Ultimate Capacities of Location Detection of Damages and Ice Coatings on Overhead Transmission Lines

Vasil Amirovich Kasimov

Abstract**: *This article investigates into ultimate capacities of location monitoring of 35–750 kV overhead transmission lines concerning detection of damages and ice deposits on wires. On the basis of theoretical and experimental location studies, minimum and maximum distances were evaluated at which short circuits and wire breakages could be detected, as well as minimum and maximum sizes of ice deposits on wires detected by location method. Daily and annual temperature variations of variables of reflected location signals are described. Sizes of ice coatings have been detected which cause tensile stresses in 35–750 kV overhead transmission lines. Maximum thickness of detectable ice walls on overhead transmission lines has been predicted and exemplified by existing overhead lines of Bugulma-110 substation, the detectable sizes exceed the ice wall thickness causing wire breakage.***

Index Terms**: *overhead transmission lines, location method, detected damages, detection of ice deposits on wires, ultimate capacities.***

I. INTRODUCTION

Overhead transmission lines (OTL) due to their significant length are the least reliable elements of power transmission system. In winter OTL are exposed to formation of ice coatings on wires. Ice deposits of excessive sizes cause breakage of wires and destruction of OTL towers. Such emergencies caused by ice coatings generally cover wide areas. In order to prevent possible emergencies caused by ice coating, it is required to monitor dynamics of ice deposits and to melt the ice deposits when necessary. Kazan State Power Engineering University (KSPEU) for more than 20 years develops location monitoring of OTL state which provides early detection and current testing of ice coating sizes as well as detection of distance to damage location (short circuit or breakage) in the case of occurrence [1–4]. Location equipment and relevant methods developed in KSPEU are unique and have no analogs, hence, it is required to study ultimate capacities of the location method of detection of damages and ice deposits on OTL.

II. LITERATURE REVIEW

Operational principle of the location method is comprised of sending impulse signal to OTL carrier link with subsequent receiving of signals reflected from heterogeneities of wave resistance. Such heterogeneities are as follows: line terminations, branch lines, transpositions, damages, and others. Location devices are connected to active transmission lines using connecting filters containing coupling capacitor which provides separation of high frequency location signals from commercial frequency voltage. In order to prevent bypassing action of substation buses, a high frequency shield is installed between the buses and connection point of communication capacitor. Such carrier links for data transfer via OTL are widely applied in Russia due to the fact that the directions of data transfer in power engineering are generally the same as directions of power transmission. Hence, the location equipment is usually connected to the existing carrier links in parallel with data communication devices (phones, telemetry, relay protection, emergency automation), which implies certain requirements to their compatibility [5].

A key factor upon location testing is attenuation of location signals in OTL carrier link. Attenuation of location impulse signal upon propagation via OTL is determined by attenuation upon passing across carrier link elements of OTL comprised of HF cable, connecting filter with coupling capacitor, HF shield, OTL wires. Procedure is developed for predicting attenuation of location signal upon its passing across carrier link of 35–750 kV OTL with consideration for line technical parameters. The main parameters for predictions are as follows: line operating voltage; line distance; existence of branch lines; existence of HF bypasses; specifications of HF cable, connecting filter, coupling capacitor, HF shield, OTL (specifications of wire, transposition and splitting, layout of phase wires, etc.).

Typical parameters of 35–750 kV OTL are summarized in Table 1.

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Vasil Amirovich Kasimov, Kazan State Power Engineering University, Kazan, Russia.

Table 1. Typical parameters of 35–750 kV OTL

Voltage, kV Parameter	35	110	220	330	500	750
Span distance, m	135	220	300	350	400	450
Wire, Grade AS (aluminum/steel cross section, mm^2)	95/16	120/19	300/39	300/39	500/64	500/64
Maximum mechanic stress, daN/mm^2	29.97	30.43	26.62	26.62	26.77	26.77
Radius, mm	6.75	7.6	12.1	12.1	15.3	15.3
Splitting	1	1	1	2	3	5
Average OTL distance between two adjacent substations, km	10	25	100	130	280	300

III. METHODS

This work is aimed at evaluation of ultimate capacities of location method of determination of sizes of ice deposits and detection of damage locations on 35–750 kV OTL in order to develop requirements to adjustment of location equipment. Herewith, it is required to solve the following problems: estimation of minimum and maximum distance of damage detection as well as estimation of minimum and maximum detected wall thickness of ice deposits. These problems were solved on the basis of theoretical evaluations, simulation; experimental location studies started in 2009 in continuous automatic mode on existing transmission lines.

