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Andrzej GOŁAŚ
Wojciech CIESIELKA
Krystian SZOPA
Paweł ZYDROŃ
Wojciech BĄCHOREK
Mariusz BENESZ
Aleksander KOT
Szczepan MOSKWA

ANALYSIS OF THE POSSIBILITIES TO IMPROVE THE RELIABILITY OF A 15 KV OVERHEAD LINE EXPOSED TO CATASTROPHIC ICING IN POLAND

ANALIZA MOŻLIWOŚCI POPRAWY NIEZAWODNOŚCI NAPOWIETRZNEJ LINII 15 KV NARAŻONEJ NA KATASTROFALNE OBLODZENIE W WARUNKACH POLSKICH*

The paper is a result of a synergic cooperation of two academic teams, i.e. power engineering and mechanical teams, and a distribution system operator. A real 15 kV overhead line exposed to a catastrophic load of ice and rime was analyzed and three solutions to improve the reliability of the tested object in such conditions were examined. Authors considered: shortening the length of the line spans, heating the main line with increased current and rebuilding the overhead line to a cable line. The researches worked out a FEM model taking into account the newest normatives, simulated the model, experimentally increased the load on the real line with measured wire temperature, and performed multi-variant calculations to determine indicators of reliability, i.e. SAIDI and SAIFI. The analyses were followed by conclusions thanks to which the reliability of power lines exposed to catastrophic icing could be increased. These inferences should be considered and applied by all distribution system operators in Poland.

Keywords: *power distribution networks, overhead lines, reliability, icing, rime.*

Praca jest efektem synergicznej współpracy dwóch zespołów akademickich: elektroenergetycznego i mechanicznego oraz operatora systemu dystrybucyjnego. Analizie poddano rzeczywistą, napowietrzną linię średniego napięcia 15 kV narażoną na katastrofalne obciążenia lodem i szadzią. Zbadano możliwość zastosowania trzech rozwiązań mogących poprawić niezawodność badanego obiektu w takich warunkach. Rozważono: skrócenie długości przęseł linii, podgrzewanie magistrali zwiększonym prądem roboczym oraz przebudowę linii do linii kablowej. W celu realizacji pracy wykonano badania modelowo-symulacyjne MES z uwzględnieniem najnowszych wytycznych normatywnych, zrealizowano eksperyment dociążenia linii wraz z pomiarem temperatury przewodów oraz przeprowadzono wielowariantowe obliczenia niezawodnościowe prowadzące do wyznaczenia wskaźników SAIDI i SAIFI. W wyniku szczegółowych analiz sprecyzowano wnioski końcowe pozwalające na zwiększenie niezawodności linii elektroenergetycznych narażonych na katastrofalne oblodzenie, które powinny być rozważone i stosowane przez wszystkich operatorów systemów dystrybucyjnych w Polsce.

Słowa kluczowe: *elektroenergetyczne sieci dystrybucyjne, linie napowietrzne, niezawodność, oblodzenie, szadź.*

1. Introduction

Electricity supplies are a very important element of living now. Reliability and continuity of energy supply, as well as minimization of power outages, are currently one of the key priorities of distribution system operators.

In view of the observed climate extremization, the problem of overhead network infrastructure exposure to difficult environmental conditions (icing, winds) is of particular importance.

The most important problem encountered by the designers and constructors of overhead lines lies in precise determining of additional loads of lines caused by ice and/or rime deposited on wires and supporting structures. This issue was dealt with, among other things, during the standardization of these loads in IEC [15].

In recent years, a lot of blackouts caused by the impact of adverse weather conditions on the elements of power systems have been noted over the whole world. Most of the world's countries located on the northern hemisphere, such as China, Germany [2], [11], north-east part of the USA and Canada [5], Czech Republic [17], North Caucasus in Russia [10], Japan [1], Finland [14], Norway [7], Romania [9], Hungary [13], United Kingdom [20], Iceland [4], [8] or part of India are struggling with the problem of ice formation on overhead lines. Also Poland experienced catastrophic failures caused by extreme weather conditions, as described in [2] and [11].

The gravity of this problem was noted and discussions followed on the international forum, e.g. CIGRE materials paid much attention to this issue [18], [19]. It is also the main topic of periodic meetings within the International Workshop on Atmospheric Icing of Structures.

