BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 68, No. 5, 2020
DOI: 10.24425/bpasts.2020.134656

Reliability improvement of power distribution line exposed to extreme icing in Poland

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Abstract. Currently, overhead lines dominate in the Polish medium and low voltage distribution networks. Maintaining their high reliability constitutes a very important challenge, especially under the severely changing climate conditions. An overhead power line exposed to high ice and rime loads has been considered. Using the finite element method (FEM), mechanical reliability of the distribution infrastructure was examined under various atmospheric conditions. Loads under the stressful conditions of rime, ice and wind were determined for the weakest section of the 30 kV overhead line, which consisted of concrete poles and ACSR conductors. SAIDI and SAIFI reliability indices and costs were determined for several variants of object reconstruction. The results allowed for determination of a solution relying on relocating the cables of all lateral branches and main line ice protection, through a system based on a weather-coordinated increase of the electrical load. To verify the solution proposed, a field experiment was conducted. The experiment confirmed the effectiveness of the solution proposed that appears to be universal. The paper is a result of synergic cooperation of two academic teams, i.e. a mechanical and electrical power engineering one, and the Distribution System Operator (DSO).

Key words: power distribution networks, overhead lines, finite element method, reliability, icing, rime, prevention of line icing.

1. Introduction

Overhead power lines, which constitute a very important element in the electrical power distribution system, should be highly reliable, robust and secure. While designing power lines, these components should always be considered with equal care [1]. Apart from the process of power line designing, the same attention should also be paid to proper maintenance and failure-prevention.

Extreme weather conditions and natural disasters [2] are particularly dangerous for overhead power lines [3, 4]. These types of phenomena may cause serious damage to the power infrastructure, leading to long-term interruptions in energy supply to consumers [5]. The analysis of occurrence and consequences of the power supply interruption in Poland [6] and world-wide [7] reveals that icing is the most dangerous phenomenon that can cause the most serious damage to overhead lines over a relatively large area.

Atmospheric icing that forms on structures results either from raindrops, snow, water vapor or cloud droplets, where the latter term includes droplets in clouds that are locally observed as fog [8]. These droplets, compared to raindrops, have distinctly smaller size and falling velocity. The liquid and/or solid particles collide with the overhead power lines, forming significant ice loads such as wet snow, rime and glaze. The detailed theoretical foundations and analytical models presenting these phenomena are described in [7, 8]. Another ice load that may form due to condensation of water vapor is hoarfrost [9], however it is negligible compared to the aforementioned types of ice accretion [10].

In Germany in 2005, due to heavy snowfall and strong wind, wet snow rolls formed around conductors, which led to the collapse of 82 transmission towers [11]. The dangerous type of atmospheric icing is glaze, because of the great density of the accretion (around 900 kg/m^3). The biggest catastrophes of overhead power lines due to glaze occurred in Canada in 1998 [12], in China in 2008 [13], in Slovenia in 2014 [14] and in many other countries.

The phenomenon of ice formation and/or ragging was studied in laboratories [15, 16] and in outside natural conditions [17]. It was found that at the time of sedimentation of successive layers of glaciated snow, the wire turned to form a fairly even ice-snow coating on the surface of the wire. The increment and specific load values should be monitored in all countries.

The observations on the frequency and intensity of deposition of various types of icing in the Polish mountains were made in the past [18, 19]. More recent research concerns analysis and predicting the occurrence of extreme atmospheric ice on power lines [20]. However, the number of studies, including experimental data and monitoring systems for ice increment on overhead power lines under Polish conditions, is still insufficient.

Reports in world literature describe a number of methods and techniques to prevent icing and to conduct the removal

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Manuscript submitted 2020-01-17, revised 2020-06-17, initially accepted for publication 2020-06-29, published in October 2020

of ice or rime from overhead power lines [7, 21–23]. These methods have been divided into six categories: passive techniques, active shield coatings, active methods for bare conductors, methods using external thermal energy, methods using external mechanical energy as well as various methods less frequently applied to ground wires or live conductors. Another classification is based on the permanent or temporary nature of the method, the necessity to modify the line and the operation mode (automated or manual), as presented in [24].

Regardless of the criterion used to discern between the methods, the primary objective is to prevent or remove ice formation (anti-icing methods) or to conduct their removal (de-icing methods).

Anti-icing methods represent two main ways to reduce the risk of icing up of conductors. The first group includes methods to reduce the force of ice adhesion to the conductor (ice-phobic coatings [25] or special polymer coatings [26]). The idea behind the second group of methods is to prevent the freezing of cooled water droplets falling on the surface of the conductors (using a thin layer of liquid lowering the freezing point [7] or maintaining a positive temperature of the conductor just above the freezing point during icing [27]). The most effective of these is the Joule method [27]. Heat is caused by the flow of current through the conductor. The solutions used here are alternating and direct current. They are most common because they both block the formation of ice as well as enable the elimination of ice deposits.

The aim of the de-icing methods is to efficiently and quickly realize the process of dropping the coating of snow or ice that is weighing upon the conductors. Two approaches dominate in these methods: mechanical and thermal methods. Mechanical methods consist of precipitating the ice directly by appropriate technical services or special equipment designed for this purpose. These devices can be special crushing robots [28, 29, 30], devices causing the cable to vibrate [31] or devices causing the cable to twist around its longitudinal axis [32]. In thermal methods, the heat source that causes the removal of the ice layer is usually the conductor itself. The heating effect is achieved by forcing a sufficiently high value of current to flow through the conductor. The current that heats up the conductor and melts the ice can result from a change in network configuration, phase shifts at the ends of a line or the use of external AC or DC energy sources [33]. The heat in thermal methods can also be supplied from special devices, i.e. lasers [34].

All above-mentioned methods and techniques concern mainly transmission networks and distinctly less solutions are available for distribution networks.

The authors of this paper have worked on this subject for years and as a result designed, performed and carried out verification tests of the Smart System of Detecting Rime and Ice [35, 36] and Smart System of Monitoring and Diagnosis of the Line [6, 35] as well as of the reliability of a 15 kV overhead line exposed to catastrophic icing in Poland [37].

This work is aimed at improving the reliability of the 30 kV overhead distribution line exposed to extreme weathering due to ice or rime. The authors present multivariate calculations of reliability indices, i.e. mechanical and electrical factors as well as the implementation costs for the variants under consideration. As a result, an original method of ice prevention was developed which could be implemented by DSOs in Poland.

The method presented is an anti-icing method, the main purpose of which is to keep the temperature of the line conductors above 0°C in a period conducive to the formation of atmospheric ice. The main purpose of its operation is to determine the probability of failure caused by the occurrence of ice and rime and to estimate the time of failure. As a result of system operation, the Distribution System Operator (DSO) will be able to undertake remedial actions developed in the form of operating procedures depending on the scale of the hazard.

2. Climatic conditions in Poland and characteristics of the research object

According to the Köppen classification [38], Poland is in the area of humid continental climate. Its climate is also referred to as a transition between warm and rainy temperate climate and snow-forest boreal climate. Different masses of air clash over the area of Poland, as a result of the location in the center of Europe and the latitudinal system of geographical lands. Polar, marine and polar-continental air masses, which determine the transitional nature of the Polish climate, have the greatest impact on weather conditions. For more than two decades, extreme weather events and natural disasters have been occurring in Poland, i.e. strong winds, volatile rains and storms, floods, landslides, snow, ice, extreme temperatures and lack of visibility.

