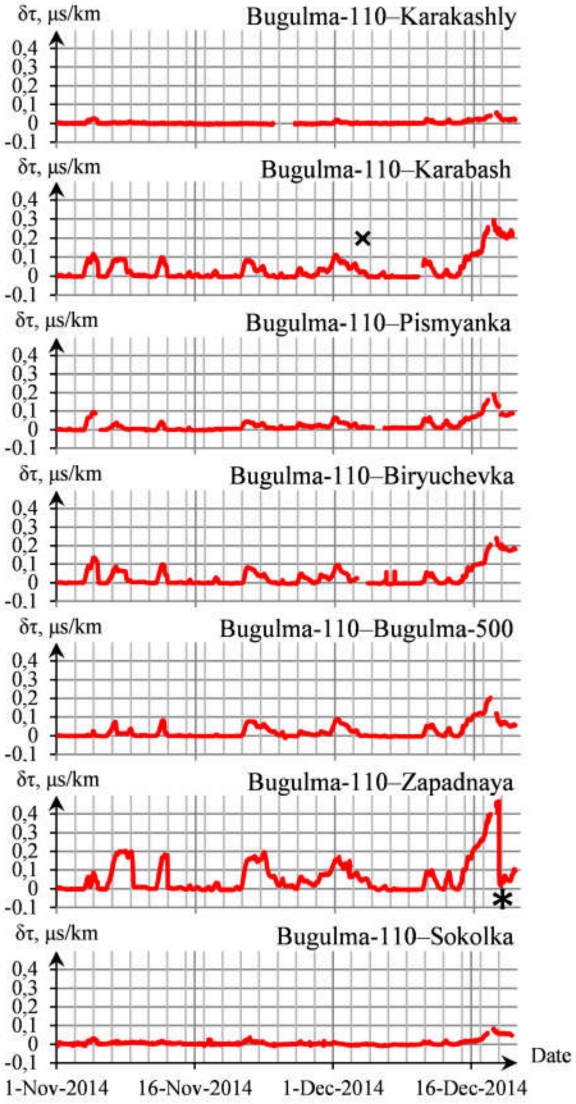

Figure 5

Example of changing the specific delay of reflected signals during formation of ice deposit on controlled OTL of substation “Bugulma-110” [1.11-20.12.2014]

As reflectometry measurements are integral measurements, in same ice condition, ΔU and $\Delta\tau$ of long lines are overvalued in relation to short lines. Therefore, more objective parameters are specific attenuation values δα (dB/km) and the delay δτ (μs/km), given to a unit length of the line, in this case length is 1 km.

According to the data of Figure 5 largest ice deposit was found on the OTL "Bugulma-110–Zapadnaya", where a breakage was made to prevent wire in December 18, 2014, ice melting (marked *) at values δα = 1.2 dB/km and δτ = 0.48 μs /km.

Figure 6 shows a photograph of frost formation on wires of OTL "Bugulma-110–Karabash" December 1, 2014 at 10 o'clock 16 minutes, which corresponded δα = 0.3 dB/km and δτ = 0.1 μs/km (snapping time is marked on Figure 5 with a cross). Naturally, this ice formation could cause breakings power line wires.

Figure 6

Frost formation on wires of OTL "Bugulma-110–Karabash" Dec 1, 2014 at 10 o'clock 16 minutes, which corresponded δα = 0.3 dB/km and δτ = 0.1 μs/km (snapping time is marked in Figure 5 with cross)

2 Determination of ice thickness

When considering modal components according to source [8], attenuation of OTL link with due regard to ice depositions is increased mainly because of attenuation change in the principal mode. Variations of attenuation coefficient Δα (dB/km) and phase coefficient Δβ (rad/km) for non-symmetrical line with identical wires, covered with ice, comparing to coefficients for the lines with identical wires ice-free are determined by the formulas [8].

Results of calculations using developed algorithm to define Δα and τ by ice thickness b as of January 2013 are depicted on Figure 7.

Maximum value of ice deposition equal to 3 mm was observed on January 4, 2013 (Figure 7). Those ice depositions could not make any harm to the coherence of OTL wires.

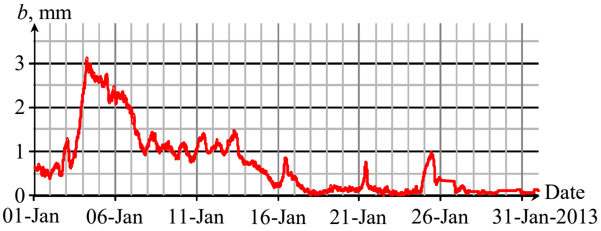

Figure 7

Results of the reflectometry control thickness of ice depositions on wires of 110 kV OTL "K Bukash–R Sloboda" [1–31.01.2013]

Drawback of reflectometry method is failure to differentiate between slight-thickness ice deposition of the long OTL and dangerous concentration of ice on its separate small areas. The method of subdividing power lines into segments with spotted imperfections is used to prevent this drawback.

