NEW GENERATION OF MICRO-ALLOYED COPPER CONDUCTORS TO FACE DISTRIBUTION SYSTEM OPERATORS CHALLENGES

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ABSTRACT

Distribution network operators are facing substantial and often contradictory challenges. A highly variable renewable energy supply and an increased focus on energy efficiency require the reinforcement of the grid. However, resistance to the construction of new lines has never been higher. Micro-alloyed copper conductors can be part of the solution. Their energy efficiency and their ability to cope with temporary capacity overloads are highly valued features. Such overloads are possible due to the higher resistance of copper against creep at high temperatures. The energy efficiency of the copper conductor compensates for its higher initial cost. As a result, the life cycle cost (LCC) of the micro-alloyed copper conductor is in the same range or lower than that of a steel reinforced aluminium (ACSR) conductor. This was the finding of two feasibility studies conducted by DNV GL (KEMA). The first study examined the construction of new lines; the second investigated the refurbishment of existing lines. The latter study also demonstrated why the higher specific weight of copper compared to an ACSR conductor does not require any reinforcement of the overhead line towers. Indeed, copper's mechanical strength makes a steel core superfluous and even more importantly, the smaller cross section combined with a hydrophobic coating, results in a much lower wind and ice load, which is a decisive factor for determining the required strength of the towers. This makes the copper conductor particularly suitable for overhead lines in cold and windy climates.

INTRODUCTION

The energy landscape is in full transition. Changing market structures combined with an increasingly distributed, variable and unpredictable type of power generation complicates electricity grid management. Transmission network operators are facing several substantial and even contradictory challenges.

Renewable energy power stations are often built in remote areas. New lines have to be built to connect them to the main grid and transport their production to the demand centers.

The growing share of renewable energy in power generation creates a **highly variable supply**. The grid is an important part of the solution to cope with this variability, since it enables the exchange of electrical energy from regions with a temporary surplus in supply to regions with a temporary peak in demand. It does however require reinforcement of the grid to cope with this new type of energy exchange.

Nevertheless, widespread **resistance to the construction of new overhead lines has never been higher**. The construction of such lines in heavily populated areas has always been a challenge. Today, the uncertainty concerning the impact of electro-magnetic radiation and increasingly stringent local regulations add to this challenge. In less populated areas, the process to gain permission for new overhead lines can be even more complicated because of their visual impact in areas of natural beauty, the necessity to protect bird populations in sensitive nature areas, or where the lines cross migration flyways. Due to the variable and unpredictable profile of renewable electricity production, transmission system operators are now more than ever forced **to run transmission lines at the limit of their capacity**. Line management would become far easier if spare capacity was available which could be used from time to time. At present however, operators are **limited by the maximum operational temperature** of the line conductor. Above this maximum temperature, the conductor material shows excessive creep and the mechanical integrity of the cable can no longer be guaranteed.

To make the situation even more difficult, there is an **increasing focus on the energy efficiency of transmission lines**. According to the IEA, the world consumes over 20,000 TWh of electricity each year, of which 7% (or 1,400 TWh per year) is lost in the wires used to supply this power. Reducing the transmission line losses by one third would reduce the annual CO2 emissions by 250 million tons . This is the equivalent of taking 50 million cars off the road. Such an improvement in energy efficiency would also replace the need for 60,000 MW of new generation capacity. For all of those reasons, regulators [1] are paying more and more attention to the energy efficiency of overhead lines and are shifting their main goal from minimizing investment cost to minimizing the life cycle cost of the networks (see article 15 of Energy Efficiency Directive in Europe). This, however, creates substantial additional challenges

for transmission network operators.

To cope with all of these challenges simultaneously, a conductor is needed that can replace the old conductors currently in use on existing rights of way. This would simultaneously increase the energy efficiency, the capacity, and the overload capacity of the line. The micro-alloyed copper conductor (CAC) answers all these needs. Overhead line conductors are traditionally the domain of aluminium, using either steel reinforced aluminium or aluminium alloys to achieve the required strength. Recognizing copper as a material for overhead lines may come as a surprise, since it is a substantially heavier material. That is in fact the primary reason its use declined several decades ago in favour of steel reinforced aluminium conductors. However, the material proposed in this paper is an **advanced alloy** rather than the copper ETP prevalent in the past. The proposed replacement offers all of the advantages of copper (high conductivity, resistance to corrosion) and addresses each of the drawbacks (mechanical and thermal strength) through micro alloying. Finally, it must be noted that weight is not the primary limiting factor for an overhead conductor, as we will explain later.