An example of extreme climate conditions was observed in January 2010. The report of the Institute of Meteorology and Water Management (IMGW) (in Poland) [39] showed anomalous weather situations that prevailed in Poland at that time (Fig. 1). These conditions were formed by a lowland front from northern Italy and a warm front moving slowly from the south into the country, followed by a wet and warmer polar air mass.

The result of these weather conditions were catastrophic failures of the electrical power infrastructure throughout the country. The winter in December and January caused more than 5000 power line breakdowns. Over 750000 customers experienced catastrophic failures, i.e. power outages lasting over 24 hours. The biggest one affected the Silesian and Lesser Poland regions, where 31 HV and 148 MV lines were damaged.

The structure being analyzed is located in the southern part of Poland. The diagram is presented in Fig. 2.

This is an overhead 30 kV line supplying 15 30/0.4 kV transformer stations and one 30/15 kV substation. In a normal configuration, one bus section of 15 kV is supplied by the analyzed line. This section supplies 61 15/0.4 kV transformer stations. In Fig. 2 all branches of the 30 kV line are marked with successive letters of the alphabet.

In Poland, 30 kV lines are a specific solution. They have been used for distributing electric energy over considerable distances through difficult terrains with variable topography, i.e. mountains or highlands. Currently, 30 kV lines are being replaced successively with 110 kV lines. This process will still take about 25 years. The process of reconstruction is confirmed by statistical

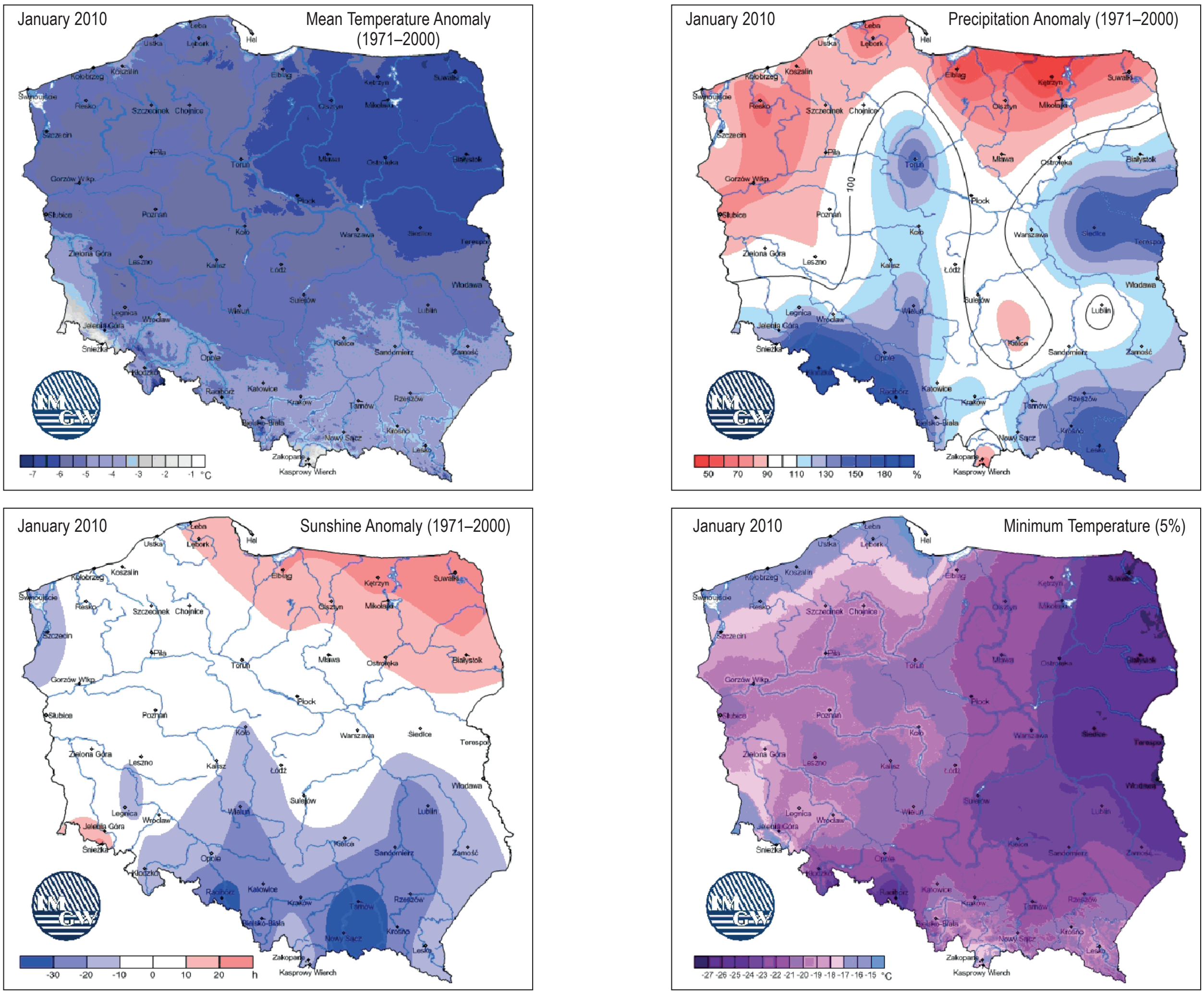

Fig. 1. Climatic conditions in Poland in January 2010 [39]

