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Comparative analysis of inner-array systems in offshore wind farms mixing copper and aluminium raw materials

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Abstract. This work presents an evaluation methodology of electrical losses in the cables of collector systems for two common options considered nowadays in large offshore wind parks, copper and aluminium raw materials. Furthermore, two additional options of study are evaluated mixing copper and aluminium cables in the same strings. Taking into account the current situation of the offshore collector systems, a summary about schemes employed in commissioned wind farms is presented.

This study plays a key role in order to cut down Levelized Cost of Energy (LCoE). Based on the calculus of electrical losses, the author selects the optimum design of the array of the wind farm combined with the most adequate rated power offshore turbines nowadays. The evaluation of power losses is based on real cable data sheets and calculated according to IEC 60287 international standard.

Key words. Array-system, offshore wind farm, power losses, energy losses

1. Introduction

Since the first offshore wind farms (OWFs) were installed in the nineties, offshore wind energy production and industry are steadily growing up. Even more, it is expected that over the next few years, offshore wind energy will increase its contribution to the different National Renewable Energy Action Plans (NREAPs). China (47,3 GW), United Kingdom (16,1 GW), Germany (9,8 GW), Netherlands (5,4 GW), Taiwan (3 GW), Denmark (2,6 GW) and Belgium (2,2 GW) are leading the worldwide installation of offshore wind power.

Among the countries that have developed this type of electricity generation, some of them adopt different models when allocating connection costs to generators. Nowadays, the most widely accepted option is that the Transmission System Operators (TSOs) to assume these costs. In this way, the electricity generator companies only pay and operate the collector system. This aspect highlights the importance of the design of this collector system, which comprises all components that allow the integration of wind energy into the transmission system. It collects power generated in turbines and adapts it to suitable levels of voltage and frequency for the transmission system. Individual wind generators, power electronic converters, medium voltage transformers, switchgears, inter-array power cables and high voltage transformers constitute the whole collector system.

Therefore, aiming for saving costs, the developers are continuously assessing different solutions such as comparative design of inner-array with both copper and aluminium raw materials of the core inside the cables. The value of LCoE usually is the main ratio, which decides the best and final solution. In this paper, a mixed raw material of the cables of strings is evaluated both energy losses as well as LCoE.

Bearing all these issues in mind, this work is divided into following sections. The second section, is focused on the current technical characteristics of raw materials. The third section shows the description of a simple comparative evaluation to calculate the energy losses and LCoE calculation. In the fourth section, a case study is developed to analyse the four different options for collector system design. Finally, some conclusions are stated.

2. Market and technical characteristics of raw materials

According to information related to User´s Guide publication [1] as well as [2]-[4] some conclusions can be drawn as follows:

- For the same current carrying ampacity the aluminium cross section area is about 60~65 % greater than the copper equivalent one.
- The mass in kilograms of 66 kV submarine copper cables is clearly bigger than aluminium one. The variation is in the range of +9 % (95 mm^2 cross section cable) to +36 % (1000 mm^2 cross section cable).
- For the same ampacity cables, the outer diameter of the aluminium cable is about 30% larger than the copper one, that's it, larger volume.
- The resistivity at 20ºC is lower for copper wires 1,72x10^{-8} Ωm than the aluminium ones 2,82x10^{-8} Ωm.

This means that for the same cross section cables the former one will provoke more power losses.

- Temperature coefficient is slightly higher for aluminium option 0,00403 compared to copper option being 0,00393 at 20ºC.
- At present the cost ratio between both raw materials is about 1:4 meaning that the copper is 4 times more expensive than aluminium. This makes a cable price ratio about 1:2 at the most.
- Connections and joint points with aluminium cables are difficult task when must be handle specially at sea environment. For transmission systems offshore cables are made by copper material in contrast with onshore cables that are made by aluminium.

3. LCoE & losses calculation models

A. Assumptions

The optimization of the inter-array design is based on minimizing the LCoE of the OWF. In economic terms, the LCoE is defined as the average cost per unit of electricity injected into the grid that would be needed to recover all the costs incurred to maintain and operate the OWF and its decommissioning process included. The total expenses and annual energy delivered (AED) to the grid are taken into account to evaluate the LCoE during the life of the wind farm in each year. The general expression of the LCoE in the case of an OWF, is stated as:

$$\mathrm{LCoE}\ (€/\mathrm{MWh}) = \frac{\sum_{t=1}^{n} \frac{I_t + O_t + M_t + D_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AED}{(1+r)^t}} \quad (1)$$

Where:
n: is the number of years that the OWF will be operational, I_t: are investment costs at year t, also known as CAPEX which is *generally* paid during development phase of the project as well as over the first years of operation (€), O_t+M_t: are operating and maintenance costs at year t respectively, divided into a series of annual payments to maintain the plant running (€), D_t: are decommission costs at year also known as DECEX, after the OWF stops permanently the production of electricity (€), *r*: is the discount rate, this rate translates the money of the future back to today´s value, *AED*: is the annual energy delivered to the grid, that is, the net energy production measured at the electricity meter (MWh).