Due to the spotted imperfections, it is possible to subdivide the 40 km "K Bukash–R Sloboda" line into 5 areas. Graph of ice thickness b behavior could be depicted for each of the line as shown on Figure 8.

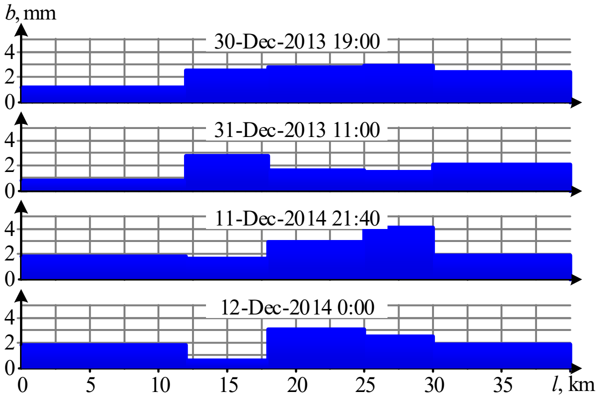

Figure 8

Propagation of ice deposition on wires along 110 kV OTL "K Bukash–R Sloboda" line during different observation days

The first two graphs show propagation of ice depositions, which started to be formed on December 30, 2013, and completely faded away on January 1, 2014. The first graph, calculated as of 19:00, December 30, 2013, corresponds to the maximum ice load per this icing incident. The thickest ice wall reached 2.9 mm value and was recorded on the 4th area (between towers №134-155). Later, ice coating started to come off from the wires, which corresponds to the moment of partial vanishing on second graph. As shown on 2nd graph Figure 8, ice thickness decreased along the most part of the line (except 2nd area): it decreased almost in half on the 4th area from 2.9 mm to 1.5 mm, however grew on the second area (between towers №40-99) from 2.5 mm to 2.8 mm.

The last two graphs on Figure 8 correspond to the icing incident as of January 11-12, 2014. Maximum values of ice depositions are indicated on January 11 at 21:40. Thickness of ice wall on the 4th area reached 4.1 mm value. Since then ice depositions started to decrease; in 2 hours ice thickness was reduced to 2.5 mm on the 4th area, though it stayed the same on 1, 3 and 5 areas. However, by 4:00 on January 12, 2014, the line was totally cleaned off the ice.

This method of line subdivision allows eliminating drawback of the reflectometry method, which is determination of integral ice thickness value along the whole line length. Thus, it will help to prevent accidents on small but highly affected to the icing areas.

3 Comparison of data obtained by method of weight sensors and by reflectometry method

Comparison of data obtained by reflectometry sensing method and by weight sensors have been carring out since 2013 in areas of substations “Baksan” (North Caucasus) and “Shkapovo” (the Urals). The complexes operate continuously in an automatic sensing mode and transmit data every 30 (60) minutes to the control center of KSPEU.

Figure 9, *a* shows the changes of reflected pulse during time delay $\Delta\tau$ for sensing 330 kV OTL (North Caucasus) with reflectometry complex, developed in KSPEU.

In Figure 9, *b*, *c*, corresponding readings *P* of weight sensors located at distances of 1.3 km (pillar number 243) and 29.3 km (pillar number 134) from the beginning of the 330 kV line are shown.

As shown in Figure 9, *a* by reflectometry data, a large ice formed on the line 2.02-4.02.2013 caused maximum pulse delay $\Delta\tau\text{max} = 4.5$ ms.

Close to pillar number 243 on line 2.02-4.02.2013 ice was not detected by weight sensors (Figure 9, *b*).

On pillar number 134 (Figure 9, *c*) on line 2.02-4.02.2013 ice of maximum load Pmax = 40 kg was detected by weight sensors.

In the interval 5.02-23.02.2013 (Figure 9, *a*, *b*, *c*) shows a small quantity of ice while using reflectometry method (D0, E0, F0, G0) and weight sensors method on pillar 243 (D1, E1, F1, G1) and on pillar 134 (D2, E2, F2, G2).

