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Evaluation of electrical losses in MVAC collector systems in offshore wind farms

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Abstract. This work presents an evaluation methodology of electrical losses in the collector systems for different topologies considered nowadays in large offshore wind parks. Taking into account the current situation of the offshore collector systems, a summary about schemes employed in commissioned wind farms is presented. Electrical layout plays a key role in order to cut down Levelized Cost of Energy (LCoE). Based on the calculus of electrical losses, the authors select the optimum design of the array of the wind farm combined with the most adequate rated power offshore turbines. Power losses evaluation is verified with real cable data sheets and the methodology is applied to a real wind farm in construction.

Key words: offshore wind farm, collector topologies, redundancy, power losses, power cables.

1. Introduction

Since the first offshore wind turbine was installed in Sweden in 1990 (Nogersund), offshore wind energy production and industry are steadily growing up. Over the next few years, offshore wind energy is expected to further increase its contribution to the different National Renewable Energy Action Plans (NREAPs) among the countries of the European Union and several countries announced offshore wind future objectives for 2020 year. United Kingdom (13 GW), Germany (6,5 GW), France (6 GW), The Netherlands (3,5 GW in 2023), Denmark (2,8 GW) and Belgium (1,5 GW) are leading the most ambitious targets in Europe for 2020 [1]. Meanwhile in Asia, China (10 GW), Japan, Vietnam (350 MW) and South Korea are taking their first steps towards higher offshore business and lower oil dependency, thereby reducing carbon emissions. [2].

During nineties 5 offshore projects were carried out [2]. These projects had a transmission system at 10 kV or 12 kV until onshore substation, and didn't need an offshore substation. After these initial projects, interest of offshore business expanded together with new design tendencies. On the one hand, the turbines rated power increased hugely allowing developers for reaching large installed capacity. On the other hand, due to the success of pioneering projects near coast, vast new offshore locations were made available for wind energy producers.

The average distances to shore, water depths and rated installed capacities of nowadays offshore wind farms, are getting increasingly bigger, in fact, in the near future Hornsea Project One (1218 MW, 120 km) and East Anglia One (714 MW, 55 km) projects are about to start construction works, comprising 174 and 102 turbines respectively [1]. Furthermore, it is evident that investment costs are higher and could explain why developers are taking into account new collector designs, especially with redundancy, efficiency/low losses and costs [3-5].

Bearing all these issues in mind, this work is divided into following chapters. Second chapter is focused on different MVAC collector system´s topologies and European projects´ status. Third chapter shows the description of the methodology applied in this paper to evaluate electrical losses in collector systems. Fourth chapter analyzes several design options and the optimal design solution for a real case and, finally, some conclusions are stated.

2. MVAC collector system´s topologies

The collector system comprises all components that allow the integration of wind energy into the transmission system [6]. 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, MV transformers, switchgears, inter-array power cables and HV transformers constitute the whole collector system.

MVAC collector systems´ layout can be designed according to the wind farm size, redundancy/reliability, turbines rated power and collector voltage level.

At present, the following configurations are being implemented:

A. Small radial string.

Small and simple electrical design similar to that used in onshore wind farms. These strings connect few turbines in series at 10 kV-33 kV rated voltage without offshore substation, therefore these feeders serve also as transmission circuits. This layout is used for test sites or small power plants and represents the first stage in offshore development plans. It is also the topology designed for the first wind farms mounted of floating structures currently under development and has been applied in Portugal´s WindFloat Prototype 1 case which uses HVDC for transmission link [7]. In some cases, two strings share the same transmission circuit in order to save costs. In general such small projects are designed aiming for gaining experience in offshore business.

B. Large radial string.

Similar to the above layout but containing offshore substation(s) to collect the total electrical power and housing HV transformers, as shown in Figure 1 [8]. The number of wind turbines connected to a single feeder is limited by the maximum capacity of the power cable to a typical voltage of 33 kV, although the voltage of 66 kV is starting to be considered. This is the simplest layout and it permits to implement telescopic power cable system making it cheaper. The main drawback of this topology is its poor reliability in case of failure, in which all the power of the feeder could be lost. Belwind 1, Thorton Bank, Nysted 1, Nysted 2, Barrow, Sheringham Shoal implemented this collector system while Belwind 2, Norther, Rentel, Gemini, Dudgeon and Neart Na Gaoithe are being constructed using large radial string system.

