Wind Farm Design and Analysis

BL40A2401 Electrical Engineering in Wind and Solar Systems

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18.4.2022

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1. INTRODUCTION

Wind energy production continues to gain momentum as the technology evolves. In year 2021 in Europe alone new wind production capacity was 17.4 GW. The forecast for coming years also shows very high demand for new wind power as seen from the figure 1.1 (Wind energy in Europe 2022). The popularity for wind power is driven by falling Levelized Cost of Electricity (LCOE) of wind energy production and momentum to switch electricity production to fossil free solutions. Added amounts of distributed energy generation (DER) brings advantages and challenges to electricity grid as the electricity production changes fundamentally.

Figure 1.1 2022-2026 new onshore and offshore wind installation in Europe. (Wind energy in Europe 2022)

With new wind power installation comes need for apt engineers able to connect this new form of energy production to the grid. Wind power plants operate in a different manner to traditional power production mostly due to their variable production and power electronic converters used. Understanding these differences and the basics of power production's grid integration is important for engineers intending to work in the field of power engineering.

This report is a summary of an assignment on wind power grid integration in the course *Electrical Engineering in Wind and Solar Systems*, LUT-University. Chapter 2 of this report describes what kind of grid was designed and the major components of it. Chapter 3 goes deeper into the electrotechnical mathematics of grid integration in different conditions and points in the grid. Lastly chapter 4 gives a summary and some analysis on the main findings of the assignment report.

2. WINDFARM LAYOUT AND GRID DESIGN

In this chapter the design of the wind farm grid is shown (Fig. 2.1), cable grid calculations and dimensioning are shown, and other main components of the wind farm are given with explanation why they were chosen.

The wind farm consists of 7 wind turbines in two strings, which are spaced 1 km apart from each other. This is to minimize wake effects of the turbines. 1 km was chosen as an arbitrary number as use of 1 km has benefits in making the calculations and troubleshooting calculation errors simpler. Each turbine has its own grid disconnector, and the strings have their own breakers and disconnectors at their substation medium voltage cells. Fig. 2.1 also shows the point of maximum short circuit current, which is at the medium voltage busbar.

The 110 kV high voltage side components, apart from the main transformer, are not under design or documentation in this assignment report.

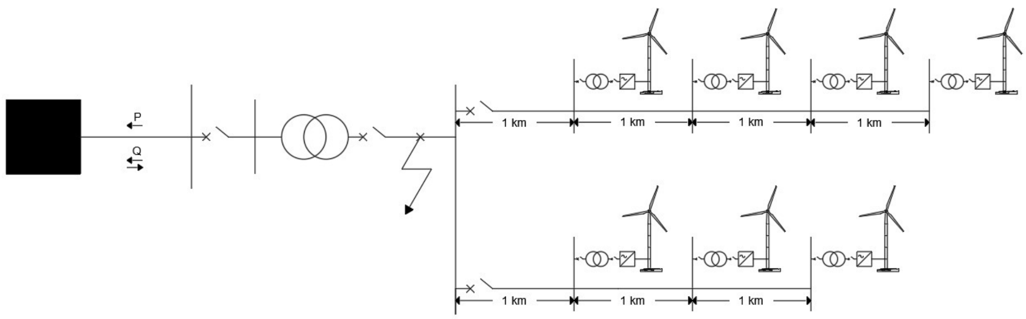

Figure 2.1. Wind farm grid with main components.

2.1 Cable grid and short circuit current

The wind farm grid operates on a 20 kV voltage level which requires cabling with sufficient insulating and thermal loading properties. Also, an important aspect is the cable's ability to withstand short circuit current. The short circuit current is at the highest when close to the 20 kV side busbar. The grid short circuit impedance and main transformer impedance are needed to calculate the short circuit current at that point. The short circuit impedance at the busbar can be calculated as follows:

$$Z_{k20} = Z_k + Z_{tr} = \frac{U_{20}^2}{S_k} i + r_k \frac{U_{20}^2}{S_{tr}} + x_k \frac{U_{20}^2}{S_{tr}} i$$

Where Z_k is the short circuit impedance of the grid, Z_{tr} the short circuit impedance of the main transformer, U_{20} is 20 kV, *Sk* the short circuit power at the wind farm connection point and S_n the transformer nominal power, r_k and x_k the main transformer short circuit resistance and reactance. The parameters and calculation results are presented in table 2.1.

