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Re-optimizing array cable systems in offshore wind farms using 66 kV voltage

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Abstract. As offshore wind energy production is taking part of overall strategy in different countries´ energy mixes, significant cost reductions are needed. One of the key improvements is stepping up inner field voltage from 33 kV to 66 kV. This work presents an inter-array power losses analysis taking into account transition to 66 kV cables instead of usual well known 33 kV solution. This paper covers and compares classical collector system voltage at 33 kV with the new 66 kV voltage level besides new optimization of collector system. Losses distribution is calculated according to IEC 60287 international standard.

Key words: LCoE, inner-array system, 33/66 kV, offshore wind farm, power losses

1. Introduction

Several countries have established offshore wind power generation goals for coming next years. In this way offshore wind farms (OWFs) are being constructed farther from the coast with nameplate capacity greater than 1 GW each. Aiming to continue to reduce grid connection costs, consequently levelised cost of energy (LCoE), designers and developers must face some challenges according to new connection concepts. In fact, larger single capacity offshore wind turbines (OWTs) are being developed in the range of 10-12 MW. This requires higher voltage to be implemented due to an efficient low power losses collector systems, hence, some developers announced that innovative 66 kV three phase voltage solutions would be widely deployed. In terms of Capital Expenditure (CAPEX) this new solution offers lower level of cost [1]-[2].

At the same time, offshore electricity grid development model is changing in some countries. This means that Transmission System Operators (TSOs) are becoming a responsible of design, operate and maintain transmission system ashore, meanwhile offshore wind farms´ developers should own and assume whole collector system, hence, making down tender prices.

Even in HVDC transmission systems 66 kV technology could become a clear trend in next future. This innovative solution permits elimination of HVAC export cable and AC offshore substation [3], making lower LCoE.

Therefore, 66 kV voltage new concept is pushing to offshore industry to adapt whole supply chain including turbine transformers, high voltage switchgears, collector system submarine power cables, terminations alongside offshore substation equipment such as power transformers. For floating foundation solutions dynamic cables of 66 kV are being manufactured too.

Bearing all these issues in mind, this work is divided into following chapters. Second chapter is focused on current status and main features involving 66 kV voltage technology, taking into account different characteristics compared with classic 33 kV option. Third chapter shows the description of the methodology applied in this paper to evaluate the influence of higher level of voltage on LCoE value, optimizing feeders design. Fourth chapter analyzes a 1.2 GW OWF real case aiming for the optimal design solution and, finally, some conclusions are stated.

2. Current status & features.

A. Current status

After testing and validation of 66 kV power cables, first offshore wind pilot projects have been commissioned during 2018 in European waters. For instance, different cable manufacturers implemented new cable solutions for three projects in Denmark (Nissum Bredning 28 MW) and United Kingdom (Blyth Demo 41,5 MW Aberdeen OWF 93,2 MW) respectively, the latest using biggest offshore wind turbines in terms of capacity 8,8 MW each.

On the other hand, ongoing several commercial OWFs are being developed in the range of 700-1400 MW announcing awarded contractors for 66 kV voltage technology. So it is a clear tendency that 66 kV grid connections will be widely implemented in the coming years. For instance The Netherlands, United States, France, Germany and United Kingdom next OWFs will feature this voltage level in collector grid according to information disclosed by energy producers.

B. Features

The main advantages of 66 kV collector option compared to 33 kV are [1]-[5]:

- Possibility of larger OWTs so less quantity is needed covering smaller area for OWF required.
- Higher power feeders, doubling power transfer capacity.
- If ring topology is assumed in the collector system, greater redundancy could be achieved.
- Some plans/projects switched to new type 66 kV solution, so it leads to become standard solution for coming years making it cheaper.
- Use less strings leads to less length cable needed, therefore, capital cost savings can be obtained due to cable purchase and installation process. At the same time, cable saturation around HVAC substation is avoided.
- Fewer substations, gas insulated switchgears (GISs) and J-tubes, required which makes the substation more compact and lower floor configuration.
- Offshore industry already has electrical equipment and infrastructure to 66 kV (GIS, cables, transformers, terminations...)
- In comparison with 33 kV less Joule losses for the same feeder.
- In case of HVDC transmission systems HVAC substation could become unnecessary.

