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Implementation of 132 kV for inner-array systems in offshore wind farms

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Abstract. Since offshore wind energy production is taking part in different countries´ energy mixes, significant cost reductions have been developed during last years. Together with offshore wind turbine power size one of the key improvements is stepping up inner-array system rated voltage from 33 kV to 66 kV or even to 132 kV expected for the beginning of the next decade.

As the offshore wind turbines that currently range between 16~20 MW are being installed and up to 26 MW have been announced recently, the increase of voltage is a need in order to make more efficient collector system and to cut down costs, consequently, reducing the levelized cost of energy.

This work presents an inner-array power losses analysis, as well as, covers and compares current collector system voltage at 66 kV with the new expected 132 kV voltage level. Losses distribution is calculated according to IEC 60287 international standard. The results show that the energy losses are reduced if compare to actually 66 kV voltage.

Key words. Array system, offshore wind farm, energy losses, 132 kV

1. Introduction

The worldwide installed capacity of offshore wind energy reaches 91 GW, being concentrated mainly in two areas such as China and the countries that share the North Sea, according to the data provided by the consulting firm TGS [1] and collected in Table I.

Table I.-Offshore wind turbines & power. Own elaboration.

Country	Turbines (Units)	Power (MW)
China	7621	47361,75
United Kingdom	2877	16102,1
Germany	1721	9877,35
The Netherlands	831	5406,2
Taiwan	374	3027,8
Denmark	666	2635,5
Belgium	399	2261,65
Vietnam	424	1621,7
France	220	1530,2
Japan	86	522,3
Rest of the world	212	917,03

Such big growth is related with several aspects, specially with big turbine power size, in fact, the offshore turbine manufacturers (OTMs) are releasing new turbine models continuously aiming for reducing overall costs of offshore wind farms (OWFs) and levelized cost of energy (LCoE). Up to now, 15431 offshore wind turbines (OWTs) are installed worldwide, even more, the coveted continuous reduction of LCoE is pushing developers to face new challenges, such as bigger OWTs.

According to Table II, the OWTs of 18 MW and above are showed according to released news by specialized press, which are expected to be used in the next future. During this decade, it will be a clear trend to increase of the nameplate capacity of these OWTs. This requires an alternative solution with respect to currently used 66 kV solution for collector systems, therefore, the submarine cable providers being full aware of the need of bigger rated voltage [2],[3] are taking the first steps towards designing, testing and validating expected cables. In this paper, 132 kV voltage is presented as preferred new standard solution as it seems to be as the most appropriate one by few literature information and reports. Although this promising solution will be the next one to be implemented, up to now there is not even a pilot project installed at this level of voltage.

Bearing all these issues in mind, this work is divided into following sections. Second section is focused on the current OWTs technology and on the present market based models. Third section shows the description of a simple comparative evaluation to calculate the power losses. In the fourth section a case study is developed to analyse the power losses difference between 66 kV and 132 kV inner-array systems of OWF. Finally, some conclusions are stated.

2. Market analysis of turbines & cables

As can be seen in Figure 1, the increase in turbine power has been continuous. The development of turbines in terms of power has been an exponential increase among Asian manufacturers, whilst European manufacturers have taken a more gradual approach, prioritizing the improvement of the quality of their turbines. Furthermore, according to Table II, this increase is expected to continue at the same rate.

However, as shown in Figure 2, the specific power of the turbines is on a downward trend, which appears somewhat contradictory. This reduction implies two things: (1) that maximizing energy production became the most important objective, and (2) that offshore emplacements with medium-low wind speed intensity are beginning to attract interest for offshore wind power development, particularly in Asia.

As can be seen in Table II, most turbines with a capacity exceeding 18 MW, are manufactured by Chinese companies, making this the global benchmark market. Some of these manufacturers are launching platforms that include flexible power generator models, adapting the turbine model to the emplacement where it will be installed. Nowadays, for OWTs above 18 MW market is clearly dominated by Permanent Magnet Synchronous Generators. While a leader manufacturer Siemens-Gamesa prefers a Direct Drive (DD) technology, that is, without a gearbox with a single low-speed (LS) axis, others have adopted turbines with medium-speed (MS) generators with 1/2/3 stage gearboxes.

