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Recent Overhead Transmission Line Technology and Environmental Measures

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Design of alternative composite core conductors for new overhead lines

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SUMMARY

When one thinks about a perfect material for supporting bare overhead conductors, one wants something very light to reduce loads on the towers, something thermally stable to reduce sag at high temperature, something strong to handle high wind events, something stiff to reduce sag during high snow events and something chemically stable to resist corrosion in coastal or industrial areas. Carbon fiber composites cores have all these properties but so far, they have been used in HTLS (High Temperature Low Sag) conductors for only 20 years. According to CIGRE TB 695, HTLS type 4 conductors are between 2 and 3 times more expensive than conventional conductors such as ACSR. However, thanks to excellent carbon fiber properties in combination with annealed aluminium, they offer two benefits for reconductoring projects: first, the possibility to double the ampacity on existing lines thanks to a higher operating temperature, and second, the possibility to reduce losses thanks to a higher aluminium cross section without any weight increase compared with previously installed ACSR conductors. The extra cost is justified by a faster project timeline and substantial savings during the conductor life.

However, many other conductor designs can be imagined in order to answer other utilities challenges such as more efficient and sustainable new overhead lines. Polymer Matrix Composite (PMC) cores are made of a mix of fibers (carbon and glass) and polymer matrix (epoxy, vinyl ester, etc). By selecting different grades of fibers, polymer matrix, and fiber/matrix proportions, different levels of performance and price can be reached. In combination with different aluminium (A1, A3, AT1, AT2), the purpose of this paper is to detail some alternative conductor designs for new overhead lines.

First, this paper will review the different grades of fibers and matrix, listing their different pros and cons and the existing applications where they are currently used. Then, it will explain how a good cohesion can be ensured between fiber and matrix in order to achieve a composite core taking full advantage of both components properties. Based on different aluminium properties such as thermal limits and elongation at break, new composite cores are designed to fit these limitations and ultimately obtain new conductors which are as competitive and efficient as possible. Such new conductor designs will be described in details. Even if these conductors cannot operate at high temperature, their low weight, corrosion resistance and good mechanical properties in combination with a more competitive price make them ideal candidates for new lines where foundations can be smaller and less reinforced towers can be used, making these new lines projects faster and cheaper.

KEYWORDS
Composite Core – Conductor – Efficiency - New Lines

1 Introduction

Carbon fibers have been industrialized in the 1950's by Japanese and United States companies, by carbonizing textile threads. In the 1960's [1], a new precursor is developed, the PAN (Poly Acrylonitrile) which improved properties and reduced costs. This new carbon fiber almost purely made of carbon atoms has outstanding properties: less creep, excellent fatigue performance, very low weight, high tensile strength, corrosion free, no thermal expansion etc.
However, this anisotropic material made of thousands of microfilaments needs to be assembled with a matrix in order to be used in most applications. This matrix is generally polymeric, linking the carbon filaments to each other's. For a long time, until the years 2000's, carbon fiber composites have been used in high tech applications such as aerospace and military. This material is now used in a wide range of application where it has been proven that the extra cost is justified by major benefits. Two emblematic markets are wind blade sparcaps, enabling the manufacturing of blades longer than 50m, and cores for overhead conductors.

