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IMPROVING THE PERFORMANCE OF EXISTING HIGH-VOLTAGE OVERHEAD LINES BY USING COMPACT PHASE AND GROUND CONDUCTORS

P. COUNESON [*]**- J. LAMSOUL**
D. DELPLANQUE
Tractebel

TH. CAPELLE - M. HAVAUX
D. GUERY
Alcatel Cable Benelux

X. DELREE

CPTE

(Belgium)

SUMMARY

Given the increasing resistance of both the population and the administrations responsible for town and country planning to the idea of constructing new high-voltage overhead lines, the Belgian utilities have re-evaluated the technologies available for meeting the increasing transit needs on the network.

Increasing the transport capacity of existing lines by using a new type of compact phase conductor - called AERO-Z® - has proved to be an especially interesting possibility from both the economic and technical perspectives.

After a brief review of the origin of compact conductors, this report describes the application of this technique to phase conductors and optical ground wire (OPGW) :

1) *Compact conductors*
   . *fundamental reason for increased use of compact conductors*
   . *main characteristics and tests*
   . *use of compact conductors in Belgium*
2) *Optical ground wires*
   . *problematic of overhead conductors with optical fibres*
   . *design of the conductors*
   . *tests performed, measurement methodologies and comparison between the OPGW conductor with round wires and the OPGW conductor with Z-shaped wires*

Key words : *conductor, OPGW, compact conductor, Z-shaped wires, corrosion, self-damping, galloping, snow, frost, overhead conductors, optical fibres.*

I. PART ONE : COMPACT PHASE CONDUCTORS

1. ORIGIN OF COMPACT CONDUCTORS

During the CIGRE session 76, Belgium presented a report on the aerodynamic characteristics of new conductors for long overhead spans [1].

This report described a first high-voltage overhead line having long spans (crossing the Escaut River), equipped with homogenous conductors made of aluminium alloy with a smooth external surface.

It was decided to use such a conductor because of the risk of oscillatory instability of the conventional conductors under constant oblique wind speeds ranging from 45 to 56 km/hour. This risk of galloping in the absence of frost constituted a major concern for the designers [2].

The 76 report detailed the reasons for choosing the conductor with smooth external surface constructed from Z-shaped wires (see figure 1). Let us briefly recall that the Z-shaped wire was preferred to the trapezoidal-shaped wire because the stranding of such wires in aluminium alloy leads to a succession of small steps at the periphery of the conductor. In addition, as the trapezoidal wires are not always perfectly contiguous, the aeolian vibrations can increase the inclination of these wires and therefore the height of the steps.

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[*] Avenue Ariane 7, B-1200 Brussels

Furthermore, if a trapezoidal wire breaks, its “wedge” form forces it outside of the conductor. By contrast, the Z-wires overlap each other, the bottom of one wire being placed under the top of the adjoining wire.

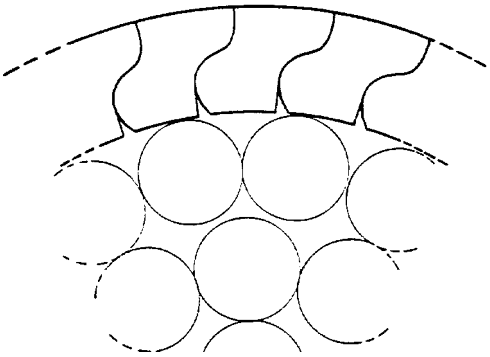


Figure 1. Sector of a cross-section of compact conductor

Nevertheless, if the technical aspect of the Z-profiles aroused the interest of users at the beginning, commercial success proved more elusive because the lamination operations of the Z-wires were expensive.

Major research projects were conducted in order to make this type of conductor competitive vis-à-vis conventional conductors.

Ultimately, this aim was attained by producing such Z-wires using a drawing process instead of a lamination process.

2. FUNDAMENTAL REASON FOR INCREASED USE OF COMPACT CONDUCTORS

Since the end of the 1980’s, construction of new high-voltage lines has faced increasing resistance, both from the population and from administrations responsible for town and country planning. This situation has led the Belgian utilities to re-evaluate the technologies available for meeting the increasing needs for transit ampacities on the network.

