Assignment Electrical Aspects

OFFSHORE RENEWABLES TECHNOLOGIES /
MARINE RENEWABLE TECHNOLOGIES

OE44170/CIEM4305

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1 Part 1: Grid Integration of Offshore Wind

The integration of large-scale wind power has many impacts on the power system. For example, the variability of the wind means that the power production of wind turbines and wind parks vary as well. An overview of the power curve and the thrust curve of a modern wind turbine is provided below. The overview indicates five operational areas, from left to right I, II, III, IV and V

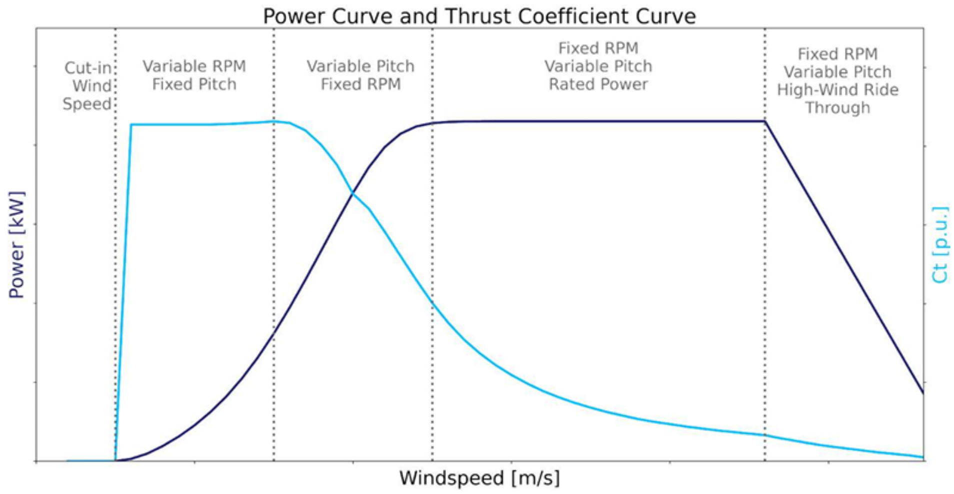

Figure 1: Overview of the power curve and the thrust curve of a modern wind turbine

1.1 What is the challenge of operational area I for power systems?

The area I describes a condition where the wind speed value is below the defined cut-in treshold of the wind turbine. This results in no power generation. A condition like this can challenge systems that demand consistency of energy supply in order to operate. That means that under these wind conditions the operator should find other plants to cover its energy demands. In addition more backup is needed since the fact that it is not predictable when the output will go from zero to a ramp, makes balancing costs go up.

1.2 What are two challenges of operational area III for power systems?

- Output still moves with the weather: as wind rises toward rated, the park can ramp quickly, which makes it harder to keep supply and demand in balance and increases the need for reserves.
- Control shifts toward pitch and converter limits: blades are actively pitched to manage loads, which tightens both active/reactive power behavior and reduces upward headroom, so voltage support and dispatch become trickier as you near rated power.

1.3 What are two benefits for power system operation of area V compared to a ‘hard cut-out’ at a high wind speed, as is the case for older wind turbines?

- The turbine rides through with a controlled derate, so power tapers instead of dropping to zero; the grid sees a ramp rather than a step, which eases frequency control and reduces stress on contingency reserves.
- The farm keeps producing during storms (even if curtailed), so it captures extra MWh that older hard cut-out machines would lose, and operators avoid the knock-on redispatch that follows a sudden full trip.

Offshore wind parks consist of a cluster of wind turbines. The power production by such a cluster of wind turbines is dependent on the wake effects: the power production of wind turbines may be reduced in the wake of other turbines. In the Excel file, tab ‘WTG Yield Wake’, the wake effect for a wind park of 80 WTGs is provided for wind speeds, measured at hub height, between 0.5 and 28.5 m/s.

1.4 For this wind park, at what wind speeds are the wake effects negligible?

Using the provided *WTG Yield Wake* data, wake losses shrink quickly above rated: they are small around 12.5–13.5 m/s and become negligible (about 1–2% or less) from roughly 14 m/s upward. Beyond that, turbine interactions barely matter, and the farm produces nearly the same energy as it would without wakes.

1.5 Explain for operational areas II, III and IV what impact the wake effects have on power production of an offshore wind park. Consider the thrust curve as part of your answer.

Wake effects vs. power (Areas II–IV)

- **Area II (variable RPM, fixed pitch):** High thrust (per the thrust curve) $\Rightarrow$ strong wakes, larger wind-speed deficit and turbulence downstream $\Rightarrow$ *largest* power losses for trailing turbines.
- **Area III (fixed RPM, pitched blades):** Increasing pitch lowers C_t $\Rightarrow$ weaker wakes $\Rightarrow$ *moderate* downstream losses.
- **Area IV (rated power):** Further reduced C_t $\Rightarrow$ *weakest* wakes $\Rightarrow$ *smallest* impact on downstream production.

