COPPER IN COMPARISON WITH ALUMINIUM AS COMMON MATERIAL IN CONDUCTORS OF LV AND MV CABLES

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ABSTRACT

The European Copper Institute (ECI) requested DNV KEMA, now part of DNV GL, to investigate the position of copper versus aluminium in the application of LV and MV cable conductors, in particular paying attention to the decision model on how utilities select copper or aluminium.

The literature survey made clear that there seems to be more failure mechanisms related to aluminium conductor than to copper conductor.

The decision model shows price as a dominant factor to the advantage of aluminium. Other, less dominating factors, like connector problems, ease of installation of joints and repair are to the advantage of copper, while lower specific weight and the compatibility with other cables are to the advantage of aluminium.

The utility industry is currently too much focused on initial costs and insufficiently aware of the benefits of copper. The move from copper to aluminium may affect technical performance of distribution networks as well as total cost of ownership. The impact of conductor choice on technical and financial performance of electricity networks merits to be better understood.

INTRODUCTION

Nowadays there is discussion with respect to the selection of copper or aluminium as common conductor materials in power cables [13], [14], [15]. Next to price differences, each material has positive and negative characteristics that affect their use in various applications. Originally copper was the only conductor material used, later aluminium was introduced as a conductor material as well. Some utilities are in favour of copper, some utilities are increasingly using aluminium. Certain properties of aluminium are favourable above copper for certain applications.

By request of the European Copper Institute (ECI), DNV KEMA, now part of DNV GL was asked to investigate on what grounds distribution utilities decide to use copper or aluminium conductors in LV and MV cable networks.

A questionnaire was prepared that was sent to about 100 distribution utilities in 25 countries, to obtain accurate and reliable written information. The questionnaire consisted of three parts, of which only the third part on the decision model how to select copper or aluminium will be dealt with in this paper.

After giving summarized information on the typical properties of copper and aluminium conductors, information on failure mechanisms related to conductor material are given followed by the results of the questionnaire. Finally evaluation and conclusions are described, followed by a list of references.

CONDUCTORS USED IN LV AND MV POWER CABLE NETWORKS

Available conductors for LV and MV cables

The international cable industry provides cables with both stranded copper and stranded aluminium conductors, usually in round construction (fig. 1), but also sector shaped constructions. Some manufacturers also provide solid aluminium conductors (fig. 2).

Figure 1 Copper and aluminium stranded conductors

Figure 2 Aluminium solid conductor

Specifically for LV cables stranded and solid aluminium and stranded copper conductors are provided in round and sector shaped construction.

In [10] the nominal cross-sectional areas, in the range of

0.5 mm^2 to 2.500 mm^2 are specified. These conductors include solid and stranded, round and sector shaped copper and aluminium conductors in cables for fixed installations and flexible copper conductors.

Typical differences between Copper and Aluminium

Copper and Aluminium differ in many aspects [3][7]. As the density of aluminium is about one third of that of copper, for equal conductance the weight of the aluminium conductor material is almost halved. However the cross-sectional area has to be increased by a factor of 1.6 and this means extra usage of insulating material, sheathing material and armouring. Because of the smaller cross-section of copper conductor cables compared with aluminium conductor cables , copper conductor cables can be stored for a longer length on a cable reel or in a cable ship in case of submarine cable, resulting in the need of fewer joints. It is still worth recalling that copper conductor cable is more ductile and less susceptible to electrical contact problems and thus offers a greater margin of safety than a corresponding aluminium conductor cable. Due to its smaller cross-section, the copper cable will also be easier to install as the stiffness of the cable depends on the square of the cross-sectional area and thus on the fourth power of the diameter. It is also possible to get very small stranded copper cable; stranded aluminium cable is only available at nominal cross-sectional areas of at least 10 mm^2 and the individual strands are still very thick compared to those in the equivalent sized copper cable. For technical reasons mainly related to the degree of elongation, so called "finely stranded" and "extra finely stranded" conductors are only available in Copper (0.5 – 6 mm^2).

Another important piece of information to consider is the fact that copper cable is most commonly used for connecting offshore wind farms. This is because the cable needs to be heavy to provide a more stable structure in the soil. Furthermore, as mentioned before, copper is preferred due to its flexibility and thus its workability.