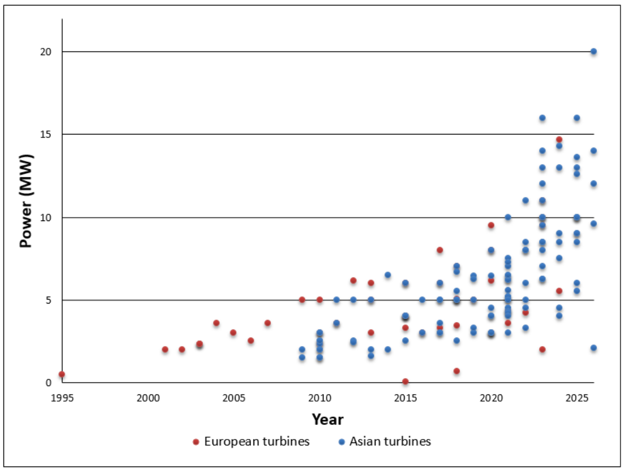

Fig.1. Power of installed offshore wind turbines (1995-2026). Own elaboration.

It is worth highlighting the 50 MW floating turbine announced by the manufacturer MingYang, which comprises two turbines on a single floating base. Both turbines of 25 MW each, are housed on a single floating platform, features the integration of two towers in a 'Y' floating dual configuration.

From the point of view of sub-component supply chain with the critical sub-components and supporting infrastructure of 132 kV technology. According to [4] it seems that the consolidated technology readiness level (TRL) and commercial readiness index (CRI) reported for each component, could be ready by 2030-2032. In [5] the readiness is announced by 2033.

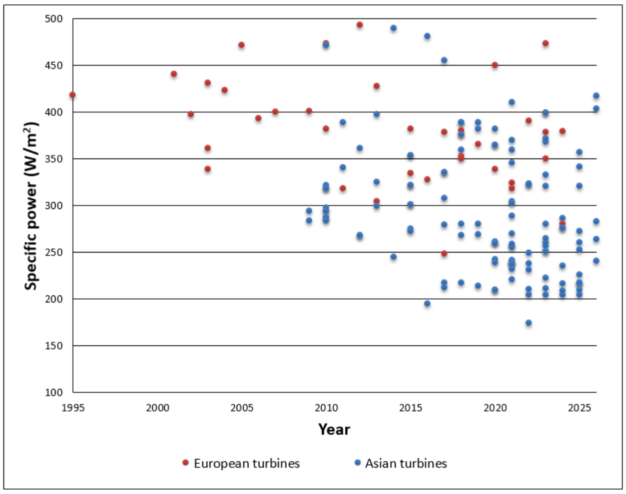

Fig.2. Specific power tendency of installed offshore wind turbines (1995-2026). Own elaboration.

Due to lack of information related with 132 kV voltage solution or installed pilot projects worldwide, a few studies are available about reactive power management and resonance analysis in [6], or floating cables risks [7]. Moreover, as prices and costs are not published or estimated yet, cost model together with LCoE calculations are not viable yet.

Therefore, the data presented in Figures 1 and 2, as well as the information provided in Table II, suggest and justify the need, in the medium term, to increase the voltage of the array system to levels higher than the current ones, as well as to study and assess the losses associated with this new solution and to estimate the technical and economic impact of this promising solution

3. Case study & sensitivity analysis

The total power losses in three-phase cables per meter are calculated from the general equation extracted from IEC 60287 as well as all corresponding formulas [8], as follows:

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

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 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:

$$R^{90}_{conductor,AC}(\Omega/m) = R^{90}_{conductor,DC}(1+y_s+y_p) \quad (2)$$

Table II.-Information related to OWTs above 18 MW available or announced. Own elaboration.

Manufacturer	Model	Power (MW)	Rotor Diameter (m)	Specific Power (W/m^2)	Generator Type
Siemens-Gamesa	SG-21.0-276	21	276	351,00	LS-PMSG
Dongfang Electric	DEW D18000-262	18	262	333,87	LS-PMSG
	DEW H18000-260	18	260	339,02	MS-PMSG
	DEW H26000-313	26	313	337,90	
Goldwind	GWH 300-20.0	20~22	300	282,94~311,23	MS-PMSG
Haizhuang	HZ260-18000	18	260	339,02	MS-PMSG
	HZ305-20000	20~25	305	273,74~342,17	
MingYang	MySE18.0-260	18/20	260/290	272,51/376,69	MS-PMSG
	MySE22.0-310	22	310	291,48	
	MySE25.0-290	25	290	378,48	
	MySE50.0-290	25+25	290+290	378,48	
Shanghai Electric	EW18000/260	18	260/300	339,02/254,64	MS-PMSG
	EW25000/310	25	310	331,22	
Windey	WD XXX-26	26/28	-	-	-
CRRC Zhuzhou	18MWD300	18	300	254,64	MS-PMSG
	20MWD260	20	260	376,69	
	26MWD300	26	300	282,94	