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

With this experience in mind, national committees of numerous countries decided to change the standards to be used by the designers of the power lines in their calculations. In Poland, the ice loading zones have been also changed [16].

Reports in the world literature document a number of methods and techniques aimed at cooling ice and removing ice and/or raking from overhead lines [6], however, their effectiveness is negligibly low in the extreme conditions of catastrophic icing. These solutions relate mainly to the transmission networks.

The present work examines three solutions that improve the reliability of the object exposed to catastrophic load icing. Special attention was paid to: reducing span length (consolidation of supporting structures), heating of the main line by an increased current and rebuilding of the overhead line to the cable line. The researches included a FEM model, taking into account the newest policy normative, simulation based on the very model, experimental increase of load on the real line with measured wire temperature, and multi-variant calculations of reliability indicators, i.e. SAIDI and SAIFI. The final conclusions give information on how to increase the reliability of the analyzed power lines.

2. Characteristics of the object

The analysis was performed on a real 15 kV overhead distribution line located in the southern part of Poland. The schematic of the line is shown in Figure 1. This is an overhead line which supplies 11 lateral branches. Three of them include cable sections. Lateral branches are marked with the successive letters. The main line is supplied from the substation PZ1, and the tie point (normally open switch) is located in the substation PZ2.

Selected data characterizing the tested MV line are presented in Table 1.

Table 1. Basic data of the analyzed 15 kV network

	Type of construction / type	Length/Number	Sum
Main line	overhead line with AFL wires	9.9 km	9.9 km
	cable line	0 km	
Lateral branches	overhead line with AFL wires	7.8 km	12.3 km
	cable line	4.5 km	
Support structures (poles)	reinforced concrete	12	174
	steel	4	
	prestressed	41	
	centrifuged	114	
	wooden	3	
Switches	manually controlled	25	28
	radio controlled	2	
	reclosers	1	
Number of MV/LV transformer stations	19		
Number of customers	945		
Annual load range (min - max)	6 A – 16 A		

In winter of 2010 the analyzed overhead line experienced catastrophic icing conditions that led to extensive destruction of the network infrastructure.

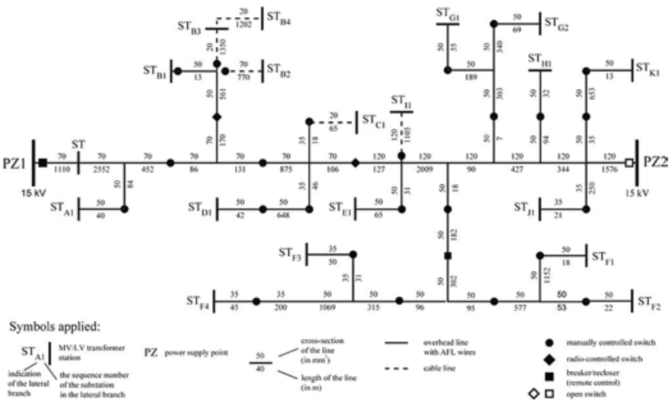

Fig. 1. Diagram of analyzed 15 kV power line

3. FEM simulation studies of selected elements of the line infrastructure for catastrophic weather conditions

The most important element of FEM model-simulation was to take into account the real catastrophic impacts that occurred in a large area on which the analyzed power line was located. In January 2010 a weather anomaly occurred contributing to the formation of icing on the overhead lines, significantly exceeding the normative assumptions (up to 18 kg/m and 15 cm in diameter). The effect of such catastrophic icing on the reaction forces at the suspension points of the wires and the force in the wire itself has been presented in this section. As the formation of such a large rime is favored by a relatively small wind, attention was mainly paid to cases involving only ice.

The purpose of the simulation tests was to determine the impact of atmospheric loads on the supporting structures and wires of the line. It was shown how the asymmetry of icing and length of the spans influenced the change of forces in the layout. The impact of these forces on the cross arms of the structure was not analyzed. The supporting structures were loaded with a static layout of forces equivalent to the forces coming from the wires to the cross arm.

First of all, a numerical model of the pole was built and the correctness of the assumptions verified.

The test was performed on a section of the analyzed 15 kV line. The pole E-12/10 was used as a support structure, which means that its length equaled to 12 m (Fig. 2), and the nominal peak force it carried was 10 kN. The structure was made of concrete class C 40/50. The steel reinforcing bars, running from the base to the apex, corresponded with the standards for reinforced concrete constructions.