Copper and aluminium are both recyclable, to be used as conducting materials in cables again, In general copper conductors will be more pure than aluminium conductors, however even assuming that both materials will contain other elements, according to the metal wheel [2] recycling of copper delivers mostly recoverable materials, as for recycling of aluminium almost all of the other elements cannot be economically recovered. This will result in a lot of scrap material when recycling aluminium and besides making the recycling process for copper more economically attractive than for aluminium.

Typical comparative properties of aluminium relative to copper (assumed value is 100) are listed in Table 1 [8].

Table 1: Copper vs Aluminium – comparative material properties in the pure state

Material Properties	Comparative Values	
	Copper	Aluminium
Electrical resistivity	100	164
Density	100	30
Weight/unit resistance	100	53
Diameter/unit resistance	100	129
Elastic modulus	100	55
Hardness	100	44
Ultimate tensile stress	100	35
Melting point	100	61
Stress fatigue endurance limit	100	62
Thermal resistivity	100	158
Corrosiveness	1)	2)
Thermal expansion	100	135

1) Copper is resistant to most organic chemicals

2) Aluminium may corrode quickly

FAILURE MECHANISMS RELATED TO CONDUCTOR

General

The ageing mechanisms affecting cable conductors generally develop more slowly and are less likely to occur than insulation failures that account for the majority of cable failures [5]. Conductor failure is very rare in MV power cables where the wires are of large diameter. In LV cables, conductors are physically smaller diameter wires and can occasionally break from metal fatigue due to long term exposure to vibration or excessive handling and termination [6].

In the ageing of joints, the connector plays an important role. The connector that joins the conductors within a joint can be vulnerable to ageing and degradation mechanisms such as vibration, mechanical stress and thermal-mechanical cycling. These mechanisms can result in metal fatigue of the conductors and/or loosening of the connector. Ingress of moisture into the interior can cause corrosion and formation of oxides at the connector. This can cause increased electrical resistance and increased heating.

Failure mechanisms related to aluminium conductor

Specifically for aluminium cable conductor cables, three main issues have been collected which can lead to failures:

- **Chemical reaction between water and aluminium** [11]. If water comes into contact with aluminium a chemical reaction happens resulting in the development of hydrogen at relatively high pressure to magnitudes which are almost impossible to contain within existing joints or connectors. Additionally, increased partial discharge (PD) activity can occur due to interface deformation. This may turn to surface discharges (tracking) and subsequent failure.
- **Oxide layer on aluminium and corrosion**. Aluminium oxidizes readily when exposed to oxygen forming a thermodynamically and chemically stable situation. This insulating oxide layer is very thin (nanometer scale), however if not properly removed before applying a connector to connect wires to each other, an extra resistance will be created resulting in overheating. Galvanic corrosion is more important for aluminium when it comes into contact in an electrolyte with a more catholic metal like Fe, Ni, Pb, Sb, Cu etc. during a connection etc. and it is more susceptible to corrosion [4]. Copper is according to the arrangement of electrochemical potential much more precious than aluminium and will therefor only corrode when it is in contact with precious metals like Ni, Ag ,Pt. In [12] the results are presented of the characterization of MV extruded cables with a corroded aluminium conductor and aged under various simulated field conditions. The results indicated that the presence of water and corroded aluminium in the conductor strands decreases cable performance.
- **Thermo-mechanical failure due to the mechanical properties of aluminium, in particular in case of solid Aluminium conductors [9].** The thermal linear coefficient of expansion for aluminium is 36 % greater than that of copper. If the proper connector is not used, high mechanical stress could occur due to uneven growth between the conductors and the connectors during thermal cycling. In case of solid conductors high mechanical forces are generated in the joints for high loads because the expansion is almost entirely in the longitudinal direction. Creep, the continuous deformation under stress, is much higher for Aluminium than for copper. If this fact was not taken into account in installation techniques or termination devices, this could contribute to heating issues at the connections. This issue has been mitigated with the use of different series of aluminium alloys (for instance 1370, 99,7% aluminium or 1350, 99,5% aluminium) and suitable connection methods and connectors. As described in [9], laboratory tests as well as theoretical calculations are carried out to explain frequent joint failures due to high cyclic loads.

