Series connection of offshore DC wind turbines
Mini project in TET 4190 Power Electronics

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Abstract
This paper presents some of the electrical challenges in an offshore wind farm, considering the transmission system, type of voltage and use of power electronics. With long transmission lines of high voltage AC (HVAC) a high reactive current occurs, which can be a problem in offshore wind power. A solution is to use high voltage DC (HVDC) link to shore, either by having a substation with AC-DC converter or by having DC output on the turbines. With a DC output and a series connection of several wind turbines it is theoretically possible to achieve a voltage level high enough to transmit the energy directly to shore. If it is practically possible the need of a large substation disappears, and the cost of the wind park will be significantly reduced.
Index

1. Introduction .......................................................................................................................... 3
2. Why wind energy? ................................................................................................................. 3
   2.1 The potential of offshore wind power ............................................................................... 4
3. HVDC vs. HVAC .................................................................................................................... 4
   3.1 Today’s AC solution ......................................................................................................... 5
   3.2 HVAC wind farm with HVDC shore link ........................................................................ 5
   3.3 DC wind farm .................................................................................................................. 5
4. Technical challenges due to series connection .................................................................... 6
5. Three-phase, full-bridge rectifier .......................................................................................... 7
   5.1 Commutation process ...................................................................................................... 7
   5.2 Limitations ...................................................................................................................... 7
6. Boost converter ...................................................................................................................... 7
   6.1 Discontinuous Conduction Mode ................................................................................... 8
7. Simulation ............................................................................................................................... 8
   7.1 Model components .......................................................................................................... 8
      7.1.1 Diode rectifier ......................................................................................................... 9
      7.1.2 DC-DC Step-up converter (Boost) .......................................................................... 9
   7.2 The Complete Model ...................................................................................................... 11
      7.2.1 Series connection .................................................................................................... 12
8. Conclusion ............................................................................................................................. 14
References ................................................................................................................................. 14
1. Introduction

The world needs more environmentally friendly energy. Part of this may be generated by offshore wind power. The problem with offshore wind power is that it is expensive and thus poor margins. Therefore wind parks often paid down for a long time. This means that wind farms are very cost sensitive. A small change in the cost of wind farms will be the difference whether a wind farm will be built or not.

The majority of wind power potential is far from land. It is important to transmit this power to land (point of common coupling) as efficiently as possible. In other words, we need to minimize losses. The losses can be reduced by either increasing the voltage or decrease resistance. Decreasing resistance is done by increasing the cross section of the cables. Cables are expensive, one therefore want to avoid a very high cross section. The issue we need to look at is increasing the voltage. That can be done with a transformer in an HVAC based system or with a DC-DC converter in a HVDC based system.

The cost of a wind power project may be minimized by using HVDC, instead of HVAC. In this project we will focus on a HVDC solution from generator to shore. Review of relevant technology will be given. We'll also examine a power electronics system suitable for AC generators with a DC output. Simulations will also be run.

2. Why wind energy?

The worlds increased need of energy, and a vision of a high percentage of the global energy should be produced by renewable resources, has increased the demand of wind energy the last decades. Fossil fuel as energy source belongs to the past, and that force us to use the more of the power in the nature and more efficiently.

In Norway, “Kjeller Vindteknikk” has measured wind all over Norway and made a wind resource map, which describes the average wind speed over a year (Figure 1). Not surprisingly it is along the coast and places high above sea level which have the highest average wind speed onshore, and therefore is the most suitable places to build wind farms. In many of those places wind farms already have been built, but the full potential around the country cannot be used, often due to local resistance and conditions. Wind power as energy resource is very good in an environmental impact point of view, but the building of wind farms make large encroachments on nature and the farms occupy large areas. The consequences can be kilometers of roads and huge substations in untouched nature. The visual aspects and the noise from wind turbines are other arguments local opponents use for not building wind farms.
2.1 The potential of offshore wind power

By moving the wind farms from shore to offshore, many of these challenges disappear (and new ones appear). You will for sure get no complaints from neighbors and the areas available are enormous. Additionally, the average wind speed is much higher compared with all alternatives onshore, which gives us a higher production potential. Since wind power per unit area can be expressed as:

\[
P = \frac{1}{2} \rho U^3 \frac{A}{2}
\]