On the other hand, the sheath losses are represented as part of 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:

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

The third metal part of the cable is the armour, so these losses are calculated in the similar way as the sheath losses with the armour loss factor λ_2:

$$\boldsymbol{\lambda_2} = \frac{1{,}23\, R^{90}_{armour}}{R^{90}_{conductor,AC}}\left(\frac{2c}{d_a}\right)^2 \frac{1}{1+\left(\frac{2{,}7710^6 R^{90}_{armour}}{w}\right)^2} \quad (4)$$

Finally the dielectric losses are calculated as follows:

$$P_{dielectric\ losses}(W/m) = W_d = 2\pi f C U_0^2 \tan\delta \quad (5)$$

4. Case study & sensitivity analysis

This emplacement selected corresponds to SIMAR 3136040 point located in Cantabrian Sea (Spain), 40 km from the city of Santander. The wind data for this study have been collected from [9]-[11] web pages. In the Figure 3, the wind rose of the site is shown, as well as the corresponding Weibull wind distribution graph.

The OWT model chosen for this case study is the generic 20 MW output power and 270 m of rotor diameter. For the calculation of a simple sensitivity analysis 4 different options have been taken into account in a comparative assessment with 66 kV and 132 kV solutions. The power curve of OWT has been modelized as [12],[13] have been proposed. The presented case study for calculations, is based on the Weibull parameters c=7,92 m/s and k=1,6 for a mean wind speed of 7,1 m/s at 150 m hub height, as well as cable data released in reference [14].

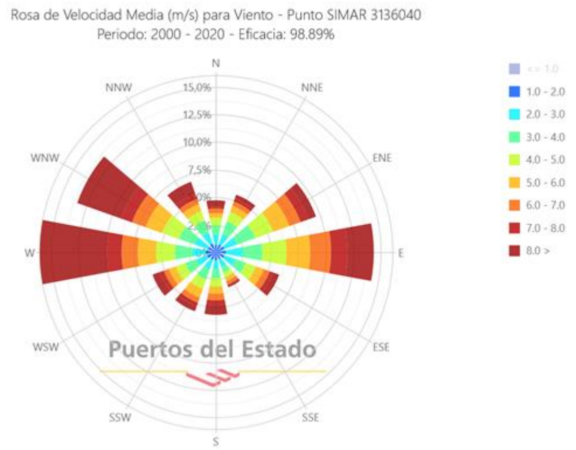

Fig.3. Wind rose of SIMAR 3136040 emplacement.

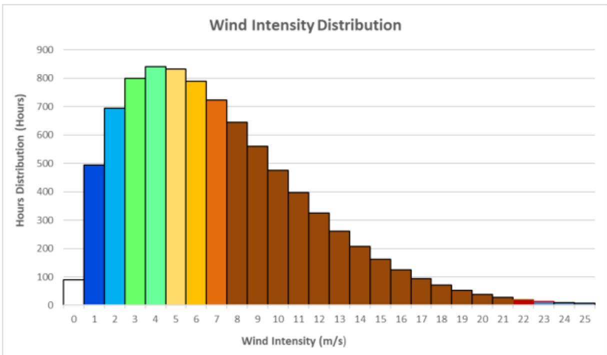

Fig.4. Wind intensity distribution graph.

All disclosed conditions for the OWFs have been collected in Table III for cable conditions and Table IV for the OWFs conditions and design parameters as follows:

Table III.-Conditions applied for cables

Maximum temperature at continuous load: 90ºC
3-core copper XLPE insulated 24/60 (72.5) kV cables
Frecuency: 50 Hz
Ambient temperature: 15ºC
Burial depth of cables: 1,5 m
Thermal resistivity of surroundings: 1.0 K.m/W
K_s and K_p coefficients: 1

Table IV.-OWFs location conditions and design parameters

Capacity:	600 MW 800 MW 1000 MW 1200 MW
Sea depth:	25 m
Seabed temperature:	15ºC
Cable burial:	1.5 m
Distance turbines prevailing direction:	10 D
Distance turbines no prevailing direction:	8 D
Power factor:	0,95
Topology:	Radial
Inter-array voltage:	66 kV
Cable cross section:	95 mm²-800 mm²

