Evaluation of corrosion of long-term exposed aluminium conductor

Hodnocení korozního napadení hliníkových vodičů po dlouhodobé expozici

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The goal of the study was to assess corrosion of a cable bundle after a forty-year exposure to atmosphere. The assessed bundle consisted of a galvanized steel wire carrying core and aluminium external guide wires. Optical microscopy, electron dispersive microscopy and X-ray diffraction techniques were used for the assessment. Aluminium oxide was identified to be the most prevailing aluminium corrosion product. The average residual thickness of the steel wire zinc coat was 33 μm , even though there were locations where the zinc coat corroded through totally. Service life of aluminium wires is limited predominantly by the pitting corrosion rate, which reached 5 $\mu\text{m}/\text{year}$.

V rámci práce bylo hodnoceno korozní napadení kabelového svazku po čtyřicetileté atmosférické expozici. Hodnocený svazek byl tvořen nosným jádrem z pozinkovaného ocelového drátu a vodičimi vnějšími hliníkovými dráty. Pro hodnocení byly využity techniky optické mikroskopie, elektronové mikroskopie s energiově disperzní analýzou a rentgenové difrakce. Jako korozní produkt hliníku byl identifikován téměř výhradně oxid hlinitý. Zinkový povlak ocelových drátů jádra měl průměrnou zbytkovou tloušťku 33 μm , i když lokálně byla zinková vrstva již odkorodována zcela. Životnost hliníkových drátů je limitována především rychlostí bodové koroze, která činí až 5 $\mu\text{m}/\text{rok}$.

INTRODUCTION

Electric power is usually transmitted through overhead power lines. In the Czech Republic (CR) the transmission services are provided by ČEPS, the Czech Transmission System Operator, through the basic lines of 440VVN Overhead Transmission Lines (OHTL). The construction of a backbone transmission network was finally completed in the 1980s. It currently consists of 400kV power lines together with 220kV lines, the construction of which was completed in the early 1970s and which are currently used mainly as reserve lines. The total length of these 440VVN lines is 3 508 km (of which 1 145 km double and multiple lines), see Fig. 1.

In order to increase the reliability of supply and to assist in further developing the EU internal electricity market, network transmission capacity has to be enhanced, bottlenecks removed and the transmission system infrastructure modernised. In 2012 the modernization of the line 452V had been realised. The replaced cables and other elements from this line had been evaluated in details to receive basic data about degradation of materials after long-term exposure.

Specification of conductor

Aluminium conductor galvanised steel-reinforced (ACSR) cable is a specific type of stranded cable typically used for electrical power delivery. Aluminium is chosen for its excellent conductivity, low weight and low cost. The centre strand of ACSR cable is made of galvanised steel for the strength required to support the weight without stretching the aluminium due to its ductility. This gives the cable an overall high tensile strength. So broken steel strands in ACSR cables have a very strong impact on the safe operation of power grids. During the long-term outdoor field service, ACSR cables may be damaged by lightning strike, atmospheric corrosion, ice-shedding, wind vibration of conductors, lines' galloping and external forces' destroy and so forth [1-3]. Much information is available on the short- and mid-term atmospheric corrosion of aluminium, in the form of corrosion data (mass loss and pit penetration) as a function of atmosphere type, corrosion mechanisms, environmental variables, surface orientation, etc. However, information on the atmospheric corrosion of aluminium over longer time periods (40 years) is scarce, despite its great usefulness [4].

Cable types for corrosion failure analysis

The ACSR cable's sample had been evaluated from line 452V located on North Bohemia region (see Fig. 1) with a service age ca 40 years after construction (constructed in 1973). Evaluated ACSR was composed of aluminium wires in the three layers and galvanised steel strand in the centre (Tab. 1). The aluminium wires had various diameters for 1st /2nd layers and for 3rd layer and they were without any surface treatment (Tab. 1). According to standard, the zinc coating area mass on central steel wires should be 230 g m⁻².

From the results of detailed analysis, variety of findings relating to corrosion characteristics of each

strands have been obtained and corrosion attack by conductor's characteristic, difference in construction of conductor and environmental effects.