A. Detection of OTL damages

Damages of OTL in the form short circuits and wire breakages cause heterogeneities of OTL wave resistance, reaching them the location signals are reflected. Herewith, the propagation time of location signal to damage location and back determines the distance of damage location. Since the wires of overhead lines are not covered with dielectric, then the location signals are propagated in air environment, the propagation speed of these signals is close to the speed of light 0.9–1 s.

Minimum distance of damage detection will be determined by minimum duration of location signals and period of reflectogram discretization. Thus, at minimum duration of location impulse of t = 0.5 µs, the impulse reflected from damage can be separately resolved starting from the distance of t*v/2, which does not exceed 0.5*3*108/2 = 75 m, and the discretization period of impulses should be not higher than 500 ns (discretization frequency: 2 MHz). Moreover, location equipment is generally connected to connecting filter using coaxial HF cable, as a rule the cable distance is in the range of 50–150 m, and the coefficient of cable shortening is about 1.5, this allows to increase minimum duration of location signals by the time required for signal propagation in HF cable, that is, by about 1 µs.

Maximum distance of damage detection on 35–750 kV OTL is determined by attenuation in carrier link. Ultimate distances of OTL damage detection were predicted using software of calculation of carrier links parameters via high voltage transmission lines.

Attenuation of location signals induced by HF cable, connecting filter with coupling capacitor and HF shield, equals in average to 12 dB. Attenuation in linear links of overhead lines is approximately defined as [6]:

$$\alpha = k_1 k_2 \sqrt{f} + k_1 k_2 f,$$

where f is the frequency, the coefficients k_1 and k_2 determine components of attenuation coefficient stipulated by losses in wires and ground, respectively, and the coefficients k_3 and k_4 take into account the influence of splitting of phase wires on attenuation of linear links.

According to predictions, for 35–750 kV OTL with typical parameters (Table 1), attenuations do not exceed 18 dB at 100 kHz. Therefore, damages on 35–750 kV OTL can be detected in the attenuation range of 30 dB covered by location complexes which would provide monitoring of damages for OTL distances of 105, 100, 137, 210, 290, 350 km for 35, 110, 220, 330, 500, 750 kV, respectively. Such variations of OTL distance upon equal attenuation are stipulated by the dependence of attenuation on wire radius, distance between wires, number of wires upon phase splitting. For lower voltages of 35 and 110 kV, the obtained maximum distances of damage detection exceed average distances between neighboring substations, however, the lines of such voltages are equipped with branch lines, each branch line without HF shield can introduce additional attenuation of 12 dB.

Upon passing via connecting filter, the front and trail of rectangular location impulses are strongly distorted (dispersed), thus, damage locations are detected using correlation analysis. Herewith, the detection accuracy of distance to damage location will depend on measurement error of propagation time of location signals. The accuracy of distance determination can be improved by special methods [7-9].

B. Detection of ice coatings on wires by location method

The location method is indirect upon detection of ice deposits on OTL. Under the influence of ice deposits, there occurs increase in linear attenuation of location signals $\delta\alpha$, propagating via OTL, and additional linear delay $\delta\tau$ appears.

Minimum ultimate sensitivity of location method can be determined using minimum values of $\delta\alpha$ and $\delta\tau$ characterizing minimum wall thickness of ice deposits which can be generated on OTL. The ultimate sensitivity of location method is determined by ultimate sensitivity of receiving instruments and level of interferences in OTL carrier link.

When an oscilloscope is connected to OTL carrier link, systematic interferences occur in receiving channel of location device stipulated by OTL operation (wire corona discharge) and operation of engineering communication systems (relay protection, telemetry, telephony), pickups of radio stations, etc.