Table 2.1. 3-phase short circuit current at 20 kV busbar.

Sk	2000 MVA
$\boldsymbol{S_n}$	50 MVA
$\boldsymbol{r_k}$	0.5 %
$\boldsymbol{x_k}$	7.35 %
$\boldsymbol{Z_{k20}}$	(0.04 + 0.788i) Ω
$\boldsymbol{I_{k20}}$	14.64 kA

The short circuit current ($\boldsymbol{I_{k20}}$) does not include short circuit current fed from turbines as they feed comparatively low amount of it. Wind power plants usually produce short circuit current, which is close to their nominal operational current, so it is negligible in this view frame. The short circuit current is not a limiting factor in the choice of cabling here as circuit breakers can cut a fault quickly enough for the cable not to damage. Also the break chopper used in the DC-link of the wind turbine converter limits the time of short circuit current being fed to the cable grid.

The highest load current appears on the cable closest to the busbar in string 1. Through this cable goes 57 % of the wind farm power. The maximum load current is slightly under 600 A.

Our cable of choice is 2x AHXAMK-W 3x185+35Cu. The load current is so large that a single cable would not be thermally suited for it, so we chose to use 2 cables. The combined thermal loading limit for these cables is 660 A. The cable grid consists of 7, 1km length pieces of this double cable. This is to make calculations easier to manage. Losses in these cables might prove to be substantial, so a techno-economic assessment could be warranted here possibly leading to a larger diameter.

2.2 Switchgear, breakers, and disconnectors

The medium voltage switchgear was chosen to be ABB Unigear ZS1 which is an air insulated switchgear rated up to 24 kV. The Unigear ZS1 uses a double busbar system. With many different rated nominal busbar currents and short circuit currents to choose from, we chose the 3150 A and 31.5 kA model. The Unigear ZS1 is depicted in figure 2.2.

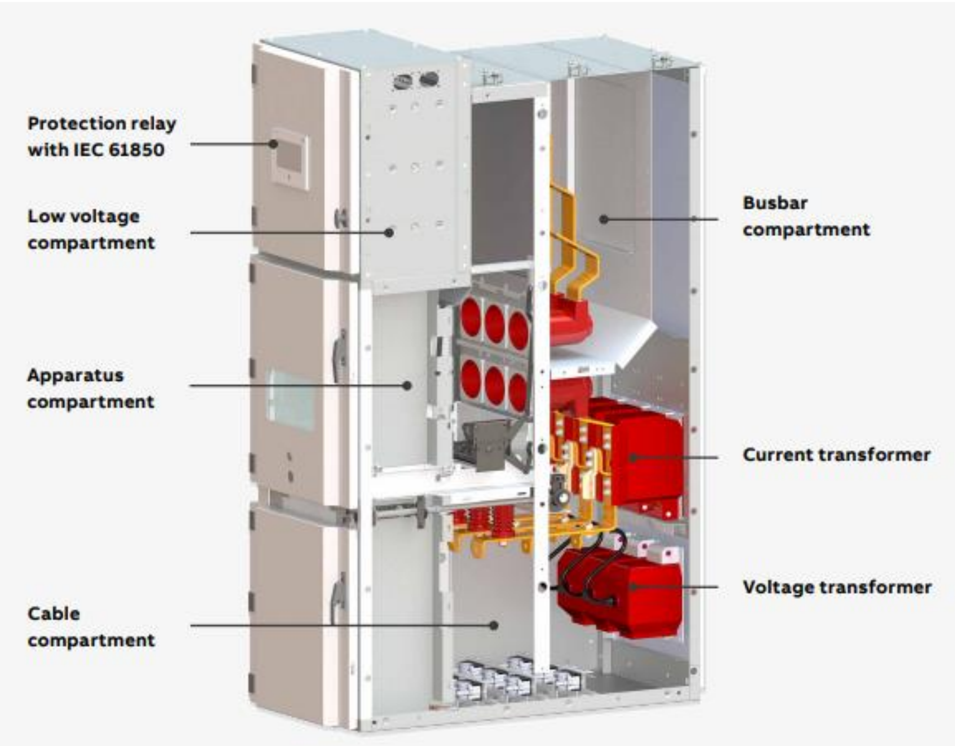

Figure 2.2. Unigear ZS1. (ABB 2021)