UTILITIES' ANSWER TO QUESTIONNAIRE REGARDING LV AND MV POWER CABLE CONDUCTORS

Introduction

This report is based on 16 questionnaires completed from distribution utilities originating from the following countries:

1. Belgium 1	2. Brazil 1
3. Brazil 2	4. Denmark 1
5. Denmark 2	6. Germany 1
7. Netherlands 1	8. Poland 1
9. South Africa 1	10. South Africa 2
11. Spain 1	12. Switzerland 1
13. Thailand 1	14. Turkey 1
15. Netherlands 1	16. Mexico 1

Although the number of completed questionnaires is rather small, the geographical spread is satisfactory: 9 from Europe, 2 from Africa, 2 from Asia and 3 from America.

Conductor selection

This part of the questionnaire (Questionnaire part III) deals with information on how utilities make their decision in selecting conductors: copper or aluminium. The following factors were selected, to be considered as important selection criteria as possible answers in the questionnaire:

1. Price per meter of cable
2. Radial size
3. Weight per meter of cable
4. Mechanical properties
5. Ease of accessory installation
6. Ease of repair
7. Cost of corrective maintenance (repair after failure)
8. Company standard or company procedures
9. Compatibility with existing cables in network

10. Environmental concern (losses)
11. Expected problems with connectors
12. Any other factor.

In the questionnaire for each factor two columns are present, one for LV and one for MV networks. The participants were asked to rate the importance of each factor concerned from 1 to 5, where 1 refers to a rating of least importance and 5 to a rating of highest importance. Furthermore the participants were asked to indicate per factor the preferred conductor material, copper or aluminium. Next to the 11 specified factors there was at the end a free row where the participant could enter a new factor not specified yet, but that did not result in an additional factor

In the tables 2 and 3 the scores are put together per factor for all the participating utilities, resulting in a total score per factor.

Table 2: LV cables, order of total scores of factors from high to low

Cu	**Al**
1. Company standard, 26	Price, 44
2. Mechanical, 26	Company standard, 26
3. Connectors, 25	Compatibility, 22
4. Compatibility, 24	Weight, 21
5. Environment, 24	Mechanical, 18
6. Repair, 23	Environmental, 18
7.Corrective maintenance., 22	Accessory installation, 13
8.Accessory installation,22	Connectors, 11
9. Radial size, 18	Corrective maintenance, 11
10. Price, 18	Repair, 11
11. Weight, 12	Radial size, 10

Table 3: MV, cables, order of total scores of factors from high to low

Cu	**Al**
1. Mechanical, 24	Price, 48
2. Connector, 24	Company standards, 31
3. Radial size, 23	Compatibility,27
4. Repair, 23	Mechanical, 20
5. Accessory install., 22	Weight, 18
6.Compatibility, 22	Accessory, 18
7. Environmental, 21	Environmental, 18
8. Company standards,20	Connector, 18
9.Corrective maintenance, 19	Corrective maintenance, 16
10. Price, 14	Repair, 11
11. Weight, 14	Radial size, 10

EVALUATION OF RESULTS

The differences in the decision to choose copper versus aluminium are according to tables 2 and table 3 noticeable. For aluminium for both LV and MV cables the dominating factor is price (score 44 for LV and score 48 for MV cables). The other factors for aluminium score significantly lower in value. For copper there is not such a dominating factor, but rather a combination of factors.

The other remarkable fact is that there exists a great similarity in decision model between LV and MV aluminium conductor cables. The order of decision factors is for LV and MV cables almost identical, as for copper conductor cables there are still some difference. It is difficult to find a satisfactory explanation. It could be that for aluminium the decision model is more structured and more company controlled than for copper

Focusing on the technical reasons to select copper above aluminium the following points can be listed:

– Mechanical properties are considered to be better
– Problems with connectors in combination with aluminium conductors seem to be in the advantage of copper conductors
– Installation of accessories and repair also seem to be topics that are advantageous for copper conductors
– The smaller radial size is an advantage.