Systematic interferences are reduced by coherent accumulation (averaging) of signals. Concerning location monitoring of ice deposit formation, the number of accumulations upon measurement of reflectograms should be selected depending on required response rate and suppression level of interferences in terms of amplitude. At present most measurements are based on 2^{10} accumulations, and the reflectogram measuring time of 1,000 counts depending on location equipment embodiment is from 0.001 to 30 s, thus, the interferences are suppressed to 30 dB, interferences of simultaneously operating instruments are narrowband and can be significantly suppressed by digital filtration of reflectograms. Due to accumulation of signals and interference suppression, the interference level of carrier link can be decreased in average by 40-50 dB.

C. Minimum sizes of detected ice deposits

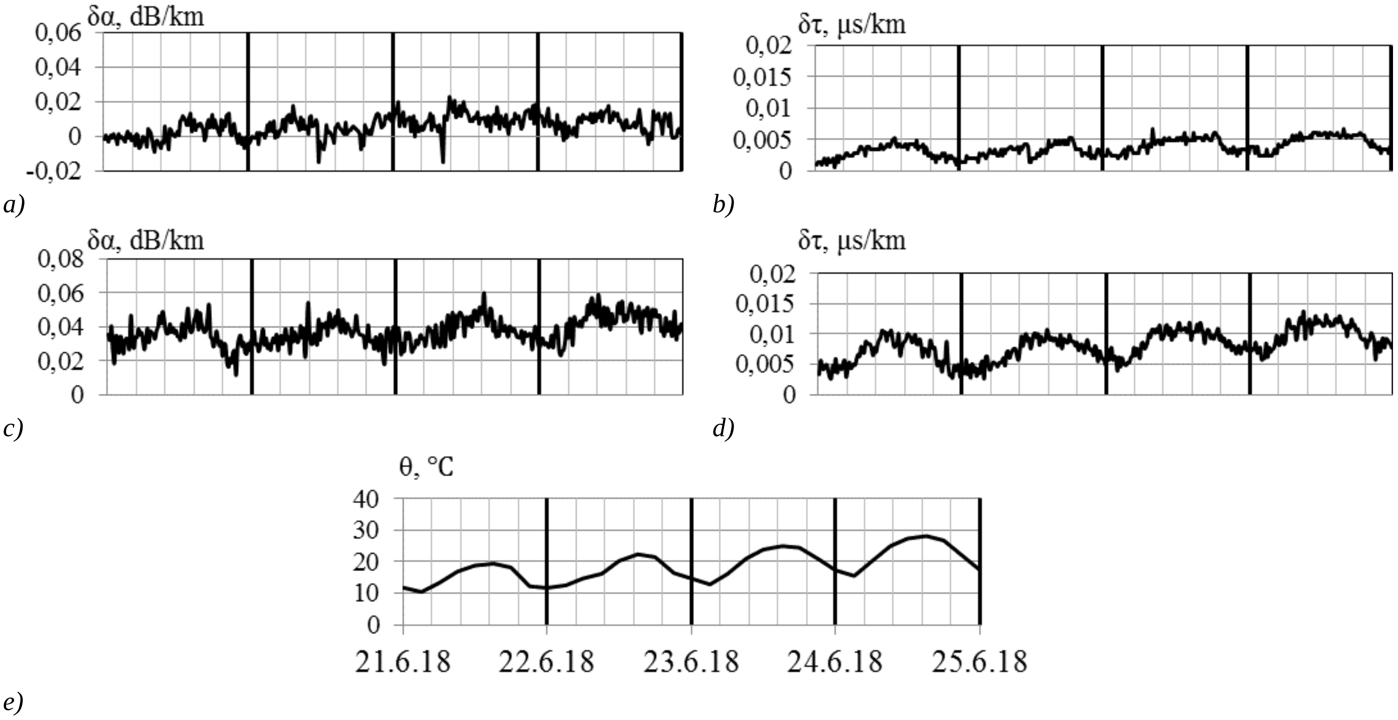
The minimum sizes of ice deposits detected by location method will be determined by interference level of OTL carrier link and daily/annually variations of attenuation $\delta\alpha$ and delay $\delta\tau$.

Long-term measurements have demonstrated that the parameters of reflectograms recorded upon similar conditions have no significant variations. However, there are daily/annual variations in the form of variations of attenuations $\delta\alpha$ and delays $\delta\tau$ of reflected location signals.