In the past decade, wind turbines have become much larger. This is true for the generator sizes [MW], but even more for the rotor diameters [m] which have become larger also relative to generator size. Compare two identical wind turbines with a fixed capacity [MW] but with different rotor sizes.

1.6 Discuss two opportunities of a larger wind turbine rotor for a wind park owner. Include the operational areas of relevance in your answer.

- **More energy at lower winds (Areas II & III):** Larger swept area reaches rated power sooner and widens the high-yield range $\Rightarrow$ higher annual energy production.
- **Smoother output (mainly Area III):** Pitch control + larger rotor reduce short-term fluctuations $\Rightarrow$ better predictability and revenue stability.

1.7 Argue if a larger rotor could be beneficial from a power system operation point of view. Consider power variations and power forecast errors in your answer.

A larger rotor offers important advantages for power system operation. By capturing more wind in low to moderate conditions, it reduces short-term power variability, resulting in smoother power ramps that make grid integration easier. Additionally, the more stable the operating profile of a larger rotor is the more it decreases forecast uncertainty, improves power scheduling accuracy and enables the provision of ancillary services such as frequency support.

2 Part 2: Inter-Array Cabling Losses

2.1 Calculation of the nominal current per wind turbine

$$I = \frac{P}{\sqrt{3}\,U_{phase}\,\cos\varphi} \tag{1}$$

$$I_{\text{turbine}} = \frac{20 \times 10^6}{\sqrt{3} \times 66 \times 10^3 \times 0.95} \approx 1.84 \times 10^2 \text{ A} \tag{2}$$

2.2 Determine the maximum number of wind turbines that can be connected to Cable 1, Cable 2 and Cable 3 without exceeding the ampacity.

Each cable has a different ampacity, thus a different number of wind turbines that can be connected without exceeding this ampacity.

$$N_{\text{max}} = \left\lfloor \frac{I_{\text{ampacity}}}{I_{\text{turbine}}} \right\rfloor \tag{3}$$

$$N_{\text{Cable 1}} = \left\lfloor \frac{424}{184} \right\rfloor = 2.3 \rightarrow 2 \tag{4}$$

$$N_{\text{Cable 2}} = \left\lfloor \frac{584}{184} \right\rfloor = 3.17 \rightarrow 3 \tag{5}$$

$$N_{\text{Cable 3}} = \left\lfloor \frac{750}{184} \right\rfloor = 4.08 \rightarrow 4 \tag{6}$$

2.3 What is the annual electricity loss as a percentage of the yield of the WTGs on the string?

In the Excel file, we need to go from the active power, which is correlated to the wind speed, to the apparent power as follows:

$$\text{Apparant power} = \frac{\text{Active power}}{\cos(\varphi)} \tag{7}$$

These apparent powers are used to compute the losses, which are summed up in the Excel file in the **IAC sheet**. The annual electricity loss, the WTG yield and the loss in percentages are depicted in Table 1.

Table 1: IAC string losses, WTG Energy Yield and Losses in percentages

IAC String Losses	1336 MWh/year
WTG Energy Yield	395260 MWh/year
Losses	0.34 % /year

2.4 How many WTGs of 20 MW could be connected to Cable 1 if it would be at 132 kV instead of 66 kV?

If the phase operating voltage would be 132 kV instead of 66 kV, the current per wind turbine would change as follows:

$$I_{\text{turbine}} = \frac{20 \times 10^6}{\sqrt{3} \times 132 \times 10^3 \times 0.95} \approx 92.1 \times 10^2 \text{ A} \tag{8}$$

The current per wind turbine decreases and, therefore, the number of wind turbines that can be connected to cable 1 also changes.

$$N_{\text{Cable 1}} = \left\lfloor \frac{424}{92.1} \right\rfloor = 4.6 \rightarrow 4 \tag{9}$$

2.5 How much would the annual losses on the wind turbine string be reduced if the voltage level would be increased to 132 kV, everything else being equal? Explain your answer

When the voltage level is increased to 132 kV, the current in the cable reduces, which reduces the resistance and the losses. In our case, cable 1 can be used for all sections between the wind turbines because we do not exceed the ampacity anymore. This can be seen in **IAC_2 sheet** in our Excel file. The losses would also reduce if we do not change the type of cable, because the current in our previous configuration would also drop, resulting in lower losses.

The losses in the new configuration, where we only use cable 1 to connect the wind turbines, is 560 MWh/year instead of 1336 MWh/year.