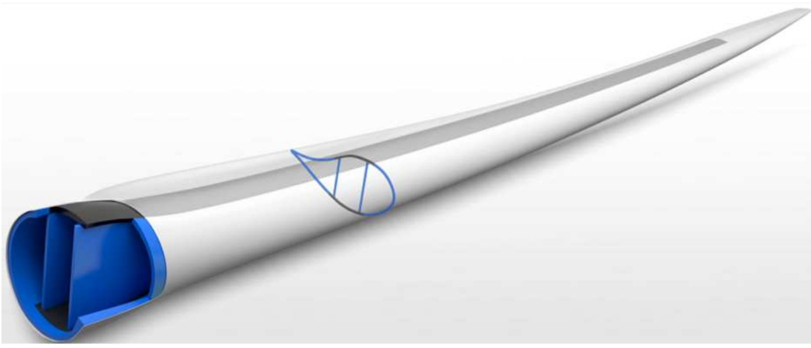

Figure 1: Spar cap (in black) of a wind blade

In bare overhead conductors, so far, composite cores have been designed to be operated at high temperature thanks to their very low coefficient of thermal expansion. Most of the time, it is used in combination with an annealed aluminum, meaning that the carbon fiber needs to be a high strength grade to compensate annealed aluminum low tensile property. In addition, operating at such high temperature requires a high glass transition temperature (see section 2.2) which is as well expensive. By reviewing the different type of fibers and matrix existing today on the market, a cost efficient composite core conductor is proposed.

2 Review of the different grades of fibers and matrix

2.1. Fibers

In the composite industry, four main types of fibers are used nowadays:

- Glass fibers, the most cost efficient, produced by melting silica. Based on its composition, different grades can be produced to increase some properties such as resistance to corrosion, tensile strength, etc [2]. Its global insulating properties combined with good mechanical and weight performance make it an ideal candidate for electrical applications, for example rods for insulators. However, its low modulus of elasticity is a disadvantage for some applications like overhead conductors.

- Aramid fibers, this synthetic fiber is mainly made of amide groups –NH-CO-. Based on the exact composition of the polymer, there are two kinds of aramid fibers: meta-aramid and para-aramid. Its excellent resistance to impact and fire makes it very popular for aerospace and military applications (resistance to bullets). It is often used in hybrid composite to protect carbon from impacts. A large range of references exists with different properties. The fiber water uptake is a point of attention during the design of the composite [3].

- Basalt fibers produced by melting crushed volcanic rock, have properties close to glass fibers. However, the control on exact initial chemical composition is less accurate based on the raw material .Its resistance to fire is an interesting property [4].

- Carbon fibers: as described in the introduction, the most common carbon fibers are made from the carbonization of PAN fiber. However, a mesophase pitch can also be used as a precursor [1]. This other grade is having very high tensile modulus but a lower tensile strength. Its price is also increased.

Table 1: Comparison between different type of fibers (it is average value, a wide range of reference exist for each type) [3][4]

	Glass fibers ECR	**Basalt fibers**	**Para-aramid fibers**	**Carbon fibers PAN**	**Carbon fibers PITCH**
Density	2.6	2.8	1.44	1.8	2.1
Tensile strength	≈ 3000 MPa	≈ 3000 MPa	≈ 3000 MPa	≈ 4000 - 5000 MPa	≈ 3000 MPa
Elongation at break	4.6 %	3 %	2.4 %	≈ 2 %	≈ 1 %
Modulus of Elasticity	80 GPa	90 GPa	120 GPa	200 - 250 GPa	400 - 700 GPa
CTE	6×10^{-6} K^{-1}	8×10^{-6} K^{-1}	-2×10^{-6} K^{-1}	-0.6 - 0.2 $\times 10^{-6}$ K^{-1}	- 1.2 – 0.1 $\times 10^{-6}$ K^{-1}
Cost	$	$	$$$$$	$$$	$$$$

Most of these fibers are covered by a sizing agent, a thin layer (< 1 µm) of a chemical component having two purpose:

- Protecting filaments against friction during the manufacturing process.
- Enhance adhesion between filaments and matrix by creating a strong chemical bond.

2.2. Polymeric matrix

Two main different kinds of polymeric matrix exist for composites:

- Thermoplastics: it is defined by its long polymer chains without strong cross -links between each other. This amorphous structure makes the material fully shapeable above a certain temperature called glass transition (Tg). Some thermoplastics are semi-crystalline, meaning that some chains are stacked and organized as a crytals. This structure brings higher thermo-mechanical properties to the polymer. Even above Tg, the crystalline parts strengthen the polymer. Melting point is the temperature at which the crystalline phase will melt and the polymer become fully viscous, it is always higher than Tg. However, from a production point of view, the high viscosity of a melted thermoplastic explain why most of the PMC are today made of thermoset.