The breaker was chosen to be the ABB VD4 vacuum circuit breaker rated for 2500 A nominal current and with a 25 kA short circuit cut-off capability. Cut-off time on this breaker is between 43-75 ms. This model fits our specification needs and is compatible with the ABB

Unigear ZS1. The breaker is depicted on figure 2.3. This breaker also doubles as a disconnect switch so separate disconnectors are not needed for the 20 kV feeders.

Figure 2.3. ABB VD4 vacuum circuit breaker. (ABB 2018)

2.3 Transformers

Windfarm grid has 3 different voltage levels, and it needs transformers to transform power between them. Our selected main transformer is 20/110kV and it has power rating of 40 MVA, which is enough to output the wind farms power even in low power factor operating conditions. The product line is ABB Hitachi's "EconiQ Power Transformer". Wind turbines also have 3-phase transformers to convert the 690 V to 20 kV. We chose ABBs "large distribution transformers" with power rating of 5000 kVA to model these transformers in the calculations. Exact model and specs of the wind turbine transformer is unclear, in real-world scenario these probably would have been delivered with wind turbines.

2.4 Wind turbine

We chose Vestas V150 4.5 MW as the wind turbine for our wind farm. Vestas is one of the largest wind energy equipment producers in the world. This model is designed to be used in low wind sites. It promises very high energy production. It has 3-blade rotor and a gearbox with two planetary stages and one helical stage. The rotor diameter is 150 meters. It can operate in wind speeds between 3 and 24.5 m/s. Figure 2.4 shows the Vestas V150 wind turbine.

Figure 2.4. Vestas V150 wind turbines.

3. ANALYSIS OF ELECTRICAL QUANTITIES

In this chapter electrical quantities in different parts of the wind farm grid are calculated and described. In chapter 3.1, electrical quantities for the generator, converter DC-link, turbine transformer and at three different locations on the cable grid are calculated at nominal and half wind speed. Also, loss estimations in different main components and own power consumption of the wind farm are estimated. In chapter 3.2 calculations of active and reactive power, current and voltage at the Point of Common Coupling (PCC) and at the far most turbine is done in two different grid conditions. Analysis calculations are carried out in MATLAB and the most important equations used are presented with the results in this report.

3.1 Electrical quantities at nominal and half wind speed

Following electrical quantities are calculated at nominal and half wind speed and with assumption that the power factor is 1. Nominal wind speed of wind turbine is assumed to be 11 m/s. Generator rotational speed is assumed to be 146.6 rad/s at nominal wind speed.

3.1.1 Generator electric quantities

Generator voltage is 690 V and power at nominal wind speed is 4.5 MW.

Generator torque $T_{generator}$ can be calculated with equation 3.1

$$T_{generator} = \frac{P_{generator}}{\omega_{generator}} \tag{3.1}$$

Where $P_{generator}$ is power of the generator and $\omega_{generator}$ is rotational speed of the generator.

Generator current $I_{generator}$ can be calculated with equation 3.2

$$I_{generator} = \frac{P_{generator}}{\sqrt{3}U_{generator}} \tag{3.2}$$

Where $U_{generator}$ is generator voltage.