On the contrary, the main drawbacks of the 66 kV wet designed cables are:

- Mechanically greater insulation material for the submarine cable, which implies a larger cable diameter, higher bending radius, hence, more difficult to manage for logistics and installing in buried configuration.
- Technically greater insulation material implies greater capacitive effect on the cables and consequently more reactive power will produce, modifying compensation system. It also implies higher dielectric losses.
- Power transfer capability could be reduced if reactive power increases, provoking less efficient cable and higher losses.
- Higher charge current.
- More expensive equipment and cables within and outside turbine.

All these changes suffered by different factors that affect the final design of entire wind farm, force to re-optimize its design. This innovation promotes and contributes to reducing LCoE thus making offshore wind renewable energy viable. These reduction costs make designers to review as well as consider different electrical layout options. Showing these different options and impact on LCoE is the main objective of the present paper.

3. Methodology

For the optimization of the design, 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 offshore wind farm, is stated as:

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

Where:

n	years OWF is operational
I_t	investment costs at year t
O_t	operating costs at year t
M_t	maintenance costs at year t
r	discount rate
AED	annual energy delivered to the grid
D_t	decommission costs at year t

The year t = 0 corresponds to the year in which the initial investment of the project is made, while the dismantling costs correspond to the year t = n + 1, that is, after the end of the useful life of the OWF. In the calculation of the LCoE, the turbines, array cables and GIS corresponding to the part that must be paid by the electric power producer have been included; therefore the transmission system has been excluded.

Because energy generated by the offshore wind farms varies simultaneously with the wind intensity at any time, the load of the cables will therefore varies accordingly. Consequently, energy production, collector electrical ohmic losses, temperature of the cables and resistance of the cables will change and will be assessed in binarized mode using IEC 60287 standard[6].

For estimating energy annual production (AEP) wind rose data along with power curve supplied by OWT manufacturer are needed. In this way, the gross AEP is calculated as follows [7]:

$$AEP\ (MWh) = \int_0^{v_{max}} P(v_i) f(v_i) 8760\, dv \qquad (2)$$

Most widely used Weibull distribution represents the statistical distribution of the wind by means of the probability density function with only two parameters, as follows:

$$f(v;k,c) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^{k}} \quad (3)$$

The AEP will be reduced due to unavailability of OWTs [8], wake effect, blockage effect [9] and inter-array cable losses, which affect cash revenues during whole lifetime of the project.

Inner array grid power losses are calculated in accordance with the international standard IEC 60287 [6], keeping on mind conditions of the standard. At this point, conditions of IEC standard for both 33 kV and 66 kV voltage levels are [10] [11]:

Table I.-Conditions applied for cables from catalogues

Maximum temperature at continuous load: 90°C
3 core copper XLPE insulated 18/30 (36) kV cables
3-core copper XLPE insulated 24/60 (72.5) kV cables
Frecuency: 50 Hz
Maximum ambient temperature: 20°C
Burial depth of cables: 1 m
Thermal resistivity of surroundings: 1.0 K.m/W
K_s and K_p coefficients: 1

For changes in conditions specified above, correction factors from [12] will be applied, so total power losses in 3-poles cables per meter are calculated from the following equation:

$$P_{losses}\,(W) = 3I^2 R^{90}_{conductor\ ,AC}(1+\lambda_1+\lambda_2) + W_d \quad (4)$$

Assessing such power losses methodology applied in [13] has been taken into account.

In this paper, 3 optimization scenarios of 66 kV are analyzed in comparison with the commonly used 33 kV option:

- Maintain the cable section and install more turbines in each string.
- Increase cable section and install many more turbines.
- Reduce the cable section and leave the same number of turbines.