Corrosion attack of cable's wires

Type and depth of corrosion attack

There were evaluated 9 samples of conductor of whole cable (all layers of wires) with length ca 20-60 m taken from various parts of the line. Each sample had been divided into 3-4 smaller parts and they had been disentangled layer after layer and each wire had been evaluated visually and then they had been evaluated by metallographic cross sections – Tab. 2. There were found three typical corrosion damages:

- layer A – outer aluminium wires – uniform corrosion – voluminous dark grey/black layer of corrosion products containing large portion of deposits (Fig. 2a), intensive pitting corrosion and the first symptom of exfoliation corrosion (Fig. 2b-e);
- layer B – middle aluminium wires – thin layer of corrosion products and deposits (Fig. 3a), intensive pitting and exfoliation corrosion (Fig. 3b-e);
- layer C – inner aluminium wires – practically without corrosion products (glossy metallic surface), small pitting and sporadic exfoliation corrosion (Fig. 4a), on specific areas the zinc corrosion products from centre galvanised steel strand penetrated on these wire (Fig. 4b-e);

Fig. 1. Scheme of distribution network of 400 VVN in the CR

Obr. 1. Schéma distribuční sítě velmi vysokého napětí v ČR

Tab. 1. Parameters of ACSR cable / Parametry kabelu

Cable type	450 AlFe 8		
aluminium strand, 2 outer wire layers	number of wires	20 + 14	
	diameter	3.75 mm	
aluminium strand, inner wire layer	number of wires	18	
	diameter	1.90 mm	
galvanised steel, centre strand	number of wires	9 + 3	
	diameter	2.36 mm	

Tab. 2. Survey of corrosion attack of cable wires / Průzkum korozního napadení kabelových drátů

Layer of cable	Type of corrosion attack	Average depth (µm)	Maximum depth (µm)
A (aluminium)	pitting	100	200
	exfoliation	20	50
B (aluminium)	pitting	75	150
	exfoliation	75	200
C (aluminium)	pitting	45	50
D (galvanised steel)	local intensive corrosion of zinc coating	20	50

a)

b)

c)

d)

e)

Fig. 2. Characteristic corrosion attack of outer aluminium wire of conductor

Obr. 2. Příklad napadení vnějšího hliníkového drátu

a)

b)

c)

d)

e)

Fig. 3. Characteristic corrosion attack of middle aluminium wire of conductor
Obr. 3. Příklad napadení středního hliníkového drátu

a)

b)

c)

d)

e)

Fig. 4. Characteristic corrosion attack of inner aluminium wire of conductor

Obr. 4. Příklad napadení vnitřního hliníkového drátu

Fig. 5. Characteristic corrosion attack of galvanised centre strand
Obr. 5. Příklad korozního napadení zinkovaného drátu jádra

- layer D – centre strand of galvanised steel wires – depending on position of the sample from cable, the surface was without corrosion, or zinc coating was covered by very thin grey layer of corrosion products (Fig. 5a), on specific areas where the humidity or precipitations penetrated into the cable centre (the middle of cable between two poles) the voluminous layer of white zinc corrosion formed and sporadically the zinc coating was corroded away and the corrosion of substrate steel started (Fig. 5b).

The published results of the investigations reveal that most of the corroded ACSR were due to internal corrosion [4]. This internal corrosion belongs to galvanic corrosion, and its mechanism is explained that zinc of the galvanised steel core is first lost, and then aluminium strands are lost. Since aluminium is corroded predominantly over steel, corrosion significantly affects the tensile strength of an inner-layer aluminium strand. This type of corrosion attack was not found on conductor from northern Bohemia line 452V even some such deterioration of zinc coating was identified.

Residual thickness of zinc coating

On the galvanised steel wires from cable centre strand, the residual thickness of zinc coating was evaluated by two methods:

- gravimetric determination according to EN ISO 1460 *Metallic coatings. Hot dip galvanized coatings on ferrous materials. Gravimetric determination of the mass per unit area* from 3 samples from each cable sample,
- metallographic evaluation according to EN ISO 1463 *Metallic and oxide coatings - Measurement of coating thickness - Microscopic method* on selected samples with local corrosion attack (Fig. 5).