The cross-section of the pole had a ring shape, the diameter of which decreased in proportion to the height of the structure (Fig. 2). The outer diameter of the pole at its base was 398 mm, and in the apical part 218 mm. 16 steel bars with a diameter of 16 mm were distributed evenly over the circumference of the pole. The size of the cross-section mesh was chosen 3 mm for reinforcing bars and 10 mm in the concrete area (Fig. 3).

The finite element model was verified and calculations were made for the destructive force $P_n = 18$ kN specified by the manufacturer. The maximum compressive stresses in concrete were 47.5 MPa (Fig. 4a),

Fig. 2. The geometry of pole E 12/10

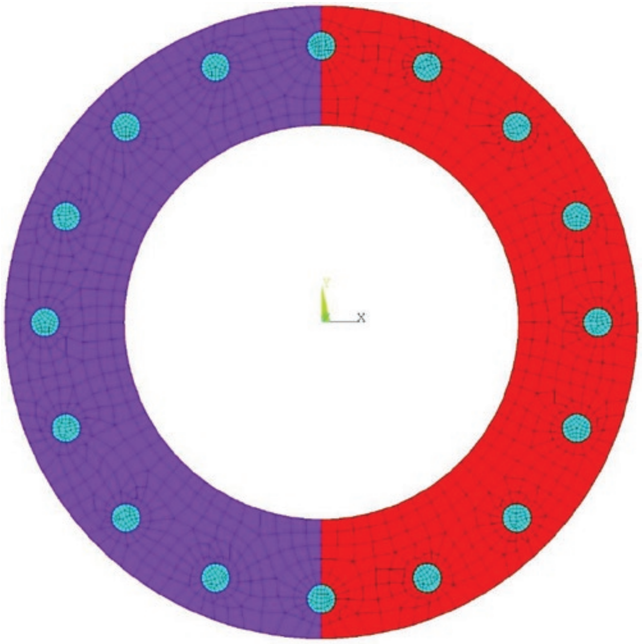

Fig. 3. The cross-section of E 12/10 pole viewed with the applied mesh

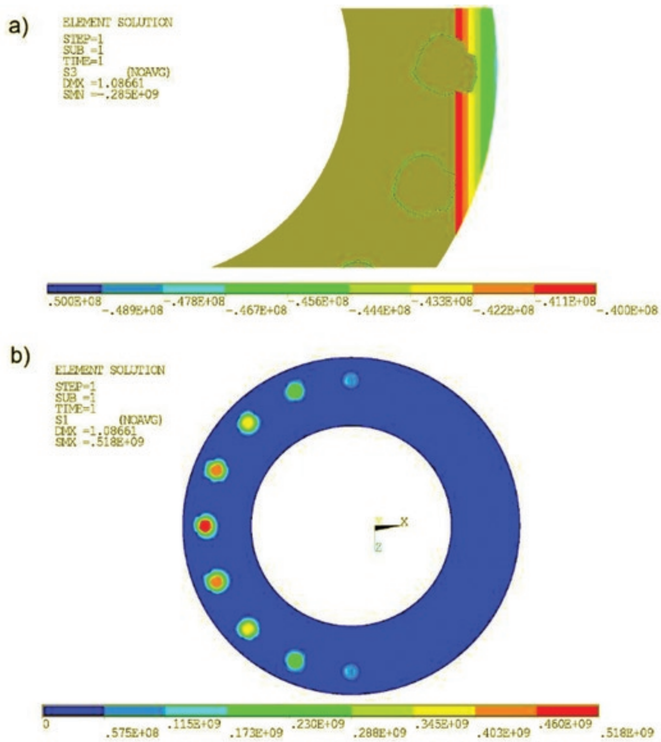

Fig. 4. Stress in power pole E 12/10 for tip bending force a) compressive in concrete, b) stretching in bars

which in principle coincided with the limit compressive stress for C 40/50 concrete equal to 48 MPa. So it should be assumed that the model was made correctly.

The parameters of the supporting structure E12/10 were calculated in view of the load determined for the suspension pole and the strain pole. Wire AFL-6 70 was selected for phase conductors because bare wires are more susceptible to the occurrence of high icing, and additionally, this type of cable is still being used in MV lines. The calculations were carried out for a replacement span length of 80 m. This value is approximately the average distance between poles used in zones with big characteristic icing, on the other hand, is adequate enough to show how large forces can occur in a relatively short span.

