EG2040 Wind Power Systems
Comments on Assignment 2 – Grid Integration of Wind Power Systems

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The comments have been divided into two sections:

1. In the section Assignment, you can find comments that are related to the assignment itself.

2. In the section Report, you can find general comments about the reports.

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1 Assignment

1.1 Direction of active and reactive power flows

1.1.1 Capacitive and inductive

Perhaps the most commonly made mistake was about defining the direction and the sign of the reactive power from the term *capacitive*. This term means that a certain device *produces* reactive power, and will thus *inject* reactive power into the grid. If a device *consumes* reactive power, it will *draw* reactive power from the grid, and is then called *inductive*. A device can be here a load, a wind turbine, ... This is summarized in Table 1.

Note that at this point, no difference is made between devices, i.e. Table 1 holds for both the load and the wind turbine in the assignment. Note also that nothing is said about the sign of the reactive power (if it is negative or positive). This means that it is not enough to know if a device is capacitive or inductive to conclude on the sign of the reactive power consumed or produced by this device (as will be seen in the next section, we need also to know the type of the device, which defines which sign convention is used – generator or load). All we know up to now is the physical direction of the reactive power.

Table 1: Definitions of *inductive* and *capacitive*

Term	Physical direction of flow of reactive power	Consumes or produces reactive power?
Inductive	From the grid to the device (=the device *draws* reactive power from the grid)	Consumes reactive power
Capacitive	From the device to the grid (=the device *injects* reactive power into the grid)	Produces reactive power

1.1.2 Two conventions: generators and loads

We now look at the formula to calculate the voltage at a bus k, U_k, *knowing*:

- the voltage at a bus j, U_j,
- the impedance of the line between bus j and k: $Z = R + jX$ (and possibly the capacitance of the line B),
- the apparent power flowing from bus k to bus j: $S_{kj} = P_{kj} + Q_{kj}$.

The formula is (see the compendium "Static Analysis of Power Systems")

$$\begin{aligned}
U_k^2 &= -\frac{a_4}{2a_3} \pm \sqrt{\left(\frac{a_4}{2a_3}\right)^2 - \frac{1}{a_3}(a_1^2 + a_2^2)} \\
a_1 &= -RP_{kj} - XQ_{kj} \\
a_2 &= -XP_{kj} + RQ_{kj} \\
a_3 &= (1 - XB)^2 + R^2B^2 \\
a_4 &= 2a_1(1 - XB) - U_j^2 + 2a_2RB
\end{aligned}$$

Now, at bus k, we know that the wind power plant injects P_w and Q_w, and that the load draws P_L and Q_L. This means that:

- $P_w > 0$ if the wind power plant *produces* active power, and $P_w < 0$ if the wind power plant *consumes* active power.
- $P_L > 0$ if the load *consumes* active power, and $P_L < 0$ if the load *produces* active power.

Note how the meaning of the signs is different for the wind power plant and for the load.

This is because different conventions are used: when we say that, for example, the wind power plant produces 200 MW, this means that $P_w = 200$ MW and that the active power flows from the power plant to the grid. When we say that a load consumes 10 MW, this means that $P_L = 10$ MW, but the active power flows from the grid to the load.

Also, by convention, if the terms *produces* and *consumes* are not used, values are positive for production when we talk about generators, and positive for consumption when we talk about loads. For example, in the assignment we have "The load varies between 100 kW and 300 kW". This means that the load *consumes* between 100 kW and 300 kW.

We have the same relation for reactive power:

- $Q_w > 0$ if the wind power plant *produces* reactive power, and $Q_w < 0$ if the wind power plant *consumes* reactive power.
- $Q_L > 0$ if the load *consumes* reactive power, and $Q_L < 0$ if the load *produces* reactive power.

With these conventions and table 1, we are now ready to define the signs of the reactive power flows for generators and loads, *given* that we know if they are inductive or capacitive.

Table 2: Signs of the reactive power flows

	Definition	Generator	Load
Inductive	From the grid to the device	$Q < 0$	$Q > 0$
Capacitive	From the device to the grid	$Q > 0$	$Q < 0$

Note how the definitions of the two terms are the same *irrespective of* the device, but the signs are different, because of the difference in conventions discussed above:

- the sign of Q_w is positive when the generator produces reactive power,
- the sign of Q_L is positive when the load consumes reactive power.

Back to the assignment, we wanted to calculate P_{kj} and Q_{kj} that were then used in the equation above to calculate U_k:

$$P_{kj} = P_w - P_L,$$
$$Q_{kj} = Q_w - Q_L.$$

In question 1., we knew that $\cos\Phi$ was 1 and thus Q_w was 0, and we wanted to calculate the voltage for different values of P_w, the *production* of the wind farm. Thus, in question 1, we have $P_w > 0$ and $Q_w = 0$. As for the load, the text reads "The load varies between 100 kW and 300 kW and the power factor can be assumed to be constant and equal to 0.8 capacitive". This means that the load *consumes* between 100 kW and 300 kW, and that it *produces* reactive power, i.e. $P_L \in [100, 300] > 0$ and $Q_L = P_L \frac{\sin\Phi}{\cos\Phi} < 0$ (the power factor of the load is $\cos\Phi = 0.8 > 0$ and $\sin\Phi$ is negative because the load is capacitive, and we use the load convention).

In question 2., the signs do not change for the load, but we know that now, "the wind farm has a constant power factor equal to 0.99 capacitive". Now according to Table 2, *capacitive* for a generator (a wind turbine is a generator) means that the reactive power is positive. Hence, $P_w > 0$ and $Q_w = P_w \frac{\sin\Phi_g}{\cos\Phi_g} > 0$ (the power factor of the wind farm is $\cos\Phi_g = 0.99 > 0$ and, this time, $\sin\Phi_g$ is positive because the generator is capacitive, and we use the generator convention).