Tab. 3. Residual thickness of zinc coating / Zbytková tloušťka zinkového povlaku

Cable sample	Gravimetric determination		Metallographic evaluation (μm)
	Area mass (g m ⁻²)	Thickness (μm)	
1	247	35	42
2	247	35	39
3	231	32	32
4	285	40	–
5	203	28	36
6	232	33	–
7	288	40	24
8	197	27	–
9	197	27	38

The results are given in Tab. 3. Average value of residual thickness of zinc coating was 236 g m⁻², i.e. 33 μm. This value corresponds to specific zinc coating thickness for new cable – this corresponds to visual evaluation when the intensive corrosion of zinc coating was found only in sporadic cases. The minimum zinc coating thickness on wire without significant corrosion attack was 167 g m⁻², i.e. 23 μm.

On areas where the corrosion of substrate steel occurred this attack was not significant – maximum depth was 150 μm, ca 5 % of original diameter of steel wire.

Analysis of corrosion products

The layer of voluminous layer of corrosion products and deposits from the outer aluminium wire were analysed by different methods:

- X-ray diffraction analysis shown quartz and alumina Al₂O₃ as dominant compounds (Fig. 6),
- on selected sample of outer aluminium wire the elementary analysis of surface layer of corrosion products and deposits were performed (Fig. 7). The results are given in Tab. 4.

Fig. 6. XRD analysis

Obr. 6. Rentgenová difrakční analýza

Fig. 7. Analysed area on outer aluminium wire

Obr. 7. Analýzovaná místa na povrchu hliníkového drátu

Tab. 4. EDS analysis of surface layer / EDS analýza povrchové vrstvy

Analysed area	concentration (wgt. %)							
	O	Mg	Al	Si	P	S	Fe	Zn
1	42.85	0.51	31.03	6.98	1.22	7.72	7.63	0.85
2	55.78	0.30	27.07	5.20	0.50	7.50	2.50	0.40
3	46.69	0.49	31.28	5.30	1.07	8.50	4.62	0.76

The thickness of dark voluminous corrosion and deposit layers was ca 10-15 µm on surface of aluminium wire, the composition of aluminium is apparent from results of analysis. The main compound of layers is aluminium oxides. Dominant corrosion stimulator was sulphur in amount of 7,5-8,0 wgt. % in corrosion layer even though the concentration of air SO₂ decreased from original average value 100 µg.m⁻³ to contemporary average value 15 µg.m⁻³ in northern Bohemia region. Accumulation of dirt on the aluminium surface can cause a reduced durability. Very often this is a consequence of long-term moisture.

Prediction of corrosion behaviour of aluminium conductor

In addition, a rational lifetime assessment method for OHTL was established using the findings of corrosion attack type and depth by the probabilistic method.

Long-term corrosion loss by means of uniform corrosion can be estimated according to EN ISO 9224 *Corrosion of metals and alloys - Corrosivity of atmospheres - Guiding values for the corrosivity categories* (Tab. 5). The corrosivity of atmosphere decreased in this region from category C4 to category C2 during last 40 years with relative quickly but significant air pollution decreased in 1994-1996. The performed tests at this locality showed that the corrosion rate of exposed metals also decreased even for metals the exposure of which had started in condition of high polluted atmosphere [5].

It can be expected that average rate of uniform corrosion of aluminium can be estimated for corrosivity category C3. In the CR, in industrial region of northern Bohemia, the long-term atmospheric corrosion of aluminium was determined for period 1981-2006 (in period 1994-6 the significant reduction of SO₂ air pollution occurred) – after 25 years of exposure the total corrosion loss by uniform corrosion was determined as 2.5 µm. The uniform corrosion of aluminium cable was not the significant factor of their service life.

More important than uniform corrosion are the localised types of aluminium corrosion - pitting and exfoliation corrosion which may resulted into low tensile strength, reduction of electric capacity of wire due to lower diameter of conductor, fracture or other damage of conductor.