COMPARISON OF CONDUCTORS

The Dutch research and consultancy agency DNV GL specializes in energy and sustainability. The technical and financial differences between two types of steel reinforced aluminium conductors (ACSR) and the innovative micro-alloyed copper conductor (CAC) [2, 3] were carried out. Starting from a base case with a current carrying capacity of 630 A at 80 °C (ACSR Hawk), two cases of extra-sizing are analyzed: ACSR Eagle and CAC 185, both offering 700 A at 80 °C.

Figure 1 - Comparing three different types of overhead line conductors.

The initial investment cost for the conductors illustrated in Figure 2 (from left to right) rises, but the energy losses decrease. This paper will discuss how those reduced energy losses have a positive effect on the total Life cycle cost of the line for average loading conditions.

The basic technical characteristics of those three types of conductors are as follows:

	ACSR Hawk	ACSR Eagle	CAC 185
Cross section (mm2)	280	350	185
Current capacity at 80 °C (A)	630	700	700
Current capacity at 150 °C (A)	-	-	1115
Weight (kg/km)	982.3	1,301.8	1,652
Electrical resistance (Ohm/km)	0.1195	0.103	0.09
Tensile strength (kN)	85	123.6	93
Elasticity (kN/mm2)	77	81	32
Thermal expansion (1/°C)	0.0000189	0.0000178	0.000017
Max operational temp (°C)	80 °C	80 °C	150 °C

Table 1 – Basic characteristics of ACSR and CAC overhad line conductors

Note that the micro-alloyed copper conductor has a much smaller cross section for a similar level of current carrying capacity at a given operating temperature. Micro-alloyed copper exhibits sufficient mechanical strength without the necessity of additional steel reinforcement. Combined with the higher electrical conductivity of copper, this results in a far smaller conductor section for the same line capacity. This capacity per cross section is further enhanced due to the reduction of the skin effect. Indeed, in the copper CAC conductor, an insulating coating is applied to each separate wire inside the conductor, resulting in a current flowing through the central wires equal to those at the outside of the conductor. The higher conductivity of copper and lower skin effect also results in a reduction of the energy losses, as shown in Table 1. **The maximum operating temperature of the micro-alloyed copper conductor is much higher** than that of its ACSR counterparts.

At first glance, the higher weight and lower elasticity of the copper conductor may appear as disadvantages. In actual practice however, this is not the case because:

The strength of the towers for supporting overhead lines is not determined primarily by the weight of the conductor, but rather by resistance against forces created by wind and ice. The smaller cross section of the

conductor, the lower these forces will be (lower drag coefficient).

The high annealing temperature of copper (> 300 °C) makes it easier to apply surface coating on the copper conductor without being concerned about a potential change in the mechanical properties of the material. Hydrophobic surface coatings can prevent ice loading.

As a result, the micro-alloyed copper conductor becomes a technically feasible and financially attractive alternative to ACSR conductors.

The ability to apply a coating on the copper conductor also brings with it another advantage: it enables a surface treatment that **reduces corona losses** as well as energy losses and the associated noise levels. Corona losses can become a substantial source of irritation for passers-by, especially in wet climates, adding to the negative image of high voltage overhead lines.

Finally, the outstanding **corrosion resistance** of the copper alloy needs to be considered. The coatings on each individual wire of the conductor result in even stronger corrosion prevention. Copper conductors perform well in salty or polluted areas, where aluminium conductors tend to corrode easily.

ECONOMIC ANALYSIS

New lines with reduced Life Cycle Cost

The Dutch research and consultancy agency DNV GL specializes in energy and sustainability. The technical and financial differences between two types of steel reinforced aluminium conductors (ACSR) and the innovative micro-alloyed copper conductor (CAC) [2, 3] were carried out. Starting from a base case with a current carrying capacity of 630 A at 80 °C (ACSR Hawk), two cases of extra-sizing are analyzed: ACSR Eagle and CAC 185, both offering 700 A at 80 °C.