Instead of systematically considering the construction of new lines, increasing the transit ampacities of existing lines proved to be a particularly interesting possibility, from both the technical and economic perspectives.

To achieve this, a new type of compact conductor - called AERO-Z® - was developed. While it still uses, for the outer layer(s), Z-shaped profiled wires instead of conventional round wires, the last layer, virtually smooth, has small helical grooves created between the upper edges of the “Z” wires with carefully chosen lay, depth and width. Together with the Von Karman Institute (Brussels), tests were conducted which focused primarily on optimising the effects of the grooves (see figure 2) [3].

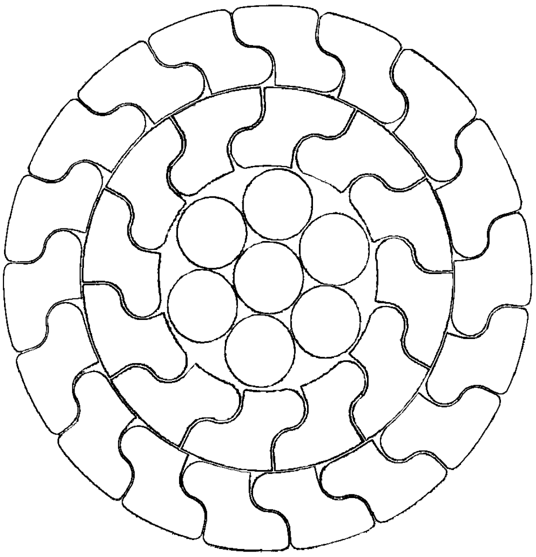


Figure 2. Cross-section of an AERO-Z® conductor

In this way, one obtains a significant reduction of the drag coefficient for the strongest winds (see table 1). This reduction induces lower stress on the towers for an equal conductor diameter, or a greater useful conducting section for an equal stress on the towers for exceptional maximum wind.

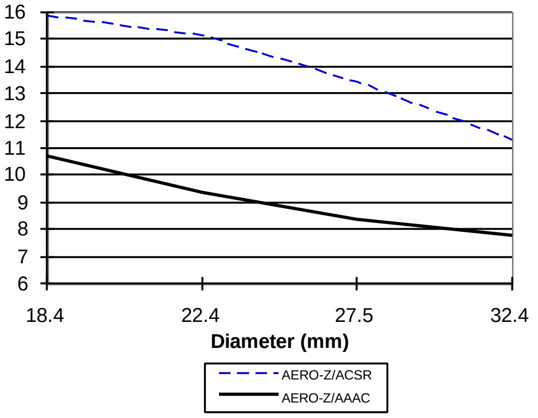
This features have been endorsed by the Belgian Regulation on Electrical Installations [4].

Table 1. - Drag coefficient by diameter class for an exceptional maximum wind (175 km/h at 10 m above the ground)

Nominal diameter of the conductor (mm)	18.90 = d < 28.35	28.35 = = d < 31.50	31.50 = = d < 36.85	36.85 = = d < 50
Nominal cross-sectional area (mm^2)	245 = S < 536	536 = S < 621	621 = S < 926	926 = S
Max. drag coefficient for AERO-Z® conductor	0.80	0.60	0.55	0.46
Max. drag coefficient for conductor with round wires	0.95	0.95	0.95	0.95

There thus results an increase (see figure 3) of the transit ampacity of existing OHL by simple substitution of conductors with equal diameter, i.e. without needing to reinforce the towers (strictly speaking, however, one must nevertheless verify the impact on angle towers of increasing the stringing tension, itself due to the increase of weight if one wishes to work at constant sag). If a greater transit uprating is necessary, the fact of using compact conductors in any case reduces the reinforcements of the towers and foundations compared to what they would have been with conventional conductors.

Figure 3. Transit ampacity gain for an AERO-Z®conductor compared to conventional aluminium alloy (AAAC) and aluminium-steel (ACSR) conductors



Apart from a significant gain in transit ampacity at equal levels of tower stress, this type of conductor offers other major advantages justifying its more systematic use. These characteristics and the tests which confirmed them are detailed below.

