EG2040 Wind Power Systems
Assignment 2 - Grid Integration of Wind Power Systems

Problem formulation

We consider the system in Figure 1, and want to determine what the maximum capacity of the wind farm is, so that the voltage at Vindeby stays within specified limits all the time.

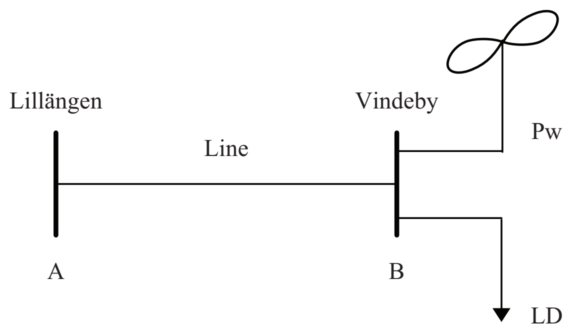

Figure 1: Electrical grid in Vindeby

Thevenin equivalent

What we want to do is to calculate a Thevenin equivalent for the grid feeding Lillängen, that is a Thevenin equivalent of everything lying to the left of Lillängen in Figure 1. A Thevenin equivalent is a voltage source behind an impedance, like in Figure 2.

The bus "CP" in Figure 2 is the bus that sees the Thevenin equivalent. In our case, that corresponds to Lillängen. Putting everything together (the Thevenin equivalent, Lillängen and Vindeby), we get Figure 3.

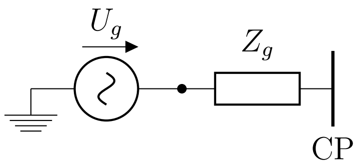

Figure 2: Thevenin equivalent

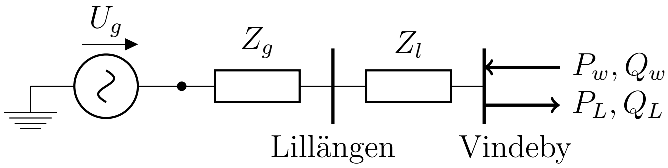

Figure 3: Thevenin equivalent at Lillängen

The impedance of the line is simply $Z_l = (10 + C)(0.1 + j0.1)$, where C is the last two digits of your personal number divided by 10. The question now is to calculate the values of the equivalent: the voltage U_g and the impedance Z_g.

Calculating the Thevenin voltage

In order to calculate the voltage, we need to use the information about how much the voltage is at Vindeby when there is no consumer nor wind power connected to the system. When there is no consumer nor wind power connected to the system, the current going from the Thevenin voltage source to Vindeby is zero, because there is no power consumption nor power generation anywhere in the system. This means that there is no voltage drop across the impedances Z_g and Z_l (the voltage drop is the current going through an impedance times the impedance), see Figure 4. This means that the voltage at Vindeby is equal to the Thevenin voltage (and also to the voltage at Lillängen, but it is not of interest in our case).

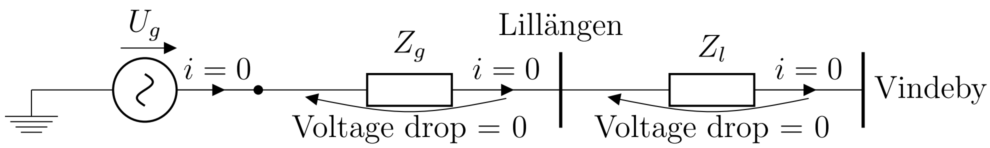

Figure 4: Situation when nothing is connected to the system

We know how much the voltage at Vindeby is in such cases (no wind power, no load):

> The voltage in Vindeby (B) is $10 \pm 2\%$ kV (different for different situations) when there are no consumers and no wind power.

Since we know how much the voltage at Vindeby is and that the Thevenin voltage is equal to the voltage at Vindeby, we can determine U_g: $U_g = 10 \pm 2\%$ kV.

Note that this means that in reality different situations can occur when it comes to the Thevenin voltage (all values between 9.8 kV and 10.2 kV). We will have in the following to investigate all these situations. For one specific situation (one specific value of U_g), other parameters can vary (such as the short-circuit capacity at Lillängen, the load at Vindeby, the amount of active power produced by the wind farm, ...). However, when stuying one specific situation of the Thevenin voltage, the latter will be constant to the value set for this situation, irrespective of the values of the other parameters.

Calculating the Thevenin impedance

The Thevenin impedance Z_g must now be calculated. To do this, we need to use two pieces of information:

1. The short circuit capacity at Lillängen varies between 15 and 18 MVA.

2. The feeding grid can be assumed purely inductive.

Let $Z_g = R_g + jX_g$ be the Thevenin impedance. Because we know that the feeding grid is purely inductive, we know that $R_g = 0$, and thus that $Z_g = jX_g$.