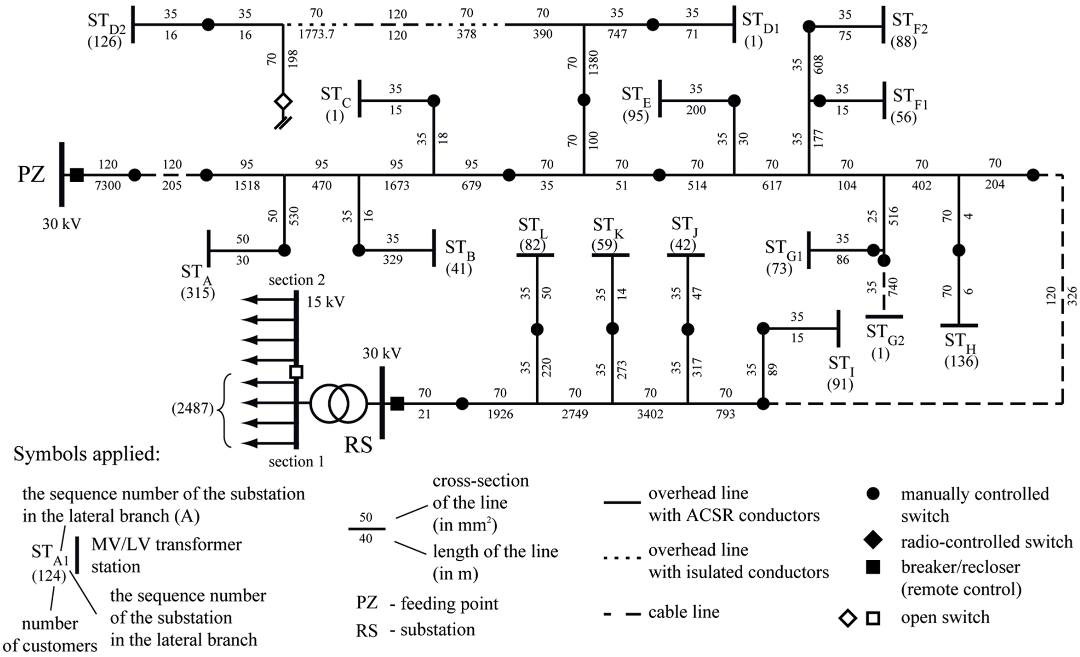

Fig. 2. Diagram of 30 kV distribution network being analyzed

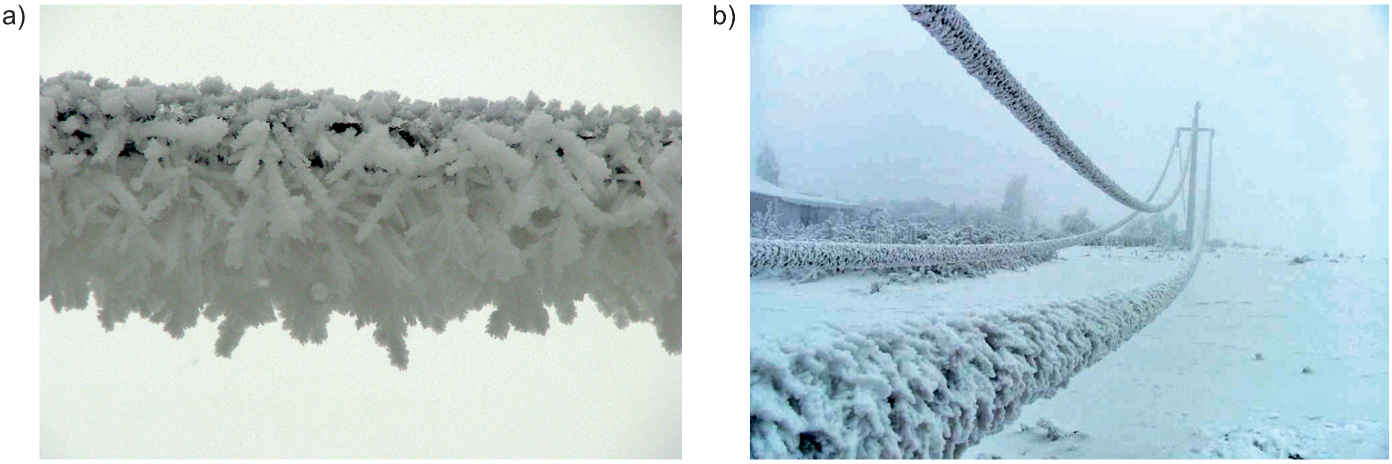

Fig. 3. Rime conditions on the 30 kV overhead line: a) soft rime; b) hard rime

data. The total length of 30 kV overhead lines in Poland was 3990 km in 2000, 3290 km in 2010 and 2635 km in 2017.

For the analyzed line, in winter of 2010 significant failures were reported. One BSW pole was damaged. Permanent deformation of the infrastructure elements forced the DSO to undertake fundamental reconstruction of the line. Fig. 3 presents the rime conditions on the 30 kV line.

Selected data characterizing the line are presented in Table 1. The main line is built using the ACSR conductors and a short cable section. The support structures are mostly pre-stressed concrete poles.

In the normal network configuration, the analyzed 30 kV line supplies one 15 kV bus section via a 30/15 kV transformer, as shown in Fig. 2. A significant increase of line load can be obtained by changing the network configuration (closing the 15 kV switch in the RS station). It will affect the peak load to over 180 A and over 90 A during the night.

Table 1
Basic data regarding the 30 kV power line being analyzed

Element	Length (km)	Number
Main line: – overhead line with ACSR conductors – overhead line with insulated conductors – cable line	22.99 22.46 0.00 0.53	–
Lateral branches: – overhead line with ACSR conductors – overhead line with insulated conductors – cable line	9.61 6.60 2.15 0.86	–
Support structures (poles): – reinforced concrete – steel – pre-stressed – centrifuged	–	270 4 34 201 31
Switches: – manually controlled – radio-controlled – recloser	–	25 24 1 0
Number of MV/LV supplied stations: – 30/0.4 kV – 15/0.4 kV	–	76 15 61
Number of customers supplied: – from 30 kV – from 15 kV	–	3694 1207 2487
Annual load range (min – max)	33 A – 90 A	

3. Finite element analysis of selected subsystems of the power line infrastructure for various weather conditions

Due to the fact that the climate is becoming more extreme and over a dozen centimeters of thick ice and rime appear on overhead lines during winter time, mechanical strength analysis of the selected network infrastructure was carried out. Model-simulation studies were performed using the finite element method, taking account of the latest normative guidelines [40] revised for Poland in 2016.

The research object is a representative section of the 30 kV overhead power line. That part of the line consists of 5 supporting structures, built of BSW-14 poles. At one end of the section there is an anchor pole, and then following there are 3 tangent poles and finally on the other end of the section there is a self-supporting post in the out-of-frame configuration with a pillar. It is a single-circuit line with three ACSR 35/6 phase conductors (35 mm^2 aluminum cross section and 6 mm^2 steel cross section).

In the 1970s–1990s BSW-12 and BSW-14 concrete poles were the basic components of the supporting structures for medium voltage lines in Poland. The double-branch concrete BSW poles have relatively good strength combined with low weight and steel consumption. Individual BSW poles were often combined into various configurations to increase the load capacity of such complex supporting structures. With the increase of reliability requirements for overhead power lines and the tightening of normative guidelines, the use of BSW construction has been limited, especially in zones with difficult climatic conditions. BSW-12/350 and BSW-14/350 pre-tensioned concrete poles were replaced with E-type spun concrete poles, characterized by better strength properties.

The BSW-14/350 pre-stressed concrete pole is 14 m long and its rated load capacity in the plane of higher stiffness is 3.5 kN, while in the plane of lower stiffness it is 1.05 kN. The structural model of the BSW-14 pole was built using the finite element method. Figure 4 shows the geometry of the pole model. The base of the post has a rectangular cross-section of 276×424 mm, while the apical section forms a rectangle of 150×200 mm. The external dimensions of the pole cross-sections decrease proportionally to the height of the structure.

Fig. 4. Geometry of BSW-14 pole

The pole is made of concrete and pre-stressed steel in the form of reinforcing bars running along the structure from the base to the top. Therefore, the individual cross-sections have been modeled as composites. Depending on the reinforcement version, the total number of bars in the BSW-14 pole ranges from several to several dozen that are located close to its four corners.

The pole has been designed according to the Timoshenko beam model, in which the perpendicularity of a deformed cross-section to the beam's axis is not required. The Timoshenko element takes account of shear deformation, making it suitable for describing the behavior of columns with large transversal dimensions or with complex cross-sections (e.g. trusses, composite poles). The finite element is described in a three-dimensional space and has 3 nodes, each with 6 degrees of freedom (3 rotations and 3 translations).