3. IMPORTANT CHARACTERISTICS AND TESTS

In addition to the conventional tests prescribed by the Belgian standard NBN C34-100 [5] relating to overhead conductors, the tests specific to the compact conductors described below were defined and successfully implemented.

3.1. Corrosion

The large contact area between two Z-wires of a same layer constitutes an effective protection against seepage of the grease towards the outside of the conductor. During production, all the internal interstices of the conductor are filled with a grease put in at ± 120 °C, thus eliminating air and moisture. The internal protection is therefore reinforced compared to conventional conductors, which are subject to a migration of the protective grease towards the outside due to the effect of the charge cycles.

The compact conductor, by contrast, maintains a constant level of protection against corrosion, thus guaranteeing slower ageing of the wires over time.

This fact was demonstrated by the measures performed on conventional conductors and compact conductors (with a single-Z layer) installed in 1970 on the same line (Lillo - Solvay) and withdrawn in 1988 due to a route modification (table 2).

3.2. Undestrandability

Even broken, a wire of an outer layer of an AERO-Z® conductor remains in place under the mechanical service stress. This property is preserved until five contiguous wires have been broken.

Table 2. Measures performed on conventional and compact conductors (with a single Z-layer) installed in 1970 and withdrawn in 1988

	Variation of the grease weight	Variation of tensile strength of wires		Variation of average elongation at break	
		Inner layers	Outer layers	Inner layers	Outer layers
Conven-tional	- 28 %	unchanged	- 5 %	- 19 %	- 26 %
Compact with 1 Z-layer	unchanged	unchanged	- 5 %	- 9 %	- 2.2 %

3.3. Self-damping

The large surface of contact between the profiles also gives the AERO-Z® better damping.

Several conventional conductors and AERO-Z® were subjected to oscillations caused by releasing a weight (25, 50 or 75 kg) suspended in the middle of the span. The recordings of the stresses at the anchorings of the tower and of the amplitude of the oscillations made it possible to compare the self-damping coefficients of these conductors.

Thus, a conductor constituted of 2 layers of Z-wires dampens itself 2 to 3 times faster than a conventional conductor in both bending and twisting oscillations.

3.4. Galloping

Moreover, the better damping of the AERO-Z® conductor in vertical and twisting self-damping significantly reduces complex galloping problems. The probability of galloping is thus much lower, and if it does occur, its amplitude is substantially smaller.

On-site observations of the galloping behaviours of AERO-Z® have confirmed the result of the wind tunnel tests performed on the first-generation compact conductor [1].

3.5. Snow and frost accretion

On-site experiments demonstrated that the AERO-Z® conductor also behaves better vis-à-vis snow and frost accretion. The formation of sleeves is rendered more difficult, even impossible. On average, the weight of the sleeve is one-half for the extreme conditions.

Furthermore, one should note that sleeves which do form detach more rapidly.

4. USE OF AERO-Z® CONDUCTORS IN BELGIUM

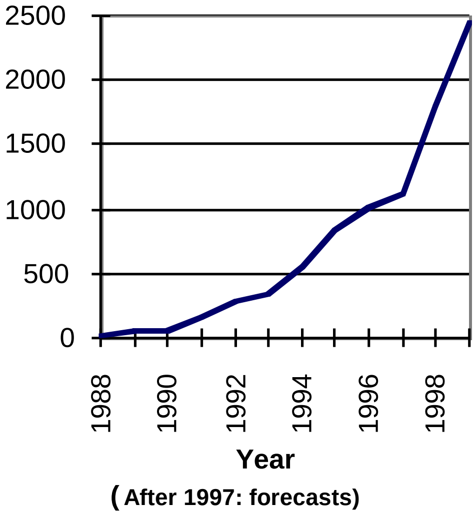
Given the important advantages linked to these AERO-Z® conductors and the good first returns of experience on overhead lines in the 1970's and 80's, the Belgian utilities decided at the beginning of the 90's to install them generally.