1.2 Comment about the two possible values of U_k

Recalling the equation giving the voltage at bus k:

$$U_k^2 = -\frac{a_4}{2a_3} \pm \sqrt{\left(\frac{a_4}{2a_3}\right)^2 - \frac{1}{a_3}(a_1^2 + a_2^2)}, \tag{1}$$

one can see that there are two possible values for U_k depending on whether we use the plus or the minus sign in $\pm$.

The plus sign corresponds to a stable operation point, while the minus sign corresponds to an instable operation point. In reality, it is therefore always the plus sign that is used to calculate the voltage from the equation above. If the two solutions are plotted on the same curve, we would get a PV curve, also called nose curve, see Figure 1.

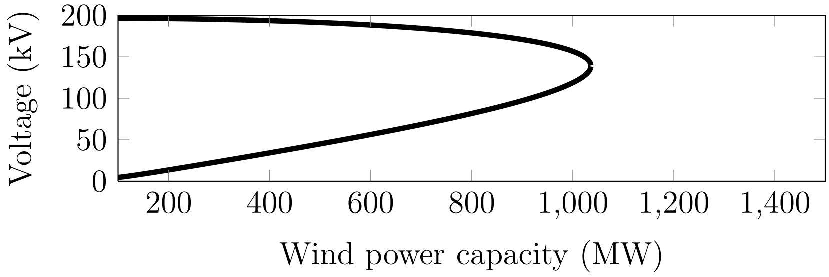

Figure 1: PV curve

If we just plot the upper part of the curve that corresponds to the solutions of interest – the stable solutions (with the plus sign in Equation (1)) – , we would get the curve in Figure 2.

Now, some of you got curves that looked like Figure 3. If you use Matlab, you would get a warning when you plot such a curve. The warning looks like:

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Warning: Imaginary parts of complex X and/or Y arguments ignored
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If you compare the right curve in Figure 2 and the wrong curve in Figure 3, you see that there is a part that goes up after 1000 MW in the wrong curve. This part is wrong.

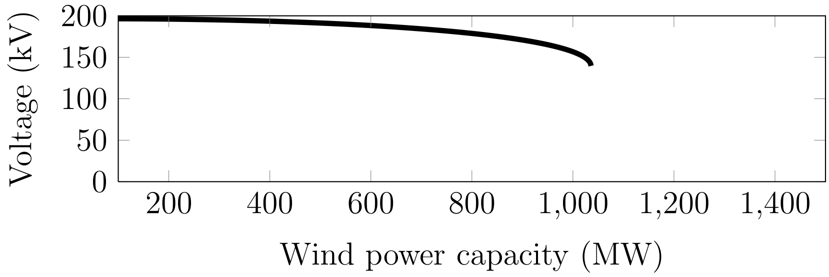

Figure 2: Upper part of the PV curve

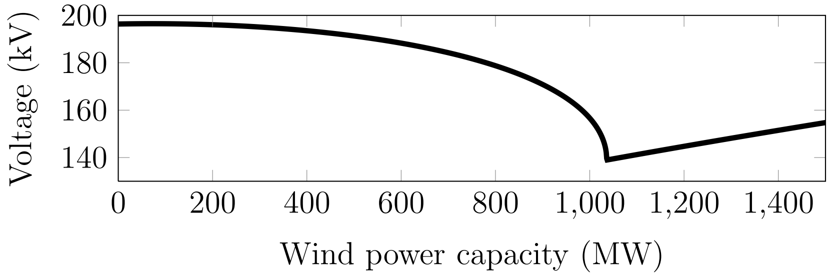

Figure 3: Wrong PV curve

For all the points on this part of the curve, Matlab will issue a warning such as the one above. These points correspond to imaginary values of U_k, i.e. when Equation (1) does not have any real solution. These points do not correspond to any physical possible situation for the electric system. This means that the electric system can never reach a point on this part of the curve. What would happen in reality is that as soon as we reach the "nose" of the curve in Figure 1, the system becomes unstable, and the voltages collapse along the lower part of the curve.

1.3 Relation between reactive power and voltages

Usually, reactive power supports the voltage. *Supporting* the voltage means that, everything else being constant, the voltages are increased if reactive power production increases. Note that, in the assignment, this meant that the capacity of the wind farm could be increased in question 2., because at a given active power production level, the wind turbine injects more reactive power than in question 1, and thus the lower voltage limit was reached for higher values of the capacity of the wind farm.

Note also that, and this happens often in reality, the production of reactive power can actually decrease how much wind power can be produced, because the upper voltage limit can then sometimes be reached for lower values of the active power production.

1.4 The eight different cases

In the assignment, the short circuit capacity was said to vary between 15 and 18 MVA, the load between 100 kW and 300 kW, and the voltage in Vindeby without any load nor generation between $10 \pm 2\%$ kV. This means that we have many cases to examine, and since Equation (1) that gives the voltage is nonlinear, it is not clear at all which case will be the worst case. Some tried to rule out some of the cases before making the computations, and in doing so actually missed the worst case.

2 Report

An overall comment is that there is generally a lack of explanation. It is important to think about how what you write will be interpreted by the reader, and if the latter can completely understand every step in your reasoning and how you came to the answer.

Some other comments about the report:

- When you are asked to calculate a value, you must give this value in the report. It is not enough to refer to a figure. For example, in this assignment, it was not enough to refer to a figure where we could see the curve representating the voltage cross the lower limit. The actual value must be given in the report.
- Explain in detail your reasoning. In this assignment, you could use the equation giving U_k right from the compendium, but you had to derive the equivalent impedance between bus k and the grid.
- See the comment about Figure 3 above. The part going up in the end after 1000 MW should not be included in the plot.