In the re-optimization of the wind farm it is also studied how far the cable optimization can go for the following two conditions:

- Using only two different cross sections of submarine cable to saving costs on the purchase process.
- Taking into account the largest cross section of the feeder and then optimizing the small one.

The prices of the different parts of the OWF have been obtained from the investments indicated in [13] as well as those published by the energy producers. Together with the percentages included in [15] - [20] 3 main blocks and the corresponding sub-blocks have been analysed:

- CAPEX (78%): Turbines
  Balance of plant (BoP)
  Development costs (DEVEX)
- OPEX (20%): Operation cost
  Maintenance costs
  Spares and storage
- Decommission costs (DECEX) (2%)

4. Case study

The proposed case study for the application of the optimal design methodology for inter-array grid is the Borssele II Zone located in the North Sea in the territorial waters of the Netherlands. The Weibull parameters *c*=10.46 m/s and *k*=2.09 for a mean wind speed of 9.26 m/s correspond for 100 m hub height [21].

Table II.-OWF location conditions and design parameters

Wind site:	Borssele
Turbines models:	MHI Vestas V164-8 MW MHI Vestas V164-9.5 MW
OWT availability:	92.83 %
Capacity:	1.2 GW
Hub height:	100 m
Sea depth:	25 m
Seabed temperature:	15ºC
Cable burial:	1.5 m
Distance turbines prevailing direction:	10D
Distance turbines no prevailing direction:	8D
Wake+blockage effect:	12 %
OWF lifetime:	20 years
Gas Insulated switchyear:	630 A
Power factor:	0.9
Topology:	Radial
Inter-array voltage:	33 kV 66 kV
Cable cross section:	150 mm^2-800 mm^2
Discount rate:	8 %

Four different cases, shown in Table III, have been assessed:

Table III.-Options applied to methodology

Option	Turbine	Voltage
Case 1	MHI Vestas V164-8.0MW	33 kV
Case 2	MHI Vestas V164-9.5 MW	
Case 3	MHI Vestas V164-8.0MW	66 kV
Case 4	MHI Vestas V164-9.5 MW	

The first thing to consider in the optimal design of each feeder, is to know the ampacity of each of the sections of the cables that constitute the inter-array grid according to the design´s conditions specified in Table I and Table II. In this way the appropriate number of turbines is established in each feeder.

In the case of using a design voltage of 33 kV, an optimal number of 4 turbines per feeder is determined for the V164-8.0 MW turbine (32 MW/feeder) while the V164-9.5 MW turbine is optimized to 3 units (28.5 MW/feeder).

For the voltage of 66 kV it is clear that the power to be transmitted can be doubled, resulting in optimization values of 8 turbines for the V164-8.0 MW (64 MW/ feeder) and 6 units for the V164-9.5 MW (57 MW/ feeder) respectively.

Optimal cable cross sections calculated for the 4 cases analyzed, are resumed in Table IV.

Table IV. – Results of the optimal cable cross section

Option	Turbines per feeder	Optimal sections
Case 1	4	500-500-150-150 (mm^2)
Case 2	3	400-400-150-150 (mm^2)
Case 3	8	4x 400+4x185 (mm^2)
Case 4	6	3x 500+3x150 (mm^2)

One of the biggest advantages of implementing 66 kV technology compared to the well known 33 kV technology, is the reduction in the number of feeders, GISs and J-Tubes, which results in a reduction in the size of the substation and electrical equipment. In Table V and Table VI this comparison can be observed.

A very high number of feeders for a single substation is unfeasible from the logistic point of view, which should be one of the unacceptable condition, in addition to the congestion of the seabed around to the substation, due to the excessive number of cables. Thus the designed methodology takes into account the number of substations to be installed with the objective that the LCoE value is minimal.