This led in 1991 and 1992 to the realisation of 5 links with this type of conductor. Even if the total length of AERO-Z® installed during these years amounted to only about 200 km, this represented 60 % of the commissioned lengths in those years.

At the end of 1997, the total installed AERO-Z® conductor length is over 1000 km.

For 1999, a total length of around 2500 km is scheduled (see figure 4).

Figure 4



II. PART TWO : OPTICAL GROUND WIRE (OPGW)

1. INTRODUCTION

To meet the growing needs for information transit between the various points of the network as well as the obligation made to the Belgian utilities to abandon the range of frequencies which had been attributed to them for the Hertzian network, the Belgian electricity sector decided to develop a new telecommunication network based on optical fibre technology.

Thus, for several years now already, providing optical links has been systematically examined for all new projects and rehabilitation of overhead lines or underground cables.

Because a significant part of this new telecommunication network uses the existing overhead lines, it was necessary to design an overhead conductor with integrated optical fibres adapted to this particular situation.

2. THE PROBLEMATIC OF OVERHEAD CONDUCTORS WITH OPTICAL FIBRES

2.1. Technology selected

Among the various technologies available making it possible to install optical fibres on existing lines, the Belgian electricity sector decided to use almost exclusively optical ground wires (OPGW) : both as ground wire for new lines and as replacement of ground wire(s) for existing lines. They thus play simultaneously the conventional role of ground wire and the role of information medium.

This choice was based on two essential criteria :

- guaranteeing the reliability of the electrical function and of the information medium;
- avoiding or reducing to a minimum the increase of stresses on the tower and therefore the tower reinforcements.

2.2. Requirements on overhead conductors with integrated optical fibres

Just like a conventional ground wire, OPGW must play a protective role vis-à-vis the phase conductors and thus have a useful conducting cross-section area able to support the imposed short-circuit current and the lightning stresses.

Furthermore, and above all in case of replacement of ground wires on existing lines, it is important to limit the external diameter in order to meet the previously defined criteria (§2.1).

In addition, like any metal overhead conductor suspended between two towers, its stress and elongation constantly vary according to the climatic conditions (temperature, wind, frost load). The influence of conductor length variations on the optical fibres must therefore be taken into account.

Two approaches can be considered :

- the optical fibres are tightly buffered to the metal elements of the wire. In this case, elongation of the wire inevitably leads to elongation of the optical fibres. It is therefore imperative that the elongation of the ground wire be limited so that, even under the most unfavourable use conditions, the elongation of the optical fibres remains below an acceptable value;
- the optical fibres are completely free within the conductor. The loose buffering is such that, under the most unfavourable use conditions, the stresses within the conductor do not mechanically stress the optical fibres. There is thus no risk of short- or medium-term breakage of the fibres due to variations in elongation of the conductor itself. For this type of conductor, the notion of ‘strain margin’ is fundamental. It is defined as the maximum value of the strain of the complete conductor beyond which the fibres are placed under tensile stress. The higher this margin, the more the fibres are mechanically loosely buffered to the conductor.

The Belgian electricity sector ultimately chose the second approach because, after testing, it proved possible to have a strain margin corresponding to more than 60 % of the breaking load of the conductor, i.e. a load well beyond the normal and exceptional service stresses.

3. DESIGN OF THE GROUND WIRES

3.1. Optical core

The optical core is constituted of a central element in aluminium with 4 slots, each containing a synthetic tube inside of which are located 12 fibres.

The optical fibres are free within the tubes and are stranded with a controlled overlength. This, together with a judicious choice of the diameter of the tubes and their stranding characteristics (length and radius of the lay), makes it possible to guarantee that no mechanical stress will appear on the fibres even when the ground wire encounters exceptional loads during its service life.

Protection of the optical fibres against moisture was considered under many aspects. On the basis of the information available, it was decided to ensure the watertightness with three components : the thixotropic gel surrounding the optical fibres, the polyamide tube and the grease covering the polyamide tube. This design appears to be the best compromise between guaranteeing that the fibre will never be subject to tensile stress and protecting it against moisture.