3 Part 3: Offshore Wind Park Electrical Design

3.1 Capacity of Export Cables and Redundancy of the Transformers?

In optimal conditions, all three export cables work. Each of these cable needs to export at least 264 MVA of power, since it is connected to 22 wind turbines with a power of 12 MVA. The total power that is exported is $264 \cdot 3 = 792$ MVA.

However, when one of these export cables is out of service, we can only export 67 % of the power which $264 \cdot 2 = 528$ MVA. Furthermore, the transformers can have a maximum power of 400 MVA for a short period of time if an export cable is out of service and the other transformers have to transform more power. Therefore, we can also choose to design the capacity of the export cable as follows $\frac{792}{2} = 396$. Table 2 illustrated the different export cable capacities we choose from.

Table 2: Comparison of three capacities per export cable

Capacity (MVA)	Power Exported (MVA)	Redundancy (%)	Reasoning
264	528	66.67	Choosing the minimum export capacity reduces the cable costs, but increases lost power when one of the cables is out of service.
297	594	75	Choosing a redundancy of 75% increases the cable costs a bit, but it also reduces the lost power when one of the cables is out of service.
396	792	100	Choosing a redundancy of 100% increases the cable costs a lot, but it removes the power loss when one of the cables is out of service.

The redundancy of the transformers is calculated as follows:

$$\text{Redundancy} = \frac{\text{Exported Power}}{\text{Nominal Power}} \tag{10}$$

3.2 Discuss three factors that you would consider in your decision to build that connection or not

In the first case in Table 2, the cables are exaclty designed for the power output of the wind turbines. There is no safety margin when one of the export cables goes out of service. This is a good choice in an ideal world where the wind turbine never has to be shut off, however this is never the case. The third row shows a redundancy of 100 % when one of the export cables shuts off. This cable is overdesigned because a transformer will not go out of service that many times to justify such a large diameter for the cable. Finally, we chose an option in the middle with a redundancy of 75 % (Green row). We have made the diameter of the cable a bit thicker to allow higher power output. This allows for 75% power output when one of the export cables is out of service.

4 Part 4: Offshore Wind Park Development and Construction

An offshore wind project visible from land is to be developed in a country without prior offshore wind projects. Each stakeholder may support or oppose the wind project for various reasons which are discussed below. Possible risk the project poses for the stakeholder:

1. The national government: A possible failure of the project could lead to large loss of taxpayer money.
2. The local government: If the local inhabitants are completely against it, then they lose their credibility in future decisions.
3. A Nature conservation society: The construction activities as well as the presence of wind turbines could negatively affect the underwater biodiversity present at the site and also birds.

4. Local fishermen: The regular paths of the fishes may get affected which could lower the number of fishes.
5. The local port: The wind turbines could obstruct navigation routes.
6. The grid company connecting the wind park: If the wind park energy production is very inconsistent and doesn't offer enough power during high demand, then it will be a useless investment.

Possible gain or opportunity the project could provide for the stakeholder:

1. The national government: It could help towards establishment of renewable sources, making the nation more energy independent.
2. The local government: Local energy pricing could become lowered.
3. A Nature conservation society: Establishment of renewable energy sources are better than traditional fossil fuels.
4. Local fishermen: Formation of artificial reefs around the wind turbines attract more fishes.
5. The local port: The local port can come under using during the construction period and also for maintenance.
6. The grid company connecting the wind park: Wind energy is much cheaper in comparison to other fossil fuels.

A permit is obtained to build the project. The construction of the project will consist of different phases. The following order should be followed:

1. The wind turbine foundations: The actual turbine itself requires the longest amount of time. Foundations also involve quite a lot of uncertainty. All other offshore components can come after the foundation is installed.
2. The offshore substation: This sets up all the needed offshore points.
3. The inter-array cables between the wind turbines: Once the foundations and substation are established, the cables can be connected.
4. The export cables between the offshore and the onshore substation: This process can take place at the same time as the stage above.
5. The onshore substation with the grid connection: All the onshore cable work can technically be performed well before the turbine foundation work while the substation itself may be constructed near the end stage but before the completion of the turbine installation.
6. The wind turbines: While all the previous stages are taking place, the wind turbine elements should already been manufactured, thus as soon as they are installed, they would be connected to the grid and power could be produced in a matter of few days.

5 Feedback

Tidal Energy: The introduction lecture did discuss a lot about tides and the energy that can be harnessed from it. But unlike wind and wave energy, the technology itself (especially the type mentioned in the assignment), was not introduced in a clear manner. It was a combination of tidal technology not being as intuitively easy to imagine and an unclear introduction. Thus, this could be improved.

Assignment Pacing: They are well set up and spaced throughout the quarter with just about enough time to complete them.