Power output of the wind turbine with half wind speed $P_{\frac{1}{2}}$ can be calculated with equation 3.3 (Pyrhönen 2021).

$$P_{\frac{1}{2}} = \left(\frac{5.5\,\frac{m}{s}}{11\,\frac{m}{s}}\right)^3 * P_{generator} \tag{3.3}$$

Torque output of the generator with half wind speed $T_{\frac{1}{2}}$ can be calculated with equation 3.4 (Pyrhönen 2021).

$$T_{\frac{1}{2}} = \left(\frac{5.5\,\frac{m}{s}}{11\,\frac{m}{s}}\right)^2 * T_{generator} \tag{3.4}$$

Generator rotational speed $\omega_{1/2}$ can be calculated with equation 3.5 (Pyrhönen 2021).

$$\omega_{\frac{1}{2}} = \left(\frac{5.5\,\frac{m}{s}}{11\,\frac{m}{s}}\right) * \omega_{generator} \tag{3.5}$$

Table 3.1 Electrical quantities at Generator

Value	**Nominal wind speed 11 m/s**	**Half wind speed 5.5 m/s**
P	4.5 MW	562.5 kW
T	30.7 kNm	7.7 kNm
ω	146.6 rad/s	73.3 rad/s
I	3.77 kA	470.7 A
U	690 V	690 V

We can see our Generators electrical quantities in table 3.1.

3.1.2 Converter DC-link electric quantities

DC-link voltage is calculated by converting the AC voltage of the generator to DC. It is done with equation 3.6

$$U_{DC} = \sqrt{2} U_{generator} \tag{3.6}$$

The current in DC-link can be calculated with Ohms law in equation 3.6

$$I_{DC} = \frac{P_{generator}}{U_{DC}} \tag{3.6}$$

Table 3.2 Electrical quantities at DC-link

Value	**Nominal wind speed 11 m/s**	**Half wind speed 5.5 m/s**
$\boldsymbol{U_{DC}}$	975.8 V	975.8 V
$\boldsymbol{I_{DC}}$	4.61 kA	576.4 A

We can see our voltages and currents at DC-link in table 3.2.

3.1.3 Turbine transformer

Turbine transformer is 0.69/20 kV ABB’s ”Large distribution transformer” with power rating of 5 MVA.

Current I_t at the transformer can be calculated with equation 3.7.

$$I_t = \frac{S_t}{\sqrt{3} U_t} \tag{3.7}$$

In which S_t is the power and U_t is the voltage of the transformer.

Table 3.3 Electrical quantities at Turbine transformer.

Value	Nominal wind speed, low voltage side	Nominal wind speed, high voltage side	Half wind speed, low voltage side	Half wind speed, high voltage side
U_t	690 V	20 kV	690 V	20 kV
I_t	3.77 kA	129.9 A	470.7 A	16.2 A

We can see our voltages and currents at turbine transformer in table 3.3

3.1.4 Electrical quantities at 3 different locations of the wind farm

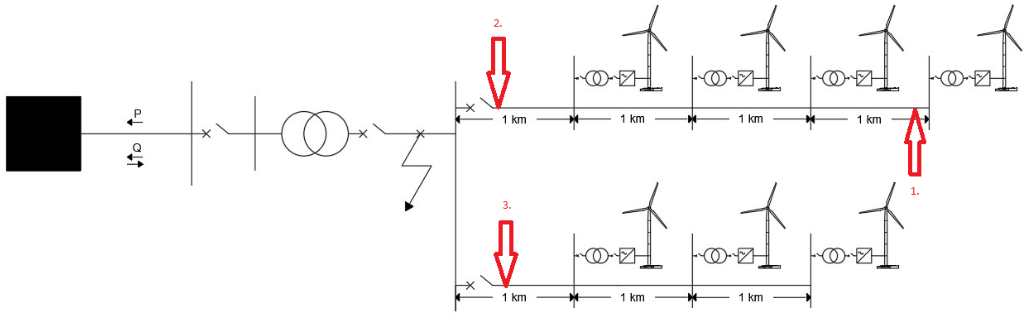

Figure 3.1. Selected calculations points in the medium voltage cable grid.

Current *I* at the power grid can be calculated with equation 3.8.

$$I = \frac{S}{\sqrt{3}U} \tag{3.8}$$

Where *S* is the power and *U* is the voltage of the power grid.

