Design, Control Simulation and Energy Evaluation of a DC Offshore Wind Park

André Madeira Marques
andre.marques@ceeta.pt

Abstract - This thesis investigates the control capabilities and energy production of a 200MW DC wind park, placed 300km offshore. The design as well as the torque and speed control of the Permanent Magnet Synchronous Generator (PMSG) is done for three converters: the boost converter, the full bridge, and the Active Three-phase Rectifier (ATR). The voltage and current control is explained for the Voltage Source Converter (VSC) onshore that delivers power to the grid. Simulations are made using MATLAB/Simulink. Loss calculations are done for all wind speeds operable.

The response time for the boost converter is 8ms, for the ATR is 5ms and 20ms for the full bridge. Using 12kV as output voltage, the converter with less losses is the ATR followed by the boost converter (both around 1%). Using 60kV as output voltage the best converter is the full bridge using duty cycle control (1.62% at rated power).

The current control of the VSC onshore is done by decoupling \( I_d \) and \( I_q \) to control the voltage in the DC submarine cable and the reactive power to the grid independently. The system responds fast and able to withstand small and large perturbations.

The best topology for the DC grid is connecting 5 turbines in parallel to 12kV, to 60kV and then to 200kV, where a submarine cable transports the energy to shore.

Keywords: DC offshore wind park, boost converter, full bridge converter, Active three-phase rectifier, Voltage Source converter, Permanent Magnet Synchronous Generator.

I. INTRODUCTION

1. Why study DC offshore wind parks?

Humanity continues to search for alternative sources to produce electricity, due to the environmental problems classical sources have, like coal, gas and oil. Wind power is one of the most promising alternative sources. Some countries have produced so much wind turbines inland that now people are complaining about noise and landscape spoiling.

One solution is to place the turbines in the sea, far from the shore for nobody to see or hear them. Also the wind is more constant and stronger than inland. When the distance from the shore is too large a DC connection is more profitable than an AC one, as previous studies have shown.

2. Layout of the article

The park to be studied has 200MW, with 100 turbines each with 2MW nominal power. The voltage in the DC cable that transports the power 300km to the shore is 200kV. First 3 converters are going to be studied to control the torque in the Permanent Magnet Synchronous Generator (PMSG): the boost converter, the full bridge converter and the Active Three-phase Rectifier (ATR). The control schemes and the losses are investigated.

Next the speed control of the turbine is studied, particularly the computation of the parameters for the regulator. Onshore there will be need of a Voltage Source Converter (VSC) to inverter the voltage to connect the park to the local AC grid. The reactive power and voltage control are explained.

Two options for the DC grid are compared in next section and with the results the yearly energy production of the park is known.

II. TORQUE CONTROL SOLUTIONS

1. PMSG with boost converter

The system in question was simulated in MATLAB using the following model:

![Fig. 1 – PMSG with boost converter.](image)

The control used was the standard PWM modulation. The reference current changed from 20 to 42A at 0.03s, a 50% change. The results for the PMSG are:
Fig. 2 – PMSG variables with the boost converter.

It was seen in other simulations that the output current has a overshoot of 10%, time response of 8ms and 10% current ripple as dimensioned in the inductor. The parameters for the PI regulator were found with the symmetry criterion:

2. PMSG with full bridge converter

The system in question was simulated in MATLAB using the following model. The output voltage was modelled as a 60kV voltage source because the output voltage of the converter will be controlled by other converters:

![Diagram of PMSG with full bridge converter](image)

Fig. 3 – PMSG with full bridge converter.

The purpose of the output inductor is to smooth the output current, and thus the current in the transformer and in the inverter [7]. The output current is compared with the reference, passes though a PI controller, and the output is the voltage control $U_c$. The drawing showing the number of the switches is in Fig. 4

![Diagram of inverter](image)

Fig. 4 – Schematic of the inverter.

The switches 1 to 4 in the inverter will have the following waveforms (switch 4 is the negative of switch 1 and switch 2 is the negative of switch 3):

![Waveforms for the switches](image)

Fig. 5 – Waveforms for the switches.

If $U_c$ is high the transformer is in voltage longer, meaning the current can be higher in steady state. The rules of Ziegler Nichols Tyreus-Luyben were applied:

![Results for the tuning rules of Ziegler-Nichols](image)

Fig. 6 – Results for the tuning rules of Ziegler-Nichols.

Looking at the figure the PI controller using the Ziegler-Nichols rules [2] (the green curve) was chosen (because it doesn’t have error), giving:

![Input currents](image)

Fig. 7 – Input and output currents, $U_c$ and input voltage.

It can be seen that at the beginning $U_c$ goes to the maximum for the current to change as fast as possible. The input current is as steady as the output current, meaning that controlling the output current is controlling the input current and thus the torque of the PMSG. The response time is 20ms for large perturbations. The variables in the PMSG are similar to the ones using the boost converter in Fig. 2. The current and voltage in the transformer is:
This control is used for the goal to decouple $I_d$ and $I_q$ [3]. $I_d$ is set to zero and $I_q$ is proportional to the torque. The switching frequency is 1 kHz and the inductance required for the current to have 10% harmonics is computed as in:

$$L_{atk} = \frac{U_o}{2\pi f \omega_i} = \frac{0.31 \times 60kV}{2 \pi \times 1000 \times 0.1 \times 8100^2} = 268mH$$

It doesn’t violate the two conditions in order for the ATR to work written in the report [1] presented next:

$$L_{atk} < \frac{U_0^2 - E_m^2}{3} \frac{60000^2}{3} \frac{8100^2}{628 \times 200} = 268mH$$

$$U_0 > \sqrt{3} \frac{E_m^2 + (L_{atk} \omega_i \omega_r)^2} = 57kV$$

The results are in Fig. 11:

**III. EFFICIENCY EVALUATION OF THE 3 CONVERTERS**

A loss evaluation for the 3 previous converters using the output voltages of 12kV and 60kV was performed. The formulas for the losses are exhibited in the report [5]. The results are:
It was concluded looking at the previous figures that for 12kV the best one is the ATR, for 60kV is the full bridge with duty cycle control. In all cases the duty cycle control was always best than the phase shift control.

