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Improved Method for Calculating Power-Transfer Capability Curves of Offshore Wind Farms Cables

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SUMMARY

The power-transfer capability curve is widely used by Offshore Wind Farms (OWFs) planner when designing their grid connection. An improved method for calculating power-transfer capability curves of OWFs cables is presented in this paper. What differentiates this method compared to the traditional approach, is the consideration of the high power variability and low capacity factors of OWFs, instead of assuming continuous nominal conditions. The method is based on an iterative approach, aiming to determine the maximum total installed power of an OWF, that a cable can support in function of its total length (effective length from the Offshore Substation, OSS, to the Onshore Connection Point, OCP); in order to do so, operational constraints such as: voltage swing limit, Surge Impedance Limit (SIL), and thermal limit are taken into account. By means of this strategy, is possible to estimate more accurately and realistically the power limits and binding constraints, hence exploiting the cables’ capacities under particular installation and operating conditions. The translation from rated conditions towards dynamic behaviours, permits the inclusion of more realistic states of the system, for instance, accounting not only for the wind speeds fluctuations, but also the variation of boundary temperatures (seabed), and other thermal parameters which have strong influence over buried cables’ thermal performance. The transmission cables are modelled considering a uniform distribution of their electrical parameters, inductance and capacitance, by means of the attenuation constant and characteristic impedance. Likewise, A Thermo-Electrical Equivalent Model (TEE) is applied for the thermal analysis given its good solution quality-computation time balance. The proposed methodology is applied to a 800 mm$^2$ cable, with the results showing an estimated increase of OWF total installed power of 110% for a total length of 120 km, when compared to the traditional method.

KEYWORDS

Offshore wind energy, transmission cables, power-transfer capability curve, dynamic temperature estimation, operating limits.

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1 INTRODUCTION

Offshore Wind Farms (OWFs) are becoming one of the fastest and most steadily growing type of technologies for electricity generation in Europe. Studies such as [1], survey that the global capacity has increased almost five times in the last seven years, reaching a globally installed power of nearly 19 GW. The location of wind turbines and the Offshore Substations (OSSs), is a matter of accentuated attention nowadays; it is a clear trend that the OSSs are being located farther away from coasts, which causes more scrutiny over classic and new types of transmission technologies, in order to obtain more efficient, effective, reliable, and cheaper systems for exporting power [2]. The impact of transmission systems over OWFs lifetime performance is critical, in terms of single-failure points [3], and economic sustainability [4].

High-Voltage Direct Current (HVDC) emerged as a competitive technology to connect OWFs to shore for large distances and installed power. Nevertheless, the technical maturity of High-Voltage Alternating Current (HVAC) is yet more developed than HVDC, and many OWFs developers still prefer the classical HVAC approach. Therefore, before exploring choices like HVDC transmission, HVAC technology could be further analyzed, taking into consideration the dynamic behaviour of important variables, such as wind power generation, seabed temperature, soil thermal resistivity, etc, instead of steady state approaches as done today following recommendations given by [5], [6], and [7].

Power-transfer capability curves are used substantially when designing the grid connection of OWFs, because they represent a fast way to discern about the required export cable type, while simultaneously choosing the Onshore Connection Point (OCP), given the location of the OSS. To the best of the author’s knowledge, those curves have been obtained, so far, by means of static conditions [8–10], assuming operation with constant generated power equal to the OWF installed power. The effect on the curve of the nominal system frequency is studied in [11], but still rated-continuous conditions are assumed. HVAC transmission systems are also subject to study in oil and gas reserves scientific fields as in [12], where analytic calculations and computer simulations are performed to obtain transfer boundary charts of cables, but of course operating conditions compared to OWFs are dissimilar.

To fill the identified gap in the scientific literature, a methodology for calculating power-transfer capability curves of OWFs cables is presented in this work. The impact of cables’ thermal and geometrical parameters, site-dependent variables (wind power generation time series, soil temperature time series, soil thermal properties variation, etc), and installation conditions (total length, buried depth, compensation units, among others) over the transmissible OWF installed power offered by cables is quantified. Real operating conditions (thermal transients, capacitive currents, and cyclic generation) are considered. The method consists of an iterative algorithm that includes all important operational constraints in function of the cable’s total length: voltage swing limit, Surge Impedance Limit (SIL), and thermal limit. For the Dynamic Thermal Estimation (DTE), a Thermo-Electrical Equivalent (TEE) model is used. The latter has been tested against experimental data in other works like [13], showing its accuracy and correctness. The calibration of the model is presented in [14]. In this case, the calculated maximum instantaneous conductor temperature is limited to 90°C as industrial practice.