Figure 1 illustrates daily variations of attenuation $\delta\alpha$ and delay $\delta\tau$ of reflected signals measured at intervals of 30 minutes during 5 days from June 21 to 25, 2018 on Bugulma-110 – Bugulma-500 (*a*, *b*) and Bugulma-110 – Biryuchevka (*c*, *d*) OTL as well as variations of ambient temperature θ (*e*).

The plots (Fig. 1) demonstrate daily variations of linear attenuations $\delta\alpha$ and delays $\delta\tau$: at 2–3 p.m. they are maximum, and at 2–3 a.m. they are minimum. The coefficients of cross correlation of $\delta\alpha$ and $\delta\tau$ variations were calculated measured, respectively, on Bugulma-110 – Bugulma-500 and Bugulma-110–Biryuchevka OTL in Fig. 1.

The highest coefficients of correlation (up to 0.83) are achieved for variations of linear delay $\delta\tau$ and temperature θ. In addition, high cross correlation (0.74) of variations of delay $\delta\tau$ on various lines is observed, which confirms that the variations of delay $\delta\tau$ on various lines are stipulated by one and the same reason: elongation of wires during daytime due to increase in ambient temperature and shortening of wires during nights due to decrease in the temperature.



a) *b)* *c)* *d)* *e)*

Fig. 1: Daily variations of specific attenuations $\delta\alpha$ (*a*, *c*) and delays $\delta\tau$ (*b*, *d*) of reflected impulses as well as of ambient temperature θ (*e*) on 110 kV overhead transmission liens Bugulma-110 – Bugulma-500 (*a*, *b*) and Bugulma-110–Biryuchevka (*c*, *d*).

Air temperature varies periodically not only during the day and night but also during the year from winter to summer. Hence, temperature variations of $\delta\alpha$ and $\delta\tau$ are observed during a year: in summer wire length increases and in winter decreases.

In order to study the temperature influence on reflected location signal, multiyear measurements of $\delta\alpha$ and $\delta\tau$ at Kutlu Bukash – Rybnaya Sloboda OTL were processed. As a consequence, it was established that during days and in summer the delays and attenuations of signals were maximum, and during nights and in winter they were minimum. Average hourly variations of attenuation and delay during day in summer reach 0.015 dB/km and 0.003 µs/km, in winter: 0.01 dB/km and 0.0015 µs/km. Average hourly annual variations are 0.03 dB/km and 0.01 µs/km, respectively [10]. The coefficients of cross correlation of variations of attenuation and delay with temperature variations during this period are 0.69 and 0.94, respectively.

It was demonstrated during 10-year experience of monitoring of these parameters on Bugulma-110 and Kutlu-Bukash substations that their daily/annual variations were about the same. Thus, using the daily/annual values of δα and δτ obtained at Kutlu-Bukash–Rybnaya Sloboda OTL, it is possible to evaluate the error and minimum wall thickness of ice deposit which can be detected by the location complex.

The wall thickness of ice deposit is determined using the set of equations:

$$\begin{cases} \delta\alpha(b,\rho,r,f,p) = \delta\alpha_{meas}; \\ \delta\tau(b,\rho,r,f,p) = \delta\tau_{meas}, \end{cases}$$

where *b* is the wall thickness of ice deposit, ρ is the density of ice deposit, *r* is the wire radius, *f* is the signal frequency, *p* is the number of wires in split phase, the subscript *meas* means experimental measurements of linear attenuation and delay. Then, the error of indirect determination of wall thickness of ice deposit is:

$$\Delta b = \sqrt{\left(\frac{\partial b}{\partial \alpha}\cdot\Delta\alpha\right)^2 + \left(\frac{\partial b}{\partial \tau}\cdot\Delta\tau\right)^2}.$$

For 35, 110, 220, 330, 500, and 750 kV transmission lines at measurement errors of Δδα = 0.005 dB/km and Δδτ = 0.0017 μs/km, the determination errors of wall thickness of ice deposit according to calculations equal to 0.09, 0.11, 0.17, 0.25, 0.45, and 0.67 mm, respectively, which provides advanced detection of ice deposit and determination of minimum wall thickness less than 1 mm for all voltages.