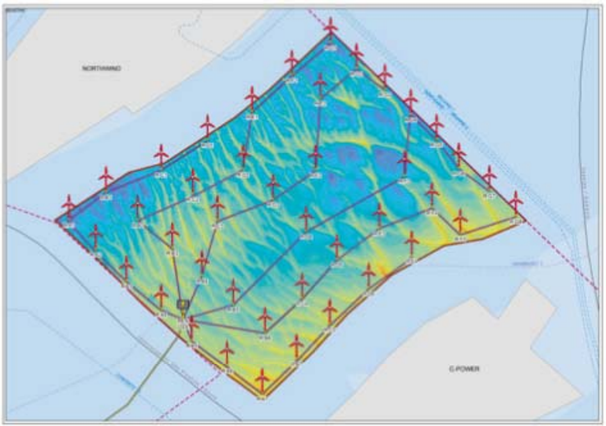

Fig. 1. Large radial string offshore grid system. [8]

C. Large dendrite shaped strings.

Dendrite shaped string allows to share the same stretch of subsea power cable by few different feeders as can be seen in Figure 2 [9]. This topology were set in Borkum Riffgrund 1, Hors Rev 1, Gunfleet Sands, Gwynt-Y-Mor, Lincs, Walney 2 and West of Duddon Sands offshore wind farms, and is also used in under construction Gode Wind 1&2, Galloper projects.

D. Radial & dentrite shape strings.

Some developers preferred a mixed design based on configurations described above. Such examples are Anholt, BARD Offshore 1, Burbo Bank Extension, Luchterduinen, Walney 1, Horns Rev 2, Thanet, Walney Extension 1&2, Lillgrund, Westermost Rought, Wikinger and Race Bank.

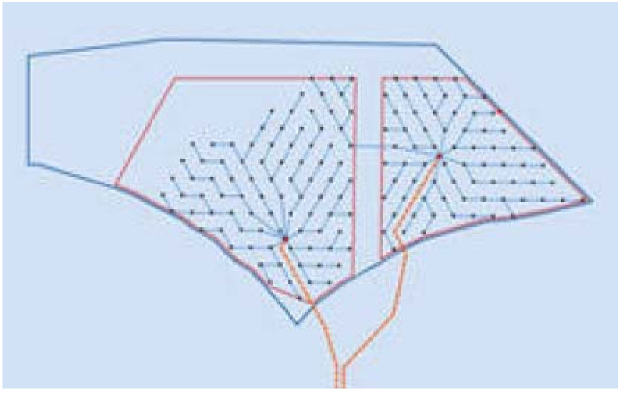

Fig. 2. Dentrite shaped offshore grid system. [9]

E. Ring shape strings.

Trying to seek additional security in the event of fault a redundant cable can be installed from last turbines of two different radial strings. The drawback of this interesting option is the need for a larger subsea power cable that in case of contingency supports the energy generated from the two mentioned radial strings. Among commissioned offshore wind farms Alpha Ventus, Amrumbank West, Butendiek, En Baltic 2, Meerwind Süd/Ost, Nordsee Ost, Trianel Windpark 1, Greater Gabbard, Humber Gateway, London Array 1&2, Ormonde, Robin Rigg and Scroby Sands chose this design option. Under construction Nordsee One, Sandbank, Trianel Windpark 2, Veja Mate, Beatrice and Rampion projects are being constructed taking into account redundancy in offshore grid system as shown in Figure 3 [9].

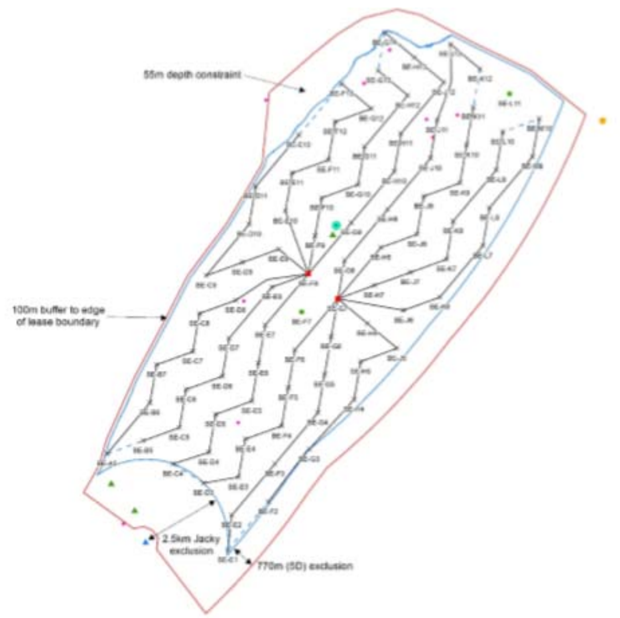

Fig. 3. Ring shape string offshore grid system. [9]

F. Interlinked strings.

Looking for extra redundancy and better behaviour during unexpected events, the radial, dendritic and ring-shaped strings can be interconnected establishing a flexible grid matrix operation. It is well known that repairing times on the sea could be quite longer than inland ones, mainly in winter, so it seems to be very interesting choice for incoming projects. This option was chosen in fully commissioned Dan Tysk, Global Tech I, Riffgat offshore wind farms and under construction Merkur OWF.