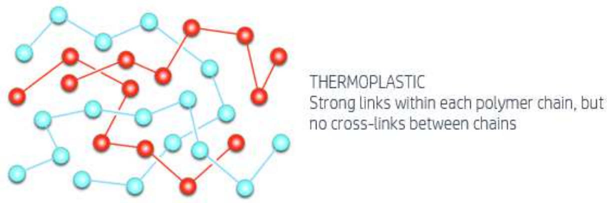

Figure 2: Schema of a thermoplastic matrix

- Thermosets: this type of matrix is usually made from a mix of liquid monomer base and a liquid monomer hardener. Under the effect of temperature, a chemical reaction between both components create a reticulated network with strong (covalent) bonding between each macromolecules (chains). As for thermoplastics, thermoset matrix have a Tg which represents the transition between a glassy state and a rubbery state based on the reversible breaking of secondary bonding between macromolecules (chains) induced by temperature. The covalent bonding of the network still exists above the Tg, explaining why thermoset resin are not shapeable like thermoplastics at such temperature.

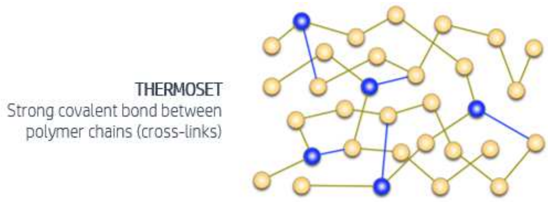

Figure 3: Schema of a thermoset matrix

Neither types are sensitive to corrosion, however ageing phenomenon resulting in breaking of covalent bonding such as thermolysis (effect of temperature) and hydrolysis (effect of water) [5] must be assessed.

Different kind of chemistry exist within the thermoset family (table 2). The cost of the matrix is usually linked to its temperature resistance. Epoxy is today the best compromise between performance, prices and process ability in pultrusion for composite cores.

Table 2: Properties comparison between different types of thermoset matrix [4]

	Polyester	**Vinyl ester**	**Epoxide**	**Polyimide**	**Phenolic**
Density	1.2	1.1	1.1 – 1.4	1.4 – 1.5	1.3
Modulus of elasticity	2.9 – 3.1 GPa	3.4 – 3.5 GPa	3 GPa	4 – 20 GPa	3.8 – 7 GPa
Tensile strength	50 – 60 MPa	70 – 85 MPa	50 - 120 MPa	30 – 40 MPa	50 MPa
Elongation at break	2 – 3 %	2 – 5 %	3 – 8 %	< 1 %	1 – 1.5 %
Maximum operating temperature	120 °C	100 – 140 °C	150 – 200°C	250 -300 °C	120 – 150 °C

3 Manufacturing of composite cores and resulting properties

3.1. Manufacturing process

Pultrusion is today the fastest way to produce unidirectional composites by impregnating fibers in a liquid resin (mostly thermoset) and curing it in a heated die. This continuous process allows the production of a constant section for kilometers. At the curing stage in the die, the very high pressure induced by an excess of resin (> 10 bars) is having two advantages:

- Very low porosities
- High V_f (fiber volume fraction). When the other composite processes as hand laying or filament winding are limited to below 60%, pultrusion reaches 70%, making the mechanical properties of the composite higher (see section 3.2.1).

3.2. Composite properties

3.2.1. ILSS (Interlaminar Shear Stress)

A "good" composite is dependent on the bonding between fibers and matrix. The first aspect to consider is the chemical match between the fiber sizing and the matrix. A chemical mismatch would lead in a poor composite. The second important aspect is the curing of the composite: being too hot or too cold could lead to a weak bonding in the meso phase (volume surrounding the fibers being a mix of matrix and sizing).