This paper is structured as follows: in the Section 2, the methods are described, on the one hand, in the Section 2.1 the traditional used currently is explained, and on the other hand, in the Section 2.2 the proposed approach is presented. A specific case study is developed in the Section 3 and finally conclusions close this work in the Section 4.
2 METHODOLOGY

In this Section both the traditional and the proposed method are presented. In essence, for more precision, the two methods require the model of a long transmission line, which implies solving the resultant differential equations after the consideration of not-lumped parameters, but rather distributed uniformly throughout the length of the lines (cables) [15]. Formulating the set of differential equations and solving them, after expressing the solution in terms of hyperbolic functions, the following equations are obtained:

\[
V_R = V_S \cdot \cosh(\gamma \cdot l) - I_S \cdot Z_c \cdot \sinh(\gamma \cdot l) \tag{1}
\]

\[
I_R = I_S \cdot \cosh(\gamma \cdot l) - \frac{V_S}{Z_c} \cdot \sinh(\gamma \cdot l) \tag{2}
\]

where \(V_S\) and \(V_R\), are the line-to-neutral voltages at sending-end (OSS) and receiving-end (OCP), respectively, measured at length \(l\) from the OSS; likewise, \(I_S\) and \(I_R\), are the line currents at OSS and OCP, respectively. The characteristic impedance (\(Z_c\)) is calculated as \(Z_c = \sqrt{\frac{V}{I}}\), and the propagation constant, \(\gamma = \sqrt{\frac{V}{I}}\). The series impedance is represented by \(z\), and the admittance by \(\gamma\). The two-port cable model is gotten by inspection of Equation (1) and Equation (2): \(A = \cosh(\gamma \cdot l)\), \(B = Z_c \cdot \sinh(\gamma \cdot l)\), \(C = \sinh(\gamma \cdot l)/Z_c\), and \(D = \cosh(\gamma \cdot l)\). Therefore, the new system of Equations is the following [15]:

\[
V_R = V_S \cdot A - I_S \cdot B \tag{3}
\]

\[
I_R = I_S \cdot D - V_S \cdot C \tag{4}
\]

Equations (3) and (4) model the balanced three-phase lines systems at highest physics complexity using the two-port model.

2.1 The traditional method

The traditional method is represented in the Algorithm 1. This method requires (5) for the permissible current rating given by [5], as follows:

\[
I = \left[ \frac{\text{Max}_\text{temp} - T_{\text{amb}} - W_d \cdot [0.5 \cdot T_1 + n \cdot (T_2 + T_3 + T_4)]}{R \cdot T_1 + n \cdot R \cdot (1 + \lambda_1) \cdot T_2 + n \cdot R \cdot (1 + \lambda_1 + \lambda_2) \cdot (T_3 + T_4)} \right]^{0.5} \tag{5}
\]

where \(\text{Max}_\text{temp}\) is the maximum allowed continuous conductor temperature (90°C is the industrial common practice), \(T_{\text{amb}}\) is the temperature of the surrounding medium under normal conditions (20°C is generally considered), \(W_d\) is the dielectric loss per unit length for the insulation surrounding the conductor in W/m (formula given in [5]), \(T_1\) is the thermal resistance between the external layers of the conductor and the metal sheath (including semiconductors layers like shields) in Km/W, \(T_2\) is the thermal resistance between the external layers of the metal sheath and armour in Km/W, \(T_3\) is the thermal resistance between the external layers of the armour and the jacket in Km/W, \(T_4\) the soil thermal resistance in Km/W, \(R\) is the alternating current resistance per unit length of the conductor at \(\text{Max}_\text{temp}\) in Ω/m, \(\lambda_1\) and \(\lambda_2\) are the ratio of losses in the metal sheath and armouring to total losses in the cable, respectively.