**IV. SPEED AND PITCH CONTROL OF THE TURBINE**

The simulink model used in order to perform the speed control is in the report. It chooses the best \( C_p \) for every wind speed, and using the equations from the turbine exhibited next [4]:

\[
T_e = \frac{1}{2} \rho \pi R_e^2 \frac{v^3 C_p}{\lambda}.
\]  
\[\theta_{ref} = \frac{\nu \lambda}{R_e} n_p n_r,\]  
\[
T = (I_d - L_d) i_d + \nu \psi. \tag{6.}
\]

And with the voltage, speed and flux of the PMSG (using the Kirchoff’s Law for voltages and applying the Park Transformation) the current is computed:

\[
\begin{align*}
\frac{di_q}{dt} &= -\frac{R}{L} i_q + \omega \psi - \frac{1}{L} u_{eq}, \\
\frac{di_d}{dt} &= -\frac{R}{L} i_d - \omega \psi \frac{1}{L} u_{eq} + \frac{1}{L} u_{eq}.
\end{align*}
\]  
\[\tag{7.}\]

The parameters for the PI are computed using a symmetry method to obtain fast responses [3]:

\[
K_p = \frac{J_{eq}}{2T}, \\
K_i = \frac{J_{eq}}{8T^2}. \tag{8.}
\]

where \( J_{eq} \) is the inertia from the system seen from the PMSG side, and \( T \) is the delay from the current controller. These parameters give very fast responses which will provoke very high changes in the torque in the PMSG which could cause mechanical stresses. To avoid this situation a 30s low pass filter was introduced in the speed reference for the changes in the speed to be slower and smoother. The results are:

![Fig. 14 – \( I_q \), speed and its reference.](image)
V. CONTROL OF THE MAIN INVERTER ONSHORE

The system to study is the standard VSC with DC voltage 200kV and AC voltage 60kV. It is assumed that the harmonics caused by the VSC are too small and so this system is exactly the same as the ATR studied before except now the speed is constant (equal to the frequency of the grid) and there is no flux in the equations of the PMSG (although there is no PMSG the grid was treated like one). $I_q$ will control the reactive power to the grid ($Q=U_{dc}I_q$, $U_d$=constant=60kV) and the $I_d$ will be the inner loop for the voltage control of the submarine cable ($U_{dc}$) presented next:

$I_q$ is the current from the whole park and $E_d$ is considered to be equal to $u_d$=60kV. $E_d/U_{dc}$ is considered to be a gain that suffers perturbations. The system is insensitive to parameter changes. As such, the parameters for the regulator were computed using the symmetry criterion considering the gain of the action loop $E_d/(C_{onsore}U_{dc})$. The results are below for large perturbations (change of 50% in $I_d$). For small perturbations they are similar:

It can be seen that $I_d$ and $I_q$ are independent from each other.

VI. ANALYSIS OF THE CONNECTION OF THE WIND PARK

In the report it was proposed that the best connection for the DC grid in the park is to join 5 turbines in parallel, and then join all turbines [6], [8]. There are two options to discuss, option 1 where the voltage in the 5 turbines (called a cluster) is 12kV. It is raised to 60kV and then to 200kV. The second one is to raise the voltage immediately to 60kV and then to 200kV. The wake effect was accounted, meaning the inside turbines have 80% wind speed. In order to compute the losses in the cables a cable length calculation must be done, which was done in the report. The efficiency in both options was computed and is presented next, where the input power is the power from
the wind and the output power is the power that arrives to the grid:

![Efficiency of wind park](image)

Fig. 19 – Efficiency of the park for both options.

The probability density function of the wind is considered to be a Rayleigh distribution with average speed 10m/s. The yearly energy produced by the park is almost the same for both options. This is due to the fact that in the figure the difference in efficiencies is in the low wind speeds where the park has very low power produced. The value computed is 709GWh.

VII. CONCLUSION

The control method for the boost converter was the symmetry criterion as the inductor resistance is too small. For the full bridge the Ziegler-Nichols rules were used. For the ATR $I_{dc} = 0$ and $I_q$ is controlled, using the symmetry criterion for the same reason. The boost converter has 8ms, the full bridge 20ms and the ATR 5ms of response time. For 12kV the converter with lowest losses is the ATR and for 60kV is the full bridge with duty cycle control.

The parameters for the speed control were obtained using the symmetry criterion, and a low pass filter of 30s was used in order to obtain smooth torques. For the voltage control in the VSC onshore the symmetry criterion was used. For the current control it was the method of dominant pole. The system takes around 9ms to stabilize.

Evaluating the total losses in the park the best topology for the park is using three voltage levels in the DC grid: 12, 60 and 200kV. However this doesn’t make difference (comparing with three voltage levels) in the yearly energy produced, which is 709GWh.

VIII. REFERENCES