The results obtained for the described case are presented in table 2. Such a large mass of icing causes very large vertical forces and the axial tension in the wire. Again, with balanced ice in adjacent spans, compressive stress is small, but problems begin to appear for cases of asymmetrical icing. If the support structure is made as a suspension pole, as in case 2c (i.e., an unbalanced longitudinal load), the compressive stresses exceed the permissible values and crush the concrete and destroy the support structure. If the support structure is made as a strain pole, then it must also satisfy the conditions of group 5. Even in a situation when a single conductor is broken (case 5a), such a large transverse force appears that the compressive stresses in concrete are on the strength limit of the structure. In contrast, if the pole was designed to transfer a single-sided horizontal tension, the icing would generate a catastrophic failure of the structure. The situations described in this paragraph assume that the wire may break (cases: 5a, 5b, 5c), or withstand the icing load of 18 kg/m (cases: 2a, 2b). The design breaking force for AFL-6 70 is 22.75 kN. The table does not include sags due to the possibility of entering the scope of plastic deformation.

The given example presents results for a specific span length, sag and icing cases, therefore additional calculations were made to determine the relationship between the magnitude of lateral forces acting on the supporting structure E 12/10 and the span's length.

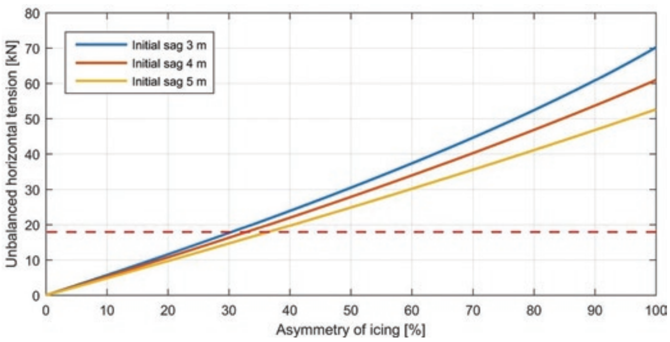

Fig. 5. The effect of the asymmetry of icing on the unbalanced horizontal tension

However, the first test was made on the effect of asymmetric icing on unbalanced tension. In this situation all the wires of one span are loaded with maximum catastrophic icing of 18 kg/m, while icing in the neighboring span changes from the maximum value ψ_I= 1 to 0. The asymmetry factor is taken here as (1-ψ_I)·100%, so for the maximum icing of both spans, this coefficient is 0%, while if one span is noticed, the asymmetry of the icing load is 100%. The analysis of the dependencies in Figure 5 reveals that for spans ≥80 m long, already with an asymmetry coefficient of 30%-37% (depending on the initial sag), the unbalanced value of tension force (from three wires) reaches the critical value of the destructive force for the pole E12/10 equal to 18 kN. This confirms previous results, where the problem was usually not so much icing, but its uneven distribution in the neighboring spans.

Subsequently, the maximum length of the span was checked for a load of 18 kg/m, assuming that the strain pole was designed to transfer one-sided tension (case 5c). The graphs presented in Figure 6 show that already for a span length of 35 m and an initial sag of 3 m, the sum of the tension components coming from three wires reaches the value of the destructive force of the chosen support structure. For comparison, assuming the maximum load according to the

Table 2. Effect of forces exerted by 18 kg/m catastrophic icing conduits on E 12/10 support structure

Case	V	H	W	N	σ_C	σ_S
	[N]	[N]	[N]	[N]	[MPa]	[MPa]
0	106.0	706.3	0	714.2	0.19	0
2a	4996.4	24133.0	0	24645.0	0.51	0
ψ_l= 0.3	157 3.1	9258.7	0	9391.4	-	-
ψ_l= 0.5	2551.2	13979.2	0	14209.1	-	-
ψ_l= 0.7	3529.3	18264.1	0	18602.3	-	-
2b	Combination of loads ψ_l= 0.5 and ψ_l=1				7.65	48.9
2c	Combination of loads ψ_l= 0.3 and ψ_l=0.7				71.10	730.0
5a	Wire breakage for icing ψ_l= 0.7				48.21	492.2
5b	75% of single-sided tension with icing ψ_l= 1				142.25	1471.0
5c	Total unilateral tension at an icing ψ_l= 1				189.20	1962.8