What happens when there is a short circuit at Lillängen as in Figure 5? In such a case, no current reaches Vindeby, and the whole power goes through the short circuit. Note in the figure that the current after Lillängen is zero because of the short circuit at this bus.

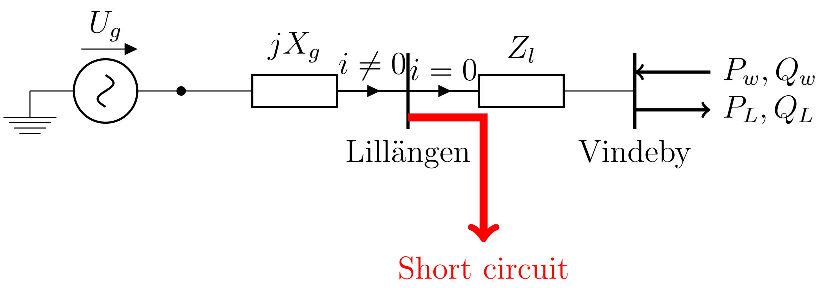

Figure 5: Short circuit at Lillängen: the current does not flow to Vindeby

The short circuit capacity at Lillängen is the apparent power flowing out of Lillängen into the short circuit, and is equal to

$$\bar{S}_{sc} = \sqrt{3}\bar{U}_g \bar{I}^*, \quad (1)$$

and

$$\bar{I} = \frac{U_g}{\sqrt{3}\bar{Z}_g}, \tag{2}$$

so that

$$\bar{S}_{sc} = \frac{U_g^2}{\bar{Z}_g^*}, \tag{3}$$

where U_g is the Thevenin line-to-line voltage (the line-to-line voltage is what is usually used). In the three equations above, the notation $\bar{\cdot}$ denotes a complex value (note that in the last equation U_g^2 does not take any bar because it is a real value). By considering the absolute value only, we get that (without any bar this time)

$$S_{sc} = \frac{U_g^2}{Z_g} = \frac{U_g^2}{X_g}, \tag{4}$$

so that

$$X_g = \frac{U_g^2}{S_{sc}}. \tag{5}$$

Note that the complex value of the Thevenin impedance is $\bar{Z}_g = jX_g$. Since the short circuit capacity and the Thevenin voltage vary, the Thevenin impedance will vary. Thus, we will also have different situations to study when it comes to the Thevenin impedance, but these situations are **not** independent of the different cases that we already got from the computation of the Thevenin voltage, because the Thevenin impedance is calculated from the Thevenin voltage.

Overall equivalent

The system can now be represented as in Figure 6, where $Z = Z_g + Z_l = jX_g + Z_l = R_l + j(X_l + X_g)$.

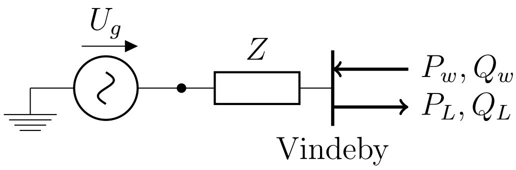

Figure 6: Equivalent single line diagram at Vindeby

We can now use this equivalent system to apply the formula given in the compendium "Static Analysis of Power Systems“, that allows us to calculate the voltage at a bus k, knowing the voltage at a bus j and the power transfers from bus k to bus j. In our case, bus j is the bus at which the Thevenin voltage is known, and bus k is Vindeby. The system in Figure 6 can be represented as in Figure 7 so that we can readily use the formula from the compendium to calculate the voltage at Vindeby U_k for all the situations and different possible values of the wind power production P_w.

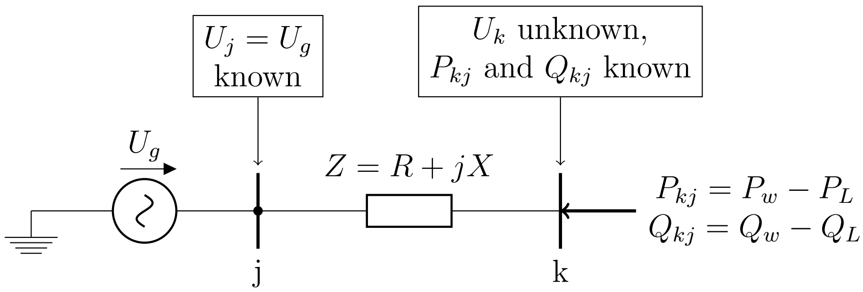

Figure 7: How to use the formula given in the compendium