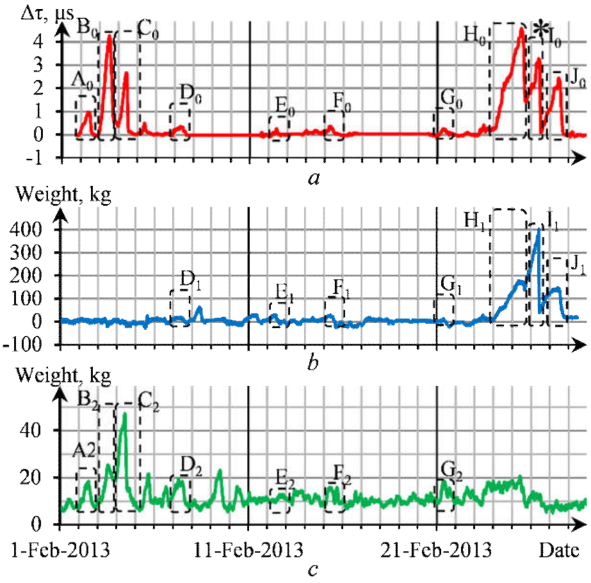

Figure 9

Comparison of registrations ice deposits on line 330 kV (North Caucasus): *a* – by reflectometry sensing (measured delay $\Delta\tau$); *b*, *c* – by weight sensors method (measured ice weight P in one passage); registration ice formations are marked by dashed ovals; * – the beginning of ice melting [1.02-28.02.2013]

Following cases of large ice deposits was observed during the period of 24.02-27.02.2013. According to reflectometry sensing (Figure 9, *a*) ice deposits on line peaked at midday of 25.02.2013 (H0) with $\Delta\tau_{max} = 4.5$ ms. Then in some sectors ice was fallen down, and again the growth of ice continued til midday of 02.26.2013 (I0) with $\Delta\tau_{max} = 3.3$ ms. At this time ice began melting (Figure 9 and indicated by an asterisk). Throwing of ice deposits as a result of the melting occurred in the afternoon of 26.02.2013. However, growth of ice deposits lasted until noon of 27.02.2013 (J0) with $\Delta\tau_{max} = 2.5$ ms. Then there was a natural ice deposits throwing occurred and the line returned to its staffing condition.

According to weight sensors data, on the pillar number 243 (Figure 9, *b*) ice deposits gradually increases until it melts in the afternoon 02.26.2013 (I1). After melting ice deposits slowly continued to increase (J1). Then, in the afternoon of 27.02.2013 deposits disappeared naturally.

As seen from a comparison of Figure 9, *a*, *b* the overall dynamics of the ice deposits formation in both registrations are the same. But there are differences in details, as reflectometry sensing monitors the entire line and weight sensors monitor only one flight line.

Comparison of sensors readings on pillar number 243 and number 134 in Figure 9 *b*, *c* show ice deposits, detected by the sensor on pillar number 243, is not detected by the sensor on pillar number 134 (and vice versa) due to uneven deposition of ice.

In reflectometry sensing all resulting ice deposits A0 – J0 are fixed precisely without loss (Figure 9, *a*).

Comparative experiments were performed to detect ice deposits in winter 2013-2014 on 110 kV OTL (Urals).

Figure 10 is a graph of weight changes of ice on wire phase *A*, obtained by using reflectometry sensing techniques (Figure 10, *a*) and by the weight sensors, which are mounted on phase conductors *A*, *B* and *C* close to pillar number 23 (Figure 10, *b*-*d*).

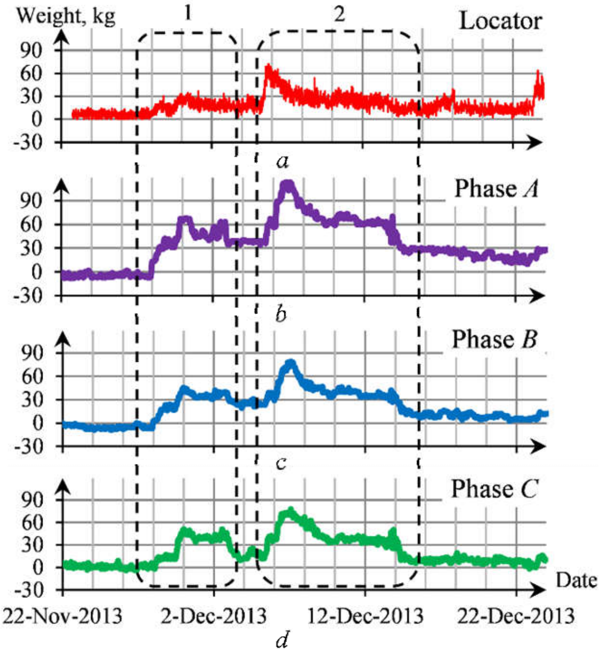

Figure 10

Changes ice deposits weight according to reflectometry device connected to phase *A* (*a*) and according to weight sensors on phases *A*, *B* and *C* (*b*-*d*) on wires of 110 kV line, where the dashed outline 1 - period 28.11-4.12 2013; 2 bar loop - 5.12-15.12.2013 period of [22.11-23.12.2013]

Figure 10 shows how formation of ice deposits began with increasing weight on all three phases on 28.11.2013 (dotted outline 1). According to weight sensors on 30.11.2013 on the wires of the three phases was observed 45-65 kg ice deposits in one passage (Figure 10, *b*, *c*, *d*).