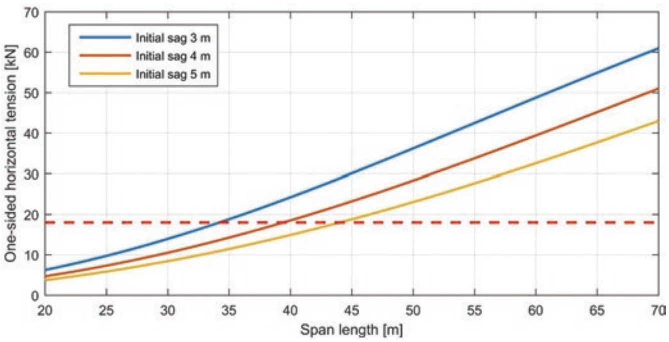

Fig. 6. The one-sided horizontal tension as a function of span length for strain pole and catastrophic icing 18 kg/m (case 5c)

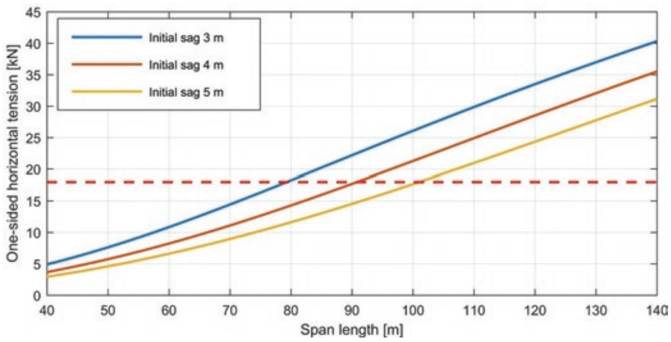

Fig. 7. The one-sided horizontal tension as a function of span length for strain pole and normative maximum icing (case 5c)

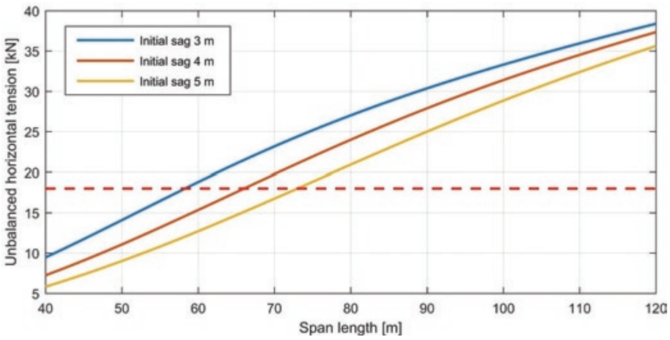

Fig. 8. The unbalanced horizontal tension as a function of span length for catastrophic icing 18 kg/m unbalanced longitudinally (case 2c)

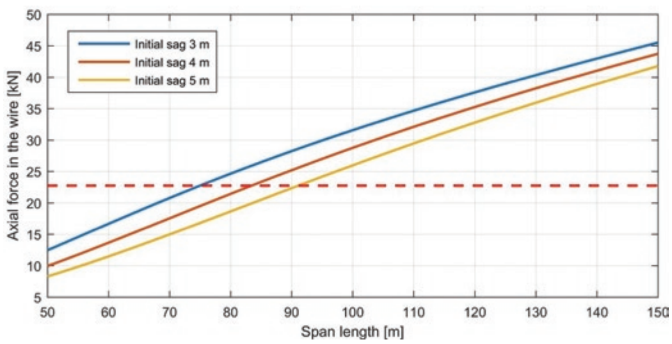

Fig. 9. The maximum axial force in a single wire as a function of span length for catastrophic icing of 18 kg/m

normative guidelines, the length of the span for pole type E12/10 could be 80 m (Fig. 7).

If the pole is a suspension pole, case 2c will be most dangerous for the considered conditions. A longitudinally unbalanced icing case will be a threat to a 58 m long equivalent span with an initial overhang of 3 m (Fig. 8).

When considering such a large icing one should obviously account for the maximum forces in wires as they are a potential source of breakage. For a wire AFL-6 70, the design breaking force of the conductor is 22.75 kN. If the wire is loaded with ice of 18 kg/m for an initial overhang of 3 m, it may break at the length of the span of 75 m (Fig. 9).