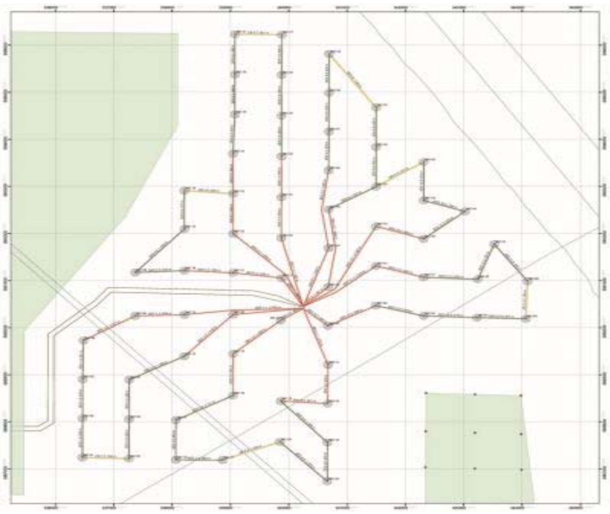

Fig. 4. Interlinked string offshore grid system [10].

3. Losses evaluation proposed methodology

Although some researchers are considering DC collector types, results of investigations state that losses and costs are slightly higher than in AC collector systems [4,5,11]. Therefore, the methodology proposed in this document will apply to AC technology to be used also in the case study.

The methodology developed for optimum OWF array design based on minimizing electrical losses consists of the following steps:

- First, the formulation to calculate the losses in the cable as a function of the power, per meter and for each phase has been developed and validated.
- Taking into account the conditions established by the Project and Site Description of the wind farm and with the restriction that the electrical losses are lower than a predefined value the study options to be optimized are established: turbine capacity, number of turbines, topology of string.
- Finally, based on power losses formulation, the best design of the wind farm and the corresponding losses for each turbine model are presented.

A. POWER LOSSES FORMULATION

The key aspects that have influence in electrical power losses are inter-array voltage, turbines capacity, operating power factor, wind rose on considered site [12], HV transformers and collector system topology. Taking into account all these issues, power losses associated with each stretch, can be easily assessed in presented formulation without making use of simulation packages.

Power losses are calculated in accordance with the international standard IEC 60287 [13], keeping on mind conditions of the standard, but also test conditions of each manufacturers. At this point, conditions of IEC standard are:

Maximum temperature at continuous load: 90^{o}C
3 core copper XLPE insulated 18/30 (36) kVcables
Frecuency: 50 Hz
Maximum ambient temperature: 20^{o}C
Burial depth of cables: 1 m
Thermal resistivity of surroundings: 1.0 K.m/W
K_s and K_p coefficients: 1

Total power losses in 3-poles cables per phase per meter are calculated from the following equation:

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

Where, I is the rated current of the cable (A).

The rest of the components in Equation (1) are calculated as follows:

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

$$R^{90}_{conductor,DC} = R^{20}_{conductor,DC}[1+\alpha_{Cu}70] \quad (3)$$

$$y_s = \frac{X_s^4}{192+0{,}8X_s^4} \quad (4)$$

$$X_s^2 = \frac{8\pi f K_s 10^{-7}}{R^{90}_{conductor,DC}} \quad (5)$$

$$y_p = \frac{X_p^4}{192+0{,}8X_p^4}\left(\frac{d_c}{s}\right)^2\left[0{,}312\left(\frac{d_c}{s}\right)^2+\frac{1{,}18}{\frac{X_p^4}{192+0{,}8X_p^4}+0{,}27}\right] (6)$$

$$X_p^2 = \frac{8\pi f K_p 10^{-7}}{R^{90}_{conductor,DC}} \quad (7)$$

$$\lambda_1 = \frac{3{,}2w^2}{R^{90}_{conductor,AC}R^{90}_{screen}}\left(\frac{2c}{d}\right)^2 10^{-14}\left[1+\left(\frac{d}{d_a}\right)^2\left(\frac{1}{1+\frac{d_a}{300\delta}}\right)\right]^2 (8)$$

$$\lambda_2 = \frac{1{,}23\ R^{90}_{armour}}{R^{90}_{conductor,AC}}\left(\frac{2c}{d_a}\right)^2\frac{1}{1+\left(\frac{2{,}7710^6 R^{90}_{armour}}{w}\right)^2} (9)$$

$$W_d = 2\pi f C U^2 \tan\delta \quad (10)$$

In equations (2)-(10) the physic meaning of the symbols are :