When considering the technical reasons to select aluminium above copper, the following can be concluded:

– The lower specific weight of Aluminium
– The compatibility with existing network.

The issue of environmental concern does not score high, both for aluminium and copper. Although copper has a higher specific conductivity than aluminium, in practical situations conductors of both materials have the same conductivity and consequently the same losses, because different cross sections are selected.

CONCLUSIONS

In this report attention is being paid to copper versus aluminium in relation to the decision model. A number of failure mechanisms in particular related to aluminium could be identified, as for copper no clear failure mechanism could be found. Summarized below:

- Chemical reaction between aluminium and water, resulting in the development of high pressure hydrogen and related joint failures
- Chemical reaction between aluminium and oxygen, resulting in high transition resistances in joints connectors and related joint failure
- Thermo mechanical behaviour of aluminium due to significant higher coefficient of expansion and related mechanical failure.

Investigation of the decision model, how to select copper or aluminium learned that there is one factor, the significant lower price of aluminium, which plays a dominating role in the decision process. The other factors that benefit the selection of copper conductors are:

- Problems with connectors in aluminium conductor cables
- Easiness in installation of joints and repair
- Mechanical properties
- Radial size.

For aluminium conductor cables the following issues showed a relatively high score:

- Lower weight per meter cable
- Compatibility with existing cables.

The utility industry is currently too much focused on initial costs and insufficiently aware of the benefits of copper. The move from copper to aluminium may affect technical performance of distribution networks as well as total cost of ownership. The impact of conductor choice on technical and financial performance of electricity networks deserves more attention.

REFERENCES

[1] R. Bartnikas, K. Srivastava, 2000, *"Power and Communication Cables: Theory and Applications"*, IEEE Press, John Wiley & Sons Inc. Publication, ISBN 0-7803-1196-5, 2000.

[2] Metal Recycling Opportunities, Limits, Infrastructure, UNEP Report 2013

[3] R. Coombs, Bateman, 2010, *"Comparison of Aluminium vs Copper Power Cables for Use in Industrial Applications"*, Installations and Contractors, July 2010.

[4] A. Mak, 2002, Senior Field Applications Engineer, *"Corrosion of Steel, Aluminium and Copper in Electrical Applications"*, Alcan Cable, 2002.

[5] J.B. Dixon, D. T. Rooney, N. T. Castello, 1992, *"Metal Migration Failures in a Hybrid Device: Interaction of Package Materials, Process residuals and Ambient Gases"*, Oneida Research Services, Inc., ISHM Proceedings, San Francisco, CA, 1992

[6] M. Villaran, R. Lofaro, 2012, *"Essential Elements of an Electric Cable Condition Monitoring Program"*, United States Nuclear Regulatory Commission (U.S.NRC), NUREG/GR-7000, BNL-NUREG-90318-2009, January 2012.

[7] L. Pryor, R. Schlobohm, B. Brownell, *"A Comparison of Aluminium vs. Copper as Used in Electrical Equipment"*, Sr. Specification Engineers, GE Consumer & Industrial

[8] G. F. Moore,1997, *"Electric Cables Handbook"*, 3rd Edition, BICC Cables, Blackwell Science Ltd., ISBN 0-632-04075 *Selecting the optimized conductor for design*, Jicable 2011 B.10.1

[9] R. Bodega, eo, 2011, *Selecting the optimized conductor for design*, Jicable 2011, B.10.1

[10] IEC 60228 Conductors of insulated cables

[11] G.J. Luzzi, 1982, *Gas pressure build up in Aluminium conductor cable*, IEEE Trans.on PAS ,Vol,PAS-101, No 6 June 1982

[12] S. Plissou, J. Cote , eo.,2003, *Influence of corroded conductors on the performance of MV extruded cables*, Jicable ,03

[13] R. Coombs, 2010 *Comparison of Aluminium vs Copper power cables for use in industrial installations*, July 2010, Vector

[14] L. Pryor eo,,2010, *A comparison of Aluminium vs Copper as used in electrical equipment*, GE Industrial solutions 2010

[15] Aluminium Wire, *WIKEDIA* September 2010