The analysis shows that the appearance of such unusual atmospheric conditions as in 2010, is accompanied by icing, the mass of which goes over the normative guidelines, even for the third ice load zone. E-type poles, which are characterized by high durability as compared to BSW constructions, may be too weak to carry such heavy loads and break. Of course, the worst case for a power line segment is when due to an excessive load, the wires are broken in one of the spans, the pole is loaded with one-sided tension and subjected to high bending forces. These are instances of 5 interaction systems. Although they refer to strain poles, it may happen that due to large icing the wire will not be able to move freely in the support or disengage from the safety holder, thereby transferring the tension on the suspension pole, and leading to its destruction.

4. Field studies using thermovision

In the next step, authors concentrated on measuring the temperature of the wires of the analyzed 15 kV line under normal and increased load conditions. The measurements were conducted on phase wires AFL-6 70. The experiment was performed on 23 Nov. 2017 for a normal configuration of the system and a specially prepared network configuration with additional load.

The test results, i.e. current, ambient temperature and wire temperature recorded during the experiment are presented in Figure 10. For safety reasons, i.e. to ensure the continuity of power supply and guarantee adequate power quality, daytime hours were selected for the test. The measurements were carried out in windless conditions, with a little cloudy sky, clouds of the middle floor appearing after 9.30 a.m. The changing degree of insolation caused a change in the temperature during the experiment. In the initial experiments between 7:45 and 9:45 the ambient temperature increased from 0.3°C to 7.9°C. In during this period, the current value varied from 8 A to 10 A, and temperature of wire from 6.3°C to 9.2°C.

At 9:52 a.m. the MV line load was increased (change of network configuration), and the normal configuration restored at 01:25 p.m. At 10.00 a.m. a current of 47 A was observed. While increasing the load, the current value stayed in the interval 46 A to 51 A. At that time the observed temperature of the wire varied from 11.3°C to 17.3°C. In the observed period, the value of the ambient temperature also changed from 7.4°C to 15.6°C.

Particularly noteworthy are the measurements between 9:45 and 10:45 a.m., when the highest increase of wire temperature (8.5°C to 14.8°C) was observed. It was accompanied by an increase of current from 10 A to 48 A, and an ambient temperature increase by 2.3°C.

The analysis of the test results revealed that during the change of the load from 36 A to 40 A, the temperature of the wire increased from 4.3°C to 6.1°C.

In addition to the wire temperature rise, a significant deterioration of the voltage conditions in end-customers was also observed. Based on analyses of the year value of current and voltage waveforms in a selected network, thermal imaging experiments, and voltage drops, it was found that the implementation of the additional load for winter conditions not make the temperature of wires rise to positive values (guaranteeing the formation of an ice-and-rash coat). In this situation no main line heating is possible for stripping ice and/or rime from the wire.

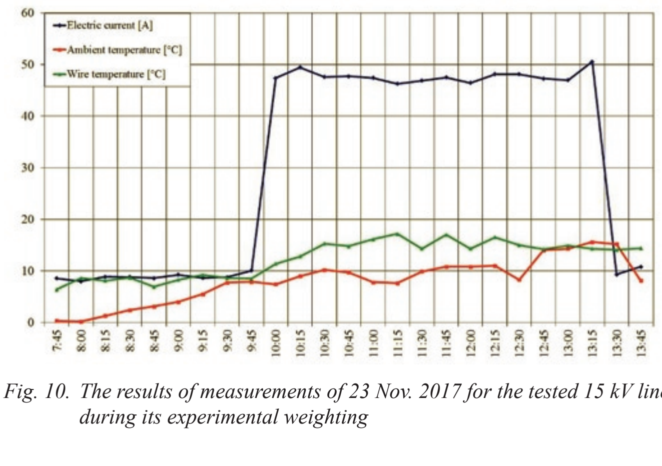

Fig. 10. The results of measurements of 23 Nov. 2017 for the tested 15 kV line during its experimental weighting

5. Structural reliability model

The reliability calculations were performed to determine SAIDI and SAIFI indicators for the analyzed MV line. For this purpose an author's dedicated software was employed. It was used for multivariate calculations, on the basis of which various scenarios of facility modernization could be quantitatively and reliably assessed.

The simulation requires information concerning the grid structures as well as the parameters of the reliability of components.

In terms of reliability parameters of the elements the same values of the average duration of failures were assumed. For the failure rate, two variants of calculations were implemented. Variant A was based on the relation of parameters after publication [3] and [21] whereas, in option B, the indicators were taken from [12]. The reliability parameters have been compiled in table 3.