The energy produced will increase a lot even the wind increases only by 1 m/s. Table 1 illustrates how big the difference is, and compares a Rayleigh-Betz turbine with a real offshore turbine. (Air density is set to 1,225 kg/m\(^3\)) A Rayleigh-Betz turbine is an optimized theoretical turbine which describes how much energy it is possible for a machine to generate. The maximum possible efficiency is calculated to be 0,593, most because of the impossibility to have zero wind speed behind the turbine. The real turbine (Vestas V164 7,0 MW) used in Table 1, has an varying efficiency depending on the wind speed, but in reality the efficiency is approximately 0,3-0,4 at ideal wind speed. (1) This turbine reaches its maximal production limit at 13 m/s, and for higher wind speeds the efficiency is therefore quite low. To have wind turbines with higher maximal production it is not economical viable, because of cost of blades and structure.

<table>
<thead>
<tr>
<th>Wind speed (m/s)</th>
<th>Power/area (W/m(^2))</th>
<th>Rayleigh-Betz machine (W/m(^2))</th>
<th>Vestas V164 (W/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>80</td>
<td>47,4</td>
<td>30,8</td>
</tr>
<tr>
<td>10</td>
<td>610</td>
<td>361</td>
<td>237</td>
</tr>
<tr>
<td>15</td>
<td>2070</td>
<td>1227</td>
<td>331</td>
</tr>
<tr>
<td>20</td>
<td>4900</td>
<td>2904</td>
<td>331</td>
</tr>
<tr>
<td>25</td>
<td>9560</td>
<td>5665</td>
<td>331</td>
</tr>
</tbody>
</table>

Table 1: Wind energy potential (2)

Most of the oil platforms along the Norwegian coast produce today their own energy with gas turbines, which have a high amount of greenhouse gases emissions. From the Oseberg-area the total emissions of CO\(_2\)-gas from production of electricity were over 800 000 tons in 2004. (3) Wind energy can therefore be an important part of reducing the amount of fossil fuel burned at the oil platforms. From the map (Figure 1) we can see the potential for offshore wind energy production is very high.

3. HVDC vs. HVAC

For transmission of electrical energy across large distances, the popular choice has been to use HVAC power lines. With this solution the voltage can easily be transformed up or down without the need of expensive converters.

For large offshore wind farms this solution poses several challenges. Due to the high capacitance pr. length in subsea AC cables, the reactive current restricts the active current capacity of the cable. Because of this compensation is required for long lengths. This leads to a limitation of the HVAC cable length to 50 – 80 km, depending on the system voltage. Also the grid connected to the HVAC system will have a large earth fault current. Therefore HVDC is used for long range high power subsea transmission. The advantages of a HVDC link are that the power losses and the voltage...
drop in the connection are very low, and there is no limitation on the connection length beyond the
cable manufacturer’s practical limitations. The downside of HVDC connections is that there must
be a converter station at each end of the link. Because of the relatively high energy losses in the
converters, and a larger unavailability of the link HVAC links are still favored for short length
transmissions. (4)

The initial cost of a wind farm is high, and so if the economical result of an offshore wind farm is
to be positive the initial cost and losses need be reduced to a minimum. This is why the HVDC
technology needs to be adapted to fit the requirements of large offshore wind farms located far off
shore.

3.1 Today’s AC solution

Today a relative small amount of wind farms are placed offshore. These wind farms are placed
close to shore and their capacity vary from about 60 MW to 370 MW. Most of the offshore wind
farms constructed in northern Europe in the early 00’s used a design with an offshore substation.
(4) The substation gathers all the wind clusters and then transforms the voltage up before
connecting it to the shore link.

Another adaption to the AC solution is used at the Kentish Flats and Scroby Sands wind farms
located of the coast of the UK. Instead of an offshore substation the wind turbine generators are
connected to the power grid via three three-core medium voltage cables. This reduces the initial
cost of the wind farm since there is no need for an expensive offshore substation.