The structural model was verified and the results of the computations were compared with the results of the experimental studies presented in the literature [41]. The calculations assume a concrete class of C35/45, whereas the steel reinforcing bars met the requirements for high-carbon wires. The compressive strength of the concrete was 43 MPa, the yield stress of the reinforcing bars was 1334 MPa, while the tensile strength of breaking was 1670 MPa.

The impact of difficult weather conditions on a 30 kV overhead line was analyzed further in the work. The calculations were carried out for a tangent supporting structure made of BSW-14 poles. The column foundation was 2.2 m deep, whereas the length of the equivalent span was determined with formula (1), where L_n was the length of subsequent spans in the tension section of the line, for $L_R = 125$ m.

$$L_R = \sqrt{\frac{\sum L_n^3}{\sum L_n}} \tag{1}$$

The terrain coefficient and the roughness of terrain were assumed for the 2nd land category, i.e. areas with low vegetation and individual obstacles. The phase conductors were made of ACSR 35/6. In the calculations, these conductors were treated as being made of homogeneous material with equivalent parameters resulting from the properties of both materials. The initial (assembly) sag of the conductor at 10°C was assumed to be $f_0 = 3$ m. A small share of the loads from the insulators was omitted.

Table 2 presents the results of performed calculations and analyses. Forces V, H and W are components derived from the weight and tension of the wire at the point of its suspension. These are the forces acting on the supporting structure computed for one span. V is the vertical force, produced by the weight of the conductor (with optional ice load), H is a horizontal component of the conductor tension force, which depends on the sag, together with the ice and wind load among other factors. Under normal operating conditions, it is balanced by the tension of the adjacent span. W is the horizontal component of the force, which comes from the wind and which is perpendicular to the route of the line. The force N is the result of these forces and corresponds to the axial force in the wire. The analysis of mathematical relations reveals that it depends primarily on the horizontal component of the tension force. The value of force N also indicates whether the breaking force of the wires has been reached. The symbol f indicates the sag of the conductors, which depends on all previously mentioned forces, and the temperature of the line.

Table 2.
Reaction forces in attachment points of the BSW-14 supporting structure. Maximum compressive stress in concrete and tensile stress in reinforcing bars

Case	V **(kN)**	H **(kN)**	W **(kN)**	N **(kN)**	f **(m)**	σ_C **(MPa)**	σ_S **(MPa)**
0	0.09	0.90	0	0.90	3.00	0.34	0.0
1	0.09	4.23	0.52	4.26	3.88	8.05	44.4
2a	1.89	11.47	0	11.62	5.14	0.79	0.0
3a	1.89	12.85	1.16	13.04	5.38	41.40	865
3b	0.62	10.08	1.45	10.20	4.89	49.80	1040
4	0.09	1.13	0	1.14	2.36	0.34	0.0
$\psi_I = 0.3$	0.63	5.07	0	5.11	3.86	–	–
$\psi_I = 0.5$	0.99	7.14	0	7.21	4.31	–	–
$\psi_I = 0.7$	1.35	8.98	0	9.08	4.68	–	–
2b (a)	–	–	–	–	–	5.20	66.3
2c (b)	–	–	–	–	–	195	2420

(a) Load combination $\psi_I = 0.5$ and $\psi_I = 1$
(b) Load combination $\psi_I = 0.3$ and $\psi_I = 0.7$

It is worth mentioning that the sag is calculated considering the maximum level of displacement, lying in the direction of resultant force in the wire. Individual loads can be reduced by the combinational coefficients: ψ_w for wind and ψ_I for icing.

The research does not include detailed models of atmospheric ice growth. The model of icing load is limited to determining the density and diameter of the ice layer for the proper zone of icing load. The stress σ_C is the maximum compressive stress in concrete, which should not exceed the limit of 43 MPa for the material assumed. On the other hand, σ_S is the maximum tensile stress in the steel reinforcing bars and should be below the yield point $R_e = 1334$ MPa, or in the worst case of failure $R_m = 1670$ MPa. Both σ_C and σ_S were determined based on a numerical model built with the finite element method.

Case 0 – the nominal operating condition of an overhead power line, with no wind load or icing, at ambient temperature $T_{ot} = 10$°C. The load comes from the weight of the construction itself. The tension force is balanced by an adjacent span and only vertical forces from the weight of the conductors (and the weight of the pole itself) act on the supporting structure. The pole is only compressed along its axis, and the forces occurring in the structure are negligibly small.

Case 1 is the maximum wind load. The wind is blowing horizontally and perpendicular to the route of the line. Here $W = 517$ N is the value of wind force from one span on a single wire, therefore the total transverse force acting on the supporting structure is equal to 3.1 kN. The structure is bent in the plane of higher stiffness, however, the maximum stress values are small, and the bending force itself is smaller than the utility force of the structure 3.5 kN.

Case 2a is an interesting instance of extreme icing. The national code PN-EN 50341–2-22:2016–04 Overhead electrical lines exceeding AC 1 kV – Part 2–22: National Normative Aspects (NNA) for Poland [40] distinguishes between three zones of icing load and various ice types (wet snow, glaze ice, soft and hard rime ice). The code gives indicative values for the density of these ice types. However, it is recommended to adopt in the calculations the density of the icing load equal to 700 kg/m^3. The nominal diameter of the conductor is 8.1 mm and its linear mass density is 0.140 kg/m. The code assumes that in the third zone of icing load, this conductor is covered by the ice layer of 66 mm diameter and the total linear mass density of the conductor and the ice load equals to 2.5 kg/m. There is significant tension in the wires, but this tension is slightly below the breaking point $F_{zr} = 12.2$ kN. The icing load is distributed uniformly along the conductors, therefore the tensile forces in adjacent spans balance out and the pole is only compressed by the axial force 11.3 kN, which is insignificant for a concrete structure. However, if extreme icing is accompanied by relatively small wind ($\psi_w = 0.33$) – case 3a – high values of horizontal wind forces are observed due to the large windward area of the wires. The maximum compressive force of concrete is 41.4 MPa and it is close to the limit value, whereas the maximum tensile stress of the reinforcing bars reaches the value of 865 MPa. Out of these two normalized cases of icing and wind combinations, case 3b, i.e. the nominal ice load ($\psi_I = 0.37$) with an unlikely wind load ($B_I^2 = 0.56$), is more dangerous for the line being considered. Large wind with moderate icing results in a transversal force coming from the wind which is three times higher than extreme wind acting on bare wires alone (case 1).

In case 3b, the BSW-14 pole does not meet the criteria adopted in the calculations. In addition, the axial forces in the wire exceed the value of braking force. It is worth mentioning that when considering the 2nd zone of the icing load, the maximum compressive stress in the concrete would be $\sigma_C = 40.5$ MPa, i.e. below the limit value. Adopting zone 3 in this area and increasing the value of partial coefficients in the latest standards means that this pole does not meet the requirements of the supporting structure.

Cases 2b and 2c are important from the point of view of the strength of the supporting structure. They correspond to extreme icing cases that are transversely and longitudinally unbalanced. A situation of asymmetrical icing may stem from local conditions which could induce the occurrence of rime, for example a situation where a section of the line is located in a wooded area. Earlier standards considered these cases exceptional, but according to the latest national annex [40], they are classified as normal, which has contributed to the increase of partial coefficients. Case 2b corresponds to a situation where wires for one phase are more or less loaded than others. Then the bending moment of the supporting structure acts in the plane normal for the route of the line. Figure 5 shows the maximum compressive stress that will occur on the wall of the pole near its apex. The values of σ_C and σ_S are small and do not endanger the safety of the power pole.