Voltage drop of the power grid can be calculated with equation 3.9

$$U_2 = U_1 - IZ \tag{3.9}$$

Where Z is the impedance of the power grid, U_2 is voltage after the impedance and U_1 is the voltage before impedance.

At location 1 as seen from the figure 3.1 and form the equation 3.8 the current is at the lowest because only one wind turbine produces power through it. At that location the voltage is also the highest because only one turbine and its components causes impedance as seen from the equation 3.9.

At location 2 as seen from the figure 3.1 and from the equation 3.8 the current is about 3 times higher than at location 1. Voltage is also lower because 3 turbines, its components and 3 km of conductors causes impedance. Same thing at location 3 but the current is about 4 times higher than at location one and voltage is the highest of the wind farms medium voltage grid because 4 turbines, its components and 4 km of conductors causes impedance.

3.2 Loss estimation

Losses occur in all components of the wind farm. Traditional gearbox with planetary and helical stage has a typical efficiency if 90-95 % according to lecture material. Modern wind turbine transmissions can achieve better efficiency even 97 % according to our sources (Giger U et all. 2011). We assume our wind turbines efficiency is 95 %.

Losses also occur in the generator of wind turbine where the mechanical energy is transferred to electricity. According to our sources the generator efficiency is between 97-99 % (Kullinger 2009). Let’s assume our generators efficiency is 98 %.

Transformers have losses occurring during operation (iron and copper losses) but also during no-load time. No-load losses do not depend on the transformers load. According to our source majority of transformers has full load efficiency between 95 and 98.5 % and lower with less load (Daware). We do not have exact models of our turbine transformer. We can assume that the turbine manufacturer provides the turbine transformer as well and its efficiency is 97 % at nominal power. ABB has given exact loss values for our 40 MVA main transformer. It has no-load loss of 21 kW at rated voltage (110 kV) and load loss of 175 kW at rated power of 40 MVA (ABB). Load loss $P_{k,1}$ at other power levels can be calculated with equation 3.10.

$$P_{k,1} = P_{kn}\left(\frac{S_{L,1}}{S_n}\right)^2 \tag{3.10}$$

Where P_{kn} is load loss at nominal power, $S_{L,1}$ is load of the transformer and S_n is transformer nominal power.

From that we can calculate that our main transformers efficiency is 99.6 % at nominal wind speed and 99.4 % at half-wind speed.

Losses also occur in transmission lines. We chose to use 2x AHXAMK-W 185- cable. It has resistance of 0.1 Ω/km if we assume power factor is 1. From figure 2.1 and with equation 3.11 we can estimate our transmission losses P_{losses}.

$$P_{losses} = I^2R \tag{3.11}$$

With nominal wind speed losses in cable transmission is estimated to be 74.2 kW and with half wind speed 1.2 kW.

All the power electronics in wind turbines also use energy to operate and they affect our overall efficiency. These power electronics include converters, safety equipment, cooling equipment, lights, control equipment etc. We can estimate that our power electronics efficiency is 97 % according to The Switch datasheet (The Switch). The cooling and fan losses of wind turbines can be assumed to be 1 % of the wind turbine power so it accounts to 45 kW at nominal wind speed and 5.6 kW at half-wind speed.

Overall power efficiency of our single wind turbine is estimated to be 90 % at nominal wind speed transferring mechanical energy to electrical energy. If we look our whole wind farm efficiency, we can expect efficiency of about 86.2 % at nominal wind speed and 84.4 % at half wind speed. These efficiencies are calculated to be from transferring mechanical energy to electrical energy and transferring it to the 110 kV transmission network.

3.3 Active and reactive power production

The two grid conditions given are:

- Condition 1: Full active power, 10 % grid undervoltage, power factor 0.95 capacitive
- Condition 2: 50 % active power, 5 % grid overvoltage, power factor 0.93 inductive
- Nominal grid voltage is defined as 110 kV

The voltage at PCC can be calculated with equation 3.12 (Pyrhönen 2022).

$$U_{PCC} = U_{grid} - \frac{Z_k Q}{U_{grid}} \tag{3.12}$$

Where U_{grid} is the grid voltage and Z_k the short circuit impedance of the grid and Q is the reactive power required by the grid.