As mentioned earlier, European grid regulators have a growing need to reduce energy losses [1]. Consequently, their focus is shifting from minimizing the investment cost of new lines, to minimizing the entire life cycle cost of the line. This life cycle cost (LCC) consists of five distinctive considerations:

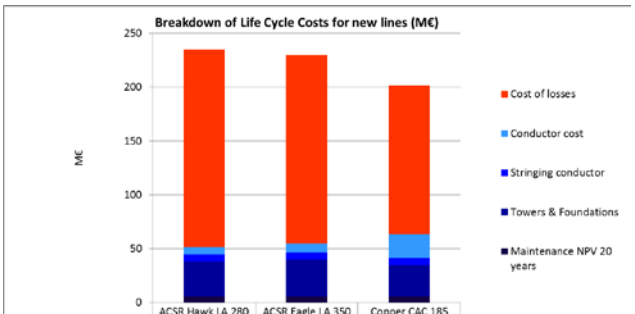
- Towers and foundations (supply and install)
- The conductor
- Stringing the conductor
- Operational maintenance
- Energy losses

The DNV GL [2] feasibility study calculated each of these costs for several different types of conductors and for different scenarios. In all of the scenarios, the energy losses represent by far the largest share of the LCC. Their share ranges between 40% and 80%, depending on the type of conductor, the duration of the life cycle, the load profile, and the electricity price.

Assume the following conditions:

- Load profile:
  - 100% of the full load 25% of the time
  - 80% of the full load 20% of the time
  - 40% of the full load 55% of the time
- Electricity price: 0.05€/kWh
- Life cycle duration: 20 years

Those assumptions lead to the following LCC calculations:



	ACSR Hawk LA 280	ACSR Eagle LA 350	Copper CAC 185
Cost of losses	183,5	174,9	138,0
Conductor cost	6,8	8,4	21,7
Stringing conductor	6,8	6,8	6,8
Towers & Foundations	32,3	33,9	29,2
Maintenance NPV 20 years	5,7	5,7	5,7

Figure 2 - Comparing the life cycle cost of a new line with a copper conductor and the same line with an ACSR conductor.

The micro-alloyed copper conductor is initially approximately three times more expensive than ACSR conductors are. But note that the conductor price represents only a small share of the total LCC. This higher investment cost is largely compensated for by the lower cost of energy losses (a reduction of at least 20%). As a result, the higher cost of the conductor is paid back in less than five years. The costs of stringing the conductor, of supplying and installing the towers, and of operational maintenance are of a similar order of magnitude for all three the conductor types. The total life cycle cost of the micro-alloyed copper conductor is reduced by 14.3% compared to ACSR Hawk.

Note that the energy losses in the conductor can also be reduced by increasing the cross section of the ACSR conductor, as it is the case with the ACSR Eagle compared to the ACSR Hawk. However, the loss reduction is not as substantial as with the micro-alloyed copper conductor. A significant portion of the investment

that is gained in this way is subsequently lost again because of the higher cost of towers and tower foundations. Indeed, the larger conductor cross section results in higher wind and ice loads, requiring tower reinforcements.

When all of the advantages of the micro-alloyed copper conductors are taken into account, they prove to be particularly well suited for linking new large-scale wind power generation parks to the main grid. A life cycle cost approach is normally used when assessing the economic feasibility of wind parks. In addition, the small cross section of the copper conductor make it a preferred choice in windy regions, as it limits the wind load and avoids the need to reinforce the towers. Finally, the fact that copper conductors can be submitted to capacity overloads of up to 60% is a major advantage for transporting the variable output of the wind park to the main grid.

Similar advantages can be observed in areas with severe weather conditions and in corrosive atmospheres.

Competitive upgrade of existing lines

For the refurbishment of an existing line with new conductors, the life cycle cost (LCC) consists of only four factors:

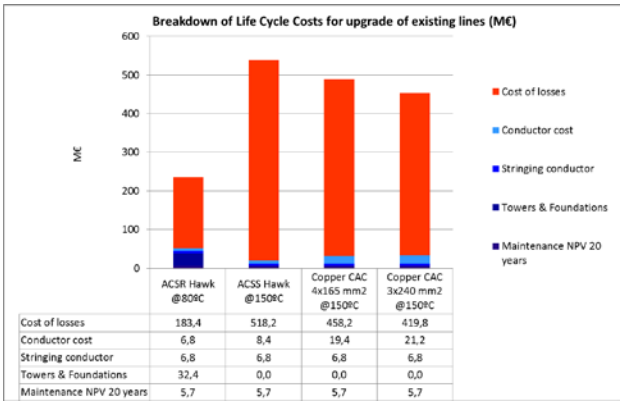
- The conductor
- Stringing the conductor
- Operational maintenance
- Energy losses

In a second study by DNV GL [3], this Life Cycle Cost for a line upgrade was calculated for different scenarios. As could be expected, the energy losses represent an even larger share of the total LCC as in the case of a new line, ranging between 85 and 95% depending on the type of conductor, the duration of the life cycle, the load profile, and the electricity price.