Corresponding readings of reflectometry method, figured out by using modal theory of high-frequency signals propagation through overhead lines, give a figure about 30 kg for a single span (Figure 10, *a*).

The discrepancy reading of reflectometry method and weight sensor method prove the fact that the distribution of the ice along the power line was uneven, i.e. in areas not monitored by weight sensor icing can be less than the place close to pillar number 23 where weight sensor is mounted.

The second period of icing began 5.12.2013 (dashed circuit 2 in Figure 10). According to the sensor reading of wire of phase *A*, were the most susceptible ice deposits. In the two half spans close to pillar number 23 ice deposits reached upto 75-110 kg (Figure 10, *b*-*d*). According reading of reflectometry system average weight of ice deposits on the wire of phase *A* in one span reached upto 70 kg (Figure 10, *a*). Weight of ice deposits formation on line 14.12.2013 was shortly reduced naturally without interference and ice melting was not required.

By comparing the curves in Figure 10, *a*-*d* it is evident that the dynamics of wire weight changes with ice deposits during icing is detected by weight sensors as well as by reflectometry sensing quite objectively. However, there are differences in details readings and these devices have different operating principles.

Registration of dynamics of ice deposits weight changes on 110 kV line (Ural) with subsequent melting shown in Figure 11. Intensive ice deposits on wires began in evening, 26.12.2013, the weight of ice reached upto 375-400 kg on 28.12.2014 in the same span according to readings of reflectometry system, and weight sensors on the wire phase *A*.

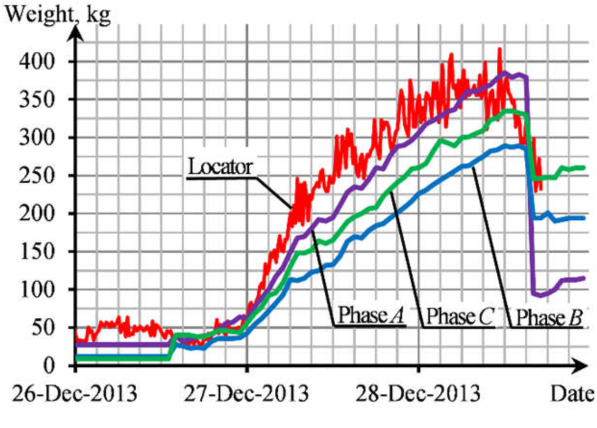

Figure 11

Changes of ice deposits weight according to reflectometry device connected to phase *A*, and according to weight sensors mounted on wire close to pillar № 23 of 110 kV OTL [26.12-28.12.2013]

To prevent accident ice melting on wires three phases line was performed. As a result of ice melting on 28.12.2013 wire weights were reduced to permissible values, as shown in Figure 11.

According to readings of weight sensors, weight of ice deposits on phase lines do not match with each other according to absolute value, as shown in Figure 11. The same phenomenon is observed in the 330 kV line, which can be explained by varying degrees of tension when they were mounted, and all weight sensors are not with similar sensitivity. Mismatching of data of weight sensors by absolute vale mounted on different phase wires of transmission line, reduces the reliability of their redings, causes difficulty to determine the critical weight of ice deposits that can cause an accident on the power transmission lines, and causes uncertainty in taking operational decisions about the beginning of the melting of ice deposits.

Reflectometry method can reliably monitor in real time the dynamics of icing on wires, allows clearly identifying the starting time of ice melting, which is necessary to prevent wire breakage on power lines. In addition, reflectometry method allows monitoring ice melting process.

Reflectometry method has the following advantages compared to the method of weighing conductors that are currently used in rare cases on some power lines:

1) pulse signal simultaneously serves as a sensor and a carrier of information about icing on wire, so there is no need to install separate sensors and data transmitters on wires, which would have collected data from sensors and then transmit data to control center, so is used small, simple and cheap structure of the equipment;

2) it ensures control of the entire line, not just a single span;

3) installation of reflectometry equipment does not require intervention in the power line structure, because reflectometry equipment is placed in the indoor substation, which increases reliability and simplifies its exploitation for operating personnel;

4) commissioning of reflectometry equipment takes a few minutes if the power line has a high-frequency channel;

5) it is possible to monitor all lines outgoing from the substation using periodical switching.

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