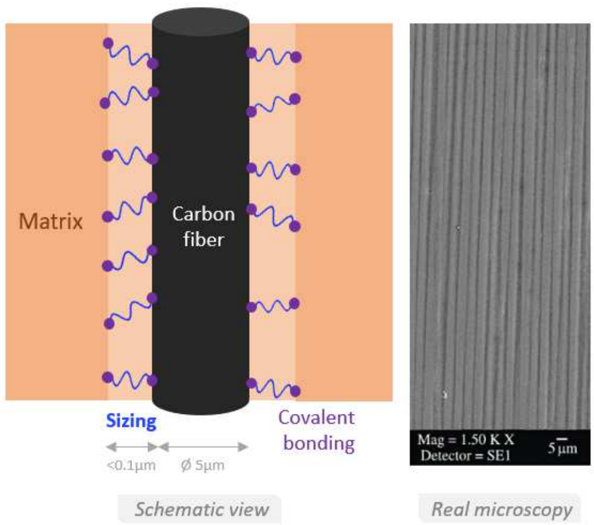

Figure 4: Schema of mesophase of a carbon filament in a PMC

In order to test the adhesion between matrix and fibers, a simple test exists: a short beam shear test also called ILSS (Interlaminar Shear Strength) defined for example in ASTM D4475 for pultruded rods. The result of this test is a shear stress which is proportional to the bonding between fiber and matrix. When off axis loads are applied on the rod, the bonding fiber/matrix becomes very important to ensure a good load transfer. Torsion and bending during installation or transverse compression in dead ends and mid span joints are good examples of such loads.

3.2.2. Glass transition Tg

To be sure to reach 100% of the targeted matrix Tg, two parameters must be closely looked at during production:

- Base/hardener proportion: a wrong balance would lead to unreacted base or hardener monomers. The molecular network would be then unbalanced with a lower Tg than expected.
- Curing: an insufficient temperature in the die would not initiate the monomers polymerization. A temperature too high would start thermolysis.

During lifetime, ageing phenomenon mentioned in section 2.2 also reduce the Tg.

The transition from glassy state to vitreous state is usually broad (10°C-20°C), different Tg can be measured based on Dynamic Mechanical Analysis (DMA) technic. It is usually recommended to have a Tg at least 25°C above the maximum continuous operating temperature to be sure that the composite operates in the glassy state.

3.2.3. Tensile

Mechanical properties are usually calculated using a simple rule mixture between fibers and matrix:

- *Modulus of elasticity:*

$$E_{composite} = E_{fiber} \times V_f$$

Mechanical properties of the matrix being very small in comparison with carbon fibers, only the V_f can be considered. In composites, modulus of elasticity is usually linked to the fibers straightness. In the case of pultrusion, fibers being pulled during curing, the alignment is almost perfect and no reduction of the modulus of elasticity is expected.

- *Tensile strength:*

$$\sigma_{composite} = (\sigma_{fiber} \times V_f)$$

For tensile strength, the formula above is valid only if 100% efficiency is reached.
However, efficiency for tensile strength is dependent on the way the manufacturer is guiding and impregnating the fibers. A wrong handling would result in damaged filaments leading to reduced tensile strength.

- *Elongation at break:*

The elongation at break of the composite is the lowest one between fiber and matrix.

4 New cores designs in accordance with different aluminum grades

To design a conductor with the same weight as ACSR but a reduced price, the right combination of aluminum and composite core must be selected.

4.1. Aluminum grades

To be cost efficient, an aluminum limited to 90°C needs to be selected. However, between A1 and A3 aluminum, the A1 aluminum has a higher conductivity, which is an important criteria to design an efficient conductor with low losses. As shown in the table 3, A1 aluminum has a higher tensile strength than AL0. However, aluminum elongation at break must be taken cautiously.

Table 3: Different aluminum used in bare aluminum conductors [5]

IEC designation	Tensile strength (MPa)	Conductivity (% IACS)	Max continuous operating T°	Elongation at break (%)
A1	160 to 200	61	90 °C	No requirement (between 1 and 2.5)
A3	320	52.5	90 °C	>3.0 (max 8)
AT1	159 to 169	60	150 °C	>1.5 (max 3)
AT2	225 to 248	55	150 °C	>1.5 (max 3)
AT3	159 to 176	60	210 °C	>1.5 (max 3)
AT4	159 to 169	58	230 °C	>1.5 (max 3)
AL0	60 to 95	63	230 °C	> 20

4.2. Core design

By selecting an aluminum A1, the composite core can be designed as follow:

- Tg: the minimum Tg needs to be at 115°C to respect a gap of 25°C between maximum continuous operating temperature and Tg. In this aspect, different matrix can be selected: polyester, vinylester or standardTg epoxy. These three chemistry having a lower Tg, curing can be faster in pultrusion, meaning that production speed can be higher, reducing the cost. In addition, they also cost less than high Tg epoxy used in HTLS conductors. A closer analysis on polyester and vinylester mechanical properties needs to be performed to be sure they meet field requirements.