Assuming again the following conditions:

- Load profile:
  - 100% of the full load 25% of the time
  - 80% of the full load 20% of the time
  - 40% of the full load 55% of the time
- Electricity price: 0.05€/kWh
- Life cycle duration: 20 years

They lead to the following LCC calculations for refurbishing a line with an ACSS Hawk or with a CAC-165 conductor:



	ACSR Hawk @80ºC	ACSS Hawk @150ºC	Copper CAC 4x165 mm2 @150ºC	Copper CAC 3x240 mm2 @150ºC
Cost of losses	183,4	518,2	458,2	419,8
Conductor cost	6,8	8,4	19,4	21,2
Stringing conductor	6,8	6,8	6,8	6,8
Towers & Foundations	32,4	0,0	0,0	0,0
Maintenance NPV 20 years	5,7	5,7	5,7	5,7

Figure 3 - Comparing the life cycle cost of a line refurbishment with a copper conductor and the same line refurbishment with an ACSS conductor.

The conductor losses of the CAC-165 are more than 10% lower than those of the ACSS HAWK. As a result, even though the initial investment is approximately 70% higher, the life cycle cost of the refurbishment with copper conductor is 8.5% lower compared to the refurbishment with an ACSS HAWK conductor. This advantage can increase up to 16% when using a different bundle configuration (3x240 mm2 instead of 4x165 mm2). Other conductor cross sections, load profiles, electricity prices, and life cycle durations lead to slightly different results, but with similar conclusions [2].

ADDITIONAL FEATURES

Better performance in extreme weather conditions

The international standard EN 50341—1:2001 [4] prescribes four categories of extreme weather conditions for which the performance of overhead lines should be tested:

- LC 1a—Extreme wind at design temperature (10 °C)
- LC 1b—Wind at minimum temperature (-20 °C)
- LC 2c—Unbalanced ice loads, different ice loads per span (-5 °C)
- LC 3—Combined wind and ice loads (-5 °C)

Micro-alloyed copper conductors have an advantage over ACSR conductors in all four of these categories. Because of the **smaller diameter**, the conductor will catch **less wind**. Thanks to the high annealing temperature of copper, several types of coating can be applied to the conductor without concerns regarding potential changes in the mechanical properties of the material. Coatings are available that make the conductor hydrophobic, thus **eliminating the risk of ice loads**.

These characteristics make the micro-alloyed copper conductors particularly suitable for overhead lines in cold, humid and windy climates.

Reduction of Corona losses

The Corona losses on high voltage line conductors represent only a minor share of the energy losses, but they result in a noise that is perceived as irritating by many people. Corona losses are particularly high in humid environments. Corona losses on micro-alloyed copper conductors are reduced due to the conductor coating, which drastically limits the impact on the human ear. This can be an important consideration in achieving acceptance for high voltage overhead lines in densely populated areas in a humid climate.

CONCLUSION

Micro-alloyed copper conductors offer an interesting alternative to steel reinforced aluminium conductors for high voltage overhead lines.

Although copper is a heavier material, the micro-alloyed copper conductor does not require reinforcement of the overhead line towers. Its mechanical strength makes a steel core superfluous. Even more importantly, the smaller cross section combined with a hydrophobic coating result in a much lower wind and ice load, which is a decisive factor for determining the required strength of the towers. This makes the copper conductor particularly well suited for overhead lines in cold and windy climates.

The lower electrical resistance of copper combined with a reduced skin effect result in significantly lower energy losses compared to ACSR conductors. Such energy losses comprise the main portion of the life cycle cost, especially for the refurbishment of a line, but for new lines as well. Consequently, even though the copper conductor requires a higher investment cost (approximately 70%), its life cycle cost will in many cases drop beneath that of ACSR conductors.

One of the most interesting features of the micro-alloyed copper conductor for overhead lines is the higher maximum operating temperature compared to that of ACSR conductors. This makes it possible to charge the conductor with overloads of at least 60% without compromising mechanical properties. Such an overload can help transmission network operators to comply with the N-1 safety criteria and to cope with periods of high renewable energy production.

REFERENCES

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[2] M.L.J. Clerx, DNV GL Energy & Sustainability: ‘New generation copper conductors for overhead lines/Feasibility Study’, M.L.J. Clerx, June 2013

[3] M.L.J. Clerx, DNV GL Energy & Sustainability: ‘New generation copper conductors for upgrading overhead lines/Feasibility Study’, August 2013

[4] CENELEC standard EN 50341 – 1:2001: http://www.cenelec.eu/dyn/www/f?p=104:110:63257080764913:::FSP_PROJECT,FSP_LANG_ID:155,25