D. Critical sizes of ice deposits on wires

When ice deposits are generated on OTL wires, the reflected location signals begin to attenuate. With further increase in weight (wall thickness) of ice deposit, the amplitude of reflected signal can decrease to the level when it is below detection threshold of location receiver. In this regard it is necessary to predict critical weight (wall thickness) of ice deposits which will result in wire breakage and then to predict the attenuation of reflected signal corresponding to such situation, since the reflected signal prior to wire breakage can be by far below the threshold of its detection and the location system could lose sensitivity before possible breakage of OTL wires.

Mechanical stress in wire and allowable wall thickness of ice deposit depend on span distance and wire grade, they are determined by equation of wire state [11]:

$$\frac{\sigma_n}{\gamma_n}\,\mathrm{sh}\,\frac{\gamma_n l}{2\sigma_n} = \frac{\sigma_m}{\gamma_m}\,\mathrm{sh}\,\frac{\gamma_m l}{2\sigma_m}\left[1 + \frac{\sigma_n - \sigma_m}{E} + \alpha(\theta_n - \theta_m)\right],$$

where σ is the stress in the lower point of wire, γ is the load on wire, *l* is the span distance, θ is the wire temperature, α is the temperature coefficient of linear elongation, *E* is the elasticity modulus, the subscript *m* indicates variables of initial mode, the subscript *n* indicates the calculated mode.

It should be mentioned that the 220 and 330 kV, 500 and 750 kV lines can operate with one and the same wire grade but due to different span distances, the allowable wall thickness of ice deposits will be different (the longer is the span, the lower are the allowable sizes). Figure 2 illustrates mechanical stress of wire as a function of wall thickness of ice deposit for OTL of various voltages.

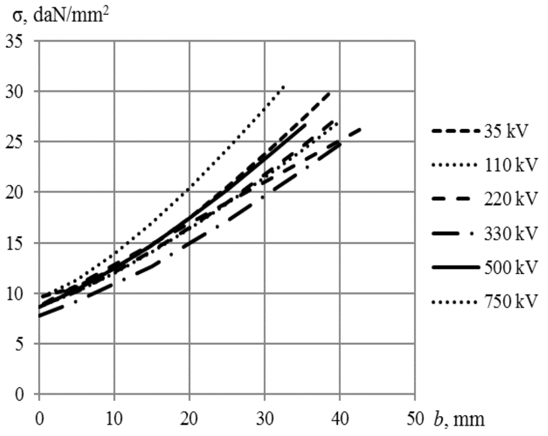


Fig. 2: Mechanical tensions of wires as a function of ice wall thickness for lines of various operating voltages.

Figure 2 illustrates that increase in wall thickness of ice deposit leads to nonlinear increase in mechanical stress in wire: the higher is the wall thickness of ice deposit, the stronger is the increase in mechanical stress. The wall thickness values of ice deposit upon mechanical stresses equaling to breaking forces are in the range of 35–49 mm and equal to 38.5, 32.5, 39.0, 35.4, 49.2, 35.4 mm for voltages of 35–750 kV. However, ice deposits [12–14] should be melted prior to achievement of such sizes of ice deposits.

According to previously developed procedure [15], attenuations of location signal were calculated in carrier links of typical 35–750 kV OTL upon formation of ice deposits on wires with the sizes causing breaking forces in OTL, they equaled to 10.4, 21.4, 70.6, 52.8, 82, 45.8 dB, respectively. It should be mentioned that the linear attenuation decreases by several times with voltage increase, which is stipulated by increase in wire radius and number of wires upon phase splitting on 330-750 kV OTL.

Therefore, in order to monitor ice deposits on 35–750 kV OTL, it is necessary to have additional overlapped range of attenuations in 82 dB.

E. Location testing of operating OTL

Aiming at verification, maximum attenuation of signals of location complex was calculated for nine existing OTL of Bugulma-110 substation without and with ice deposits with wall thickness equaling to allowable value; the obtained results are summarized in Table 2. Signal/noise ratios are based on actual measurements. On the basis of minimum allowable signal/noise ratio, Table 2 shows reserve of sensitivity of location signal where Δ1 is the additional attenuation caused by ice deposits, dB, Δ2 is the difference between actual and minimum (3.5 dB) signal/noise ratio, dB.