The watertightness was then further reinforced by use of Z-shaped wires in the outer layer of the armouring layers, according to the AERO-Z® conductors technique presented above.

3.2. Armouring layer

3.2.1. Number of outer layers of wires

The first generation of OPGW installed on the Belgian network include an optical core protected by a single layer of metal wires. Although the conductor thus had the smallest diameter, all other things being equal, this structure rapidly revealed two major drawbacks :

- this conductor with a single-layer of armouring, presents a high torque value during stringing. The use of an anti-twist device is therefore required. It renders this operation very delicate; this device has even caused damage to the external layer;
- tests performed on conductors of the Belgian network, corroborated by the results of similar tests done abroad, demonstrated that protection of the optical core against a lightning strike is much better achieved by the choice of two layers of wires associated to respect of a minimum wire diameter for the armouring layer.

In 1995, a second generation of OPGW was thus developed in order to meet the above requirements. This time, the armouring layer consisted of two layers of wires stranded in opposite directions.

3.2.2. Composition of the outer layers of wires

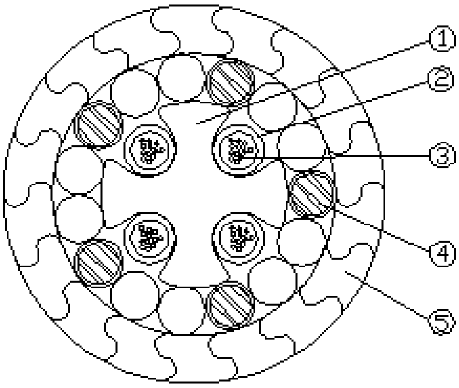
The second generation with double outer layer has itself undergone two major successive developments :

- the first generation : the OPGW 225/31 consists of an outer layer of 21 round wires in aluminium alloy and an inner layer of 15 round wires, of which 10 are in aluminium alloy and 5 in aluminium-clad steel. The strain margin of this variant was first 0.5 %, then 0.7 % following adaptation of the stranding characteristics of the slots;

- the second generation : the OPGW 253/31 developed in 1996 consists of an optical part identical to the preceding one, of an outer layer of 18 Z-shaped wires in aluminium alloy and an inner layer of 15 round wires, of which 10 are in aluminium alloy and 5 in aluminium-clad steel. The AERO-Z® thus obtained had the same diameter as the conductor of the first generation in order to keep the same fitting materials (figure 5).

The fact of providing the steel wires in the inner layer results from lightning tests. Because a lightning strike can break several wires of the outer layer, the remnant mechanical strength is always higher if the steel wires are in the inner layer, where they are less likely to be affected.

Let us note also that the composition of the two layers of the metal armouring layer (aluminium-clad steel wires inside, aluminium alloy wires on the outside) means that the twisting torques of the two layers are equivalent and that the conductor thus obtained is virtually inert.



1. Aluminium slotted core
2. Thermoplastic tube (PA)
3. Optical fibres (4 x 12)
4. Aluminium-Clad Steel wires
5. All Aluminium Alloy wires

Figure 5 - Cross-section of an OPGW 253/31-1Z wire (48 optical fibres)

3.2.3. Role and structure of the steel wires

The role of the aluminium-clad steel wires is to limit the elongation of the conductor for a given stress.

The aluminium-clad steel wires were chosen rather than the galvanised steel wires for two reasons :

- to achieve better resistance over time against corrosion;
- to avoid a galvanic corrosion reaction between the zinc and the aluminium.

4. TESTS PERFORMED, MEASUREMENT METHODOLOGY AND COMPARISON BETWEEN THE OPGW 225/31 (STRANDED) AND THE OPGW 253/31-1Z (AERO-Z®)

4.1. General

The specifications which guided the tests performed on the conductors were inspired by the draft IEC standard 1396 [6].

The two tests regarded as being the most critical were the stress-strain test and the sheave test (passage of the conductor on pulleys). The first test was intended to analyse all the phenomena to which the conductor and above all the optical fibres were subjected while tensile stresses are applied to the conductor. The second test was intended to verify that the stringing of a conductor even in the most severe conditions would not affect the optical fibres.