3.2 HVAC wind farm with HVDC shore link

One way of solving the problem regarding the high reactive current in the HVAC link is to use a
HVDC link instead. This solution connects all the wind turbines to a conventional AC bus before
connecting to an offshore substation. The upside to this solution is that there is little need for
power electronics. Since the wind turbines are connected to an HVAC bus we can use a
conventional transformer to transform the voltage to the required level. Therefore only the
substations AC-DC converter needs to apply power electronics. This configuration reduces the
system losses. The downside is that there still is a need for an offshore substation.

3.3 DC wind farm

A DC solution is a future option for a wind farm relatively far from shore (over 80km) (5). The
voltage is rectified to DC at the wind turbines and then inverted to AC at a point of common
coupling.

In power production AC generators are preferred. So in a HVDC wind farm this AC generator will
be coupled with a rectifier to create the DC output voltage. The rectifier is then connected to a DC-
DC converter. This converter is used instead of a conventional AC transformer to increase the
rectified voltage to the required level for the local wind turbine grid. The output voltage from the
rectifier depends on several factors such as wind speed, type of generator and control strategy. (6)

The DC output from the rectifier can be connected either in series or parallel. For a parallel
solution one will require a common converter to step-up the voltage before transportation to shore
(except for short distances). If a series solution is used, the cluster output voltage will be amplified
by the number of turbines in series. So if a sufficient number of turbines are connected together
one will not need a common step-up converter.

A system with a common converter can be controlled in two different ways; a fixed output voltage
at the wind converter or a fixed voltage at the common converter. The result is the same, a fixed voltage at the DC cable from offshore to shore. (6)

In a HVDC wind farm line costs will be lower because of less need for cables (only two) and no need for compensation on long lines.

4. Technical challenges due to series connection

With a series connected wind farm some technical challenges appear. One problem can be the insulation. If for example three DC wind turbines with a 10 kV output voltage are series connected to achieve 30 kV on the bus, the electric potential to earth will be a challenge. For the first wind turbine in the series connection there is no problem, but for the last turbine the terminals will have 30 and 20 kV potential difference to earth. This wind turbine will have a much higher insulation requirement compared to the first turbine. The tower and the sea water will have earth potential and needs to be separated from the conductors. Therefore the requirement of cables withstand strength will be difference along the series connection of wind turbines. The phase to ground potential of the last turbine can be reduced by placing the system ground in the middle of the series connection. With even more turbines in series the challenge will be larger.

Series connection of wind turbines also faces a challenge regarding a constant grid voltage. If one of the wind turbines needs maintenance or repair and must be disconnected from the series connection, it is not acceptable for the voltage to drop. With six-eight wind turbines in the series connection the problem can be solved by having a 10-20 % generated voltage margin on each wind turbine. This solution will not be suitable if the series connection consist of two-three wind turbines. Due to economical considerations it will be too costly to have 50-100 % voltage margin on each turbine, and you may have to stop the production on the whole series connection because of a
simple error on one of the turbines.

5. Three-phase, full-bridge rectifier

A six pulse diode rectifier is used to make DC voltage from an AC voltage. A diode conducts when current flows from anode to the cathode and it will conduct until the current becomes zero. Unlike a thyristor rectifier the diode rectifier cannot be controlled. Therefore the output voltage from the diode rectifier is given by the input voltage multiplied by a factor:

\[ V_d = \frac{3\sqrt{2}}{\pi} \cdot V_{LL} \]

Figure 2: Six pulse diode rectifier (7)

5.1 Commutation process
If the source is not ideal it will be a finite series inductance which gives us a current commutation process. Current commutation is a process when four diodes are conducting at the same time; therefore the source is short circuited. Current commutation will reduce the average output voltage. If a finite series inductance is placed between an ideal source and the diode rectifier the output voltage from the diode rectifier will be given by:

\[ V_d = V_{d0} - \frac{3}{\pi} \cdot \omega \cdot L_s \cdot I_d \]

5.2 Limitations
The diode rectifier allows no regulation of the reactive power, therefore the generator will have to operate with a \( \cos \varphi \neq 1 \). Power out from a generator is given by:

\[ P = \sqrt{3} \cdot V_{LL} \cdot I \cdot \cos \varphi \]

With a diode rectifier one will therefore have to buy a larger generator than with a full bridge rectifier or add a capacitor bank in parallel with the generator to get the same output power.