Table 2. Prediction of sensitivity reserve of location complex for Bugulma-110 substation upon detection of ice deposits on wires

Tested overhead lines	Allowable thickness of ice coating with regard to wire carrying capacity, mm	Actual signal/noise ratio, dB	Attenuation, dB				
			w/o ice deposit	with ice deposit	Δ1	Δ2	Δ1-Δ2
Bugulma-110 – Sokolka	25.5	26	14	21.6	7.6	22.5	14.9
Bugulma-110 – Zapadnaya	38.8	30	23.71	29.8	6.09	26.5	14.1
Bugulma-110 – Bugulma-500	33.6	61.3	15.3	26.2	10.9	57.8	46.9
Bugulma-110 – Biryuchevka	32.5	32.7	15.6	26.6	11	29.2	17.2
Bugulma-110 – Biryuchevka, base *A*	32.5	56	15.6	26.6	11	52.5	41.5
Bugulma-110 – Pismyanka	29.0	46.2	15.6	25.2	9.6	42.7	33.1
Bugulma-110 – Pismyanka, base *B*	29.0	17.2	15.1	21.5	6.4	13.7	7.38
Bugulma-110 – Karabash	30.9	27	39	61.3	22.3	23.5	1.2
Bugulma-110 – Karakashly, Yutaza branch	29.0	29.2	36.6	54.7	18.1	25.7	7.6

It can be seen in Table 2 that for all lines there exists reserve in terms of sensitivity of location instruments which permits to detect ice coatings on all lines upon allowable maximum ice deposit walls which are determined by carrying capacity of OTL wires. On least noisy and short lines this reserve is 40 dB and higher, in the case of longer lines and noisy lines this reserve decreases to minimum (1.2-7 dB) as for Bugulma-110 – Pismyanka, base *B*; Bugulma-110 – Karabash; Bugulma-110 – Karakashly lines. Therefore, the results obtained for existing power transmission lines correspond to estimations obtained for typical power transmission lines.

IV. RESULTS

Final estimations of ultimate capacities of location method upon detection of damages and ice deposits on wires of 35–750 kV OTL are summarized in Table 3, the obtained results are used upon development of location monitoring instruments for detection of ice deposits on wires and OTL damages.

Table 3. Ultimate capacities of location method upon detection of damages and ice deposits on wires of 35–750 kV OTL.

Voltage, kV Parameter	35	110	220	330	500	750
Distance of damage detection (upon attenuation of signals not exceeding 30 dB), km	105	100	137	210	290	350
Error of ice deposit thickness, mm	0.09	0.11	0.17	0.25	0.45	0.67
Critical thickness of ice deposit, mm	38.5	32.5	39.0	35.4	49.2	35.4
Additional attenuation upon critical ice deposits in OTL (dB) / linear (dB/km)	10.4 / 1.04	21.4 / 0.857	70.6 / 0.706	52.8 / 0.406	82.0 / 0.293	45.8 / 0.153

According to Table 3 in order to determine damages on typical 35-750 kV OTL, it is sufficient to have reserve in terms of overlapped attenuation equaling to 30 dB; in order to monitor ice deposits on wires, this reserve should be increased. Maximum requirements to overlapped attenuation upon ice deposits (82 dB) occur upon ice deposit monitoring on 500 kV OTL, which is stipulated by the fact that the distance of these OTL is longer more than twice in comparison with the OTL of the previous class of 220 kV, as well as they have lower span distance than the OTL of the next class of 750 kV, due to this they are more resistant against ice deposits which, in their turn, cause higher attenuation of signals.

Since ice deposits cause lower attenuation of location signals at higher voltages, then higher distances can be monitored on OTL of higher voltages; however, the errors of ice wall thickness at higher voltages will also increase to 0.67 mm which can be allowed.

V. CONCLUSION

Therefore, on the basis of theoretical and experimental studies, minimum and maximum distances of detection of damages as well as the minimum and maximum sizes of detectable ice deposits on OTL were evaluated by location method. These evaluations specify ultimate capacities of location monitoring of OTL state. All considered existing lines are characterized by reserve in terms of sensitivity of location equipment, which permits to detect ice deposits up to their critical (breaking) sizes.

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