B. Generation model

For estimating Annual Energy Production (AEP), an open source library named FLOw Redirection and Induction in Steady state (FLORIS) developed by NREL is used [5]. This tool optimizes the AEP together with wake effect losses aiming to design the best solution of OWF turbines layout.

C. Losses model

Overall losses in an OWF can be divided as follows:

- Air losses

Air losses model comprises both wake and blockage effects. Wake effect losses correspond to a specific project, being multiple issues which can influence when developers are seeking a precise estimation of losses.

The main drivers that influence in these losses are: the specific power (SP) of selected OWT, wind conditions defined by wind rose, turbine spacing, turbine layout, as well as capacity density of OWF whereby involving great uncertainty when developers try to asses wake losses accurately. The study in [6] presents a wide range of wake losses of approximately 5~20 % compared to the total energy losses of an OWF. In the same way blockage effect is becoming increasingly important being of about 2% of energy produced.

- Electrical losses

As explained before, the IEC 60287 [7] standard has been used to calculate the losses in the cables installed comprising collector system.

$$P_{losses}\,(W/m) = 3I^2 R_{conductor,ac}\,(1+\lambda_1+\lambda_2) + W_d \quad (2)$$

Where: *I* is the current flowing in the conductor (A), $R_{conductor,ac}$ is the AC resistance of conductor (Ω), λ_1 is the sheath loss factor, λ_2 is the armour loss factor and W_d are the dielectric losses (W/m).

The losses of the cable can be divided into core losses (Joule losses), sheath losses and armour losses. On the other hand, dielectrical losses are related with the square of the voltage.

For the core losses, the conductor´s resistance calculation has been made taking into account that the maximum tolerable operational temperature is 90ºC for cross-linked polyethylene (XLPE) insulation cables, according to data provided by cable manufacturers:

$$\mathbf{R^{90}_{conductor,AC}(\Omega/m) = R^{90}_{conductor,DC}(1 + y_s + y_p)} \quad (3)$$

The sheath losses are proportional with the Joule losses with the sheath loss factor $\boldsymbol{\lambda_1}$. These losses are calculated in IEC 60287 and the calculation for a three-core type cable is as follows:

$$\boldsymbol{\lambda_1 = \frac{3{,}2w^2}{R^{90}_{conductor,AC} R^{90}_{screen}} \left(\frac{2c}{d}\right)^2 10^{-14} \left[1 + \left(\frac{d}{d_a}\right)^2 \left(\frac{1}{1+\frac{d_a}{300\delta}}\right)\right]^2} \quad (4)$$

The armour losses, as well as the sheath ones, are related with Joule losses too, so these losses are calculated in the similar way as the sheath losses with the armour loss factor λ_2:

$$\lambda_2 = \frac{1{,}23\, R^{90}_{armour}}{R^{90}_{conductor,AC}} \left(\frac{2c}{d_a}\right)^2 \frac{1}{1+\left(\frac{2{,}77 10^6 R^{90}_{armour}}{w}\right)^2} \quad (5)$$

Finally the dielectric losses are calculated as follows:

$$P_{dielectric\ losses}(W/m) = W_d = 2\pi f C U_0^2 \tan\delta \quad (6)$$

- Unavailability losses

The unavailability of any cable array (F_{array}) of the OWF can be calculated as follows:

$$F_{array\ i,j}(hours/year) = d_{cable\ i,j}.\lambda_{array}.MTTR_{array} \quad (7)$$

Where, *i* is the string number, *j* is the cable/turbine number per string and $MTTR_{array}$ is the average time needed to repair a damaged array cable (hours). Assuming that the failure rate and the MTTR are the same for all the cables and taking into account that the distance is cumulative because the cables are in series connection, the expression for accumulated unavailability AF_{array} in each cable *n* of a specific string *i* can be written as:

$$AF_{array\ i,n}(hours/year) = \lambda_{array}.MTTR_{array}.\sum_{j=1}^{n} d_{cable\ i,n} \quad (8)$$

For inter-array cables $MTTR_{array}$ and λ_{array} values are surveyed and collected in [8].

D. Cost model

All prices and costs assumed in this paper have been obtained from [9]. Deserve to be mentioned that each OWF has unique distinctive features being a project specific solution. In addition, nowadays´ uncertain economic situation is making the prices volatility of raw materials, increasing maritime logistic costs, variable exchange rates, the rise in inflation rate and delays in the supply chain. All prices from references have been updated to today´s value.