Case 2c is very important. It illustrates a situation where the load from the ice on one of the spans is clearly greater than that of the neighboring one. This leads to considerable imbalance in the tensions in the adjacent spans. The purpose of the tangent poles is to transfer mainly vertical forces from the weight of the conductors and possibly horizontal wind forces perpendicular to the route of the line. In the case of the longitudinal imbalance due to heavy icing, the horizontal forces will be transferred to the tangent pole. In the analyzed case, the difference in tensile forces for 3 conductors in adjacent spans is

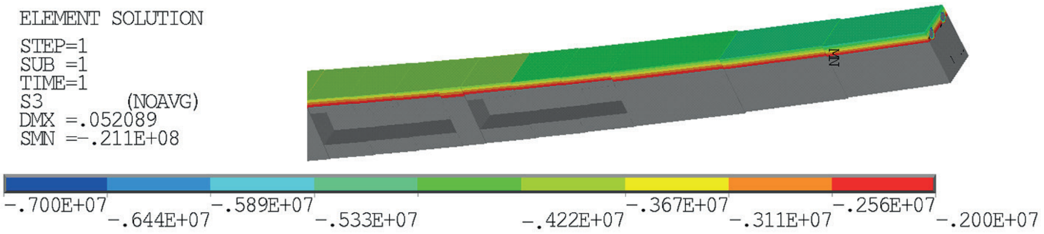

Fig. 5. Compressive stress levels in concrete – case 2b

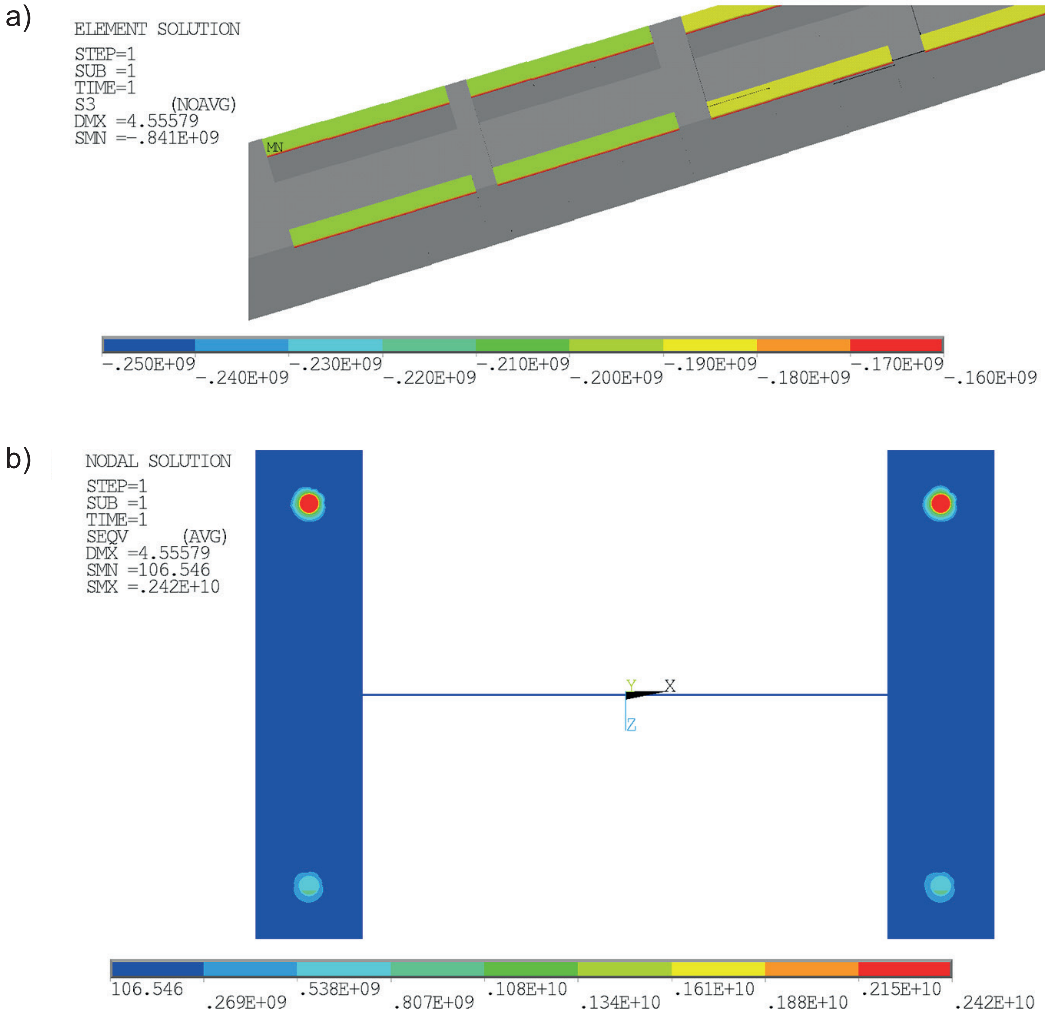

Fig. 6. Stress levels for the 2c case of extreme longitudinal unbalanced icing a) compressive in concrete, b) tensile in reinforcing bars

11.7 kN and this value should also be applied to the top of the pole and, in addition, in the plane of its lower stiffness. This results in the creation of enormous stress, far greater than the permissible limit values in construction (Fig. 6). This type of load is the most dangerous one and leads to the cascade failure of supporting structures.

Summing up the calculations and analysis of the medium voltage line with BSW-14 supporting structures, it can be concluded that the effects of variable conditions depend on their combined factors and their individual effects on the line cannot be considered separately. The case of a uniform load along the line with ice or rime causes the tensile forces in the adjacent spans to compensate for each other, and the poles are exposed only to the axial compressive forces coming from the weight of the poles themselves along with the weight of the ice. This problem is much more serious in the case of extreme icing and asymmetry of its distribution, especially in the direction of the line route. This primarily affects situations where there are significant differences in the tensions. These forces are transmitted to the supporting structures, the pole is bent towards its weaker side and, as a result, it breaks.

4. Structural reliability model

A thorough modernization of the distribution network in the area under consideration is currently the subject of DSO’s preliminary study. In the long-term perspective, the existing 30 kV line will be completely replaced by a 110 kV and 15 kV system. The cost of such a solution is estimated at USD 10 million. In the meantime, the 30 kV line should meet the growing reliability requirements of the customers. The obvious need to limit investment expenditures during this period justifies considering many variants of its reconstruction. In order to limit the impact of failures on end-users and to minimize interruptions in energy supply, the MV overhead power lines should be replaced with cable lines. Such a course of action will result in a significant reduction of reliability indices, bringing them closer to the Western European level.

The authors suggested the following: successive reconstruction of lateral branches, simultaneous reconstruction of all branches and reconstruction of the whole line. In all cases reconstruction means replacing overhead sections with underground cable lines. Multivariate calculations were aimed at presenting the cost-effective strategy for a transitional period taking account of the environmental conditions and improving reliability. In each case, the measure of reliability was used in the form of SAIDI and SAIFI [42] indices (2) and (3).

$$SAIDI = \frac{\sum U_i N_i}{\sum N_i} \tag{2}$$

where U_i is the annual outage time, N_i is the number of customers for location i,

$$SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i} \tag{3}$$

where: λ_i is the annual failure rate of interruptions.