For estimating energy annual production (AEP) wind rose probability data $f(v_i)$ along with power curve $P(v_i)$ are needed. In this way, the gross AEP is calculated as follows:

$$\text{AEP (MWh)} = \int_0^{v_{max.}} P(v_i)f(v_i)8760\,dv \qquad (6)$$

$$P(v_i) = \frac{1}{2}\rho v_i^3 C_p \eta_{eff} \qquad (7)$$

Where: η_{eff} is the efficiency of the turbine electrical equipment, C_p is the power coefficient and ρ is the air density. Taking into account the parameters from [13] the power curve from the turbine of 20 MW and 270 m can be assessed:

$$C_p = 0{,}22\left(120\frac{1}{\lambda_i} - 5\right)e^{-\frac{12{,}5}{\lambda_i}} \qquad (4)$$

The statistical distribution of the wind is represented by Weibull distribution in Figure 4:

$$f(v_i;k,c) = \frac{k}{c}\left(\frac{v_i}{c}\right)^{k-1} e^{-\left(\frac{v_i}{c}\right)^k} \qquad (5)$$

The Weibull distribution consists of two parameters, first, the scale factor *C* in (m/s) and, second, the dimensionless shape factor *k*.

5. Conclusions

As the main conclusion of the study, it is clear that energy losses and the power losses of the cables comprising the inner-array system are lower in the case of 132 kV. According to results collected in Table V and Table VI, it is clear that the energy losses are lower if the 132 kV solution is used. The bigger the OWF the bigger the energy savings in terms of percentage comparing with AEP. The dielectric losses are directly proportional to the square of the voltage so bigger losses are expected in this field. The lower the losses means that the LCoE will be lower for the whole project.

Table V.-Results of the OWFs designs according to optimized solution.

OWF Capacity (MW)	Voltage (kV)	Turbines	Strings	Turbines per string	String design optimized	Array cable length (km)
640	66	32	8	4	2x800 mm² & 2x185 mm²	94,26
	132	32	4	8	3x800 mm² & 5x240 mm²	88,19
800	66	40	10	4	2x800 mm² & 2x185 mm²	115,86
	132	40	5	8	3x800 mm² & 5x300 mm²	109,79
1040	66	52	13	4	2x800 mm² & 2x185 mm²	159,70
1120	132	56	7	8	3x800 mm² & 5x400 mm²	153,32
1200	66	60	15	4	2x800 mm² & 2x185 mm²	189,94
1280	132	64	8	8	3x800 mm² & 5x400 mm²	180,66

Table VI.-Results of the OWFs productions & annual losses.

OWF Capacity (MW)	Voltage (kV)	AEP (GWh)	Annual cable losses (GWh)	Annual cable losses (%)	Annual overall losses (GWh)	AED (GWh)
640	66	1972,57	16,53	0,83	361,33	1611,24
	132		14,09	0,71	361,02	1611,55
800	66	2465,71	20,06	0,81	451,07	2014,64
	132		17,21	0,69	451,92	2013,79
1040	66	3205,42	28,54	0,89	588,85	2616,57
1120	132	3452,00	23,12	0,72	632,26	2819,74
1200	66	3698,57	34,31	0,92	680,82	3017,75
1280	132	3945,14	26,67	0,67	723,52	3221,62

On the other hand, it must be noticed that 132 kV solution could reduce the number of offshore substations or even not necessary the use of it, as can be employed as transmission rated voltage mainly for floating OWFs.

The shift to 132 kV in the offshore wind industry represents the new evolution for upcoming of larger and more efficient OWTs. In this way, this new solution permits the use of more powerful OWTs, so scaling up OWF energy production, reducing costs, and integrating massive renewable energy into the grid.

As the main advantages of the 132 kV solution, deserve to be mentioned the possibility of larger OWTs so less quantity is needed, covering smaller area for OWF required as power strings can double power transfer capacity.

The use of less number of strings makes shorter length overall cable needed so capital cost savings can be achieved due to cable purchase and installation process. At the same time, cable saturation around HVAC substation is avoided. Even more, fewer gas insulated switchgears (GISs) and J-tubes are required which makes the substation more compact and expensive offshore space is saved.

On the contrary, some of the main drawbacks can be mentioned as higher dielectric losses. Mechanically greater insulation material for the submarine cable implies a larger cable diameter, higher bending radius, hence, more difficult to manage for logistics and installing in buried configuration.

From the point of view of technical side, greater insulation material implies greater capacitive effect on the cables and consequently more reactive power will produce as well as higher charge current, modifying compensation system. Finally, more expensive equipment and cables is to be expected.

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