Finally, \(n\) is the number of load-carrying conductors in the cable (\(n = 1\) for single-core cables, and \(n = 3\) for three-core cables). The model in Equation (5) is based on a Single-Core Equivalent Thermal Model (SCETM), and when \(n = 1\), then \(T_4 = 0\). Corrections of this model to increase accuracy for large cables is being under study in [16], however for the purposes of this
paper, the SCETM representation is considered satisfactory, as validated in [13] and [17]. The SCETM model is applied and the result is used to fix the value of the current magnitude at OCP, i.e. $|I_R|$. The values of $R$, $T_1$, $T_2$, $T_3$, $T_4$ depend on the cable’s geometrical and thermal properties, and along with mathematical expressions given in [18] and [19], they can be estimated for single-core and three-core cables, respectively. Ratio of losses $\lambda_1$ and $\lambda_2$ are assumed to be 5% each.

The traditional method also evaluates the voltage swing limit (6) and the SIL (7). The maximum voltage swing ($Max_{swing}$) between open-circuit and full-load conditions at the receiving-end, is considered to be 0.05 in (6). Meanwhile, the angles of $\vec{A}$ and $\vec{B}$ are $\alpha$ and $\beta$, respectively, in (7).

$$P_{SWING} = \left\{ P \in \mathbb{R}^+ : |\vec{V}_S \cdot \vec{A} - \left( \frac{P}{\sqrt{3} \cdot |\vec{V}_S| \cdot pf} \right) \cdot \arccos(pf) \cdot |\vec{B}| = |\vec{V}_S \cdot \vec{A}| \cdot (1 - Max_{swing}) \right\}$$  \hspace{1cm} (6)

$$P_{SIL} = \frac{|\vec{V}_S| \cdot |\vec{V}_R|}{|\vec{B}|} - \frac{|\vec{A}| \cdot |\vec{V}_R|^2}{|\vec{B}|} \cdot \cos(\beta - \alpha)$$  \hspace{1cm} (7)

---

**Input:** $\vec{V}_S$, $|I_R|$, $pf$, $Initial_{length}$, $\Delta_{length}$, $Max_{length}$, $Cable_{type}$

**Output:** $P_{OWF}$, $Cable_{length}$

1. for ($Cable_{length} = Initial_{length} : \Delta_{length} : Max_{length}$) do
2.  Get $\vec{A}, \vec{B}, \vec{C},$ and $\vec{D}$ for given $Cable_{type}$ and $Cable_{length}$.
3.  Get $\vec{I}_S$ with $\vec{V}_S$, $|I_R|$, $pf$, $\vec{A}, \vec{B}, \vec{C},$ and $\vec{D}$ in (2).
4.  if ($\vec{I}_S$ is feasible) then
5.      $P_{THERMAL_{Classic}} = \sqrt{3} \cdot |\vec{V}_S| \cdot |\vec{I}_S| \cdot pf$
6.  else
7.      $P_{THERMAL_{Classic}} = 0$
8.  end if
9.  Get $P_{SWING}$ with (6).
10. Get $P_{SIL}$ with (7).
11. Get $P_{OWF} = \min(P_{THERMAL_{Classic}}, P_{SWING}, P_{SIL})$.
12. Save point $\{Cable_{length}, P_{OWF}\}$.
13. end for

---

**Algorithm 1:** The traditional power-transfer capability curve method

Algorithm [1] requires as main inputs the voltage at OSS ($\vec{V}_S$), the static thermal limit ($|I_R|$), power factor at OSS ($pf$), and resolution for total length sweeping ($\Delta_{length}$, $Max_{length}$, and $Initial_{length}$). The output is the the power-transfer capability curve using the traditional method represented by the pair-set ($Cable_{length}, P_{OWF}$). After certain value of length, the two-port model parameters $\vec{C}$ and $\vec{D}$ turn Equation (2) into infeasible for $\vec{I}_S$, under the pre-set conditions $\vec{V}_S$, $|I_R|$, and $pf$ (power factor at OSS).

The disadvantage regarding this method is the impossibility to include the natural power fluctuation inherent to OWFs. Equation [5] allows getting the continuous current $I$ to be transmitted during infinite time, in order to obtain a continuous conductor temperature equal to 90 °C. The latest value is considered as the rated limit to not compromise the cable’s lifetime following a deterministic approach [20].
2.2 The proposed method

The following methodology is able to cover up the limitations of the traditional approach: power fluctuations of OWFs, and their impact over cables’ power-transfer capability curves, are taken into consideration. The general flowchart of the proposed method is presented in the fig. 1.