6. Boost converter
A boost converter (also known as step-up converter) is a DC to DC converter with output voltage greater than the input voltage. A boost converter is made with an inductance, a diode and a transistor (modeled as an ideal switch). When the switch is on the source voltage equals the
voltage over the source and the inductance. The current will therefore build up until the switch is turned off. When the switch is turned off all the current will have to flow through the diode. The output voltage equals the voltage over the inductance when the switch is off. To minimize ripple on the output voltage a capacitor is connected in parallel with the load. The relationship between input and output voltage in boost converter is (in continuous conduction mode):

$$\frac{U_o}{U_d} = \frac{1}{1 - D}$$

![Boost Converter](image)

Figure 3: Boost Converter (7)

6.1 Discontinuous Conduction Mode
If the current through the inductance goes to zero in the end of a period, the boost converter goes into discontinuous conduction mode. This happens when the load is very low (power $\rightarrow 0$). When the current through the diode is zero, the voltage over the load will also be zero in the end of the period.

7. Simulation
As a part of the rapport a simple model of two series connected wind turbines with a diode rectifier and a step up converter were made. The model should be constructed using ideal components so that converter and transmission losses can be neglected. To construct the model and to post process the results Matlab with Simulink was used.

Simulink in combination with the Simpower Systems toolbox gives the possibility to easily construct the model by intuitive circuit construction, and then perform the wanted analysis. The Simpower toolbox has a wide variety of components and the possibility to make most components ideal.

7.1 Model components
In order to create the model of the series connected wind turbines we needed to construct an six pulse diode rectifier and an step-up converter. The Simpower toolbox already contains these components, but for the purpose of this project we wanted to construct our own. This would give a broader understanding of the model since it would not just be built up by several “black boxes”.

8
7.1.1 Diode rectifier

The first component we constructed was the six pulse diode rectifier. Ideally the rectifier should be constructed using IGBT. An IGBT rectifier requires an extensive control system and for the purpose of simplicity a diode rectifier is used in this rapport. The diodes in the model are set to the ideal setting since the snubber resistance is set to unlimited and the capacitor is set to zero. Also the lead voltage drop over the diode is set to zero. To measure the diode current a current measurement above diode three was added. To make the complete model comprehensible the diode rectifier model was converted to a subsystem. Our diode rectifier model is shown in Figure 4.

![Figure 4: Diode rectifier.](image)

If we insert a three-phase voltage with phase to phase amplitude of $3300\sqrt{2}$ into the diode rectifier model we get an output signal as shown in Figure 5. As you can see from the figure the output signal matches what Figure 5-32b in “Power Electronics – Converters, application and design” (7), and we can therefore verify the quality of the model.

![Figure 5: Diode rectifier output voltage](image)

7.1.2 DC-DC Step-up converter (Boost)

From the output of the diode rectifier we needed a step up converter to boost the voltage to the required bus voltage. For the switch needed in the step-up converter we used an ideal switch block. The ideal switch block does not correspond to any physical device, but is used to model simplified semiconductor devices such as the GTO or MOSFET. This block was also made ideal by setting the internal resistance to zero.

To control the switching a simple pulse generator was used. This block provides an alternating signal between zero and a wanted value. It is also possible to adjust the frequency and the pulse
width of the output signal. This gives us the possibility to control the duty cycle of the step-up converter.

The values of $L_s$ and $C$ are very important to make the model more accurate, even though realistic values for these components are hard to obtain. The values of $L_s$ and $C$ must be of such magnitude that the converter does not enter discontinuous mode during any form of normal operation, but also minimize the current and voltage ripple.

Also this model was turned into a subsystem to make the complete model comprehensible.