4. Case study & sensitivity analysis

In this case study the following assumptions in the Table I have been made:

Table I.-Data assumed for case stydy

Capacity	1200 MW
Turbine model	WTG 15 MW-236
Array voltage (kV)	66
Sea depth (m)	25
Seabed temperature (ºC)	15
Cable burial (m)	1,5
Distance turbines prevailing direction	10 D
Distance turbines no prevailing direction	8 D
Power factor	0.95
Topology	Radial
Cable cross section	185 mm^2-800 mm^2
Maximum temperature (ºC)	90
Frequency (Hz)	50
Seabed temperature (ºC)	15
Burial depth of cables (m)	1.5
Thermal resistivity of surroundings (K.m/W)	1
K_s and K_p coefficients	1

A proposed case study, is based on the Weibull parameters c=9,53 m/s and k=2,2 for a mean wind speed of 8,44 m/s at 150 m hub height.

Applying all the formulation explained before the design of the OWFs has been optimized according to the lowest value of LCoE. The final results of the case study can be observed in Table II for the four options analysed in each OWF. Three OWFs have been evaluated: first case of 1 GW, second case of 1,2 GW and third case of 1,4 GW. Each of case presents 4 options for the design of the inner-array system is made up by 2 different cross sections because of simple purchase order for the cable manufacturer is achieved. For ampacity reasons the biggest cross section cable for each string 2 options are evaluated for 630 mm^2 and 800 mm^2.

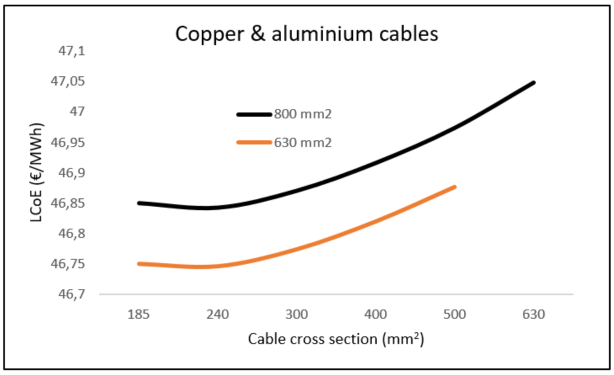

Fig.1.-LCoE vs cable cross section for OWF of 1 GW.

The Figure 1 shows the relationship between different cross cable sections if mixed raw materials are used for OWF of 1 GW of nameplate power. The study shows that the lowest LCoE value will be achieved if 5 turbines per string are installed, being 2x630 mm^2 of copper for the first 2 OWTs of the string. The remaining 3x240 mm^2 cables of the string are composed of aluminium material. The rest of possible combinations represent higher values of LCoE.

In the same way the Figure 2 present the same optimize solution for the OWF of 1,2 GW. The study shows that 16 strings would be formed with 5 OWTs in the same configuration, that is, 2x630 mm^2 of copper cables together with 3x240 mm^2 of aluminium cables.

On the contrary, the Figure 3 changes the optimization of the strings of the 1,4 GW OWF. In this case the solution which offers the lowest value of LCoE corresponds to a greater cross section of cable of 800 mm^2. So the structure of the inner-array of the OWF is composed by 19 strings with 2x800 mm^2 (copper) & 3x185 mm^2 (aluminium) as the most appropriate solution in terms of cos of energy delivered to the grid.

Additionally for each consider solution for the 3 OWFs several information is provided. The inner-array annual cable losses in terms of energy (GWh) and in terms of percentage (%) in relation with the total annual energy produced (AEP).

The total energy losses, that is, the air losses together with electrical losses and unavailability losses, are clearly related with the size of the OWFs. The main reason of this phenomena consists in the losses of unavailability of the first cable of the string, making the whole string to be damaged so all the production of the string will be lost without any alternative to inject into the grid generated energy.

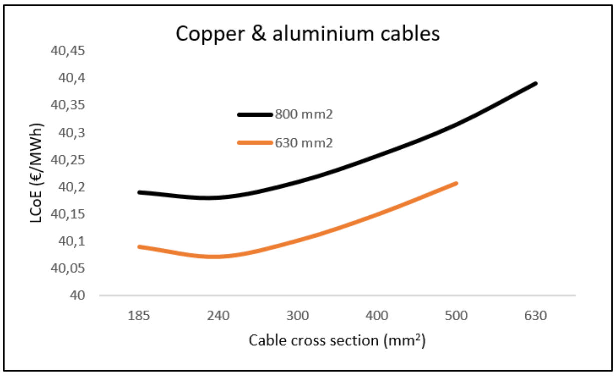

Fig.2-LCoE vs cable cross section for OWF of 1,2 GW.