However, other tests were also performed : notably the lightning test already mentioned above and which is intended to study the behaviour of the conductor during a lightning strike, the short-circuit test, as well as the torsion, repeated bending, impact and crushing tests. Tests of aeolian vibrations and thermal cycles were also performed.

The compatibility of the conductor with the accessories and their fitting on the towers were tested and validated.

As in Belgium, the overhead conductors are systematically strung under mechanical load, the OPGW 225/31 and 253/31-1Z were also subject to a stringing test under these conditions, between two worksite bullwheel pullers and tensioners. These tests were intended to verify the inert character of the conductor when twisted and the behaviour of the conductor during pulling (formation of bird cages).

4.2. Measurement methodology

At the outset, it appeared that the optical fibres could be perfectly verified by means of an Optical Time Domain Reflectometer (OTDR). This method, based on the attenuation of the fibres, provides a graph representing the local condition in terms of punctual attenuation of the optical fibre at each point along the entire length measured, as well as an overall attenuation value. This value is an integration of all the local attenuation measurements. This measurement method offers the significant advantage that it only needs to have access to a single end of the fibre to verify and that it can reveal the importance of a local defect which creates a punctual attenuation.

However, it rapidly became apparent that OTDR is not enough to identify all the phenomena involved, nor to ensure that the optical fibre was not in any way subject to mechanical stresses.

Further investigations thus demonstrated that not all the stresses acting on the optical fibres are revealed by OTDR. In fact, it is essentially the macroscopic and microscopic bending stresses and the micro-cracks in the optical fibres which create optical losses detectable by the reflectometer. By contrast, up to a certain limit, the tensile stresses do not cause punctual attenuation. Reflectometry which only measures the attenuation thus cannot reveal the limit load in the conductor beyond which the optical fibres are submitted to stress.

To meet this objective, the method based on the principle of phase variation in the optical fibre was used. This method consists of a very precise measurement of the optical path, thus of the length of the optical fibre. By comparing the signal injected with the one received at the outlet of a fibre, it is possible to measure this “phase variation” and to deduce from it the beginning of the elongation due to overall tensile stress. Given the sensitivity of the measurement, one must compensate for the effect of temperature. It is thus possible to detect the tensile stresses on the fibres well before additional attenuation becomes perceptible.

4.3. Comparison of OPGW 253/31-1Z (AERO-Z®) and OPGW 225/31 (stranded)

The different tests performed on these two types lead to the following observations.

4.3.1. Watertightness of the conductor

The overlapping of the Z-wires confers on the outer layer a "tubular" structure which concretely plays a barrier role affording additional watertightness. Moreover, this effect was at the basis of the development of this type of conductor.

4.3.2. Mechanical aspect

By its design, the AERO-Z® OPGW can absorb greater tensile strengths than the conventional OPGW before attaining the limit of its strain margin;

The OPGW 253/31-1Z presents a lower drag coefficient under high wind. This reduces the stresses on the towers by nearly 17 % under exceptional wind loads (175 km/h at 10 meters above the ground) compared to the stresses under the same wind for the OPGW 225/31.

4.3.3. Electrical aspect

Electrically, the AERO-Z® OPGW presents a higher useful conducting cross-section area for a same diameter. Thus, under identical heating, it can accept a 12 % higher short-circuit current, or again, for a given short-circuit, the temperature of the conductor rises less than that of the conventional OPGW under the same circumstances; the reduction is on the order of 15°C.

4.3.4. Other aspects

The AERO-Z® OPGW presents, like any AERO-Z® conductor, interesting characteristics in the following areas : corrosion, undestrandability, self-damping, behaviour under galloping, snow and frost accretion.

III. CONCLUSION

Initially designed to solve the cases of long spans across rivers, a compact conductor has been developed in Belgium since 1970.

This was the origin of the AERO-Z® conductor, whose general characteristics and notably its higher ampacity and lower drag coefficient vis-à-vis conventional stranded conductors led the Belgian utilities to generalise its use.

These same overall features also led to the development of a compact OPGW.

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