- Tensile strength: A1 aluminum having a tensile strength almost 3 times higher than AL0, a carbon fiber with a lower tensile strength can be selected. In figure 5, the same graphic shows all the carbon fibers available in the market (both PAN and pitch precursors). In the red circle, are all = eligible ones, to be combined with A1.

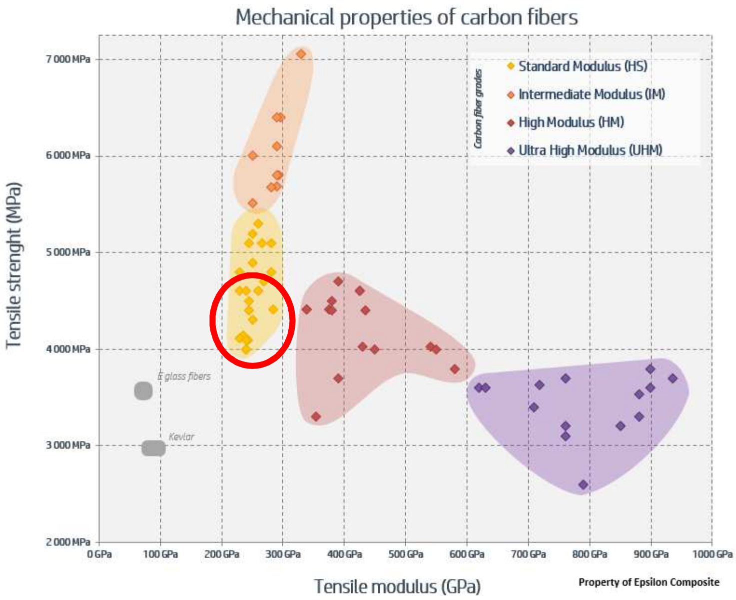

Figure 5: Graph of the different carbon fibers on the market based on their tensile strength and tensile modulus

- Modulus of elasticity :

  By selecting an aluminum with a lower elongation at break, it is very likely that aluminum will break before the composite core. That is why only the tensile stress at 1% elongation (and not the tensile strength of the core) can be considered. Composite cores being fully elastic, the stress at 1% elongation is very easy to calculate:

$$\sigma_{at\ \ 1\%}(MPa) = \ E_{composite}(MPa) \times 0.01$$

  The tensile modulus of the selected carbon fiber is around 235 GPa, however the idea would be to design a more flexible composite core. In that sense, glass fibers can be used, which also provides a galvanic protection layer between carbon and aluminum.

$$E_{composite} = E_{glass\ \ fiber} \times V_{gf} + \ E_{carbon\ \ fiber} \times V_{cf}$$
$$E_{composite} = 80 \times 0.42 + \ 235 \times 0.28$$
$$E_{composite} = 100\ \ GPa$$

- ILSS :

  ILSS properties cannot be anticipated as they depend a lot on the production parameters and chemical compatibility between matrix and sizing (sizing chemical composition is not shared by fiber suppliers). Therefore, it needs to be assessed after the first prototype produced.