Indices were calculated with a statistical approach based on combinatorial reliability analysis. Dedicated software developed by the authors takes into consideration: the types of sectionalizing switches, their locations and the possibilities of alternative supply of the line. The annual failure rate 8.14/100 km for the overhead line with ACSR conductors, 4.48/100 km for the overhead line with insulated conductors, and 0.814/100 km for the cable line was assumed based on the literature data [43, 44]. The average duration of failure was assumed at 5 hours. As a result of calculations for the current state (Fig. 2), the annual SAIDI index was 131 min/customer, and SAIFI stood at 3.07 int./customer.

In the case of a catastrophic mass failure, the total repair time and restoration of power to all customers could reach even several hundred hours. In such extreme conditions, all the customers (Table 1) have no supply for 14 days (assumption). The calculations were made for two cases: total power failure (all customers without power) and the failure of all lateral branches (main line in service). In both cases, the obtained annual SAIDI index was about 20160 min/customer and 6587 min/customer, respectively. Any major structural failure resulting from atmospheric loads identified in Chapter 3 will result in a dramatic increase in reliability indices. The level of this increase results from the scale of the failure, equipment used for its elimination, organization of works as well as atmospheric and field conditions. It may reach 2 orders of magnitude in relation to indices for typical situations (period without mass failure).

Table 3 presents the results of multivariate calculations. The number of customers, the length of modernized line segments, the SAIDI and SAIFI indices as well as the variant costs are given.

All lateral branches were marked with successive letters of the alphabet (Fig. 2). Branches length and the number of customers mainly decide about the values of SAIDI and SAIFI indices obtained.

The branch marked "D" is the longest one and feeds a significant group of customers. Reconstruction of this lateral branch allows SAIDI to be limited to 91.3% and SAIFI to 90.5% with reference to the current state. Additionally, the cost of this reconstruction is approx. 58% of the total cost of reconstructing all branches.

Table 3
Results of calculations of reliability analysis

Variant of reconstruction	N (cus.)	L (km)	SAIDI (min/cus.y.)	SAIFI (int./cus.y)	Cost (10^3 USD)
Current state	3694	31.208	131	3.07	–
One lateral branch:					
"A"	315	0.560	128.3	3.03	41
"B"	41	0.345	129.7	3.04	25
"C"	1	0.033	130.5	3.06	2
"D"	127	5.070	119.2	2.77	372
"E"	95	0.230	129.9	3.05	17
"F"	144	0.875	126.7	3.00	64
"G"	74	0.602	128.0	3.02	44
"H"	136	0.010	130.5	3.07	1
"I"	91	0.104	130.2	3.06	8
"J"	42	0.364	129.3	3.04	27
"K"	59	0.287	129.5	3.05	21
"L"	82	0.270	129.6	3.05	20
All branches	1207	8.75	105.2	2.51	642
Whole network	3694	31.208	13.73	0.33	2588

Assuming that the reconstruction is to bring the SAIDI annual value down (assuming, for example, to 120 minutes/customer), three variants are possible: reconstruction of the entire line, reconstruction of lateral branches only and reconstruction of the lateral branch "D" only. It should be noted that the most expensive variant also includes reconstruction of the main line. It is the part of the network in which reliable operation determines the continuity of supply to a large group of customers connected to the 15 kV substation (RS on Fig. 2). From the point of view of SAIDI and SAIFI reduction, the most effective solution is the complete relocation of all overhead components underground. This solution is most expensive but it practically eliminates all disturbances in network operation due to weather conditions.

Figure 7 presents a comparison of the results of reliability analysis and the estimated cost of line reconstruction. Here the SAIDI and SAIFI values were referenced to the same indices calculated for the existing configuration. The order of branches presented in Fig. 7 is determined by the degree of SAIDI reduction. Besides that, the order of modernization activities was also ranked in Table 4, also taking other criteria into account.

Due to the high cost of reconstructing the entire line as a cable network, it is obvious that this particular variant will

Table 4
Ranking list of branch reconstruction according to different criteria

Criteria	Ranking list of order of branch reconstruction
SAIDI	D – F – G – A – J – K – L – B – E – I – C – H
SAIFI	D – F – G – A – J – B – K – L – E – I – C – H
Length of branch	D – G – F – A – J – B – K – L – E – I – C – H
Number of customers	A – F – H – D – E – I – L – G – K – J – B – C

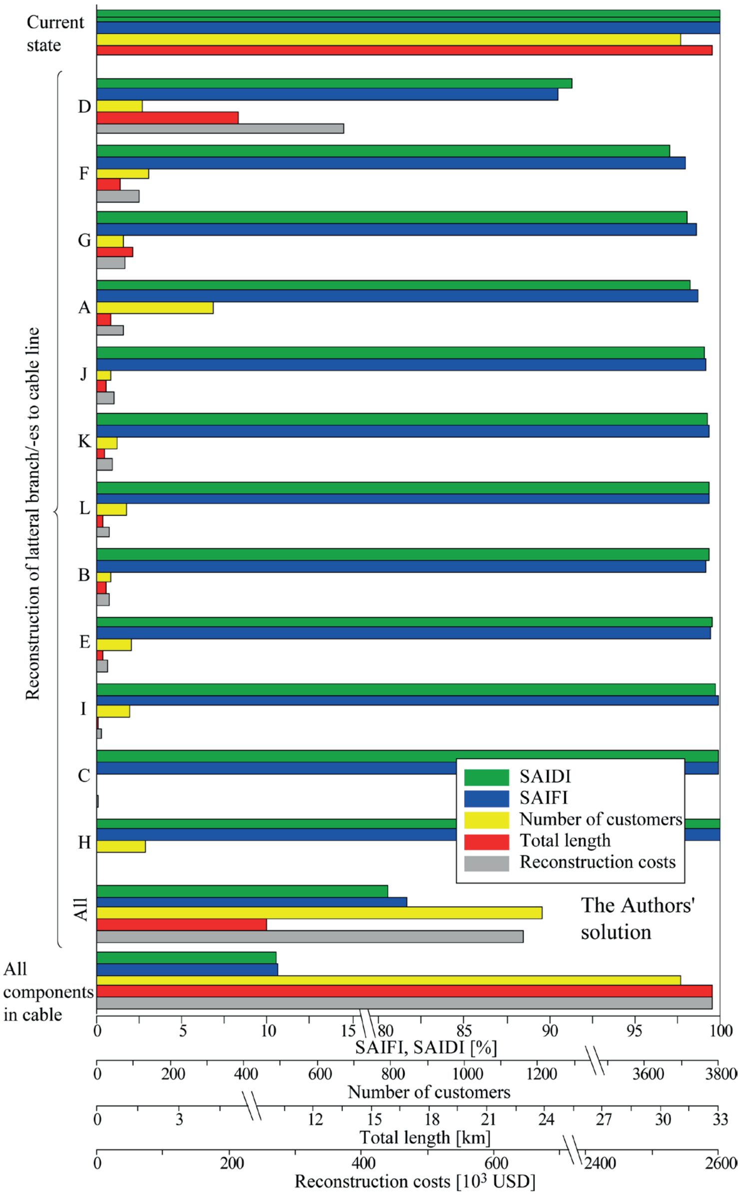

Fig. 7. Comparison of reliability analysis results (ranking of variants according to SAIDI index changes)

never be implemented. This problem is associated with the planned expansion of the 110 kV network. To reduce cost and reliability indices, reconstruction of all the branches of the analyzed 30 kV line as cables is proposed. Simultaneously, the overhead main line in service should be maintained. In this variant, the annual SAIDI value could be 105 min/customer.