Short circuit impedance Z_k can be calculated as follows (Pyrhönen 2022):

$$Z_k = \frac{U_{grid}^2}{S_k} \tag{3.13}$$

Where S_k is the short circuit power of the grid at the wind farm connection point (2000 MVA).

Reactive power Q can be calculated as follows (Pyrhönen 2022):

$$Q = P\sqrt{\frac{1}{PF^2} - 1} \tag{3.14}$$

3.3.1 PCC electrical quantities

The current at PCC can be calculated with equation 3.X

$$I_{PCC} = \frac{\sqrt{P^2 + Q^2}}{\sqrt{3}U_{PCC}} \tag{3.15}$$

Where P is active power production of the wind farm at PCC when simplified estimated power losses of the cable grid and turbine transformers (-5 %) are considered.

Results of PCC current, voltage, active, reactive, and apparent power calculations are shown in table 3.4. In condition 2 as the power is halved the PCC current drops respectively. The grid undervoltage in condition 1 causes a need for reactive power production which is seen as a positive Q_{PCC} value. Hence the voltage of PCC is higher than the grid voltage. In condition 2 the overvoltage causes a need for consumption of reactive power which in turn lowers the PCC voltage in comparison to the grid.

Table 3.4 Electrical quantities at PCC.

Z_k = 6.05 Ω (110 kV)	**Condition 1**	**Condition 2**
I_{PCC}	181.3 A	81.2 A
U_{PCC}	99.6 kV	115.2 kV
P_{PCC}	29.9 MW	14.9 MW
Q_{PCC}	10.4 MVar	-6.2 MVar
S_{PCC}	31.7 MVA	16.2 MVA

3.3.2 Electrical quantities of the furthest turbine

The same electrical quantities will be calculated at the furthest wind turbine which is located at the end of string 1. To calculate the reactive power production of a single turbine, a reactive power balance needs to be calculated. The grid components either produce or consume reactive power depending on the amount of current or grid condition. This power balance is shown in figure 3.2. The bars in figure 3.2 depict the production or consumption of reactive power by component. The bar on top shows the grid reactive power consumption, followed by main transformer consumption, cable grid sum production, turbine transformer sum consumption and turbine sum production.