Table V. – Results of the optimal design methodology of the wind farm at 33 kV

Feeders	Substations	Optimal capacity (MW)	MWh/MW ratio	C.F. (%)	M€/MW ratio	AED (GWh)	Total losses (GWh)	Array losses (GWh)	LCoE (€/MWh)
Case 1 - MHI Vestas V164-8.0MW 33 kV									
40	1	1280	3421.9	39.03	3.139	4380.05	1058.73	70.50	119.40
40	2	1280	3436.0	39.19	3.130	4398.08	1040.70	52.47	118.67
36	3	1152	3434.9	39.18	2.708	3957.03	937.86	48.47	106.20
Case 2 - MHI Vestas V164-9.5 MW 33 kV									
44	1	1254	3362.5	38.35	2.995	4216.69	1012.62	62.45	116.72
40	2	1140	3380.0	38.55	2.997	3853.20	900.72	36.93	116.19
42	3	1197	3377.1	38.52	3.019	4042.46	949.16	42.18	116.92

Table VI. – Results of the optimal design methodology of the wind farm at 66 kV

Feeders	Substations	Optimal capacity (MW)	MWh/MW ratio	C.F. (%)	M€/MW ratio	AED (GWh)	Total losses (GWh)	Array losses (GWh)	LCoE (€/MWh)
Case 3 - MHI Vestas V164-8.0MW 66 kV									
20	1	1280	3429.70	39.12	2.977	4390.02	1048.76	60.53	114.34
20	2	1280	4297.71	39.02	3.911	4400.86	1037.92	49.69	118.07
18	3	1152	3439.10	39.23	3.416	3961.85	933.05	43.65	127.03
Case 4 - MHI Vestas V164-9.5 MW 66 kV									
20	1	1140	3378.95	38.54	2.690	3852.00	901.92	35.17	104.74
20	2	1140	3385.31	38.61	2.773	3859.26	894.66	30.87	106.85
21	3	1197	3386.06	38.62	2.704	3474.09	804.43	27.02	104.74

In view of the results and the indicators obtained, the following conclusions can be obtained. For case 1 and case 2 it is not possible to build the wind farm with a single substation due to the high number of feeders and the large distances between the first turbine of the feeder and the substation. This makes the array losses higher. In terms of LCoE, the most interesting option can be considered the installation of 3 substations in case 1, with a generation cost of 106.20 €/MWh. However, this value is due to the fact that the wind farm has a slightly lower installed capacity (1152 MW), which causes the AED to be also lower (3957.03 GWh), reducing revenues from the sale of generated energy.

On the other hand, case 2 demonstrates that greater turbine capacity does actually reduce the value of the LCoE (between 2%-2.2%), even reducing the number of substations needed. Deserve to be mentioned that nowadays turbines of greater capacity around 10 MW-12 MW are in process of testing and certification, which will make the value of LCoE continue to decline even more intensely.

By increasing the voltage to 66 kV, the savings are even more evident. On the one hand, the number of feeders is reduced considerably, since they can contain two times OWT quantity. This circumstance makes it possible to re-optimize feeders, new cable sections, reduce the number of substations as well as losses. The optimal design option combines both aspects of improvement, that is, increasing the power of the offshore turbine to 9.5 MW and increasing the voltage for the offshore array network to 66 kV with a single collecting substation. In this way a reduction of 12.2% in the LCoE is obtained compared with the first turbine option of 8 MW at 33 kV. This makes the initial investment of the project per installed MW the minimum of all the options studied (2.690 M€/MW).

These benefits outweight increased cost making possible saving overall cost.

5. Conclusions

Moving from 33 kV to 66 kV in offshore wind farms collector systems of has been assessed. This movement seems to be reasonable and technically feasible in terms of reducing LCoE. Different design options have been made focused on cost-effective solution, besides risk assumed based on redundancy level.

Nowaday´s state-of-the-art is showing that offshore wind industry manufacturers launch electrical equipment enough for developers of new projects, offering all supply chain products for 66 kV. In general, it is clear that it has positive impact on wind energy generation costs, moreover, making any project profitable.

The best optimized solution can be shown if feeders' number is reduced and made larger, although a turbine with bigger nameplate capacity offers really lower LCoE values. More powerful turbines means reducing the number of them, less naval logistic and less cables. Finally, as a result of development of 66 kV power cables less transformer stations need to be built in each wind farm.

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