To initialize the process of the fig. 1, the following inputs (sorted by a top-down approach and marked in red in Figure 1) are required:

- Site-dependant inputs: OWF power time series, seabed temperature time series, and seabed thermal parameters (thermal resistivity and thermal specific heat). The seabed-related parameters are considered to be spatially-uniform for simplicity reasons but the method can be extended to account for spatial variations throughout the cable’s trajectory.

- Project-dependant inputs: In this input set is encompassed: project’s electrical system data (nominal frequency, nominal voltage at OSS, power factor at OSS, compensation units, export cable type with all its geometrical, thermal, and electrical information, and cable installation conditions, like buried depth and phase spacing).

- Simulation setting-dependant inputs: Inputs conceiving the total length calculation resolution, such as, \( Initial_{length} \), \( \Delta_{length} \), and \( Max_{length} \); additionally, inputs for the DTE model, like seabed sub-layers number \( N \), as described in [14], number of samples per
hour, the temperature resolution $\text{Max}_{\text{dev}}$, and $\text{Max}_{\text{temp}}$. After getting the aforementioned inputs, (5) is applied, providing input ($P_{\text{thermal}}$) for calculating $P_{\text{thermal,classic}}$ (see Algorithm 1). After this, the outer loop is started, changing the total length value. In the inner loop, for a particular distance $\text{Cable}_{\text{length}}$, the power limits are computed: $P_{\text{swing}}$, $P_{\text{SIL}}$, and $P_{\text{thermal,classic}}$. The value of $P_{\text{thermal,classic}}$ is used to start up the variable $P_{\text{Dyn}}$, that scales-up the power time series representing the total installed power of the OWF; this is followed by the call of the DTE model (see fig. 2), in order to estimate the maximum instantaneous conductor temperature $\theta_{\text{peak}}$, value that is compared to $\text{Max}_{\text{temp}}$ to get the calculated temperature deviation. In case this deviation is higher than $\text{Max}_{\text{dev}}$, the process is repeated using the recursive function $P_{\text{Dyn}} = P_{\text{Dyn}} + \text{Acc}_{\text{factor}} \cdot (\text{Max}_{\text{temp}} - \theta_{\text{peak}})$ to update the value of the OWF installed power. It should be noticed that an important key in this process is $\text{Acc}_{\text{factor}}$; this parameter, if too low, makes impossible to force $\theta_{\text{peak}}$ close to 90 $^\circ$C, and if too high, causes oscillations around the desired point. This parameter has been calibrated in this work using different sizes of test sets, concluding $\text{Acc}_{\text{factor}} = 5$ when the temperatures are in $^\circ$C and the power in MW.

![Figure 2: The dynamic temperature estimation method.](image)

Focusing on the DTE model (fig. 2), along with the inputs definition, the parameter $\text{Distances to analysis}$ must be selected in function of the power time series at OSS, and the compensation units. In case no shunt-series compensation units are installed, it is enough to consider a single point $\text{Distances to analysis} = \{100\%\}$ for any instantaneous value of power, because the current strictly increases with the total length; nevertheless, compensation units may alter the longitudinal current profile, shifting the maximum current point to an intermediate value lower than the OCP, i.e., $\text{Distances to analysis} < 100\%$, consequently $\text{Distances to analysis} = f(t)$.

If shunt-series compensation units are installed, in the worst-case scenario the number of instances to run the TEE model are $|\text{Distances to analysis}| = 8760$ (if a resolution of one hour and a normal year are chosen). At the end, the output of this model is the calculated maximum instantaneous conductor temperature $\theta_{\text{peak}}$ for all the instances. When $\theta_{\text{peak}}$ is close enough to 90 $^\circ$C, the dynamic analysis is terminated, and the corresponding power is compared to $P_{\text{swing}}$ and $P_{\text{SIL}}$, saving the point $\{\text{Cable}_{\text{length}}, \min(P_{\text{swing}}, P_{\text{SIL}}, P_{\text{Dyn}})\}$.