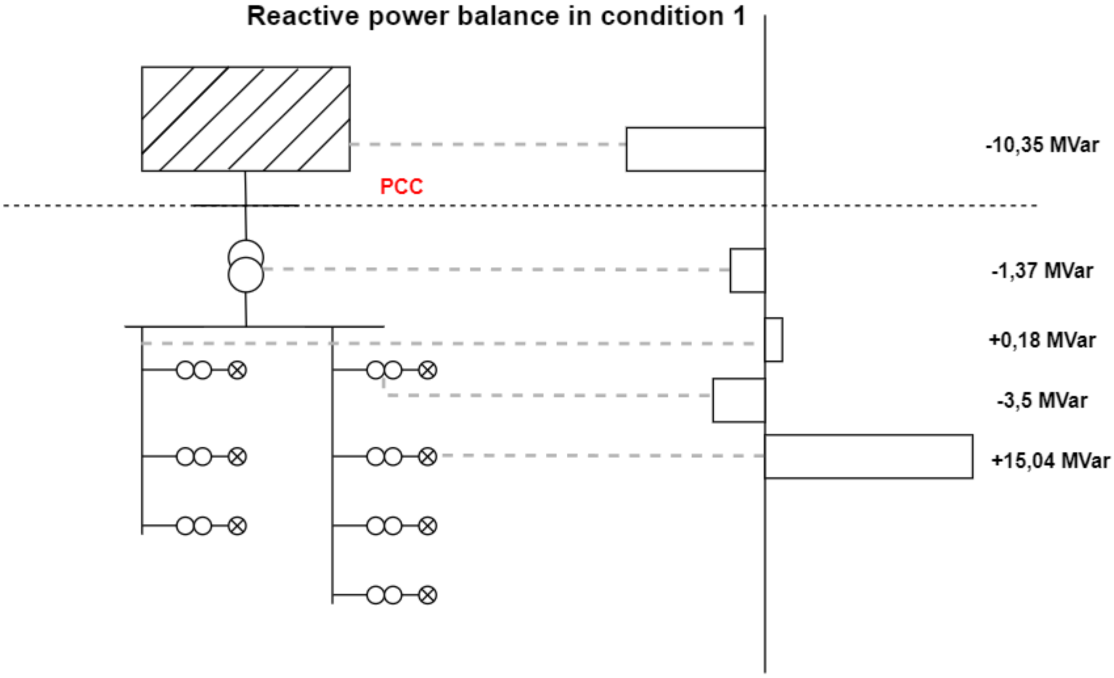

Figure 3.2. Reactive power balance of the wind farm grid in condition 1.

The main transformer's and turbine transformers' reactive power consumptions were calculated as follows:

$$Q_{transformer} = x_k \left(\frac{S}{S_n}\right)^2 S_n \tag{3.16}$$

Where x_k is the short circuit reactance of the transformer (%), S the apparent power and S_n the nominal apparent power. x_k was assumed to be 5 % for the main transformer and 10 % for the turbine transformers.

The reactive power production of the cables was calculated as a sum of each 1 km cable with the following equation (Virtanen 2020):

$$Q_{cable} = \omega C U^2 - 3\omega L I^2 \tag{3.17}$$

Where ω is 2πf, C is the capacitance of the cable and L the inductance. Voltage U was assumed to be 20 kV in all situations to make calculations more manageable. Current I changes by cable part and grid condition. The capacitance and inductance are from the AHX-AMK-W datasheet but have been modified to accommodate the use of 2 cables. Closest to the busbar, in string 1, the cable section consumes reactive power due to high current flow while all the other parts produce reactive power.

The turbine reactive power production needed is then calculated from the sum of all components' reactive power production and consumption. In condition 1 a turbine needs to produce 2.1 MVar of reactive power and in condition 2 consume 0.8 MVar.

Other calculation parameters and information:

- 21/115 kV main transformer turns ratio
- Total wind farm current is calculated at 20 kV busbar and divided to turbines (each produces the same amount of current)
- PCC voltage dictates 20 kV bus voltage through transformer's turns ratio (no tap changer used)
- 2x AHXAMK-W 185 impedance is (0.1 + 0.0915i) Ω/km

In table 3.5 the electrical quantities at the furthest turbine (T4) are presented.

Table 3.5 Electrical quantities at the furthest turbine (T4).

	Condition 1	**Condition 2**
I_{T4}	150.3 A	66.4 A
U_{T4}	18.5 kV	21.1 kV
P_{T4}	4.5 MW	2.3 MW
Q_{T4}	-2.1 MVar	0.8 MVar
S_{T4}	5.0 MVA	2.4 MVA

The voltage level in condition 1 is quite low. This means active voltage level adjustment with the main transformer tap changer would be needed. The voltage level is calculated from the busbar by adding the voltage increase in each 1 km section of cable in the string.

4. SUMMARY AND ANALYSIS OF RESULTS

Calculations were simplified where we felt made sense to do so. These simplifications make the results somewhat inaccurate when comparing them to what the real results might be. For example, the power losses in the cable grid and other components could be calculated more accurately. Now we assumed the losses to be 5 % of the active power. To be more precise it would require an iterative process of guessing a current and going through the calculations.

The cable grid is not realistic. With no budget incentive, we chose to use 1 km length pieces of double AHXAMK-W 185 throughout the grid. A more realistic approach would be to use for example a 2x240 cable in high current density part of the grid and then use lighter cables in lower density areas. Also, realistically the turbines would probably not be placed exactly 1 km apart, but this was done to make calculations easier to manage. Shorter cables would be more economical and result in lower power losses, different reactive power production or consumption and voltage levels. A circular grid structure operated radially could also be an option to prepare for cable fault situations.

Use of tap changer in the main transformer was not considered in the calculations but it would be necessary to keep voltage levels at reasonable range.

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