To verify the quality of the step-up converter a simple DC signal was inserted on the primary side of the converter. If the duty cycle is set to 50 %, the switching frequency to 100 kHz and the load was adjusted so that the converter did not enter discontinuous mode. The output voltage became as shown in Figure 7. It must be noted that a switching frequency of 100 kHz is very high for a converter designed to transfer power in the MW scale.

Figure 6: Step-up (Boost) converter.

Figure 7: DC-DC Step-up converter output voltage.

Figure 7 shows the output from the step-up converter. It is an almost constant voltage with twice the magnitude of the input voltage, except for some small ripple. If we compare this signal with Figure 7-17 in “Power Electronics – Converters, application and design” (7), we see that the signals
match. The difference is due to the smoothening of the voltage caused by the output capacitor. We can therefore verify that this model is correct.

If we observe the current through $L_s$ (Figure 8) we can see that the converter is almost at the boundary between continuous and discontinuous mode of operation. Discontinuous mode is not an acceptable point of operation in power production and therefore the design of the wind turbine must be such that it never enters this mode.

![Figure 8: Inductor current](image)

### 7.2 The Complete Model

By combining the individual parts we now have a complete model of one wind turbine with a diode rectifier and a step-up converter (Figure 9). As a model for the wind turbine generator we used three AC voltage sources with a phase shift of 120 degrees connected together in a wye connection. We also added a series inductance ($X_s$) to represent the armature reactance of a synchronous generator. Also to smoothen the voltage from the diode rectifier a capacitor was added between the rectifier and the step-up converter.

![Figure 9: The complete model of one wind turbine](image)

If we take a look at the output voltage (Figure 10) from this model we can still see, even though it has been smoothened by the capacitor, the ripple from the rectifier. We can also see that the ripple has been amplified by the step-up converter. The thickness of the curve is due to the high frequency output ripple from the step-up converter. The transfer ratio of:

$$V_d = \frac{3\sqrt{2}}{\pi} \cdot \frac{V_{LL}}{1-D}$$

is no longer valid due to the fact that we need to take the commutation losses created by the series
inductance in to consideration. Therefore the new equation for $V_d$ is:

$$V_d = (\sqrt{2}V_{LL} - \alpha L_r) \cdot \frac{3}{\pi(1 - D)}$$

**7.2.1 Series connection**

To increase the voltage further a possibility is to create clusters of wind turbines where all the turbines in each cluster are connected together in series. As discussed earlier this will result in some challenges due to a rise in phase to ground voltage on the last turbine in chain. A solution for this is to place the ground potential in the middle of the chain.

Since we now have a working model of one wind turbine, it would be interesting to see what would happen in such a case. Our model of the series connection system is shown in Figure 11.

The output voltage of the series rectifier with a switching frequency of 2 kHz is shown in Figure 12. The values of $L_s$ and $C$ are modified in the step-up converters to prevent the system for entering discontinuous mode, and also to reduce the output voltage ripple. The time scale is the same as in Figure 10.
Figure 12: Series connection output voltage

Since the value of the load is the same as for one turbine the \( I_d \) in each step-up converter has increased. The result of this is that the effect of the commutation losses has also increased. This means that the output voltage is not twice as high as it was with only one turbine. The increase in commutation losses is important to take into consideration when designing power electronics for series connection of wind turbines.

This result shows that it is at least theoretically possible to connect several turbines in series, and achieve a high enough DC voltage to directly transport the energy to shore.
8. Conclusion

The project reflects the difficulties of long HVAC connection links and the possibilities of using a HVDC connection. In the course of this project we have discussed different possibilities of combining power electronics to create a solution for offshore wind farms located far of shore. To avoid one of the most expensive components in today’s offshore wind farms we were asked to look into a solution where several wind turbines, with a DC output, is connected together in series.

Our goal was to build a simple ideal model of a series connected wind turbine, and evaluate the results based on the theory learned in the power electronics course. As shown in the simulation chapter we have successfully built a basic model of a wind turbine and connected them in series. The model gave us the opportunity to see how the different components in the diode rectifier and the step-up converter affect each other, and also a great insight in the process of power electronic equipment design.

The model illustrates that it is at least theoretically possible to achieve a high enough voltage by a series connection of wind turbines to remove the need for a common offshore substation.

References