3 CASE STUDY

3.1 Inputs definition

An OWF to be constructed in the Baltic Sea is considered as a case study. The site-dependant inputs are presented in the Table 1; the histogram of power time series is also illustrated in the fig. [3] where it is appreciable that only 40% of the time, power between 0.9 and 1 pu is produced, according to the OWF power time series (in p.u.) simulated by means of the model.
described in [21]. For the cable’s surrounding temperature, a synthetic time series based on info from the Bornholm Basic area [22] was created, due to the scarcity on real information; the temperature profile ranges between 1°C to 10°C, including seasonal variations. Likewise, project-dependant and simulation setting-dependant inputs are presented in the table[2] and table[3] respectively.

Table 1
Site-dependant inputs.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
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<tr>
<td>fig 3</td>
<td>[1 10]</td>
<td>1</td>
<td>2 · 10⁶</td>
</tr>
</tbody>
</table>

![Figure 3: Histogram of power time series.](image)

Table 2
Project-dependant inputs.

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Voltage [kV]</th>
<th>pf</th>
<th>Series-shunt compensation</th>
<th>Cable</th>
<th>Buried depth [m]</th>
<th>Spacing [m]</th>
</tr>
</thead>
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<tr>
<td>50</td>
<td>275</td>
<td>1</td>
<td>No</td>
<td>800mm²</td>
<td>1</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 3
Simulation setting-dependant inputs.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>0.1</td>
<td>10</td>
<td>200</td>
<td>10</td>
<td>1</td>
<td>90</td>
<td>1</td>
</tr>
</tbody>
</table>

3.2 Results
The comparison between the curves using the traditional and the proposed method is presented in fig. 4; the orange line accounts for the power fluctuation, and therefore for each evaluated distance its magnitude is always higher than the traditional method (blue line), which assumes constant power. The crossing-point with the abscissa is unaffected as expected; in fact, to increase the reach in terms of total length, lower voltage levels or lower nominal frequencies should be evaluated. The curve obtained through the traditional method was validated against other works as [10] and [11]. Mathematically, the proposed method preserves the exponential trend given the low-degree polynomial relation between \( P_{OWF} \) and \( \theta_{peak} \). Both curves are defined by the thermal limit turning this one as the binding constraint; for these values of installed
power and total length, the voltage swing is maximum 0.9% for the traditional method, while for the proposed method is 1%, albeit the curve is more steep throughout the distance range (with voltage phase variation lower than 30 °C). Secondly, the SIL limit is always in the order of GW, hence not representing a threat. The traditional method requires only a couple of seconds to be calculated, whilst the proposed method lapses up to 5 hours; however, this computation time is negligible with respect to OWF planning time.

Figure 4: Comparison between the traditional curve method and the proposed curve method.

The evolution of the gain in power in function of the total length is illustrated in the fig. [5] the greater the distance the larger the gain. Indeed, for the greatest length (120 km), the installed power of the OWF could be 2.1 times the power calculated using the traditional method. This shows that for very large export route lengths, the under-use of the cable is increasing. It also indicates that HVAC-based solutions could be more thoroughly assessed in front of the HVDC counterpart, in benefit of the first one. Further computational experiments point out that the power gain is larger for greater values of soil thermal resistivity, for instance, for a total length of 120 km, an additional increase of OWF installed power of 39% can be achieved, when the soil thermal resistivity is 20% greater than the base value shown in table [1].

Figure 5: Gain of OWF total installed power.
4 CONCLUSIONS

The proposed method provides a realistic and efficient approach for calculating the power-transfer capability curve of OWF cables, with special interest on export cables, as the effect of technical constraints over transmissible power, in function of the total length, is thoroughly investigated. Technical constraints encompass thermal limit, voltage swing limit, and SIL limit. It has been identified that the binding constraint for submarine cables is the thermal limit, and this restriction can be relaxed if the power fluctuations are taken into account, consequently enlarging the search space, making possible to obtain larger values of installable OWF power for a given cable type, under specific operating conditions. The case study results show an increase of OWF total installed power of 110% for a total length of 120km, when a cable 800mm\(^2\) is used. Additional simulation results project further increases on this value for larger values of thermal resistivity. The computational expenses must be considered, the proposed method converges on approximately 5 hours, and larger memory resources are needed, nevertheless, they do not represent any challenge at any extent using a normal PC.

The proposed methodology is dependent on the accuracy of the inputs, as the power generation cycle, seabed soil temperature, and thermal properties of the soil and the cable. Future work includes uncertainty analysis of these parameters, and the inclusion of several power production case scenarios.

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BIBLIOGRAPHY