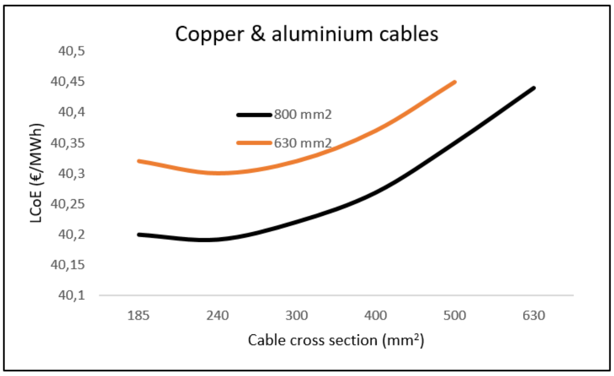

Fig.3.-LCoE vs cable cross section for OWF of 1,4 GW.

As can be seen in the Table II and Table III, the best results correspond to a mix solution of biggest section of copper and small section of the cables of aluminium in each of the 3 OWFs. The main reason of these results lies in carrying the high current near the substation across copper cables because of lower resistance makes the losses smaller. On the other hand, the stretches where the current is smaller the aluminium choice is better suited because the lower price of this raw material.

Table II.-Results of sensitivity analysis for 3 different OWFs and related 4 options.

OWF (MW)	Strings	Turbines per string	Turbines	String Design Optimized	Array cable length (km)	LCoE (€/MWh)
1050	14	5	70	2x630mm^2 (Cu) & 3x240mm^2 (Cu)	148,45	59,18
1020	17	4	68	2x630mm^2 (Al) & 2x185 mm^2 (Al)	191,57	46,91
1050	14	5	70	2x630mm^2 (Cu) & 3x240mm^2 (Al)	148,45	46,74
1020	17	4	68	2x630mm^2 (Al) & 2x240mm^2 (Cu)	191,57	59,36
1200	16	5	80	2x630mm^2 (Cu) & 3x240mm^2 (Cu)	182,13	59,10
1200	20	4	80	2x630mm^2 (Al) & 2x185 mm^2 (Al)	239,92	40,21
1200	16	5	80	2x630mm^2 (Cu) & 3x240mm^2 (Al)	182,13	40,07
1200	20	4	80	2x630mm^2 (Al) & 2x240mm^2 (Cu)	239,92	59,28
1425	19	5	95	2x800mm^2 (Cu) & 3x240mm^2 (Cu)	231,69	59,03
1440	24	4	96	2x800mm^2 (Al) & 2x185 mm^2 (Al)	303,06	40,43
1425	19	5	95	2x800mm2 (Cu) & 3x185mm2 (Al)	231,69	40,19
1440	24	4	96	2x800mm2 (Al) & 2x240mm2 (Cu)	303,06	59,21

Table III.-Results of sensitivity analysis for 3 different OWFs and related 4 options.

OWF (MW)	AEP (GWh)	Inner-array energy losses (GWh)	Inner-array energy losses (%)	Annual overall energy losses (GWh)	AFH (Hours)
1050	4494,35	34,91	0,77	820,52	3498
1020	4109,12	24,85	0,60	743,12	3299
1050	4494,35	31,77	0,70	817,39	3501
1020	4109,12	25,38	0,61	743,66	3298
1200	5136,40	44,50	0,86	942,34	3495
1200	5136,40	36,08	0,63	1023,70	3855
1200	5136,40	41,23	0,80	935,67	3993
1200	5136,40	38,09	0,74	1025,17	3426
1425	6099,47	54,37	0,89	1120,56	3493
1440	6163,68	44,10	0,71	1121,51	3501
1425	6099,47	50,23	0,82	1129,56	3487
1440	6163,68	47,08	0,76	1126,44	3498

5. Conclusions

The choice of raw material for the submarine cables for the collector system in OWFs mainly depends on the technical specifications and value of LCoE of any specific project. In this paper, four different alternatives have been presented and evaluated.

All options presented and studied suggest that mixing copper and aluminium cables in the array systems offer the minimum value of LCoE, being the greater cross section of copper raw material and smaller cross cable section of aluminium material. In the same way, it could be confirmed that copper is recommended to be used for stretches where biggest currents are flowing.

As the main conclusion of the study, it is clear that power losses are well dependent from the cross section of the cables and therefore strongly depends on the raw material prices. Although aluminium cables have a higher electrical resistance the currents are smaller per string because less turbines are arranged than in cooper solution. The price of aluminium cable is about one fourth in comparison with cooper one so in the case of big OWFs the total cable length is a key role, which establishes the optimal solution.

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