$R^{90}_{conductor,AC}$: conductor resistance at 90°C in AC (Ω/m).

$R^{90}_{conductor,DC}$: conductor resistance at 90°C in DC (Ω/m).

$R^{20}_{conductor,DC}$: conductor resistance at 20°C in DC (Ω/m).

y_s : skin effect factor.

y_p : proximity effect factor.

α_{Cu} : cooper coefficient of resistance variation with temperature.

d_c : conductor diameter (mm).

s : distance between conductor centers (mm).

c : distance between conductor and cable centers (mm).

d : average screen diameter (mm).

d_a : average armour diameter (mm).

δ : armour equivalent thickness (mm).

R^{90}_{screen} : screen resistance at 90°C (Ω/m).

R^{90}_{armour} : armour resistance at 90°C (Ω/m).

w : pulsation (rad./s).

W_d : dielectric losses (w/m/phase)

f : frequency (Hz)

C : cable capacitance (F/m)

U : inner-array voltage (V)

$tg\ \delta$: cable insulation loss factor.

B. VALIDATION OF THE FORMULATION

The developed formulation has been validated with the results provided by the manufacturer of medium voltage cables. In a previous work [14], authors applied and validated the power loss calculation based on ABB cables data sheet. However, they had to make some extrapolations because cable internal geometry data were not provided by the manufacturer. In the present work, datasheet of Nexans have been used that offer the widest amount of electrical data as well as internal cable geometry [15].

Table I shows the electrical losses of the cable given by the manufacturer's datasheet and those calculated with the proposed methodology for each section. Calculations of the electrical losses have been made at rated current since the Nexans manufacturer supplies loss data at full load.

It can be observed that the error of power loss estimation is less than 1.21%. Thanks to having more precise information of geometric data, y_s skin effect factor and y_p proximity effect factor could be calculated more accurately than in previous works [14], leading to inferior errors in the calculation of electrical losses.

Table I.-Comparison between Nexans-Methodology

Cable (mm^2)	Nexans (W/m/phase)	Methodology (W/m/phase)	Difference (%)
95	24,33	24,42	-0,37
120	25,33	25,18	0,59
150	26	26,06	-0,26
185	26,66	26,91	-0,93
240	27,66	27,92	-0,93
300	28,33	28,67	-1,21
400	29,66	29,90	-0,79
500	31	30,98	0,04
630	32,33	32,46	-0,39

4. Case study for proposed methodology

The proposed case study for the application of the optimal design methodology for offshore wind farms is the Borssele II Zone located in the North Sea in the territorial waters of the Netherlands. Characteristics and wind data collected in the zone from 01/01/1987 to 01/01/2014 were published so that the interested companies had the necessary data for the appropriate design and for their subsequent valuation at the time of the adjudication auction of the site. Figure 5 shows the wind rose corresponding to Borssele II. [16].

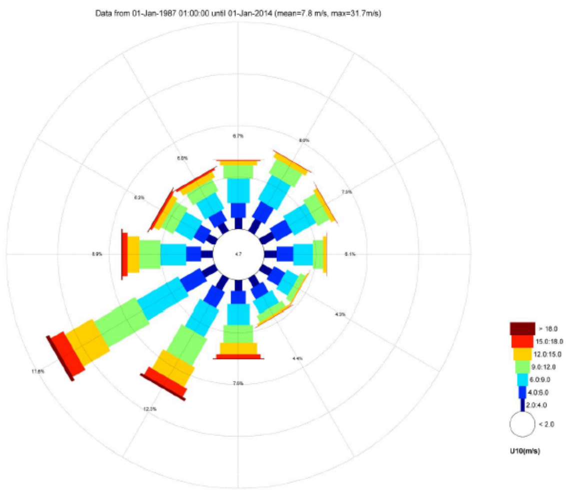

Fig. 5. Wind rose for Borssele Site II

At the same time Project and Site Description (PSD) was published setting out conditions to be fulfilled for correct design of the offshore wind park [17]. The most important conditions according to PSD are the following:

- Rated turbines range 4 MW-10 MW.
- Wind park nominal power 350 MW.
- Maximum number of turbines: 95.
- Minimum distance between turbines: 4 times rotor diameter.
- The minimum tip lowest level is 25 m above sea level (MSL).