The results of calculations of SAIDI and SAIFI reliability indicators are presented in Figure 11. The values of indicators for the current state constitute a reference level for all simulated cases.

Table 3. Used failure parameters of the MV distribution network

Element	Unit *j*	Failure rate -variant A [1/(*j*· year)]	Failure rate -variant B [1/(*j*· year)]	The average duration of failure [h]
MV overhead line (AFL)	100 km	8.14	11.02	5
MV cable line		0.814	10.16	5

In variant B, the successive rebuilt of the overhead line to the cable line, minimally improved the reliability, whereas in variant A, a significant improvement in the reliability of the facility was observed as a result of its reconstruction and modernization. Therefore the latter set of parameters seems more correct in the context of the operational realities of distribution networks.

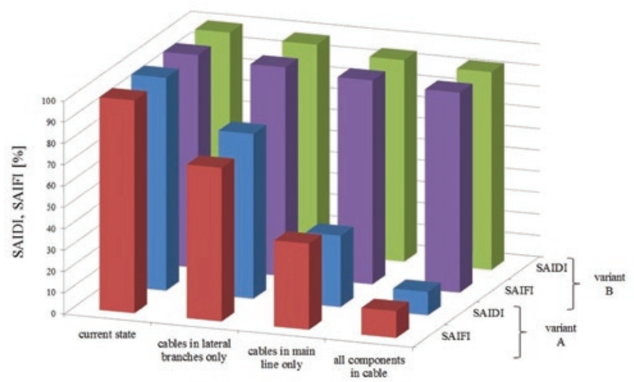

Fig. 11. The expected rate of reduction of reliability indicators for various variants of reconstruction of the analyzed 15 kV line

6. Summary and conclusions

The work tackles an extremely important problem of operation of medium voltage lines exposed to catastrophic icing. In Poland, that kind of line is located in the operation area of four distribution system operators, covering over 20000 km of length.

The aim of the work was to identify methods to improve the reliability of the analyzed object, counteracting the effects of disastrous icing. For this purpose FEM model simulation, infrared temperature measurement of wires and multivariate calculations of SAIDI and SAIFI indicators were performed.

The analysis of the FEM model simulation indicates that the analyzed object can withstand catastrophic loads, provided the span lengths are reduced to the length of 35 meters.

The experimental (planned) increase of current load in a wire and the thermovision measurements reveal that the effective use of preventive heating of the line with an additional current is not possible in the analyzed case. Line load in the normal work configuration is negligible, and reconfiguration thrust is significantly limited by voltage conditions.

Substantial elimination of climatic impacts (both winter and summer) may be achieved by the reconstruction of the analyzed object into a cable line. Apart from the effect of full climatic screening it will undoubtedly influence the operational reliability of the facility, and the degree of this impact will be significantly conditioned by the reliability parameters of elements of this network.

The overhead networks dominate in the national distribution network, therefore some strategy of dealing with the problem of impact of extreme atmospheric phenomena on overhead distribution infrastructure has to be worked out. Such a strategy should take into account a number of factors such as the state of technical infrastructure, percent of amortization of cushion property, local setting conditions, and functions of individual elements in the distribution network.

Concluding, the desired guidance presented in this paper allows for increasing the reliability of distribution power lines exposed to catastrophic icing and should be considered and implemented by all distribution system operators in Poland.

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Andrzej GOŁAŚ
Wojciech CIESIELKA
Krystian SZOPA
AGH University of Science and Technology
Faculty of Mechanical Engineering and Robotics
Department of Power Systems and Environmental Protection Facilities
Al. Mickiewicza 30, 30-059 Kraków, Poland

Paweł ZYDROŃ
Wojciech BĄCHOREK
Mariusz BENESZ
Aleksander KOT
Szczepan MOSKWA
AGH University of Science and Technology
Faculty of Electrical Engineering, Automatics, Computer Science and Biomedical Engineering
Department of Electrical and Power Engineering
Al. Mickiewicza 30, 30-059 Kraków, Poland

E-mails: ghgolas@cyf-kr.edu.pl, ghciesie@cyf-kr.edu.pl, kszopa@agh.edu.pl,
pzydron@agh.edu.pl, wojbach@agh.edu.pl, mben@agh.edu.pl, akot@agh.edu.pl,
szczepan@agh.edu.pl