Taking account of the presented conditions and structure of the analyzed network, it is particularly important to maintain the main line in service under all weather conditions. This will prevent an extreme loss of reliability of supply to customers (significant increase in SAIDI and SAIFI indices). In such a case the icing of wires can be prevented by applying an additional electrical load in the line. The object structure analyzed allows for a significant increase in the line load by means of the 15 kV network reconfiguration.

5. Field experiment

In order to be able to predict the condition of the line in terms of the occurrence of atmospheric ice, it is necessary to design and implement two systems: monitoring and diagnostics system (SMD) and control system. These systems will support the management of electricity transmission and distribution. The SMD system's measuring elements for data collection are the WXT520 weather station and digital cameras: visible light and thermal imaging. The elements of the control system include the existing infrastructure presented in Fig. 2. Continuous operation of the SMD system should be integrated with data recorded by monitoring stations of the Institute of Meteorology and Water Management. Synergic cooperation of the above-mentioned systems enables prediction of emergency states and thus provides the required time to make proper decisions, e.g. application of preventive overhead line heating (anti-icing), mechanical icing removal (de-icing) or even potentially switching off energy subsystems.

On the basis of literature data and own observations of the phenomenon of ice and rime formation carried out under laboratory conditions [6, 35] and in the field [35, 37], the most unfavorable conditions for ice and rime formation in Poland were determined. The highest intensity of icing events occurs in the air temperature range from 0 to –5°C and at wind speed from 0 to 5 m/s. In Poland the research was carried out by Sadowski [45], Baranowski [19] and Orlicz [18] and also reported by Makkonen [10].

Usually, ice or rime is formed most intensively when the temperature drops below 0°C. Favorable conditions include: rain or drizzle (leading to the formation of glassy ice), wet snow sticking to the pipes or structure and the formation of fogs that freeze to cover both pipes and structure. Factors influencing the abundance of ice are mainly: the proximity of waters, marshlands, wet meadows, terrains, sewage, etc., producing a lot of vapor or fog, as well as areas with a large height difference, e.g. in mountain areas. The heaviest icing occurs when the falling snow dissolves in the warm layer of atmosphere it passes through and then freezes again in the cold layer, sticking to the frozen network infrastructure, e.g. overhead power line. Therefore, the main objective will be to keep the conductors of this 30 kV line at a temperature above 0°C. This possibility had to be verified. The calculations made on the basis of two CIGRE [46] and IEEE [47] standards confirmed the possibility of obtaining positive temperatures of the conductors for the above-mentioned conditions of atmospheric ice.

According to the results of the analyzes presented in Section 3, asymmetrical mechanical loads might be very dangerous for an overhead power infrastructure. In such situations, poles could be damaged and wires irreversibly deformed. A controlled increase of line electrical current (rise of conductor temperature) could prevent line icing on the main line and significantly reduce the risk of mass failures and, consequently, reduce the energy not supplied.

For verification of such an idea, a field experiment was organized. Electrical current of the analyzed line was increased through network reconfiguration. During the experiment, the

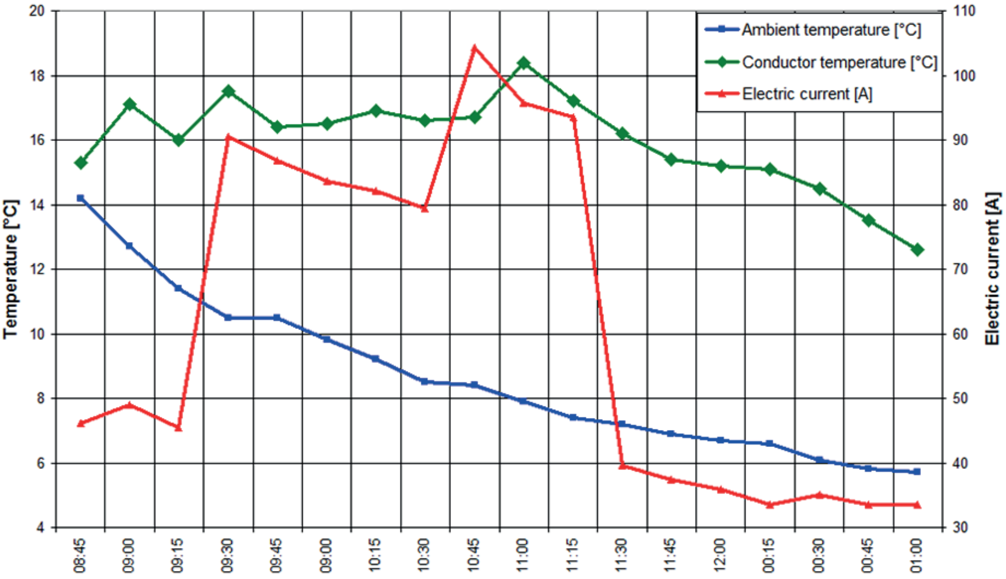

Fig. 8. Results of measurements of the analyzed line during the experiment

electrical current of the line and the conductor temperature were registered. The conductor temperature was measured by thermal imaging at the 30 kV side of the 30/15 kV transformer (Fig. 2) for the ACSR 95/15 conductor. A FLUKE Ti32 thermal imaging camera was used. The experiment was performed on May 2018 from 8:45 p.m. to 1:00 a.m. on the following day.

Figure 8 presents data recorded during the experiment: line current, ambient temperature and conductor temperature.

The experiment was carried out after sunset for a cloudless sky. On that day the wind conditions were very changeable around the line. Throughout the day, a cold wind blowing from the north perpendicular to the power line was recorded. The maximum velocity of the wind gusts was 9.25 m/s. During the experiment, the direction of the wind did not change, but its velocity varied between 0 and 5.14 m/s and the average was 3.2 m/s. At the moment the line was loaded at 9.24 p.m. and 10.30 p.m., the instantaneous wind speed was 0 m/s. In the initial phase of the experiment from 8.45 p.m. to 9.15 p.m. a reduction in the ambient temperature was observed from 14.2°C to 11.4°C. In this period, the line current varied from 46 A to 49 A, and the conductor temperature was 15.3°C to 17.1°C.

The load increase of the 30 kV line was realized in two stages. First at 9.24 p.m. both 15 kV bus sections of RS were connected (Fig. 2). Then between 10.32 p.m. and 10.36 p.m. the 15 kV network was reconfigured by the operation of radio-controlled sectionalizing switches. Closing the 15 kV switch in the RS station results in connecting 4 new 15 kV lines fed from the second section of the RS station to the analyzed network. In addition, operations using radio-controlled switches increase the area of the 15 kV network fed by the analyzed line. From 11.15 p.m. to 11.19 p.m. normal configuration of the analyzed network was restored.