Based on the selected glass/carbon ratio, table 4 summarizes the core properties:

Table 4: Properties for the new composite core design

Modulus of elasticity	100 GPa
Stress at 1% elongation	1 000 MPa
Coefficient of thermal expansion	2.3
Density	1.95
Tg minimum	115 °C

5 New conductor design

In the table 5, a conductor design is proposed with a conductor diameter of 21.8 mm and a core diameter of 6.6 mm. In addition to the excellent corrosion resistance of composite cores, many benefits can be seen in table 5:

- Weight: similar to ACSR.
- CTE: higher than ACSR because of aluminum cross section. However, it is lower than full aluminum solutions.
- Tensile strength: equivalent to ACSR
- Modulus of elasticity: in between ACSR and full aluminum solutions
- Ampacity at 90°C: in comparison with ACSR, it offers a 15% additional capacity.
- DC Resistance and Joules losses: among all solutions, it is the one with the lowest losses, which justifies the extra cost by a return of investment calculation.

Table 5: Comparison between the new design and other type 0 solutions

Solutions	**ACSR**	**AACSR**	**AAC**	**AAAC**	**ACAR**	**Aero-Z**	**Proposed design**
Ø conductor	21.84 mm	21.84 mm	21.8 mm	21.84 mm	21.84 mm	21.7 mm	21.8 mm
Cross section	Alu : 243 mm² Steel : 39.5 mm²	Alu : 243 mm² Steel : 39.5 mm²	Alu : 282.9 mm²	Alu : 282.9 mm²	Alu : 282.5 mm²	Alu : 324 mm²	Alu : 321 mm² Comp. : 34.2 mm²
Linear weight	980 kg/km	980 kg/km	780 kg/km	780 kg/km	778.5 kg/km	898 kg/km	955 kg/km
CTE	18.9 x 10-6/°C	18.9 x 10-6/°C	23×10^{-6} m/°C	23×10^{-6} m/°C	23×10^{-6} m/°C	23×10^{-6} m/°C	19.9×10^{-6} m/°C
Tensile strength	85.1 kN	116.7 kN	46.7 kN	83.45 kN	51.75 kN	95.57 kN	86 kN
Modulus of Elasticity	77 GPa	77 GPa	57 GPa	57 GPa	57 GPa	57 GPa	64 GPa
DC resistance at 20°C	0.1188 Ω/km	0.1368 Ω/km	0.0999 Ω/km	0.1150 Ω/km	0.1019 Ω/km	0.1030 Ω/km	0.0900 Ω/km
Ampacity at 90°C	706 A	664 A	764 A	721 A	759 A	761 A	804 A
Losses by Joules effect at 650 Amps	64 W/m	72 W/m	52 W/m	60 W/m	53 W/m	53 W/m	47 W/m
Price base (100)	100	110	90	110	110	130	160

Another approach can be considered for new lines. By selecting an equivalent DC resistance ACSR conductor, table 6 shows that the weight is reduced by 30% and the diameter is reduced by 13%. Such reductions allows an optimized design of towers and foundations, thus reducing the price of the installation, as conductors and fittings prices would be equivalent.
However, the tensile strength is 23% lower. A detailed sag analysis is needed. If the tensile strength is too low, different strategies can be used to improve it: increase the carbon glass ratio, or consider a higher elongation at break for aluminium. This analysis will be the topic of a separate paper.

Table 6: Comparison between new design and an equivalent DC resistance ACSR

Solutions	**ACSR**	**Proposed design**
Ø conductor	25.15 mm	21.8 mm
Aluminum cross section	321 mm²	321 mm²
DC resistance @ 20°C	0.0897 Ω/km	0.0900 Ω/km
Linear weight	1300 kg/km	955 kg/km
Tensile strength	112 kN	86 kN
Price	Same	

CONCLUSION

The different components of polymeric matrix composites have been reviewed and it shows that many opportunities are offered based on material selection and process optimization. A new "low" temperature conductor is defined, 50% cheaper than HTLS conductors yet offering the same weight benefits, and having a thermal limitation linked to aluminium annealing and not matrix ageing.

These benefits can be used in different scenarios: either reconductoring to replace old conductor by more efficient conductors with an increased capacity of 15%, or to reduce loads on towers for reconductoring and new lines with electrical losses equivalent to usual ACSR.

This design is just a proposition, by selecting other aluminium types, fibers and matrixes we can imagine different designs with different operating temperatures, different prices and different ampacity increase (between +15% and + 100%).

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