Pitting corrosion is the most common corrosion form seen on aluminium. It starts from a weak point in the oxide layer, and after initiation, the reactions within the pit will reduce the pH and increase the chloride concentration and in this way sustain the reaction. The development of pit depths follows a time function of the form:

$$D = K \cdot t \cdot c$$

where D is the depth of the deepest pit, K is an alloy-, surface area- and environment-dependent constant, t is time, and c is an environment-dependent parameter which often is close to 1/3.

The pits can be of different shapes, wide or narrow. The narrow pits can often be dangerous because the attack can be deep and difficult to detect.

Tab. 5. Atmospheric corrosion loss of aluminium (µm) – uniform corrosion / Úbytek hliníku způsobený rovnoměrnou korozi v atmosféře

Corrosivity category	Corrosion loss in the 1 st year according to EN ISO 9223 (µm)	Steady state corrosion loss (µm) according to EN ISO 9224		
		10 years	20 years	40 years
C1	negligible	negligible	negligible	negligible
C2	< 0.02	0.11	0.18	0.29
C3	0.02 < 0,7	1.92	3.19	5.28
C4	0.7 < 1.8	6.68	11.1	18.3
C5	1.8 < 3.6	14.4	23.9	39.6
CX	intensive localised form of corrosion			

Long-term exposed aluminium material's evaluation shows that the most intensive growth of pit depth occurred during the first years of exposure (ca 5 years) and following progress is relative slow (Fig. 8). After 40 years exposure in industrial atmospheres the pitting corrosion was evaluated [6]:

- maximum depth of corrosion pits 150 μm ,
- average depth of corrosion pits 50 μm

The exposure of aluminium standard samples in industrial atmospheres of northern Bohemia was performed in period 1986-1995. The yearly average concentration of SO_2 during this period was $67 \mu\text{g m}^{-2}$. The results of this exposure are given in Tab. 6 and they are in excellent correspondence with published data (Fig. 8) and results of evaluation as aluminium conductor. It can be predicted that the pitting corrosion of aluminium conductor wires would follow with maximum rate ca $5 \mu\text{m/a}$ and average rate $1 \mu\text{m/a}$. The decrease of pitting corrosion is positively affected by reduction of SO_2 air pollution and atmospheric corrosivity in region of northern Bohemia.

There are not similar data for exfoliation corrosion but it is known that the kinetic of exfoliation corrosion is practically constant with time, i.e. The depth of exfoliation corrosion increases linearly [7, 8]. The maximum rate of exfoliation corrosion of aluminium conductor wires was estimated as $5 \mu\text{m/a}$.

Fig. 8. Rate of pitting corrosion; (1) - San Gioacchino church in Rome

Obr. 8. Rychlost penetrace bodové koroze; (1) - kostel sv. Gioacchina v Římě

Tab. 6. Evaluation of influence of atmospheric corrosion on aluminium / Hodnocení vlivu atmosférické koroze na hliník

Type of exposure	Corrosion loss (μm)	Pitting corrosion depth (μm)	
		Average	Maximum
open atmosphere	1.93	52.2	80.0
shelter	3.04	19.7	76.0

CONCLUSION

This paper presents the findings on conductor corrosion obtained from investigations on the sampled conductors and various test results, and describes a probabilistic lifetime estimation method. Probabilistic Lifetime Estimation Method is based on estimation of corrosion rate of every observed corrosion attack of aluminium conductor. Considering the maximum corrosion determined on aluminium wires after 40 years of exposure the total reduction of all aluminium wires was 11%. If the local form of aluminium corrosion progress in the same rate, the total reduction of all aluminium wires will be 14 % after next 10 years of exposure.

There were performed also other evaluation of withdrawn cables including mechanical properties as the tensile strength. It was referred a decrease of the tensile strength of the aluminium strand by about 20 % over 50 years of service in environment with high corrosivity category [9].

The study will continue for cables from other lines with different exposure conditions and exposure periods to find the better model for service life prediction of them.

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