- The maximum tip highest level is 250 m above sea level (MSL).

Therefore, taking into account the above conditions, the turbine models shown in Table II will be included in the case study.

Table II.-Borssele Site II OWF design options.

Turbine	Quantity	Type	Rated Power (MW)	AEP (GWh)
SWT-4.0-130	90	SCIG	360	1793,61
SWT-7.0-154	50	PMSG	350	1605,57
V164-8.0	44	PMSG	352	1583,47
5M-126	70	DFIG	350	1516,11
6M-126	60	DFIG	369	1456,62
6M-152	60	DFIG	369	1769,49
Haliade 6.0-150	60	PMSG	360	1673,38
AD 5M-116	70	PMSG	350	1449,13

In Table II the amount of annual energy generated by the wind turbines (AEP) is calculated by multiplying the power generated as function of wind speed, probability of occurrence of the wind speed and the number of hours in a year as in [4]. Turbine power generation data are obtained by turbine manufacturers' datasheets [18]-[22].

Table III shows electrical losses of the OWF for the turbines defined in Table II for the case of two different array designs: radial case and dendrite shaped strings. Components and total cost of the OWF for the case of the turbines are calculated based on prices and cost equations demonstrated in previous works [23]-[25].

The conditions for the design of the OWF are:

Array power factor: 1 ,
Array Voltage: 33 kV,
Distance between turbines: 7* rotor diameter,
Seabed temperature: 15 ºC,
Strings limited to maximum power: 32-35 MW

Results of the site show that for all turbines analyzed, the price of electricity generated is smaller the higher the turbine. This is due to the fact that at higher unitary power in turbines, the number of stretch is lower, which reduces both prices and installation costs.

Between the two designs analyzed, for the same turbine model, the electrical losses for the dendrite shaped string are smaller than for the radial string. This is due to the fact that the same amount of cables is used to build the park, but these have smaller section. In addition, the current flowing through each cable is smaller and taking into account that the losses are calculated as a function of the square of the current, this factor becomes especially important.

The data shown in Table III are the basis for assessing wind farm design options. Including the electricity tariff in each country and the life of the park, wind energy producers will decide the optimal design for the given site.

5. Conclusions

This paper presents a simple methodology to the design of the offshore wind farms that can be implemented easily on a spreadsheet.

As the first stage, based on the IEC 60287 standard, a formulation for electrical power losses assessment in submarine cables has been developed. This formulation has been validated with actual data from cable manufacturers.

The complete methodology has been applied to the real site of Borssele, in The Netherlands. Based on the conditions imposed to the site, different options of turbines currently available in the market have been evaluated.

The results of the analyzed case show that the optimal solution in terms of electricity generation costs consists on installing larger turbines and internal arrays with dendrite topology.

The methodology would be a technical and practical solution in development of collector arrays saving engineering time and associated costs.

TABLE III.-Components costs, electrical losses and electricity generation costs comparative

Turbine	Turbine cost (M€)	Foundation cost (M€)	Cable cost (M€)		Total cost (M€)		Electrical Losses (%)		Electricity generation (M€/MW)	
			Radial	Dendrite	Radial	Dendrite	Radial	Dendrite	Radial	Dendrite
SWT-4.0-130	369,693	194,618	73,682	62,762	637,994	627,074	0,999	0,548	1,772	1,742
SWT-7.0-154	302,678	230,168	61,529	47,071	594,377	579,918	0,553	0,356	1,698	1,657
V164-8.0	288,016	243,346	52,687	41,938	584,051	573,302	0,532	0,246	1,659	1,629
5M-126	340,501	191,271	64,779	52,244	596,552	584,018	0,655	0,382	1,704	1,669
6M-126	335,285	206,828	51,813	43,457	593,927	585,571	0,690	0,328	1,610	1,587
6M-152	335,285	240,269	62,399	52,335	637,954	627,890	0,831	0,395	1,729	1,702
Haliade 6.0-150	330,029	232,104	61,285	51,401	623,419	613,535	0,789	0,377	1,732	1,704
AD 5M-116	340,501	183,790	60,600	48,874	584,892	573,166	0,613	0,297	1,671	1,638

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