At 9.30 p.m. 90 A current was observed. Over the course of one hour the current successively decreased and at 10.30 p.m. it reached the value of 79 A. During this time, the conductor temperature observed varied from 17.5°C to 16.6°C. And in the period observed, the value of ambient temperature was also reduced by 2°C, from 10.5°C to 8.5°C. By 11.00 p.m. the conductor temperature was observed to further increase from 16.6°C to 18.4°C. Ambient temperature was then 7.9°C. After returning to normal operation of the 30 kV line, the current value decreased from 94 A to 34 A. During this period, the conductor temperature and ambient temperature were systematically decreasing: from 17.2°C to 12.6°C, and from 7.4°C to 5.7°C, respectively.

The experiment revealed that a 45 A increase of the line current was accompanied by a 1.5°C increase of the conductor temperature. When there was an increase of 59 A, it caused a temperature increase of 2.4°C.

The selected thermal images for normal and temporary configuration are presented in Figs. 9–12.

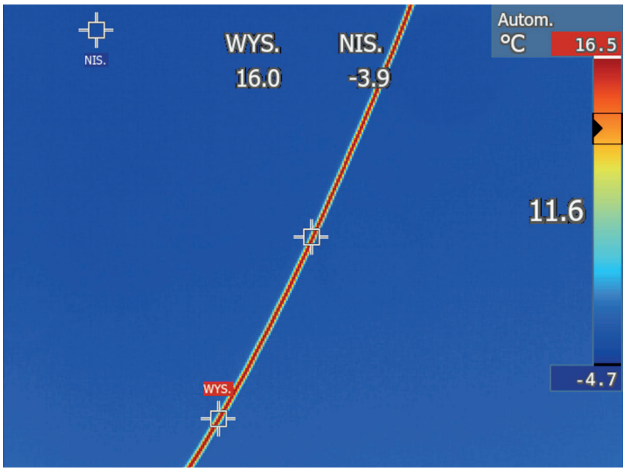

Fig. 9. Thermal image of the conductor at 9.15 p.m. Conductor temperature 16.0°C. Ambient temperature 11.4°C. Current 46 A

Fig. 10. Thermal image of the conductor at 9.30 p.m. Conductor temperature 17.5°C. Ambient temperature 8.5°C. Current 90 A

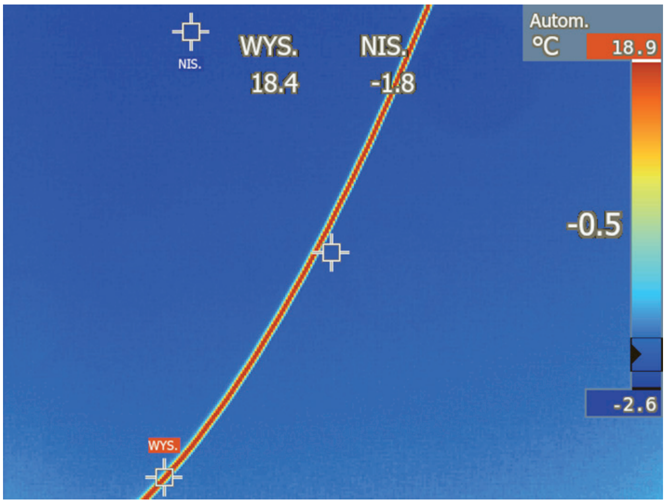

Fig. 11. Thermal image of the conductor at 11.00 p.m. Conductor temperature 18.4°C. Ambient temperature 7.9°C. Current 96 A

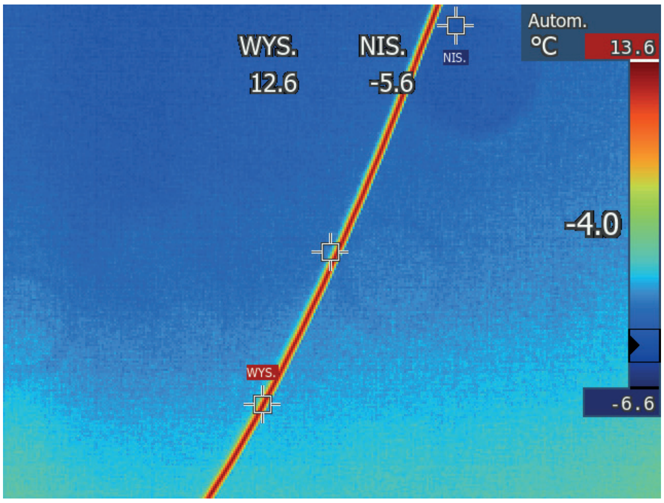

Fig. 12. Thermal image of the conductor at 01.00 a.m. Conductor temperature 12.6°C. Ambient temperature 5.7°C. Current 34 A

Ultimately, the developed and verified anti-icing method should be applied in autumn or winter conditions: when the air temperature and dew point is 0°C, and 90 percent rain or snowfall is expected to occur along with wind conditions between 0 and 5 m/s.

It is worth noting that under autumn and winter conditions, the analyzed line could be loaded to the value of 180 A during the day and to 90 A at night. The current carrying capacity of the line is 280 A.

6. Summary

This paper is devoted to an important and valid issue of reliability of overhead distribution networks under the conditions of rime or ice hazard. Over the last half-century, many of short and long-term failures have occurred in Poland due to ice and rime. The most serious of them took place in 2010.

Nowadays the 30 kV network in Poland is under successive reconstruction. Such networks are replaced with 110 kV networks. Bearing in mind that this process is long, time-consuming and these objects are constantly exposed to violent atmospheric conditions, it is rational to seek effective and reliable solutions for the transition period (of about 25 years). Such a solution for the object analyzed was proposed in the paper. It relies upon relocating all lateral branches underground and preventive heating of the main line through additional load.

For the analysis of mechanical reliability, the finite element method was used, taking account of various atmospheric conditions. The work included the latest normative guidelines, which were changed for Poland in 2016. The model simulation revealed that two cases were most dangerous for the analyzed line. The first case is when the line is uniformly loaded with ice or rime, and the line elements are indirectly destroyed due to their deformation. Here, despite the lack of a catastrophic situation, the infrastructure needs to be modernized and reconstructed. In the second situation, the asymmetry of the ice or rime load on the line leads directly to the cascade failure of the supporting structures.

The SAIDI and SAIFI indices were used to assess the structural reliability of MV networks under typical and extreme conditions. Taking into account the reliability and costs, a strategy for reaching a transitional solution was proposed.

Measurements preformed during the field experiment confirmed the possibility of using an additional load to prevent the creation of an ice coat on the bare conductors.

The novelty value of the proposed solution lies in the line condition prediction and its early enough loading with additional current based on synergic information from the local SMD and IMGW systems.

In conclusion, from this work promising results were obtained, which could prove useful for Polish distribution system operators. The results of this research suggest that an electrical load increase may be an effective way to protect the main line against ice or rime build-up. It is crucial to increase the main line electrical load well-enough in advance of adverse conditions occurring in order to expect tangible results. The local SMD and IMGW system could prove helpful in such case.

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